Heavy neutrino and lepton number violation at high-energy muon collider

Li, Tong (李佟)
Nankai University

based on JHEP 09 (2023) 131
with Chang-Yuan Yao and Man Yuan (Nankai)

第17届TeV物理工作组学术研讨会
南京，2023.12.15-19

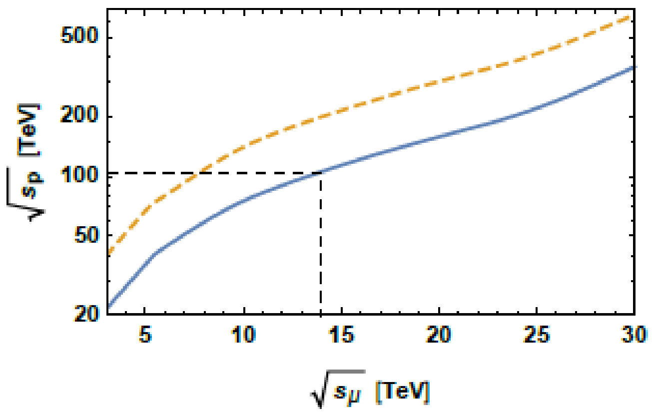
Outline

- Why a muon collider?
- Production features
- Heavy neutrino and lepton number violation
- Summary

Why a muon collider?

- The past and ongoing particle colliders (LEP, Sp$\bar{p}$S, PETRA, SPEAR, SLC, Tevatron, and LHC) made important measurements for the SM and BSM. They have so far seen no conclusive evidence of BSM physics.
- What kind of environment is ideal to reach higher energy and higher luminosity?

- Large muon mass ($m_\mu / m_e \approx 207$) suppresses the synchrotron radiation by a factor of 10^9, compared with electron beams.
- A circular muon collider with smaller ring 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.
- Lower background



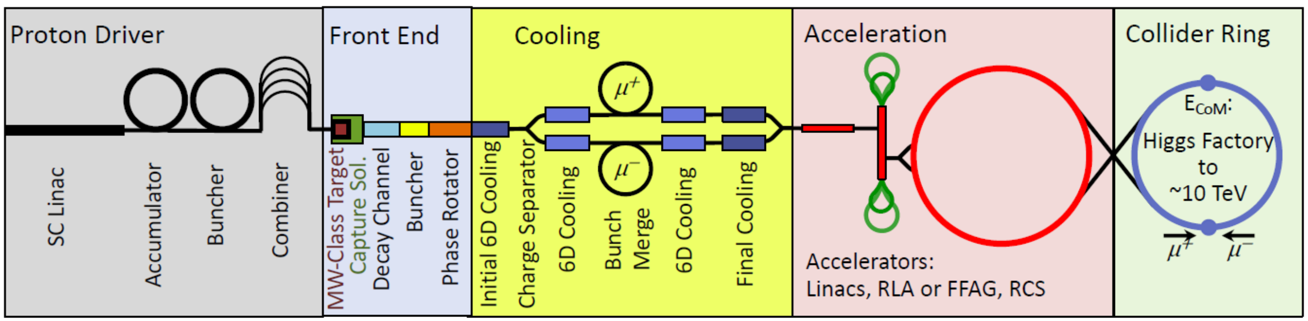
1901.06150

- 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, e.g. proton

1901.06150



Muon Accelerator Program (MAP)

- Short lifetime (2 μs) and cooling

MICE collaboration, Nature 578(2020)53

- Luminosity scaling scheme: $\sigma L \sim$const. and luminosity goals

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

1 ab^-1/yr

1901.06150

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

MuCol

Funded by the European Union

Grant Agreement No: 101094300

MuCoL

A Design Study for a Muon Collider complex at 10 TeV centre of mass

Horizon Europe Framework Programme

EU MILESTONE

TENTATIVE PARAMETERS AVAILABLE

MILESTONE N° 3

Due date of milestone:	31/10/2023 (M8) – previously 31/08/2023 (M6)
Justification for delay:	New deadline approved by EU Project Officer
Document version:	1.0
Release date:	30/10/2023
Work package:	WP1
Lead beneficiary:	CERN
Document status:	Final

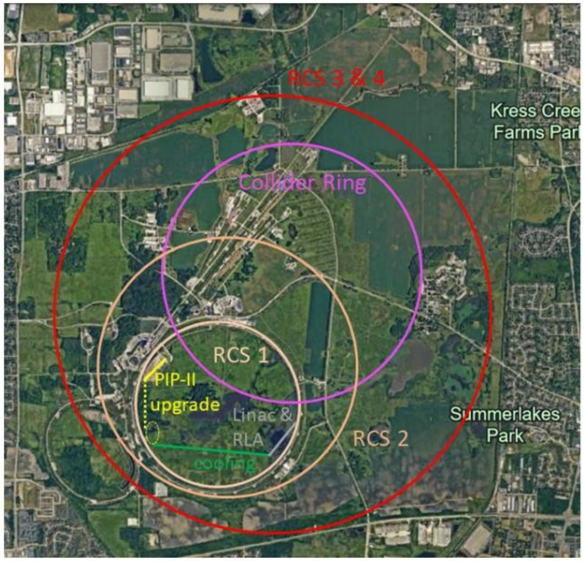
Abstract:

This document comprises the collection of tentative parameters for the key pa collider. Particular attention has been given to regions of the facility that are greater technical uncertainty in their de-sign and that have a strong impact on th consumption of the facility. The data is collected in form a living document in ove version is from October 30th, 2023.

