LNV & LFV signatures from Majorana neutrino dipole moments at a muon collider

Natascia Vignaroli

Based on *M. Frigerio, NV, JHEP 04 (2025) 008*

CLFV Searches with the MU2E Experiment: LNF Workshop, 9-13 June 2025

Giunti, Studenikin, Rev.Mod.Phys. 87 (2015) 531

$$\mathcal{L}_{NMM} = \frac{1}{2}\mu_{\alpha\beta}\,\bar{\nu}_{L_\alpha}\sigma^{\mu\nu}N_{R_\beta}\,F_{\mu\nu} + \text{H.c.}$$

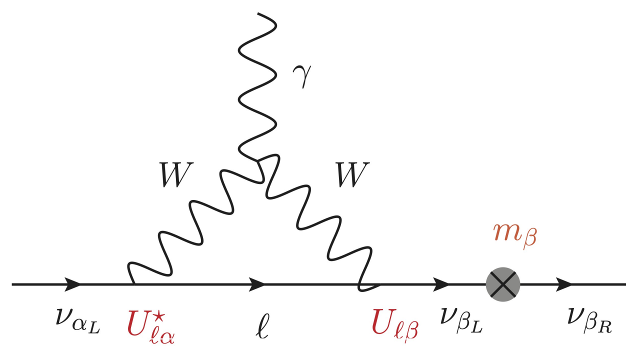
Dirac neutrinos

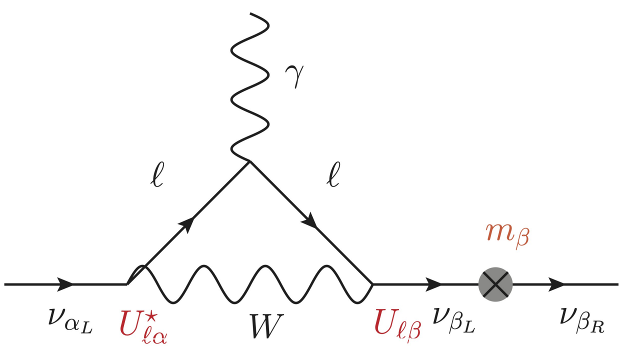
Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254

In the simplest extension of the SM with three right-handed neutrinos:

$$N_{R_\beta} = \nu_{R_\beta}$$

$$\Delta L = 0$$





$$\mu^D_{\alpha\alpha} \simeq \frac{3eG_F m_\alpha}{8\sqrt{2}\pi^2} \simeq 3.2\cdot 10^{-19}\mu_B\left(\frac{m_\alpha}{\text{eV}}\right)$$

neutrino mass suppression

$$\mu^D_{\alpha\beta} \simeq -3.9\cdot 10^{-23}\mu_B\left(\frac{m_\alpha \pm m_\beta}{\text{eV}}\right)\sum_\ell U^\star_{\ell\alpha}U_{\ell\beta}\left(\frac{m_\ell}{m_\tau}\right)^2$$

Transition Magnetic Moments are further GIM-suppressed

Giunti, Studenikin, Rev.Mod.Phys. 87 (2015) 531

$$\mathcal{L}_{NMM} = \frac{1}{2}\mu_{\alpha\beta}\,\bar{\nu}_{L_\alpha}\sigma^{\mu\nu}N_{R_\beta}\,F_{\mu\nu} + \mathrm{H.c.}$$

Majorana neutrinos

J. Schechter, J.W.F. Valle, Phys. Rev. D 24 (1981) 1883 , Erratum D25 (1982) 283. J. F. Nieves, Phys. Rev. D 26 (1982) 3152. B. Kayser, Phys. Rev. D 26 (1982) 1662. R. E. Shrock, Nucl. Phys. B 206 (1982) 359. L. F. Li and F. Wilczek, Phys. Rev. D 25 (1982) 143.

$$N_{R_\beta} = \nu^c_{L_\beta} \quad (\Delta L = 2)$$

$[\mu]_{\alpha\beta} = - [\mu]_{\beta\alpha} \rightarrow$ There exist only GIM-suppressed **Transition Magnetic Moments** (TMMs)

$$\mu^M_{\alpha\beta} \simeq -7.8 \cdot 10^{-23}\mu_B\, i\,(m_\alpha + m_\beta)\sum_\ell \mathrm{Im}\,[U^\star_{\ell\alpha}U_{\ell\beta}]\left(\frac{m_\ell}{m_W}\right)^2$$

Giunti, Studenikin, Rev.Mod.Phys. 87 (2015) 531

$$\mathcal{L}_{NMM} = \frac{1}{2}\mu_{\alpha\beta}\,\bar{\nu}_{L_\alpha}\sigma^{\mu\nu}N_{R_\beta}\,F_{\mu\nu} + \text{H.c.}$$

Majorana neutrinos

J. Schechter, J.W.F. Valle, Phys. Rev. D 24 (1981) 1883 , Erratum D25 (1982) 283. J. F. Nieves, Phys. Rev. D 26 (1982) 3152. B. Kayser, Phys. Rev. D 26 (1982) 1662. R. E. Shrock, Nucl. Phys. B 206 (1982) 359. L. F. Li and F. Wilczek, Phys. Rev. D 25 (1982) 143.

$$N_{R_\beta} = \nu^c_{L_\beta} \quad (\Delta L = 2)$$

There exist only GIM-suppressed **Transition Magnetic Moments** (TMMs)

$$\mu^M_{\alpha\beta} \simeq -7.8\cdot 10^{-23}\mu_B\, i\,(m_\alpha + m_\beta)\sum_\ell \text{Im}\,[U^\star_{\ell\alpha}U_{\ell\beta}]\left(\frac{m_\ell}{m_W}\right)^2$$

However large enhancements to TMMs are possible
Beyond the Standard Model

NMM Beyond the Standard Framework

Extra particles from the BSM sector (for example a W_R), contribute to enhance NMMs. However, in general, they will also contribute to neutrino masses (same diagrams without the photon)

For Majorana neutrinos, the BSM (symmetric) neutrino mass contribution is typically smaller than the (antisymmetric) TMM, because of Yukawa coupling suppression

