

(Future) collider probes of neutrino magnetic moments

Nataschia Vignaroli



Based on *M. Frigerio, NV, [arXiv:2409.02721](https://arxiv.org/abs/2409.02721)*

NOW 2024, Otranto

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

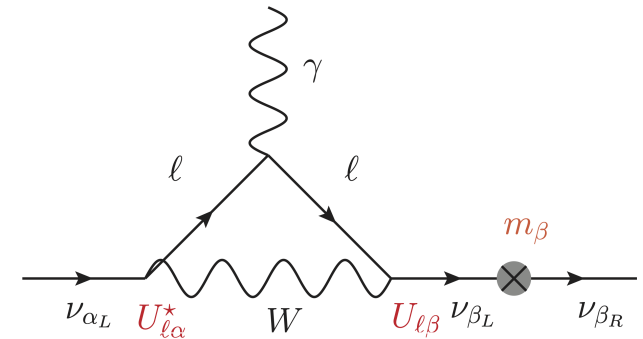
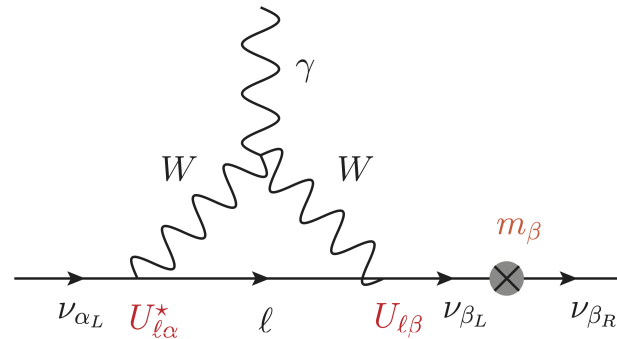
Dirac neutrinos

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:

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

$$\Delta L = 0$$



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

neutrino mass
suppression

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

Transition Magnetic
Moments are further
GIM-suppressed

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

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.

$$N_{R\beta} = \nu_{L\beta}^c \quad (\Delta L = 2)$$

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

$$\mu_{\alpha\beta}^M \simeq -7.8 \cdot 10^{-23} \mu_B i (m_\alpha + m_\beta) \sum_\ell \text{Im} [U_{\ell\alpha}^* U_{\ell\beta}] \left(\frac{m_\ell}{m_W} \right)^2$$

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

Majorana neutrinos

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

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.

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

$$\mu_{\alpha\beta}^M \simeq -7.8 \cdot 10^{-23} \mu_B i (m_\alpha + m_\beta) \sum_\ell \text{Im} [U_{\ell\alpha}^* U_{\ell\beta}] \left(\frac{m_\ell}{m_W} \right)^2$$

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 $10^{-15} \mu_B$ 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)

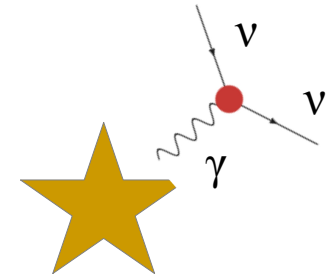
Compelling BSM scenarios predict **electron-muon TMMs** for **Majorana** neutrinos of the order of $10^{-12} \mu_B$ which **become accessible experimentally**

For example:
M. Lindner, B. Radovic 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

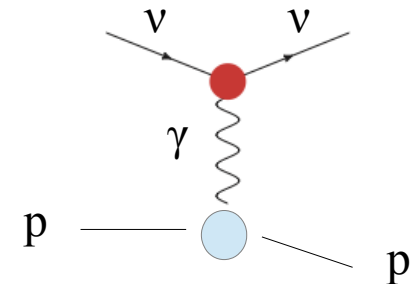
[Capozzi, Raffelt, PRD 102 (2020) 8, 083007]

