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

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based on JHEP 09 (2023) 131

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高亮度和高精度前沿缪子物理研讨会 北京 2024.4.19—4.22

Outline

- Motivation
- Production features
- Heavy neutral lepton and lepton number violation
- Summary

Motivation

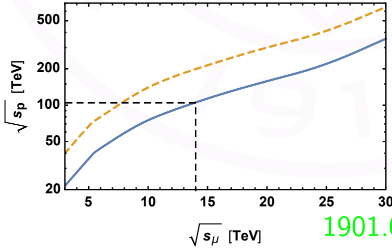
Why a muon collider ?

- The past and ongoing particle colliders (LEP, S$p\bar{p}$S, PETRA, SLC, Tevatron, LHC...) made important measurements for the SM and BSM. So far, we haven't seen any conclusive evidence of BSM physics.

- What kind of collider is an ideal environment to reach higher energy and higher luminosity?

Motivation

- Large muon mass ($m_\mu/m_e \sim 207$) suppresses the synchrotron radiation by a factor of 10^9, compared with electron beams.
- Compare to a circular electron-positron collider, muon collider with smaller size would have the potential to reach above TeV c.m. energies.
- A 14 TeV muon collider has potential similar to that of a 100 TeV pp collider.
- Higher luminosity
- Lower background



1901.06150

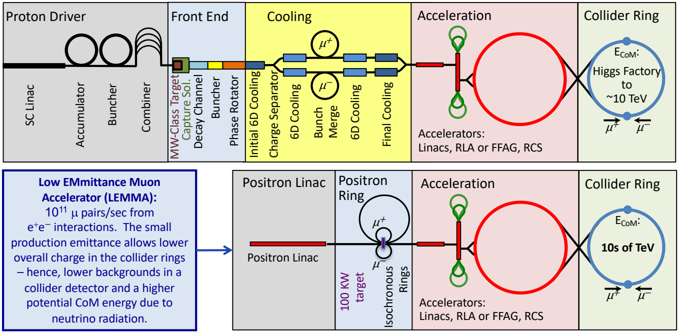
Motivation

- The idea of muon collider introduced in 1980’s.

Skrinsky, Parkhomchuk, Sov.J.Part.Nucl.12(1981)223
Neuffer, Part.Accel.14 (1983) 75-90, AIP Conf.Proc.156(1987)201-208
Barger, Berger, Gunion, Han, PRL75(1995)1462-1465, Phys.Rept.286(1997)1-51

- Proton/positron driver scheme.

Muon Accelerator Program (MAP)



Motivation

- Due to the short lifetime (2μs) of muon, cooling process is the biggest challenge on its construction. **MICE collaboration, Nature 578(2020)53**
  - Recently, due to the technological development, muon colliders have received much attention in the community.
- Luminosity scaling scheme: $\sigma\mathcal{L} \sim$ const. and luminosity goals

$$\mathcal{L} \gtrsim \frac{5 \text{ years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10 \text{ TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

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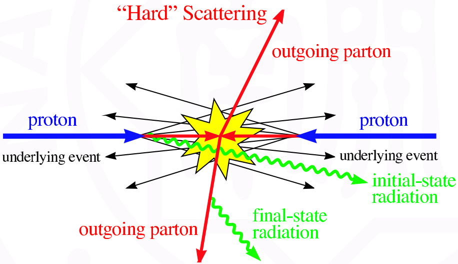
Production features

- **Recall the hadron colliders: $p\ p$ collision at LHC**



Factorization formalism:

PDFs $\otimes$ partonic cross section

$$\sigma(AB \to X) = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b\, f_{a/A}(x_a, Q) f_{b/B}(x_b, Q)\ \hat{\sigma}(ab \to X)$$

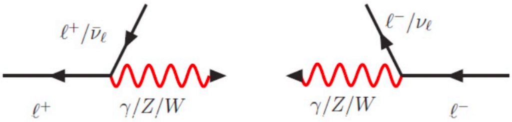
- a, b are the "partons" from the beam particles A, B
- $f_{a/A}(f_{b/B})$ are PDFs, defined as the probabilities of finding partons a (b) from the beam particles A (B) with the momentum fractions $x_a(x_b)$