While **TMMs** are allowed to be **naturally large** for **Majorana** neutrinos

N. F. Bell, M. Gorchtein, M. J. Ramsey-Musolf, P. Vogel and P. Wang, Phys. Lett. B 642, 377-383 (2006); S. Davidson, M. Gorbahn and A. Santamaria, Phys. Lett. B 626, 151-160 (2005)

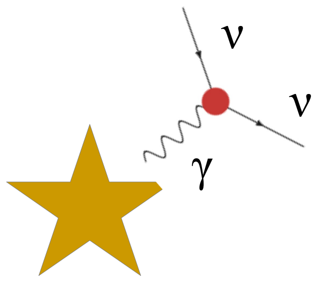
Dirac NMMs exceeding about 10^{-15} μ_B would not be natural, as they would **induce unacceptably large neutrino masses**

N. F. Bell, V. Cirigliano, M. J. Ramsey-Musolf, P. Vogel and M. B. Wise, Phys. Rev. Lett. 95, 151802 (2005)

Compelling BSM scenarios predict **electron-muon TMMs** for **Majorana** neutrinos of the order of $\mathbf{10^{-12}}$ $\boldsymbol{\mu_B}$ which **become accessible experimentally**

For example:
M. Lindner, B. Radovcic and J. Welter, JHEP 07, 139 (2017)

Probes of Neutrino Magnetic Moments



- Astrophysical and cosmological observations

Astrophysical bounds from stellar energy loss measurements

$$\mu_\nu \lesssim 2 \times 10^{-12}\, \mu_B$$

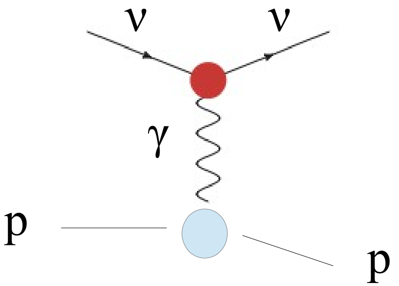
From the red giant branch of modular clusters

[Capozzi, Raffelt, PRD 102 (2020) 8, 083007]

Bounds from CMB and BBN measurements of the effective neutrino number

$$\mu_\nu \lesssim 3 \times 10^{-12}\, \mu_B$$

[Li, Xu, *JHEP* 02 (2023) 085]



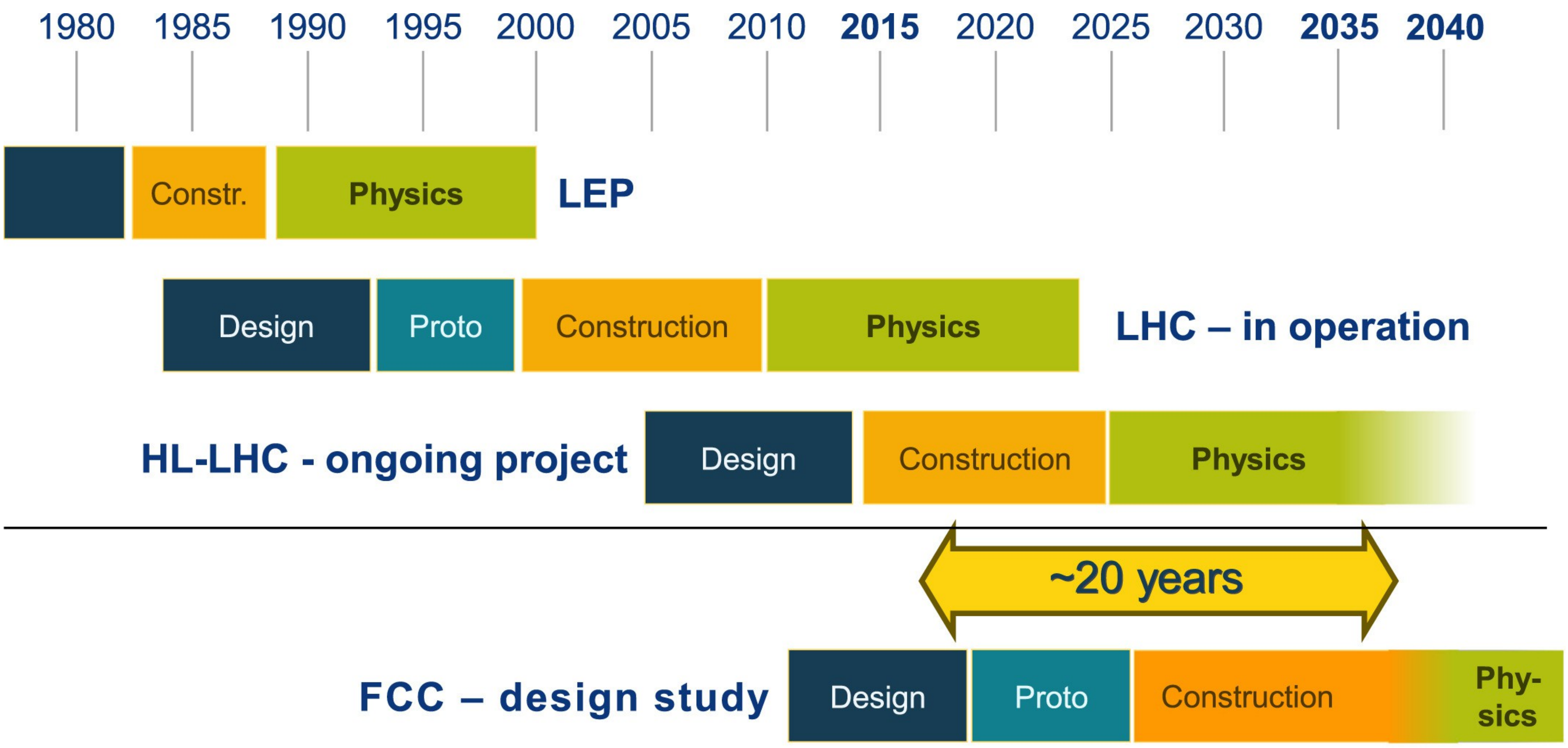
- Low energy (solar) neutrino scattering experiments