Keywords: Collider, muon, accelerator physics, technology

Muon Collider at Fermilab

- **10 TeV MuC** concept is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (4 stages)
  - Linac + RLA → **173 GeV**
  - RCS #1 → **450 GeV (Tevatron size)**
  - RCS #2 → **1.7 TeV (col. ring size)**
  - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long
  - Could be combined with RCS #2
- In the next 5-7 years we like to have a baseline design including a neutrino flux mitigation system



P5 recommendations:

"The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design."

Muon Collider Physics Benchmark Workshop

16–18 Nov 2023

US/Eastern timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Logistics

Contact

- pittpacc@pitt.edu
- kex10@pitt.edu
- arnabdasgupta@pitt.edu

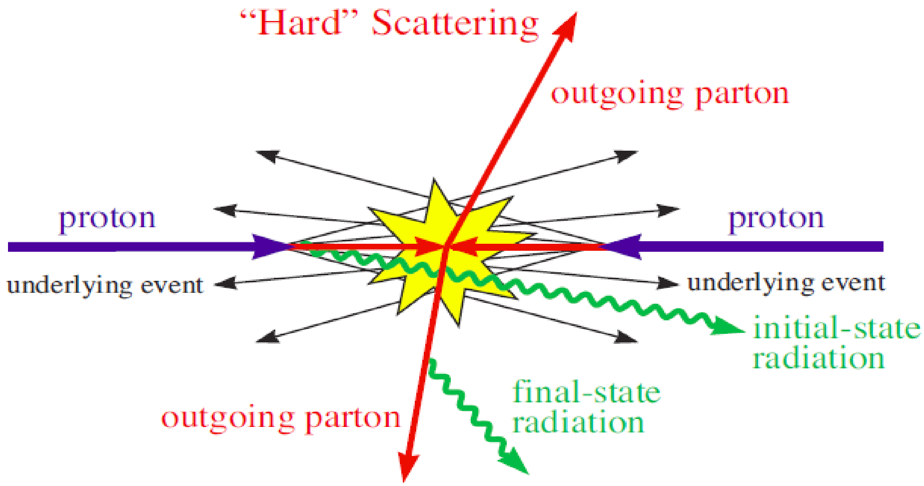
In comparison with electron colliders and hadron colliders, the muon colliders incorporate both advantages of the clean environment of lepton colliders and the high-energy reaches of muon beams. As a consequence, a high-energy muon collider suits as an ideal machine to advance our understanding of the fundamental particles and interactions in high-energy physics. A few techniques have been demonstrated that a multi-TeV or 10 TeV muon collider is feasible in the future. It is thus the time to lay the physics cases to guide the machine and detector designs, and to identify the unique physics benchmarks to fully exploit its capability.

The physics topics include Standard Model bread and butter physics, WIMP dark matter, precision Higgs physics, new physics models, neutrino physics synergy, etc.

ORGANIZERS: Nathaniel Craig (UCSB), Tao Han (Pitt PACC), Da Liu (Pitt PACC), Zhen Liu (Minnesota), Donna Naples (Pitt PACC), Isobel Ojalvo (Princeton), Lian-Tao Wang (Chicago), Andrea Wulzer (Barcelona), Keping Xie (MSU)

Production at high-energy lepton colliders

- Recall the hadron colliders: pp($p\bar{p}$) collision at Tevatron or LHC



Factorization formalism: PDFs $\otimes$ partonic cross sections

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

- 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>MZ: $\frac{v}{E} = \frac{v}{10\ \mathrm{TeV}} \to 0$
- The SM gauge symmetry is restored and all EW states are dynamically activated.
- We should take into account the four EW gauge bosons (B, W^i)

$$\sigma(\ell^- + a \to \ell^- + X) = \int \mathrm{d}x\, f_{\gamma/\ell}\hat{\sigma}(\gamma a \to X)$$