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

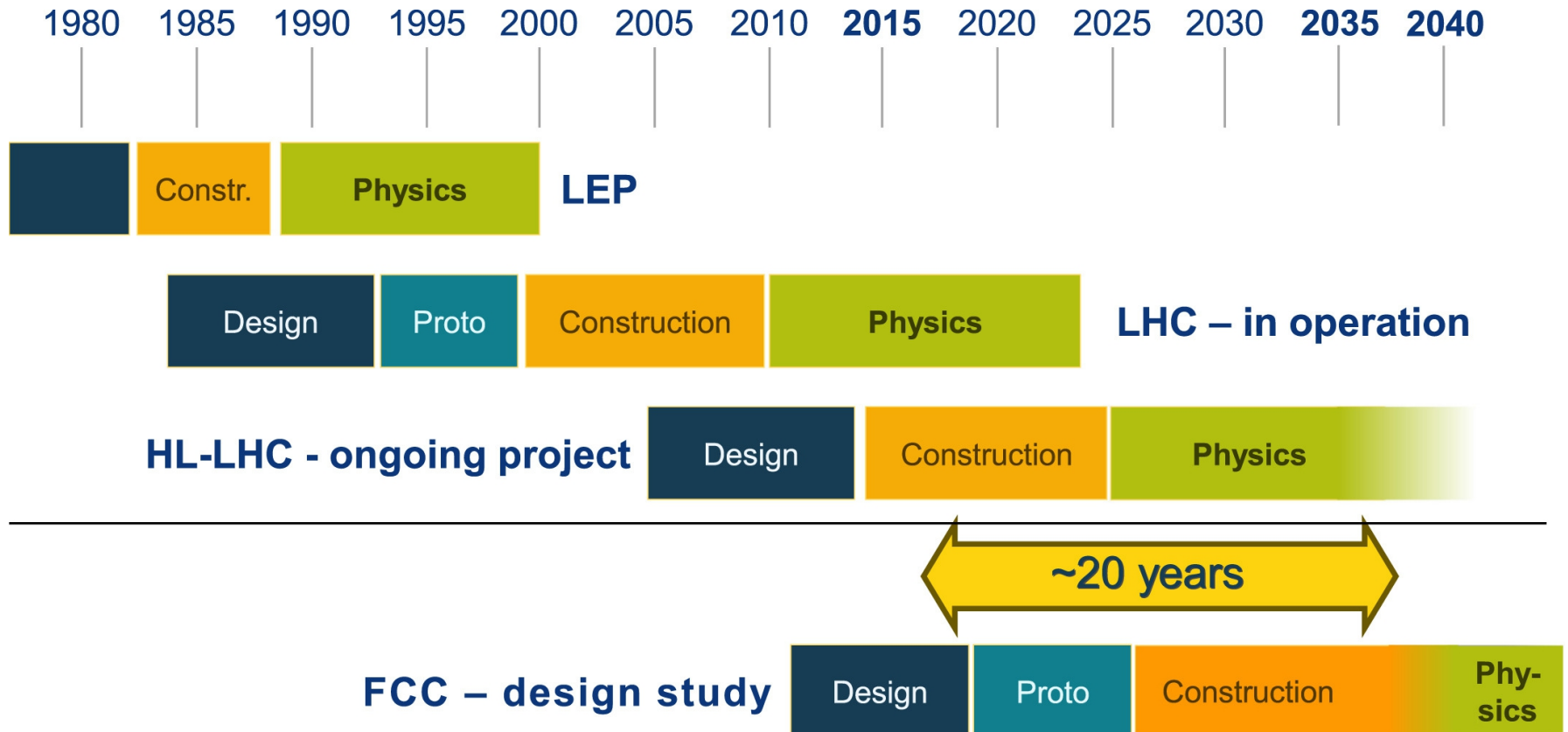
$$\mu_\nu \lesssim 6.2 \times 10^{-12} \mu_B$$

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

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

$$\frac{\mu_{\alpha\beta}}{2} \bar{\nu}_\alpha^c \sigma^{\mu\nu} P_L \nu_\beta A_{\mu\nu} \leftarrow \begin{cases} (O_B)_{\alpha\beta} = g' (\bar{L}_\alpha^c \epsilon H) \sigma^{\mu\nu} (H^T \epsilon L_\beta) B_{\mu\nu} \\ (O_W)_{\alpha\beta} = ig \epsilon_{abc} (\bar{L}_\alpha^c \epsilon \sigma^a \sigma^{\mu\nu} L_\beta) (H^T \epsilon \sigma^b H) W_{\mu\nu}^c \end{cases}$$