$\mu_\nu \lesssim 6.3 \times 10^{-12}\, \mu_B$ XENONnT Phys.Rev.Lett. 129 (2022) 16, 161805

$\mu_\nu \lesssim 6.2 \times 10^{-12}\, \mu_B$ LUX-ZEPLIN Phys.Rev.Lett. 131 (2023) 4, 041002

(Future) Collider Probes

F. Zimmermann, Nucl. Instrum. Meth. A 909, 33-37 (2018)



(Future) Collider Probes: theoretical framework

$$\mathcal{L}_{BSM} = C^{B}_{\alpha\beta}(O_B)_{\alpha\beta} + C^{W}_{\alpha\beta}(O_W)_{\alpha\beta} + \text{H.c.}$$

$$\frac{\mu_{\alpha\beta}}{2}\,\bar{\nu}^c_\alpha \sigma^{\mu\nu} P_L \nu_\beta\, A_{\mu\nu} \Leftarrow \begin{cases} (O_B)_{\alpha\beta} = g'\left(\overline{L^c_\alpha}\,\epsilon H\right)\sigma^{\mu\nu}\left(H^T \epsilon L_\beta\right) B_{\mu\nu} \\ (O_W)_{\alpha\beta} = i g \varepsilon_{abc}\left(\overline{L^c_\alpha}\,\epsilon \sigma^a \sigma^{\mu\nu} L_\beta\right)\left(H^T \epsilon \sigma^b H\right) W^c_{\mu\nu} \end{cases}$$

After SSB

$$(O_B)_{\alpha\beta}|_v = -\frac{g' v^2}{2}\left(\overline{\nu^c_\alpha}\,\sigma^{\mu\nu}\nu_\beta\right)\left(c_w A_{\mu\nu} - s_w Z_{\mu\nu}\right)$$

$$(O_W)_{\alpha\beta}|_v = -g v^2\left(\overline{\nu^c_\alpha}\,\sigma^{\mu\nu}\nu_\beta\right)\left[s_w A_{\mu\nu} + c_w Z_{\mu\nu} + ig(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\right]$$

$$-\frac{g v^2}{\sqrt{2}}\left(\overline{\nu^c_\alpha}\,\sigma^{\mu\nu}\ell_\beta + \overline{\ell^c_\alpha}\,\sigma^{\mu\nu}\nu_\beta\right)\left[W^+_{\mu\nu} + igW^+_\mu(s_w A_\nu + c_w Z_\nu) - igW^+_\nu(s_w A_\mu + c_w Z_\mu)\right]$$

(Future) Collider Probes: Hadron Colliders

$$\mathcal{L}_{BSM} = C^B_{\alpha\beta}(O_B)_{\alpha\beta} + C^W_{\alpha\beta}(O_W)_{\alpha\beta} + \text{H.c.}$$

$$\frac{\mu_{\alpha\beta}}{2}\,\bar{\nu}^c_\alpha \sigma^{\mu\nu} P_L \nu_\beta\, A_{\mu\nu} \Leftarrow \begin{cases} (O_B)_{\alpha\beta} = g'\left(\overline{L^c_\alpha}\,\epsilon H\right)\sigma^{\mu\nu}\left(H^T \epsilon L_\beta\right) B_{\mu\nu} \\ (O_W)_{\alpha\beta} = ig\varepsilon_{abc}\left(\overline{L^c_\alpha}\,\epsilon\sigma^a\sigma^{\mu\nu} L_\beta\right)\left(H^T\epsilon\sigma^b H\right) W^c_{\mu\nu} \end{cases}$$

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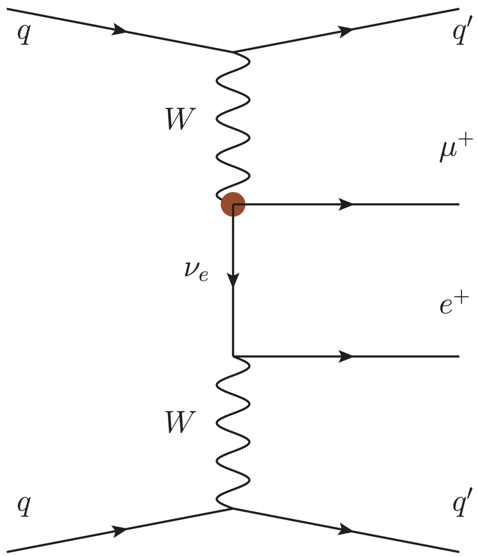
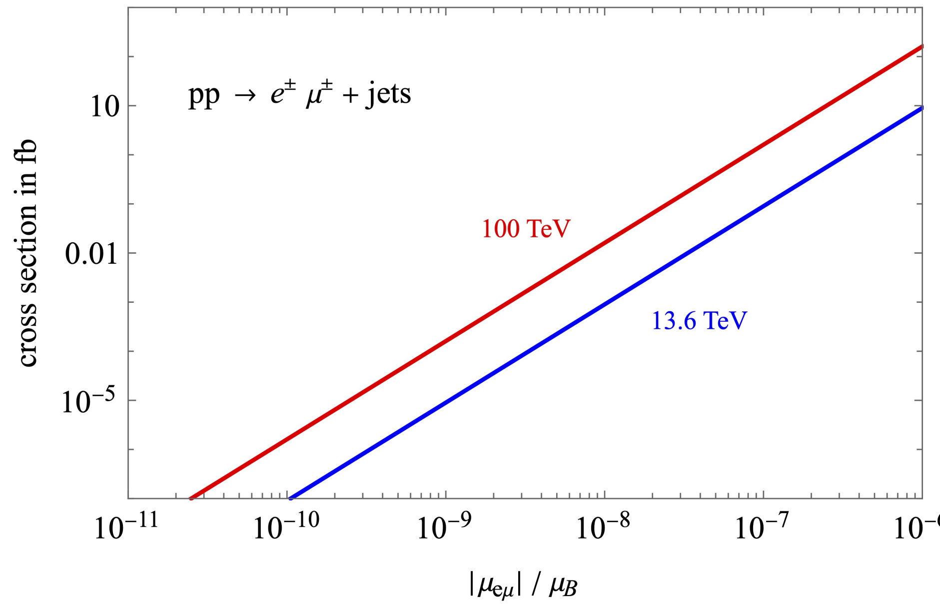
(Future) Collider Probes: Hadron Colliders

$$C^W_{\alpha\beta}(\Lambda_{NP}) = -\frac{[\mu]_{\alpha\beta}}{2v^2 e}$$





Background evaluated from a recast of the ATLAS search [arXiv:2403.15016 [hep-ex]].
"Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states via WW scattering in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"