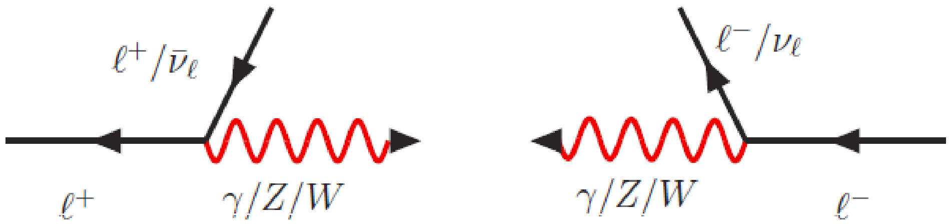
EW PDF:

$$f_{\gamma/\ell,\mathrm{EPA}}(x_\gamma, Q^2) = \frac{\alpha}{2\pi}\frac{1+(1-x_\gamma)^2}{x_\gamma}\ln\frac{Q^2}{m_\ell^2}$$

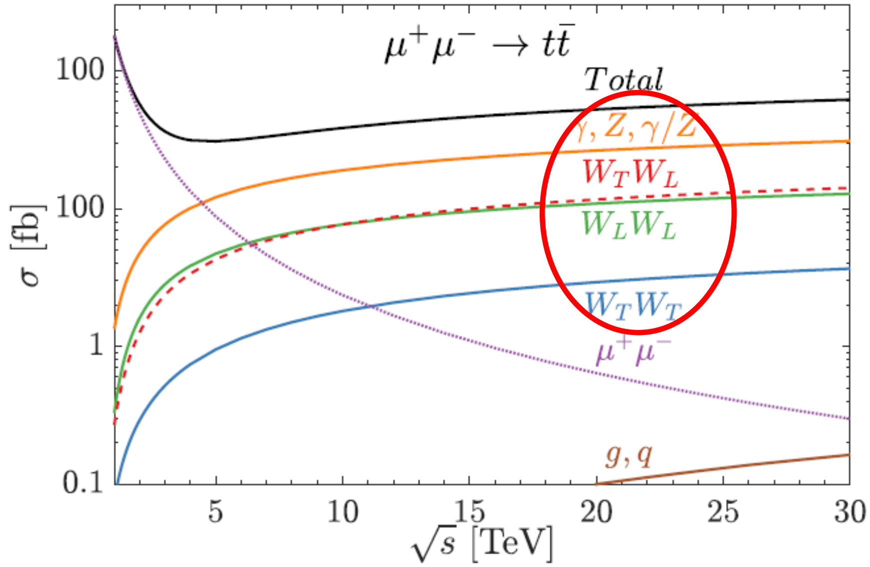
"Equivalent photon approximation (EPA)"

"Effective W Approximation (EWA)"

G.Kane, W.Repko, W.Rolnick, PLB148(1984)367
S.Dawson NPB 249(1985)42



Inclusive production cross section



T. Han, Y. Ma, K. Xie, 2007.14300

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

Heavy Majorana neutrino

- Neutrino mass generation: right-handed neutrino or "Weinberg operator" in the SM content: $\ell_L \ell_L HH$
- The minimal UV realization: Type I seesaw

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

Minkowski 1977; Yanagida 1979; Glashow 1979; Gell-Mann, Ramond, Slansky 1979; Mohapatra, Senjanovic 1980

- Light neutrino mass: $m_\nu \sim {y_\nu}^2 v^2 / M_R$ and TeV-scale heavy Majorana neutrino when $y_\nu \sim y_e$
- Mixing matrix $V_{\ell N}$: $\nu_\ell = \sum_{m=1}^{3} (U_{\text{PMNS}})_{\ell m} \nu_m + \sum_{m'=1} (V_{\ell N})_{\ell m'} N_{m'}^c$

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

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

- The search of Majorana neutrino at colliders

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

Signatures for Majorana Neutrinos at Hadron Colliders

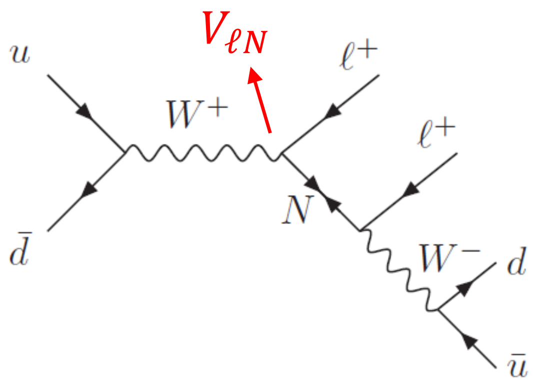
Tao Han[1,2,3,*] and Bin Zhang[2,†]

[1]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*
[2]*Center for High Energy Physics, Tsinghua University, Beijing 100084, People's Republic of China*
[3]*Institute of Theoretical Physics, Academia Sinica, Beijing 100080, People's Republic of China*