After SSB

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

$$(O_W)_{\alpha\beta}|_v = -gv^2 (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [s_w A_{\mu\nu} + c_w Z_{\mu\nu} + ig(W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+)]$$

$$-\frac{gv^2}{\sqrt{2}} (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \ell_\beta + \bar{\ell}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [W_{\mu\nu}^+ + igW_\mu^+ (s_w A_\nu + c_w Z_\nu) - igW_\nu^+ (s_w A_\mu + c_w Z_\mu)]$$

(Future) Collider Probes: Hadron Colliders

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

$$\frac{\mu_{\alpha\beta}}{2} \bar{\nu}_\alpha^c \sigma^{\mu\nu} P_L \nu_\beta A_{\mu\nu} \leftarrow \begin{cases} (O_B)_{\alpha\beta} = g' (\bar{L}_\alpha^c \epsilon H) \sigma^{\mu\nu} (H^T \epsilon L_\beta) B_{\mu\nu} \\ (O_W)_{\alpha\beta} = ig \epsilon_{abc} (\bar{L}_\alpha^c \epsilon \sigma^a \sigma^{\mu\nu} L_\beta) (H^T \epsilon \sigma^b H) W_{\mu\nu}^c \end{cases}$$

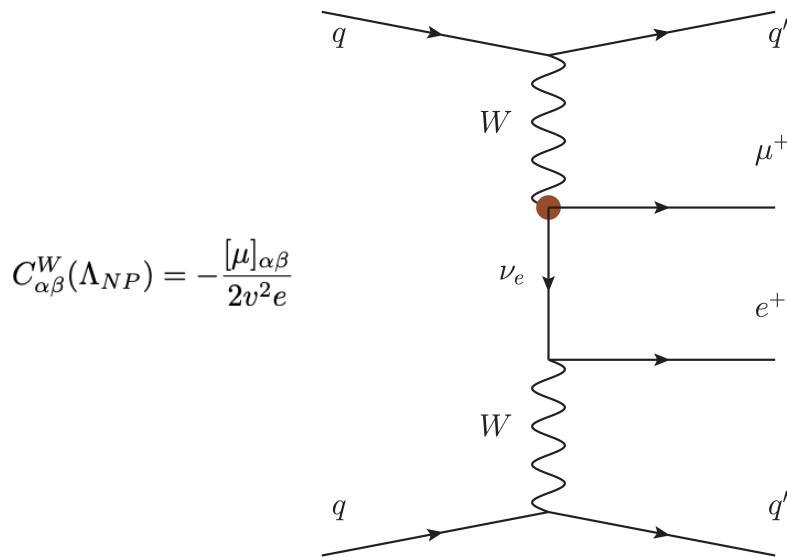
After SSB

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

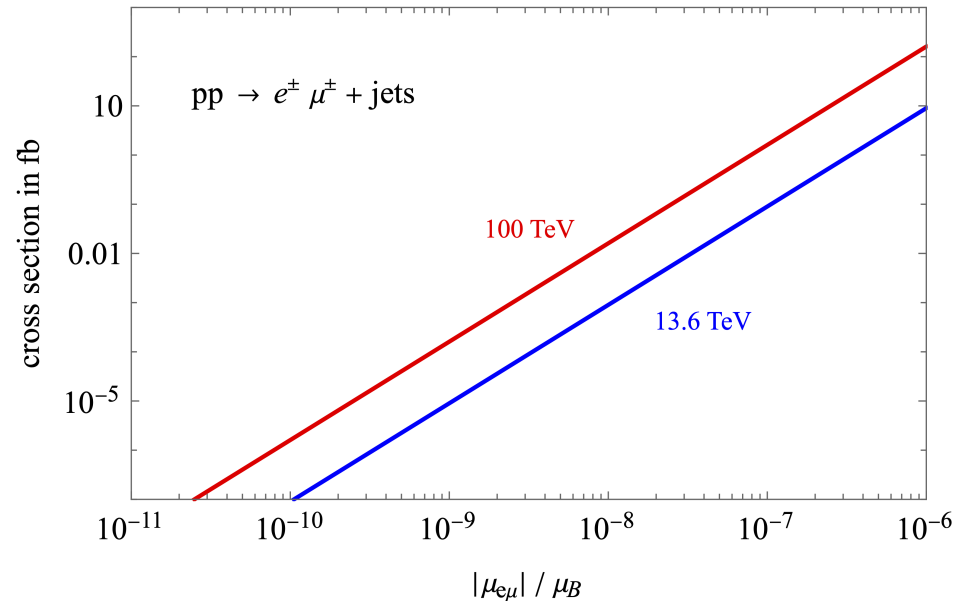
$$(O_W)_{\alpha\beta}|_v = -gv^2 (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [s_w A_{\mu\nu} + c_w Z_{\mu\nu} + ig(W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+)]$$

$$-\frac{gv^2}{\sqrt{2}} (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \ell_\beta + \bar{\ell}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [W_{\mu\nu}^+ + igW_\mu^+ (s_w A_\nu + c_w Z_\nu) - igW_\nu^+ (s_w A_\mu + c_w Z_\mu)]$$

(Future) Collider Probes: Hadron Colliders



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



Background evaluated from a recast of the ATLAS search [arXiv:2403.15016 [hep-ex]].

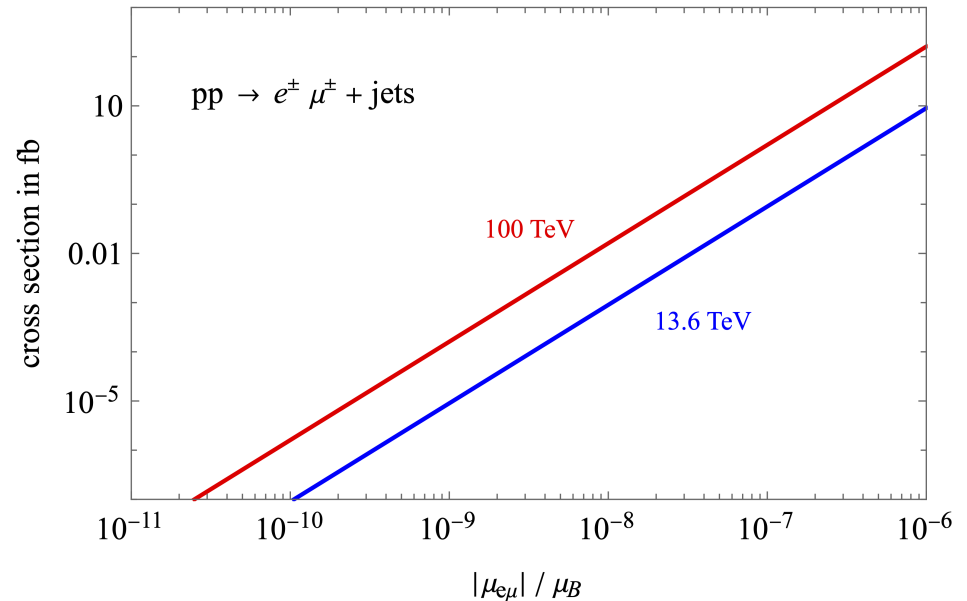
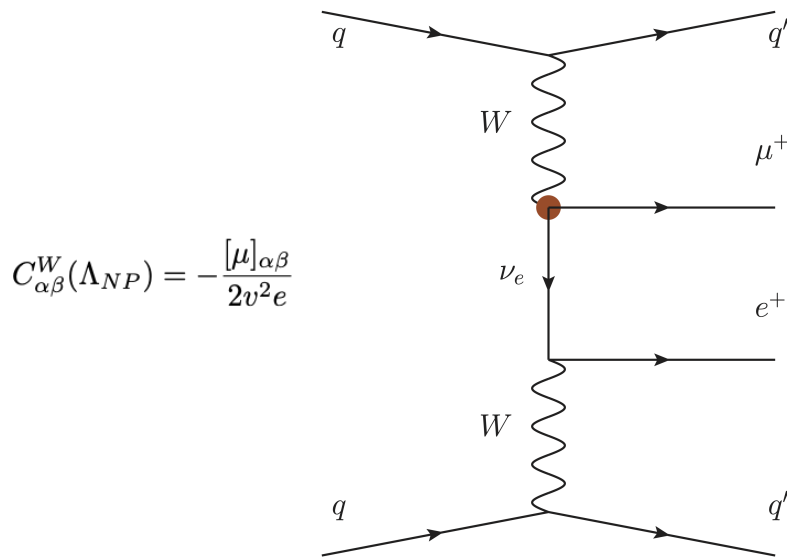
“Search for heavy Majorana neutrinos in $e^\pm e^\pm$ and $e^\pm \mu^\pm$ final states via WW scattering in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”