2σ excl. sensitivity

HL-LHC	$\lvert\mu_{e\mu}\rvert < 2.0 \cdot 10^{-7}\,\mu_B \quad \{300\,\mathrm{fb}^{-1}\},$	$\lvert\mu_{e\mu}\rvert < 1.1 \cdot 10^{-7}\,\mu_B \quad \{3\,\mathrm{ab}^{-1}\}$
FCC-hh	$\lvert\mu_{e\mu}\rvert < 3.4 \cdot 10^{-8}\,\mu_B \quad \{3\,\mathrm{ab}^{-1}\},$	$\lvert\mu_{e\mu}\rvert < 1.9 \cdot 10^{-8}\,\mu_B \quad \{30\,\mathrm{ab}^{-1}\}$

(Future) Collider Probes: Hadron Colliders

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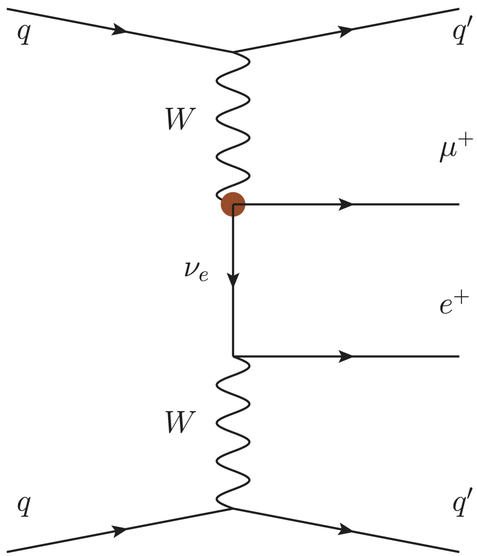

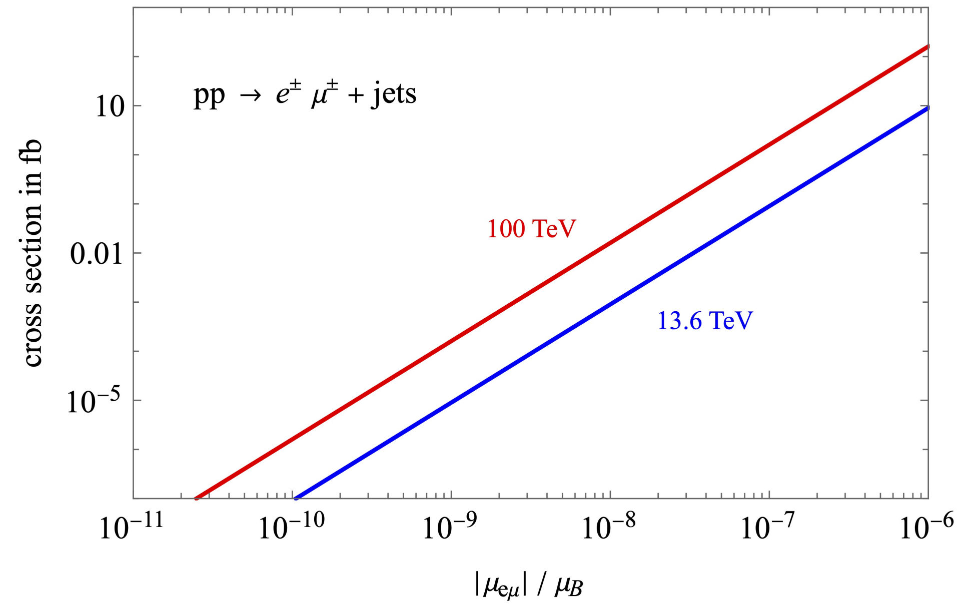

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2σ excl. sensitivity — In the most optimistic case of a **negligible background**

HL-LHC	$\lvert\mu_{e\mu}\rvert < 6.1 \cdot 10^{-8}\,\mu_B \quad \{300\,\mathrm{fb}^{-1}\}$,	$\lvert\mu_{e\mu}\rvert < 1.9 \cdot 10^{-8}\,\mu_B \quad \{3\,\mathrm{ab}^{-1}\}$
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A Future Muon Collider

key point of the strategic plans for the development of particle physics both in Europe (ESPP '20) and in the USA (P5 recommendations '23)

D. Stratakis et al. (Muon Collider), A Muon Collider Facility for Physics Discovery, (2022), arXiv:2203.08033, K. M. Black et al., Muon Collider Forum Report, (2022), arXiv:2209.01318 [hep-ex]; C. Accettura et al., Towards a Muon Collider, (2023), arXiv:2303.08533 [physics.acc-ph].

mu+ mu- in a circular collider with a ring of the size of the LHC, 27 Km (possibly using the LHC ring)

Energy and Luminosity design targets:

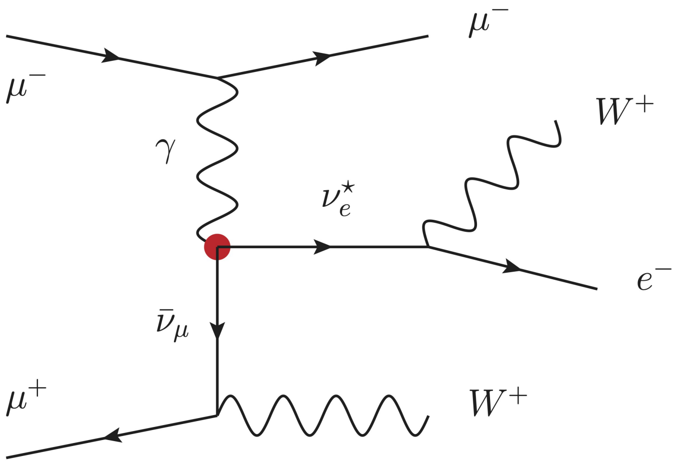
$\sqrt{s} = 1, 3, 10, 20, 30, 50$ TeV $\quad L = 0.1, 0.9, 10, 40, 90, 250 \text{ ab}^{-1} \quad L = 10 \left(\frac{\sqrt{s}}{10\,\text{TeV}} \right)^2 \text{ab}^{-1}$