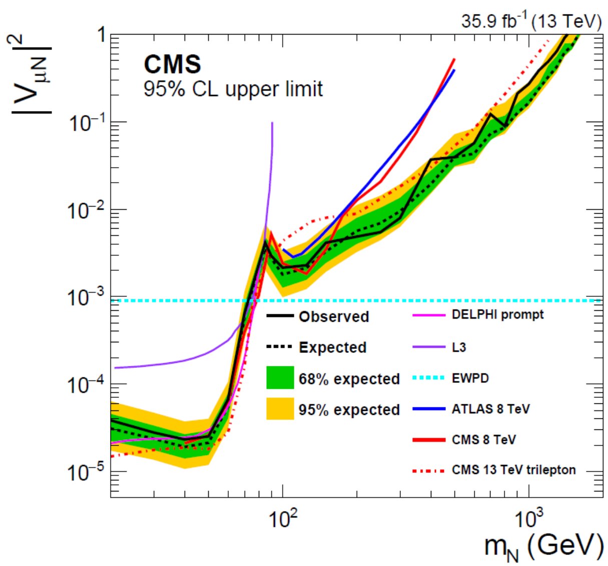
(Received 11 April 2006; published 25 October 2006)

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 $\rightarrow \ell^{\pm}\ell^{\pm}$jj

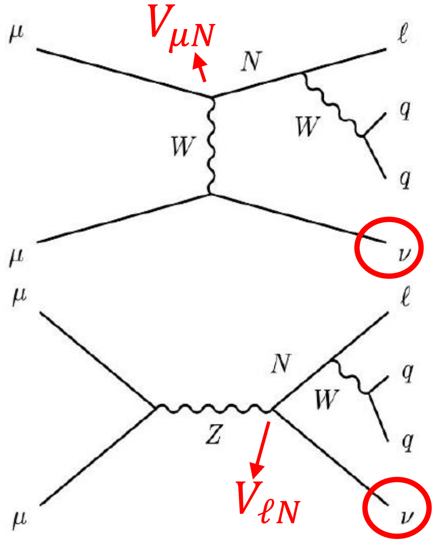


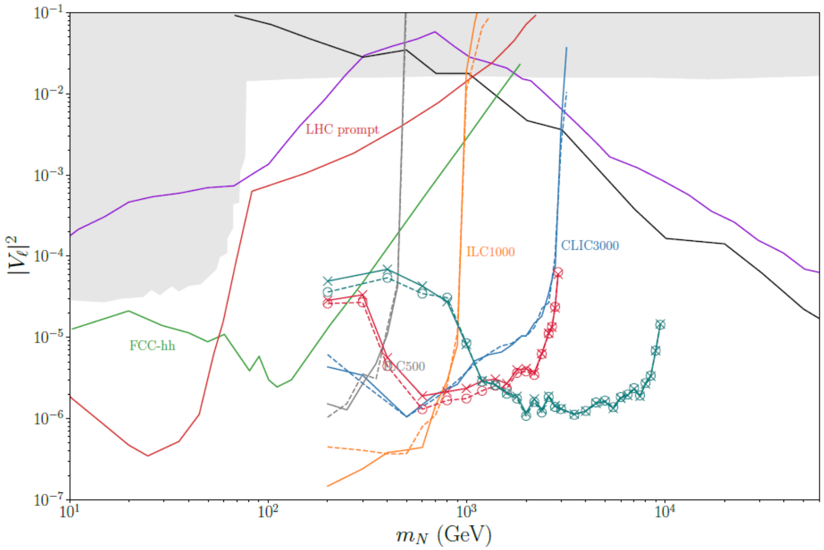
See review:
Y. Cai, T. Han, TL, R. Ruiz, Front. in Phys. 6 (2018) 40

Heavy N search at muon collider

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

K. Mekala, J. Reuter, A. F. Zarnecki, 2301.02602
T. H. Kwok, L. F. Li, T. Liu, A. Rock, 2301.05177; P. Li, Z. Liu, K. F. Lyu, 2301.07117