2 σ excl. sensitivity

| | | | | |
|--------|--|-----------------------------|--|-------------------------|
| HL-LHC | $ \mu_{e\mu} < 2.0 \cdot 10^{-7} \mu_B$ | $\{300 \text{ fb}^{-1}\}$, | $ \mu_{e\mu} < 1.1 \cdot 10^{-7} \mu_B$ | $\{3 \text{ ab}^{-1}\}$ |
|--------|--|-----------------------------|--|-------------------------|

| | | | | |
|--------|--|---------------------------|--|--------------------------|
| FCC-hh | $ \mu_{e\mu} < 3.4 \cdot 10^{-8} \mu_B$ | $\{3 \text{ ab}^{-1}\}$, | $ \mu_{e\mu} < 1.9 \cdot 10^{-8} \mu_B$ | $\{30 \text{ ab}^{-1}\}$ |
|--------|--|---------------------------|--|--------------------------|

(Future) Collider Probes: Hadron Colliders



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”

2 σ excl. sensitivity

In the most optimistic case of a negligible background

HL-LHC $|\mu_{e\mu}| < 6.1 \cdot 10^{-8} \mu_B \quad \{300 \text{ fb}^{-1}\}, \quad |\mu_{e\mu}| < 1.9 \cdot 10^{-8} \mu_B \quad \{3 \text{ ab}^{-1}\}$

FCC-hh $|\mu_{e\mu}| < 3.4 \cdot 10^{-9} \mu_B \quad \{3 \text{ ab}^{-1}\}, \quad |\mu_{e\mu}| < 1.0 \cdot 10^{-9} \mu_B \quad \{30 \text{ ab}^{-1}\}$

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:

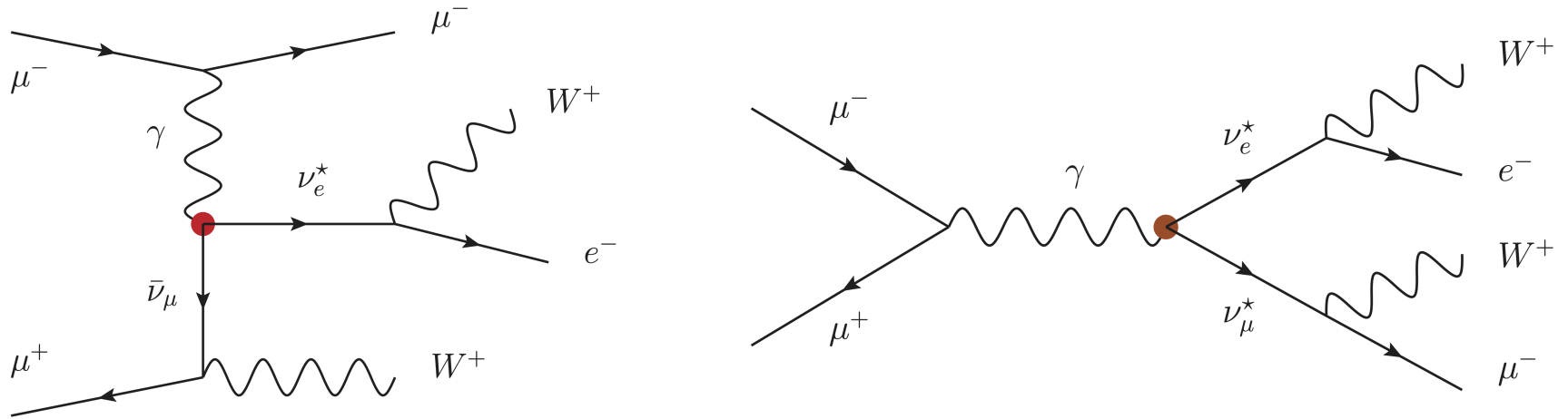
$$\sqrt{s} = 1, 3, 10, 20, 30, 50 \text{ TeV} \quad L = 0.1, 0.9, 10, 40, 90, 250 \text{ ab}^{-1} \quad L = 10 \left(\frac{\sqrt{s}}{10 \text{ TeV}} \right)^2 \text{ ab}^{-1}$$