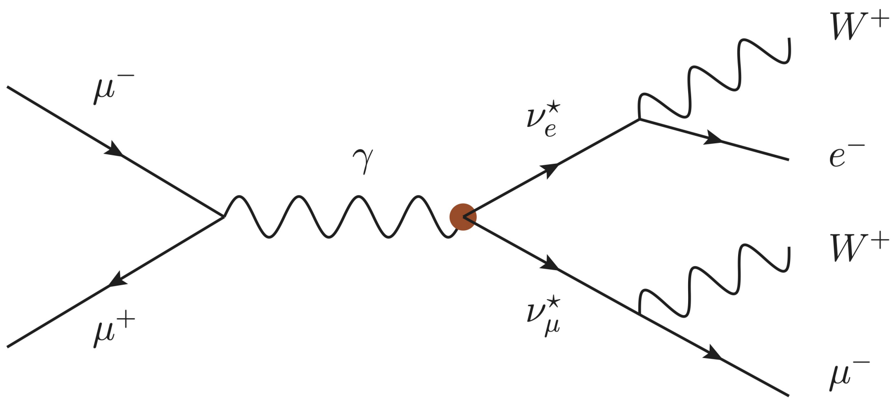
Advantages:

- typically higher effective collision energies (hadron colliders pay for PDFs, e+e- for sinchrotron radiation effects)
- lower background (compared to hadron colliders)