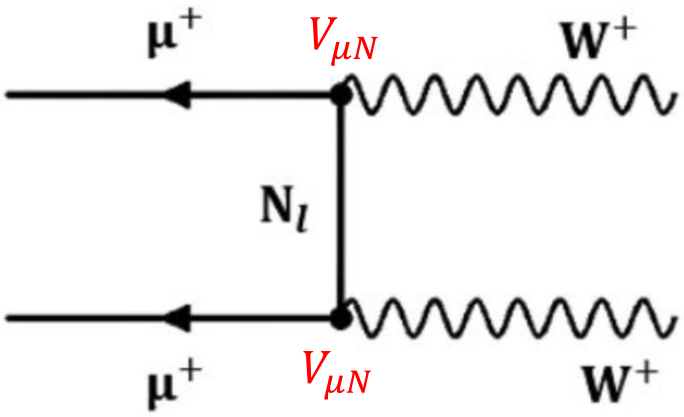


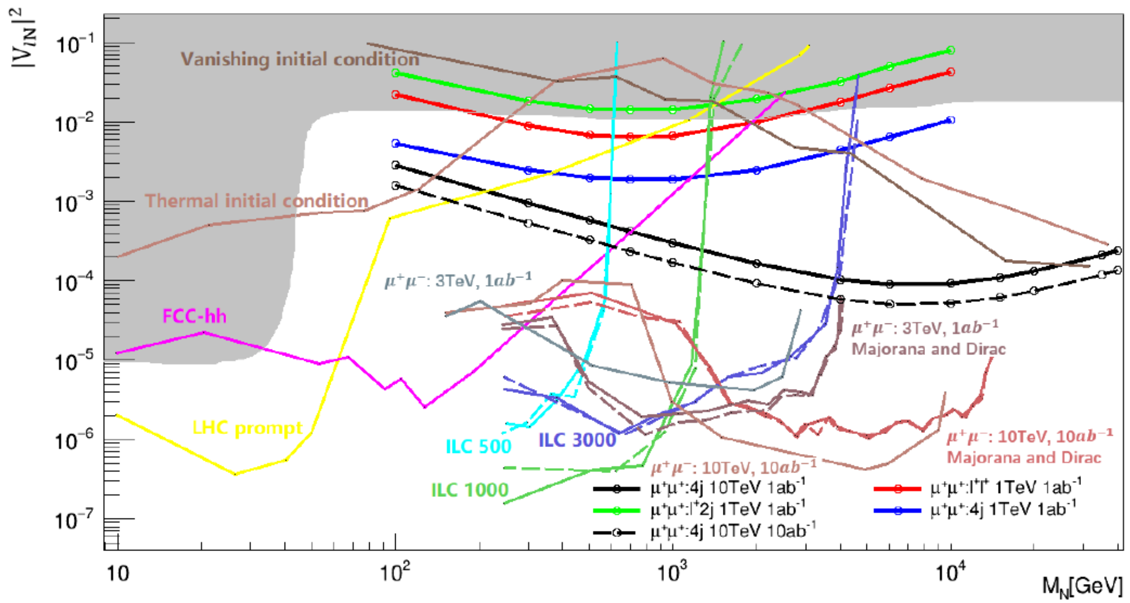
- features:

1. light ν in final states, Majorana or Dirac?
2. t channel only sensitive to $V_{\mu N}$
3. $V_{\ell N}$ in s channel

- Signal at $\mu^+\mu^+$collider:

J. L. Yang, C. H. Chang, T. F. Feng, 2302.13247
R. Jiang, Q. Li et. al., 2304.04483





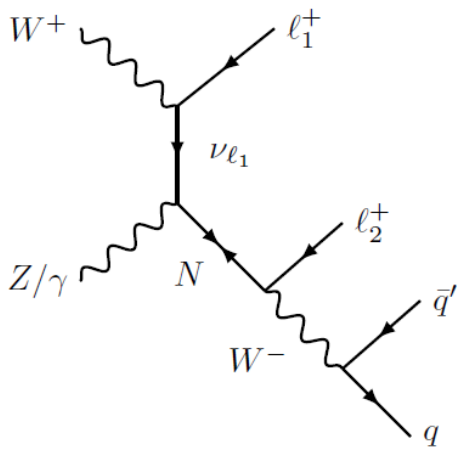
- features:

1. can probe heavier N
2. $\sigma \propto |V_{\ell N}|^4$ weaker than $\mu^+\mu^-$, only sensitive to $V_{\mu N}$
3. LNV through W's hadronic decays, suppressed by $BR(W \to qq')^2 \sim 40\%$

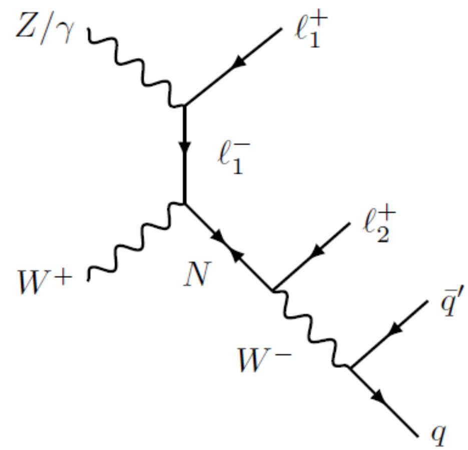
Our proposal: LNV through vector boson scattering (VBS)

- Signal at $\mu^+\mu^-$ collider: $V_i\, V_j \to \ell_1^\pm N \to \ell_1^\pm \ell_2^\pm q\, \bar{q}'$