• EW PDF

- Ultra-high energy at muon collider $Q > M_Z$: $\frac{v}{E} = \frac{v}{10\ \text{TeV}} \to 0$
- The SM gauge symmetry is restored and all EW states are dynamically activated.
- EW PDF:

  "**Equivalent photon approximation (EPA)**"

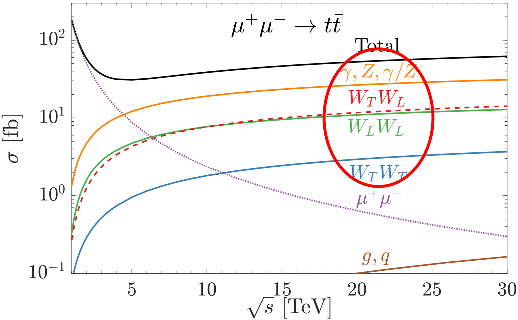
  "**Effective W Approximation (EWA)**"



PLB 148(1984)367
NPB 249(1985)42

- We should take into account the four EW gauge bosons $(B,\ W^i)$

• Inclusive production cross section



2007.14300

- Sum over all partonic contributions and calculate the inclusive production cross section, e.g. $t\,\bar{t}$
- The direct $\mu\mu$ annihilation falls as 1/s and vector boson scattering (VBS) takes over it at high energies
- VBS is important at high energies

Heavy neutral lepton

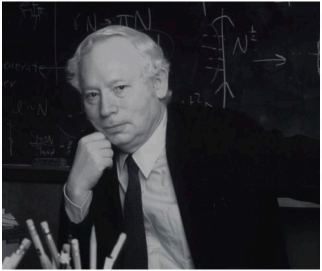
Torn between identities – tau-, electron- or muon-neutrino?

- Since the last century, a large number of neutrino oscillation experiments provide clear evidences that neutrinos have tiny masses. Obviously, it is contrary to the prediction of SM (neutrinos are massless)!!!

- It is well-known that, an economical way to generate neutrino mass in the SM content is through the dim-5 effective operator —— “ Weinberg operator ”

$$\ell_L \ell_L H H$$

Phys.Rev.L.43,1566(1979)



- There are only three ultraviolet (UV) completions of this "Weinberg operator" at tree level : PLB 67,421(1977), Conf.Proc.C 7902131,95(1979) Conf.Proc.C 790927,315(1979), PRL 44,912(1980) NATO Sci.Ser.B 61,687(1980), PRD 24,1232(1981)
  - Type-I Seesaw $\to SU(2)_L$ fermion singlet
  - Type-II Seesaw $\to SU(2)_L$ scalar triplet — PLB 70,433(1977) PRD 22,2227(1980) PRD 22,2860(1980) Nucl.Phys.B 181,287(1981)
  - Type-III Seesaw $\to SU(2)_L$ fermion triplet — Z.Phys.C 44,441(1989)

- The heavy neutral lepton (**HNL**) can be realized in canonical Type I Seesaw mechanism

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

- Mixing matrix $V_{\ell N}$: $\nu_\ell = \sum_{m=1}^{3} (U_{\rm PMNS})_{\ell m}\nu_m + \sum_{m'=1} (V_{\ell N})_{\ell m'} N^c_{m'}$

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

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

- The search of Majorana neutrino at hadron colliders

PRL **97,** 171804 (2006) PHYSICAL REVIEW LETTERS week ending 27 OCTOBER 2006

Signatures for Majorana Neutrinos at Hadron Colliders

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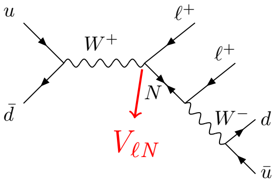
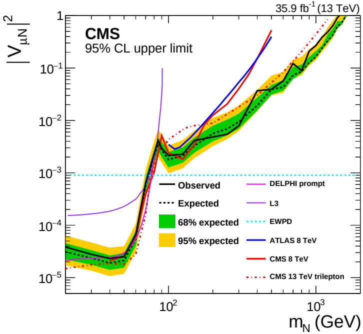
The Majorana nature of neutrinos may only be experimentally verified via lepton-number violating processes involving charged leptons. We explore the $\Delta L = 2$ like-sign dilepton production at hadron colliders to search for signals of Majorana neutrinos. We find significant sensitivity for resonant production of a Majorana neutrino in the mass range of 10–80 GeV at the current run of the Tevatron with 2 fb^{-1} integrated luminosity and in the range of 10–400 GeV at the CERN LHC with 100 fb^{-1}.