Main challenge: short life-time of muons

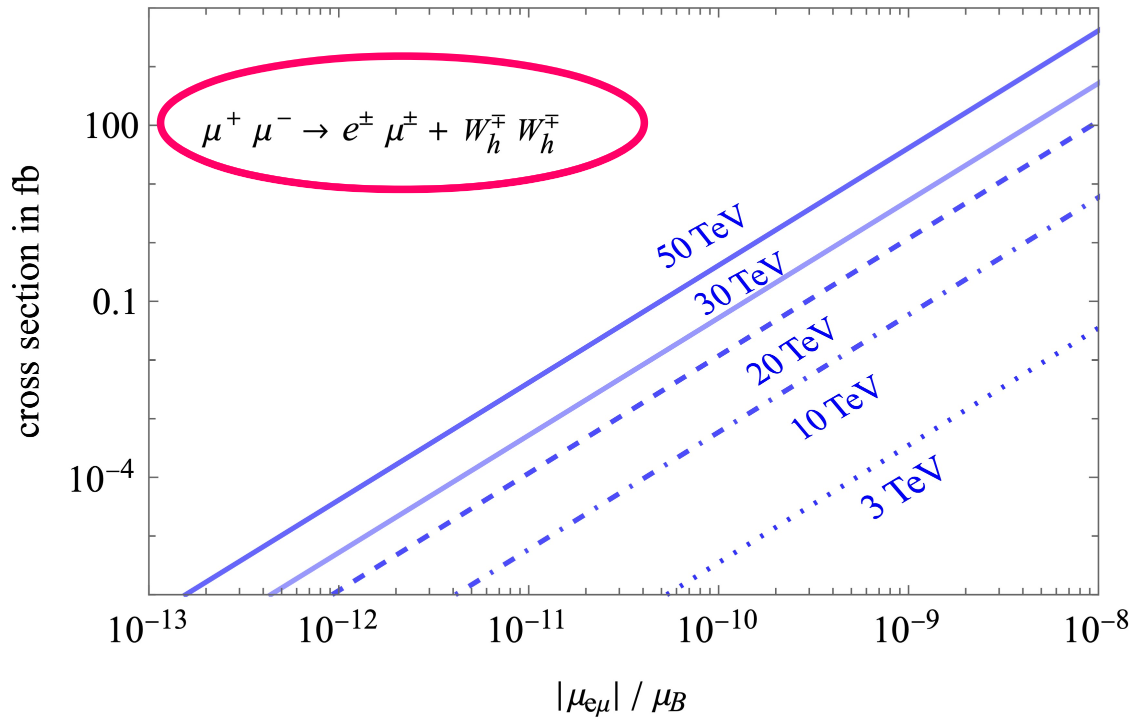
Neutrino TMM at a Muon Collider



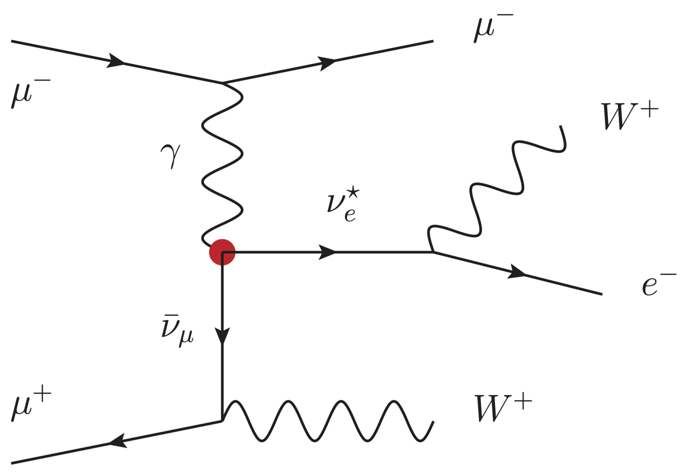


Peculiar LNV process

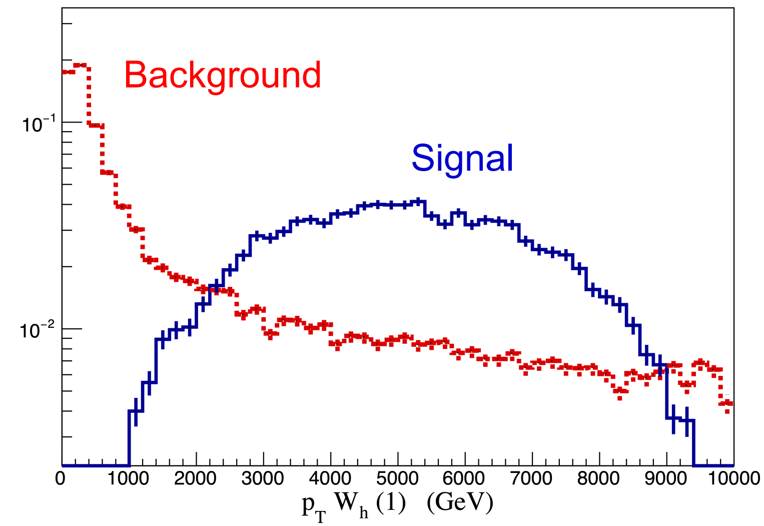
Background at a very low level: few ab
(mainly from llW_hW_h events with misidentified lepton charges and flavours, and from $W_{lep}W_{lep}W_hW_h$)



Neutrino TMM at a Muon Collider



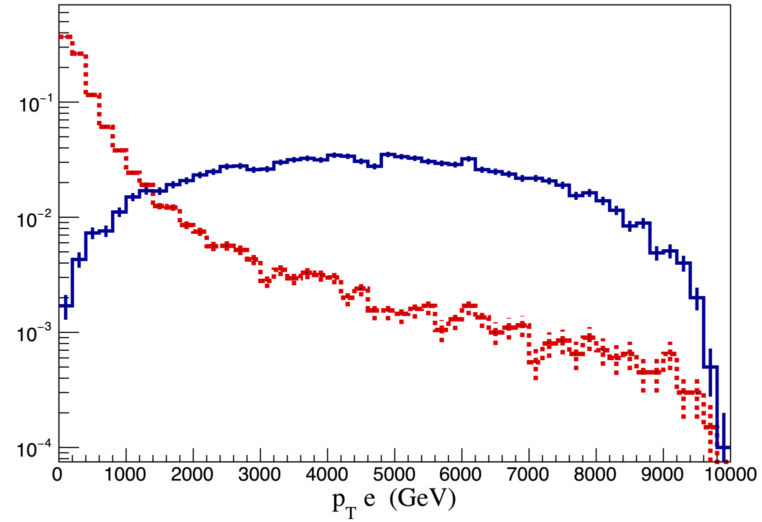
Peculiar kinematics for the signal



Peculiar LNV process

Background at a very
low level: few ab

Can be further reduced to an almost
negligible level



Neutrino TMM at a Muon Collider

2σ sensitivities

$$L = 10 \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}} \right)^2 \mathrm{ab}^{-1}$$

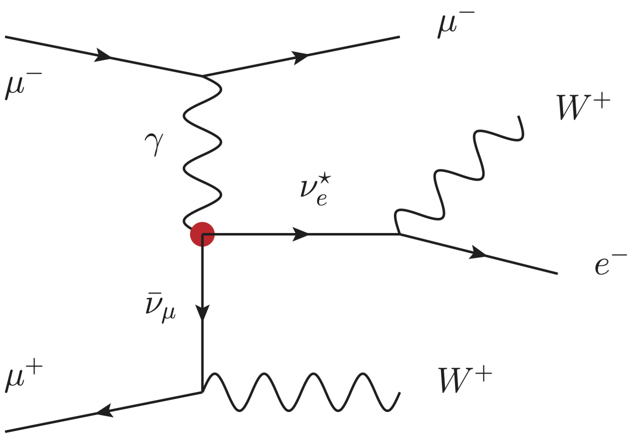
$\sqrt{s} =$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\frac{\lvert\mu_{e\mu}\rvert}{\mu_B}$	$2.7 \cdot 10^{-9}$	$7.5 \cdot 10^{-11}$	$9.5 \cdot 10^{-12}$	$3.3 \cdot 10^{-12}$	$7.5 \cdot 10^{-13}$

A 3 TeV Muon Collider already more than one order of magnitude more sensitive than the FCC-hh

~20-30 TeV Muon Collider competitive with laboratory experiments,
which give **“flavor-independent”** bounds: $2\mu_\nu \lesssim 6 \cdot 10^{-12} \mu_B$

+30 TeV Muon collider at the level of (or even better) than latest astrophysical and laboratory sensitivities

Neutrino TMM at a Muon Collider at the 7-dim operator level



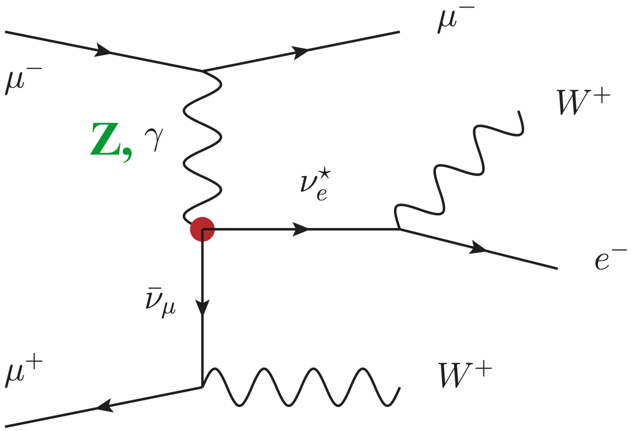
$$(O_B)_{\alpha\beta}|_v = -\frac{g' v^2}{2} \left(\overline{\nu^c_\alpha}\, \sigma^{\mu\nu} \nu_\beta\right) \left(c_w A_{\mu\nu} - s_w Z_{\mu\nu}\right)$$

$$(O_W)_{\alpha\beta}|_v = -g v^2 \left(\overline{\nu^c_\alpha}\, \sigma^{\mu\nu} \nu_\beta\right) \left[s_w A_{\mu\nu} + c_w Z_{\mu\nu} + ig(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\right]$$

$$-\frac{g v^2}{\sqrt{2}} \left(\overline{\nu^c_\alpha}\, \sigma^{\mu\nu} \ell_\beta + \overline{\ell^c_\alpha}\, \sigma^{\mu\nu} \nu_\beta\right) \left[W^+_{\mu\nu} + ig W^+_\mu (s_w A_\nu + c_w Z_\nu) - ig W^+_\nu (s_w A_\mu + c_w Z_\mu)\right]$$