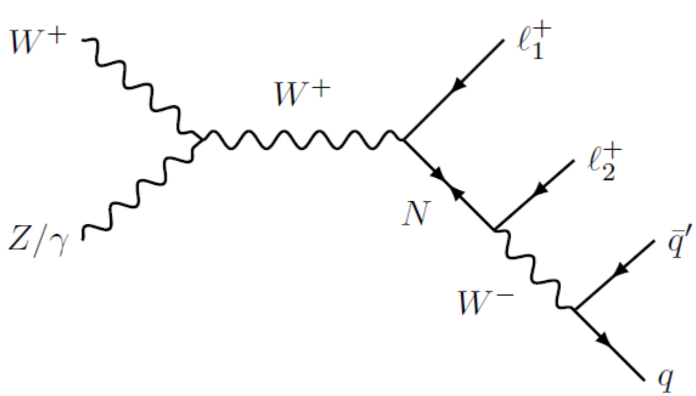
clear LNV signature

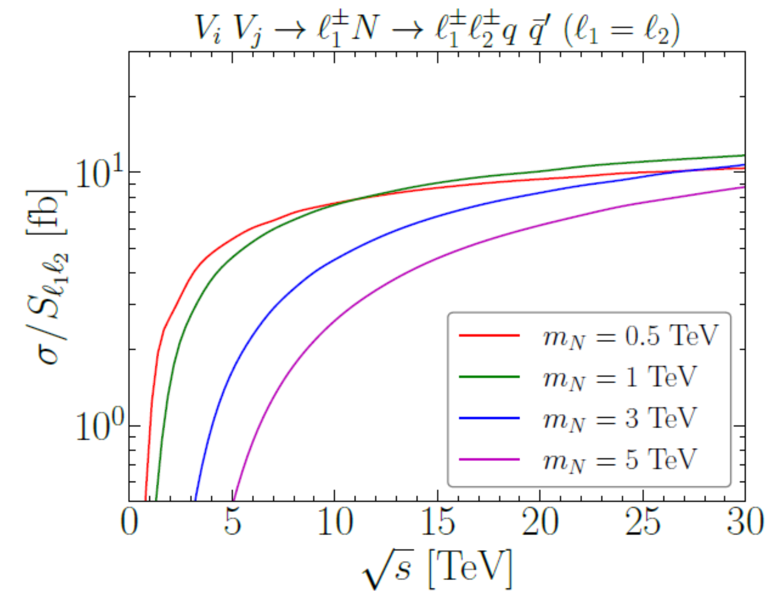


(a)



(b)