DOI: 10.1103/PhysRevLett.97.171804 PACS numbers: 14.60.Pq, 13.15.+g, 13.85.Qk, 14.60.St

Lepton number violation (LNV) signature: $pp \to \ell^\pm \ell^\pm jj$





- **The search of HNLs at muon colliders**

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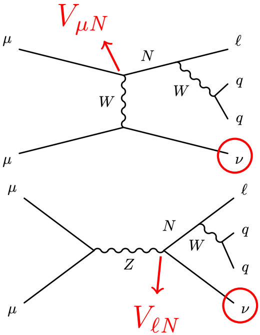
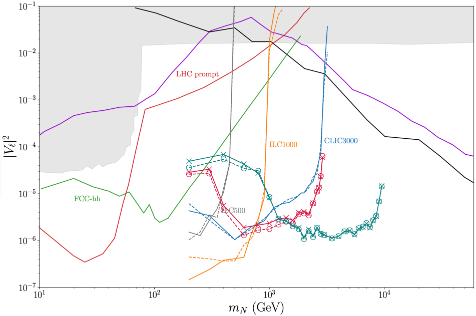
2301.05177
2301.07117

- ▶ The signal at $\mu^+\mu^-$ collider: $\mu^+\mu^- \to N_\ell + \bar{\nu}_\ell$



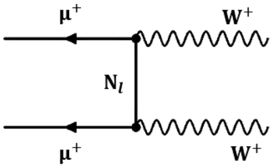


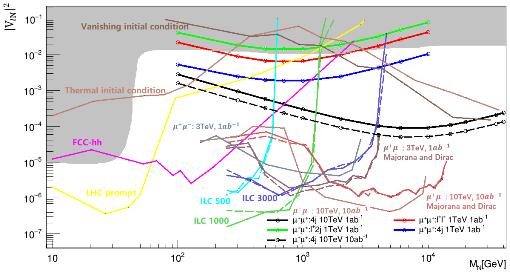
- ▶ Features :
  - ■ light ν in final states, but Majorana or Dirac type?
  - ■ t-channel only sensitive to $V_{\mu N}$
  - ■ $V_{\ell N}$ in s-channel

- **The search of HNLs at muon colliders**

2302.13247
2304.04483

▶ The signal at $\mu^+\mu^+$ collider: $\mu^+\mu^+ \to W^+W^+$



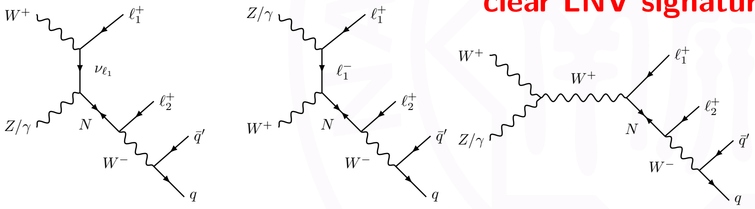


▶ Features :

- it can probe HNLs with heavier mass
- only sensitive to $V_{\mu N}$, but $\sigma \propto |V_{\nu N}|^4$ is weaker than $\mu^+\mu^-$
- LNV through W ' s hadronic decays, but it be suppressed by BR$(W \to qq')^2 \sim 40\%$

- **Our proposal: LNV through vector boson scattering (VBS)**
  - The signal at $\mu^+\mu^-$ collider: $V_i V_j \to \ell_1^\pm N \to \underline{\ell_1^\pm \ell_2^\pm q\bar{q}'}$