Neutrino TMM at a Muon Collider

at the 7-dim operator level



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Neutrino TMM at a Muon Collider
at the 7-dim operator level

Negative interference between diagrams induced by single-W effective interactions and the ones with two bosons

$$(O_B)_{\alpha\beta}|_v = -\frac{g' v^2}{2} \left(\overline{\nu_\alpha^c}\, \sigma^{\mu\nu} \nu_\beta\right) \left(c_w A_{\mu\nu} - s_w Z_{\mu\nu}\right)$$

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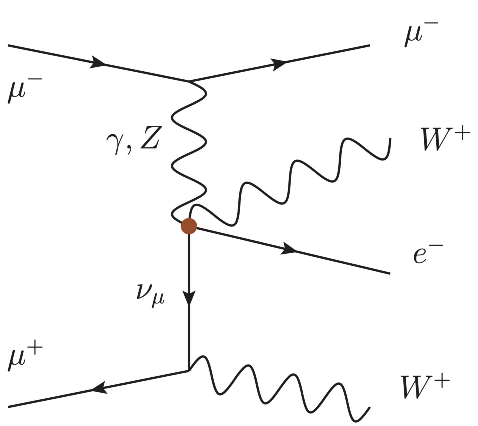
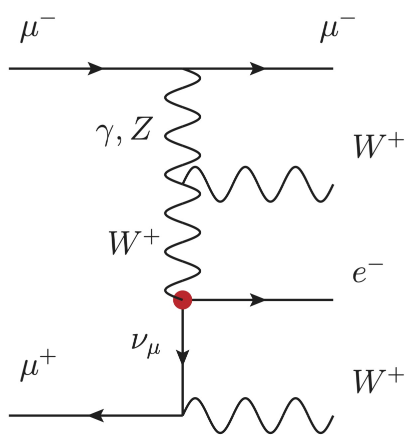
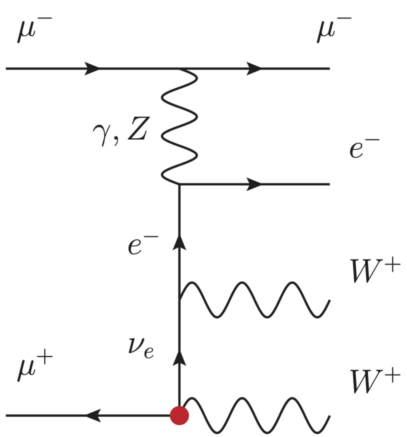
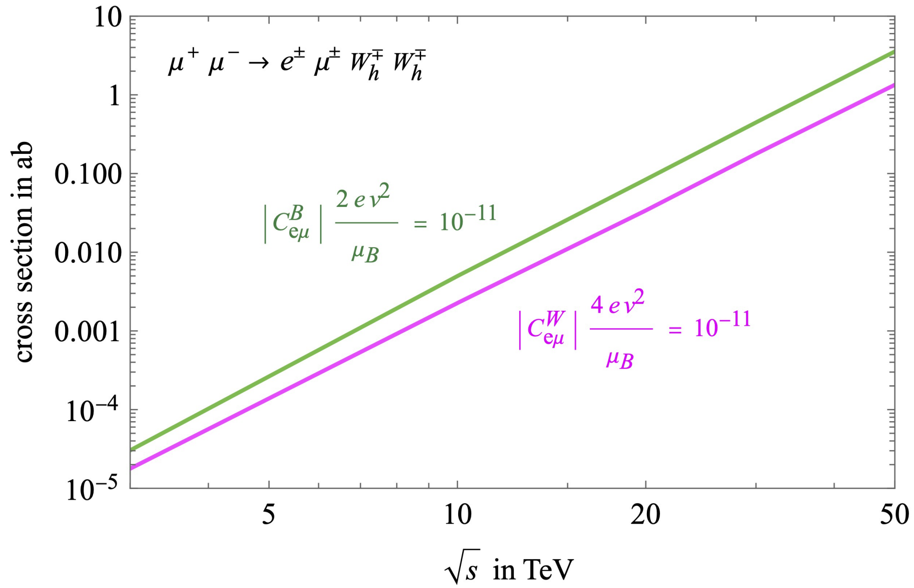
$$-\frac{g v^2}{\sqrt{2}} \left(\overline{\nu_\alpha^c}\, \sigma^{\mu\nu} \ell_\beta + \overline{\ell_\alpha^c}\, \sigma^{\mu\nu} \nu_\beta\right) \left[W_{\mu\nu}^+ + ig W_\mu^+ (s_w A_\nu + c_w Z_\nu) - ig W_\nu^+ (s_w A_\mu + c_w Z_\mu)\right]$$







Neutrino TMM at a Muon Collider at the 7-dim operator level



2σ sensitivities for a completely O_B-generated TMM

$\sqrt{s} =$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\frac{\lvert\mu_{e\mu}\rvert}{\mu_B}$	$2.0 \cdot 10^{-9}$	$6.0 \cdot 10^{-11}$	$8.0 \cdot 10^{-12}$	$2.5 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$

2σ sensitivities for a completely O_W-generated TMM

$\sqrt{s} =$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\frac{\lvert\mu_{e\mu}\rvert}{\mu_B}$	$2.6 \cdot 10^{-9}$	$8.6 \cdot 10^{-11}$	$1.2 \cdot 10^{-11}$	$3.9 \cdot 10^{-12}$	$9.4 \cdot 10^{-13}$