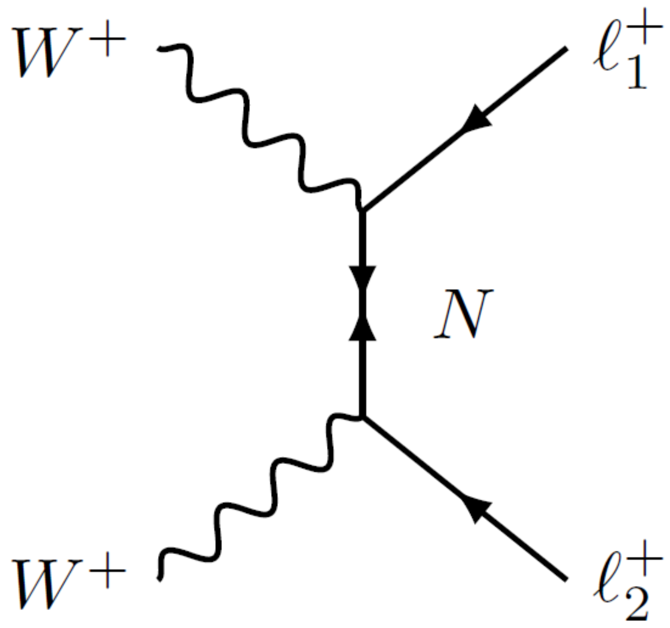


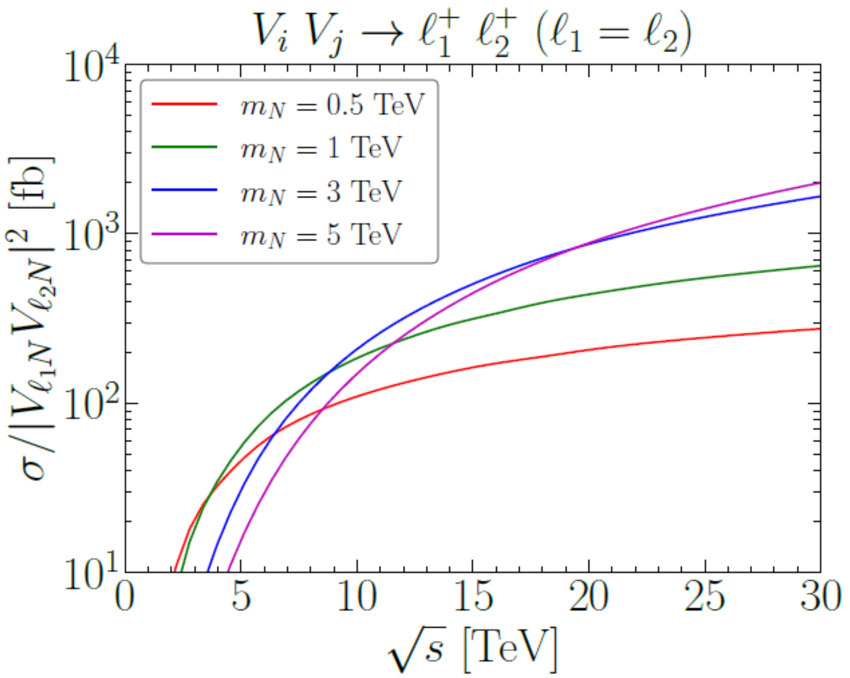


TL, C.-Y. Yao, M. Yuan, 2306.17368

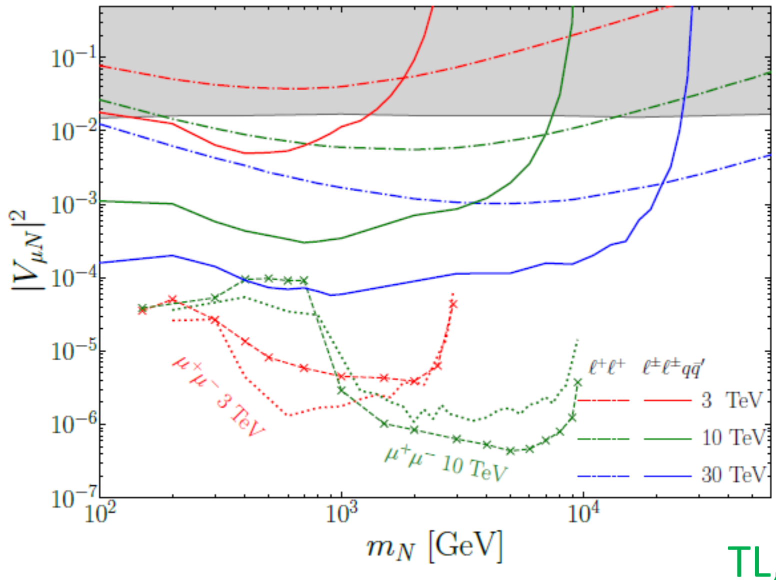
- Signal at $\mu^+\mu^+$ collider: $W^+W^+ \to \ell^+\ell^+$

clear LNV signature



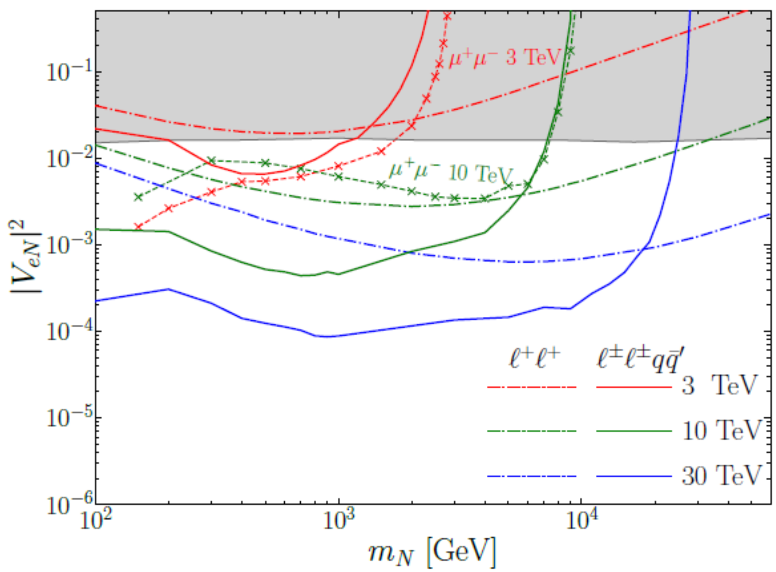


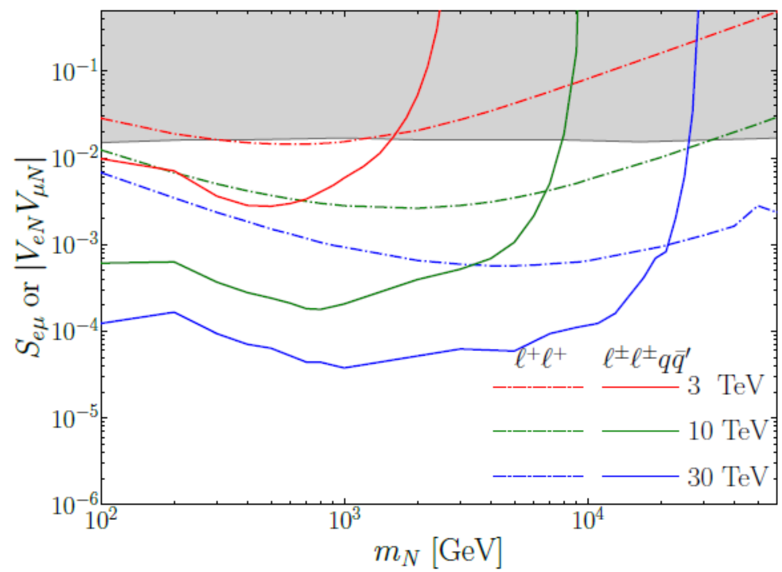
TL, C.-Y. Yao, M. Yuan, 2306.17368



VBS worse than annihilation for $V_{\mu N}$

TL, C.-Y. Yao, M. Yuan, 2306.17368





VBS better for V_{eN} with $\sqrt{s} = 10$ TeV or above

VBS 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 to search for heavy Majorana neutrino at both $\mu^+\mu^-$ and $\mu^+\mu^+$ colliders.