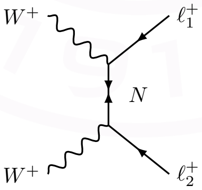
clear LNV signature



  - The signal at $\mu^+\mu^+$ collider:

$$W^+ W^+ \to \underline{\ell^+ \ell^+}$$

clear LNV signature



T. Li, C.Y. Yao, **M. Yuan**, JHEP 09 (2023) 131

HNLs

- We simulate to investigate HNLs at muon collider, by using the MadGraph, Madspin, Pythia and Delphes ···

MADGRAPH 5 MadGraph5_aMC@NLO

generate parton-level envents

JHEP 07(2014)079

parton-shower

PYTHIA 8.3

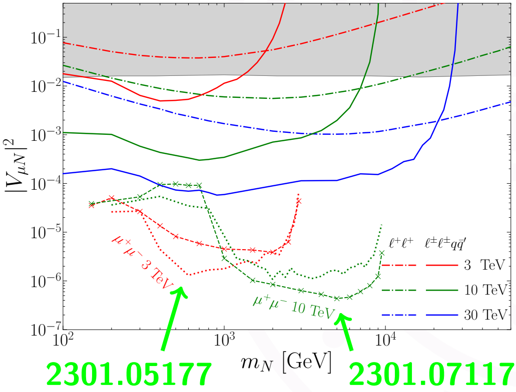
Comput.Phys.Commun.191(2015)

simulate the detector of collider

DELPHES fast simulation

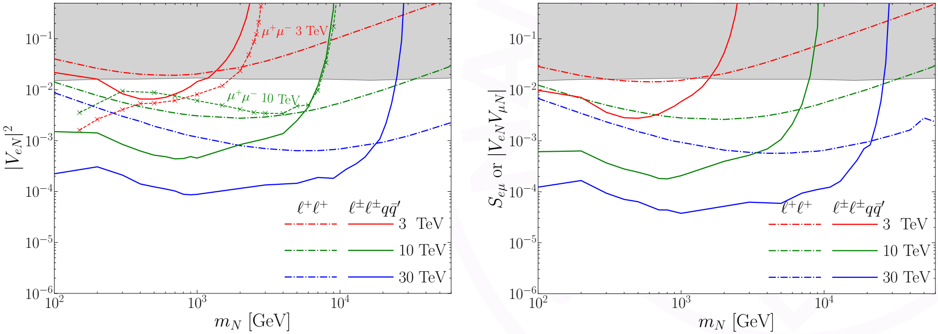
JHEP02(2014)057

- **2σ exclusion limits for $|V_{\mu N}|^2$**



- The probing potential of $|V_{\mu N}|^2$ is worse that from other annihilation channel.
- But we provide smoking-gun LNV signatures as a complement by the VBS process.

- **2σ exclusion limits for $|V_{eN}|^2$ and $|V_{eN}\ V_{\mu N}|$**



- The probing potential of $|V_{eN}|^2$ is stronger than that from $\mu^+\mu^- \to N\,\nu$ channel with $\sqrt{s} = 10$ TeV or above.

- It can probe lepton flavor combination

Summary

- High-energy muon colliders are potentially ideal machines in both energy and precision frontiers.
- We propose a clear LNV signature through VBS process to search for the heavy neutral lepton at both $\mu^+\mu^-$ and $\mu^+\mu^+$ colliders.

Thank you!

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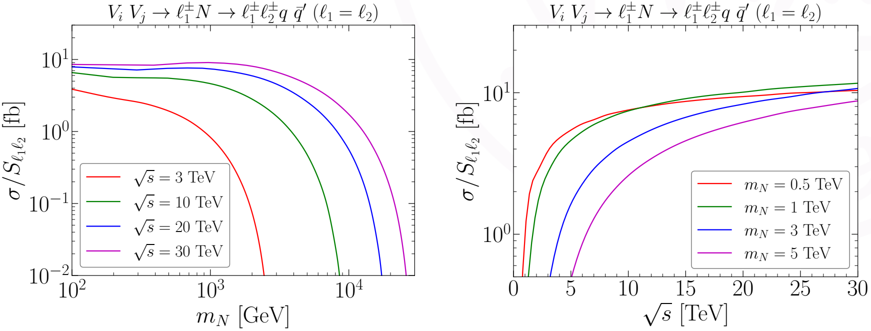
- **The LNV signature:** $W^{\pm} Z/\gamma \to \ell_1^{\pm} N \to \ell_1^{\pm}\ell_2^{\pm} W^{\mp} \to \ell_1^{\pm}\ell_2^{\pm} q\bar{q}'$
  - The parameter-independent cross section