EFT validity

By using Naive Dimensional Analysis (NDA),
calling m* and g* the typical mass and coupling of the heavy particles in the ultraviolet theory, and recalling that dipole operators arise from loops, one can write:

$$C_{\alpha\beta}^{B,W} = c_{\alpha\beta}^{B,W} \frac{1}{(4\pi)^2} \frac{(g_* \epsilon_H)^2 (g_* \epsilon_\alpha)(g_* \epsilon_\beta)}{m_*^3}$$

where ϵ_H (ϵ_α) quantifies the coupling between the SM Higgs doublet (lepton doublet) and the UV particles, in units of g*, while the coefficients $c^{B,W}$ are expected to be of order one

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⇓

$$\frac{|\mu_{\alpha\beta}|}{\mu_B} \simeq 2 \cdot 10^{-11} |c_{\alpha\beta}^B + 2 c_{\alpha\beta}^W| \left(\frac{10 \text{ TeV}}{m_*} \right)^3 \left(\frac{g_*}{4\pi} \right)^4 \left(\frac{\epsilon_H}{1} \right)^2 \left(\frac{\epsilon_\alpha \epsilon_\beta}{10^{-3}} \right)$$

$g^*=4\pi$ corresponds to a strongly-coupled UV theory, $\epsilon_H=1$ corresponds to a composite Higgs. The parameters ϵ_α quantify the degree of partial compositeness of lepton doublets

EFT validity

By using Naive Dimensional Analysis (NDA),
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$$\Downarrow$$

$$\frac{|\mu_{\alpha\beta}|}{\mu_B} \simeq 2 \cdot 10^{-11} |c^B_{\alpha\beta} + 2 c^W_{\alpha\beta}| \left(\frac{10\ \text{TeV}}{m_*}\right)^3 \left(\frac{g_*}{4\pi}\right)^4 \left(\frac{\epsilon_H}{1}\right)^2 \boxed{\left(\frac{\epsilon_\alpha \epsilon_\beta}{10^{-3}}\right)}$$

ϵ_α should be sufficiently small to comply with precision lepton observables, especially LFV ones

Ex. [Frigerio, Nardecchia, Serra, Vecchi, JHEP 10 (2018), 017]

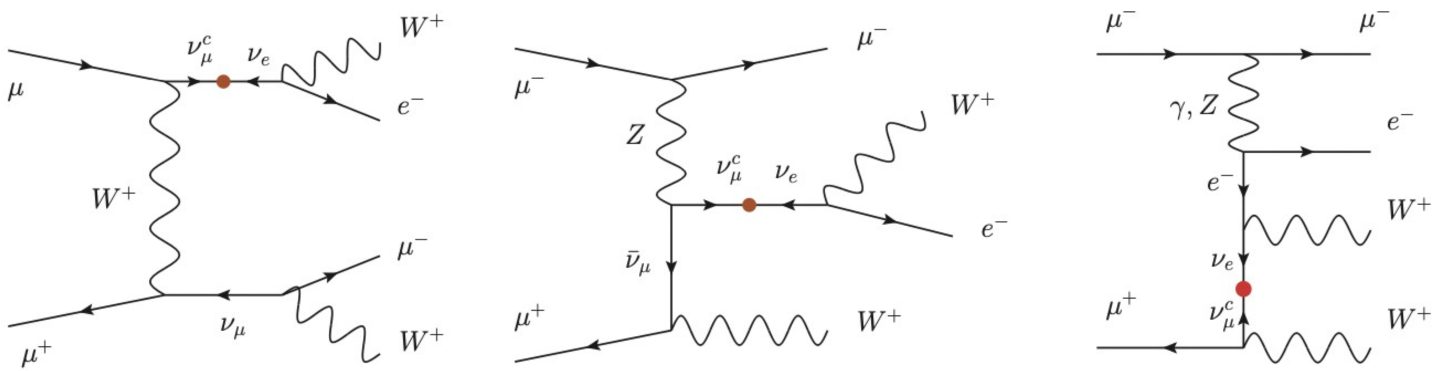
In a `flavour-anarchic' scenario, $\epsilon_\alpha \epsilon_\beta = 10^{-3}$, is sufficiently small to respect most constraints, except those from e-mu transitions, which would require $\epsilon_e \epsilon_\mu \sim 10^{-6}$.
However, one can consider instead `flavour-symmetric' scenarios, where some UV flavour symmetry suppresses dangerous processes, effectively allowing for larger couplings

LNV test at a muon collider: The Weinberg operator

Hadron collider sensitivities have been recently estimated in
B. Fuks, J. Neundorf, K. Peters, R. Ruiz and M. Saimpert, Phys. Rev. D 103, no.11, 115014 (2021)

LNV process $\mu^+\mu^- \to \ell^\pm\ell^\pm + W_h^\mp W_h^\mp$

also sensitive to the Weinberg operator (Majorana neutrino masses)



2σ sensitivities:

$\sqrt{s} =$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\lvert m_{e\mu}\rvert$	110 MeV	3.2 MeV	0.50 MeV	140 KeV	36 KeV
$\lvert m_{\mu\mu}\rvert$	300 MeV	10 MeV	1.5 MeV	420 KeV	84 KeV

improvement of up to three orders of magnitude for a ~20 TeV muon collider on the estimated sensitivities of the FCC-hh

Conclusions

- Neutrino dipole moments can provide evidence of new physics beyond the Standard Model (BSM). Large electron-muon transition moments of the order of $10^{-12}\ \mu_B$ for Majorana neutrinos can appear in BSM scenarios, which become accessible experimentally
- The current most stringent limits are set by astrophysical observations and by low-energy neutrino scattering experiments (XENONnT, LUX-ZEPLIN), with bounds of the order of a few $\bullet\ 10^{-12}\ \mu_B$
- We estimate for the first time the collider sensitivity to electron-muon neutrino TMMs:

  A **LNV** and **LFV** signature $\mu^+\mu^- \to e^\pm\mu^\pm + W_h^\mp W_h^\mp$

  at a future muon collider would provide an important complementary probe for TMMs. A muon collider with a collision energy of ~20-30 TeV would be competitive with the latest astrophysical observation and laboratory experiments. Contrary to the latter, the muon collider would be sensitive to the flavor (and LNV) of the TMMs, providing important additional information on the neutrino properties in the event of a (near) future observation at low-energy experiments.