Summary

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

Thank you!

- EW DGLAP equations

$$\frac{\mathrm{d} f_i}{\mathrm{d} \log Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{ij} \otimes f_j$$

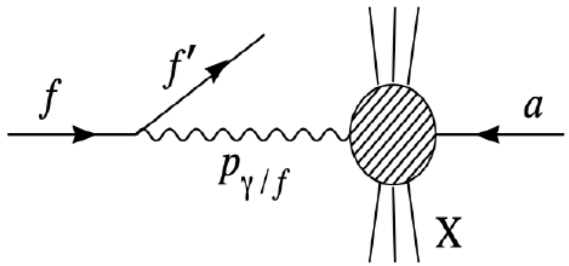
- EW PDFs: $f_i(x, Q^2)$
- I: gauge group
- P: splitting function

- The simplest parton of a lepton: photon
- "Equivalent photon approximation (EPA)": collinear photon radiation off the high-energy leptons

C.F.von Weizsacker, Z.Phys.88,612(1934), E.J.Williams, Phys.Rev.45,729(1934)

$$\sigma(\ell^- + a \to \ell^- + X) = \int \mathrm{d}x\, f_{\gamma/\ell}\, \hat{\sigma}(\gamma a \to X)$$

$$f_{\gamma/\ell,\mathrm{EPA}}(x_\gamma, Q^2) = \frac{\alpha}{2\pi} \frac{1 + (1 - x_\gamma)^2}{x_\gamma} \ln \frac{Q^2}{m_\ell^2}$$

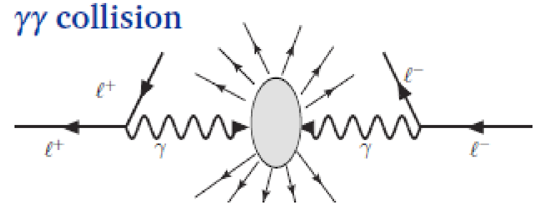


- Production cross section at lepton colliders

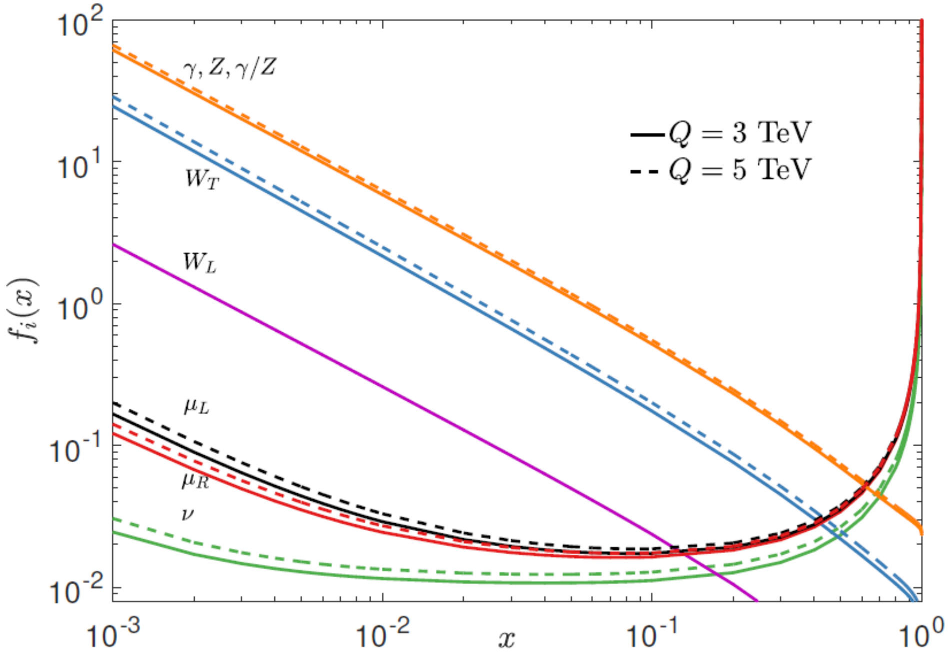
$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^{1} d\tau \sum_{ij} \frac{d\mathscr{L}_{ij}}{d\tau}\, \hat{\sigma}(ij \to F),\ \tau = \hat{s}/s$$

Partonic luminosities

$$\frac{d\mathscr{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$



- EW PDFs for muon collider



T. Han, Y. Ma, K. Xie, 2007.14300

- The muon PDF peaks at collider energy $x \approx 1$.
- The gauge boson PDFs are dominant at low partonic energy.