$$\sigma\ (V_i\ V_j \to \ell_1^{\pm}\ell_2^{\pm} q\bar{q}') \approx \sigma\ (V_i\ V_j \to \ell_1^{\pm} N) \times \mathrm{BR}(N \to \ell_2^{\pm} q\bar{q}') \times (2 - \delta_{\ell_1\ell_2})$$
$$\equiv \frac{|V_{\ell_1 N} V_{\ell_2 N}|^2}{\sum_{\ell=e,\mu,\tau} |V_{\ell N}|^2} \times \sigma_0 \times (2 - \delta_{\ell_1\ell_2})\ ,$$



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- The benchmark choices of the collider energies and the corresponding integrated luminosities are

$\sqrt{s}$	3 TeV	10 TeV	30 TeV
$\mathcal{L}$	1 ab^{-1}	10 ab^{-1}	90 ab^{-1}

- The SM backgrounds we are considering

$$\mathrm{B}_1: \quad V\, V \to W^{\pm}\, W^{\pm}\, W^{\mp} \to \ell^{\pm}\ell^{\pm} \overset{(-)}{\nu_\ell} \overset{(-)}{\nu_\ell}\, q\, \bar{q}' \,,$$

$$\mathrm{B}_2: \quad V\, V \to t\, \bar{t}\, W^{\pm} \to b\; W^{+}\bar{b}\; W^{-}\, W^{\pm} \to b\; \bar{b}\; \ell^{\pm}\ell^{\pm} \overset{(-)}{\nu_\ell} \overset{(-)}{\nu_\ell} + X\,,$$

where X denotes the decay products of the opposite-sign W boson in B_2 background, i.e., $X = \ell^{\mp} \overset{(-)}{\nu_\ell}$ or $q\bar{q}'$.

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- Based on the difference between distributions of signal and backgrounds, we employ some cuts for the final states to suppress the background

  - identify final states

    $N_\mu \geq 2,\ \ N_J \geq 1,$

    $65 \ \leq m_J \leq 95 \text{ GeV}$

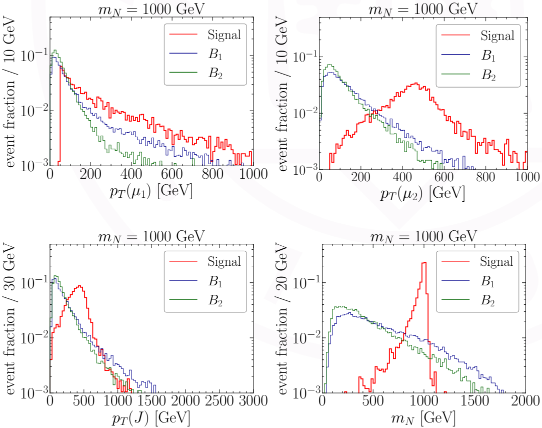
  - some basic cuts

    $p_T(\mu),\ \ |\eta(\mu)|,\ \ \Delta R_{\mu\mu}\ \ldots$

  - kinematic cuts

    $p_T(\mu, J) > m_N/4$

    $0.8\ m_N < \ m_{\mu_2 J}\ < 1.1\ m_N$



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- We use the following formula to evaluate the significance

$$\mathcal{S} = \frac{N_{\rm S}}{\sqrt{N_{\rm S} + N_{\rm B}}},$$

$$N_{\rm S} = \sigma_0 \; S_{\ell_1\ell_2} \times \epsilon_{\rm S} \times \mathcal{L}$$

$$N_{\rm B_i} = \sigma_{{\rm B}_i} \times \epsilon_{{\rm B}_i} \times \mathcal{L} \;\; , i = 1, 2$$

- 2σ exclusion limits for $|V_{\mu N}|^2$

The probing potential of $|V_{\mu N}|^2$ is worse that from other annihilation channel.

But we provide smoking-gun LNV signatures as a complement by the VBS process.