Advantages:

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

Main challenge: short life-time of muons

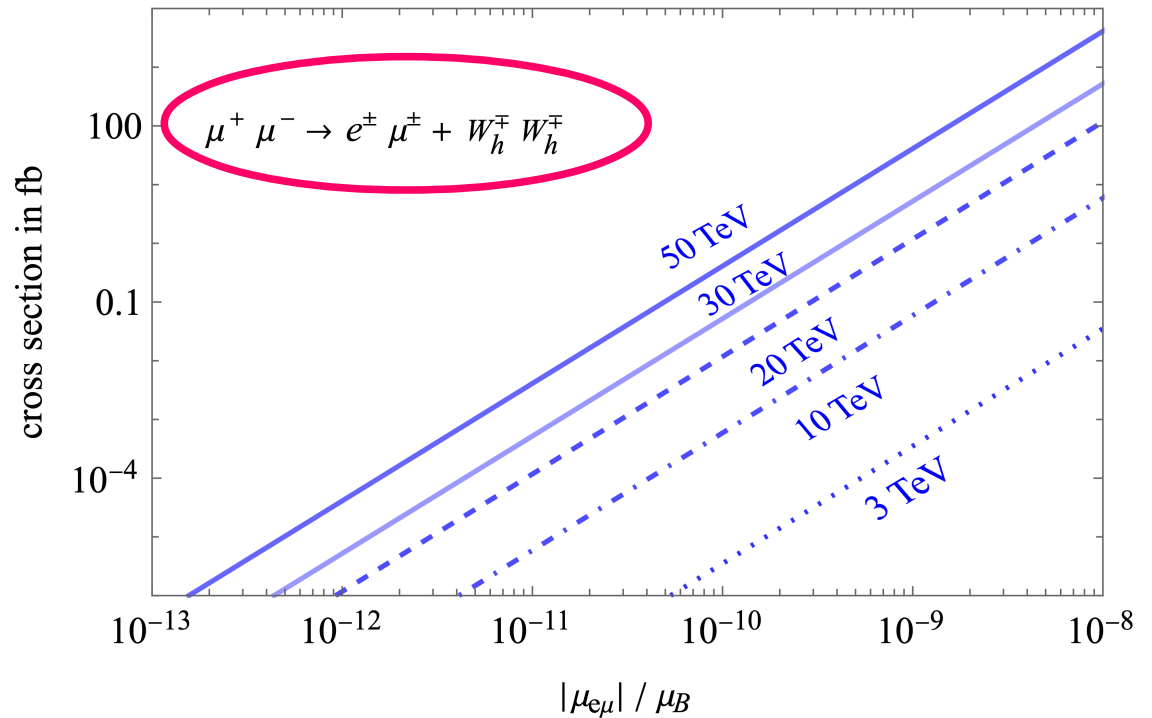
Neutrino TMM at a Muon Collider



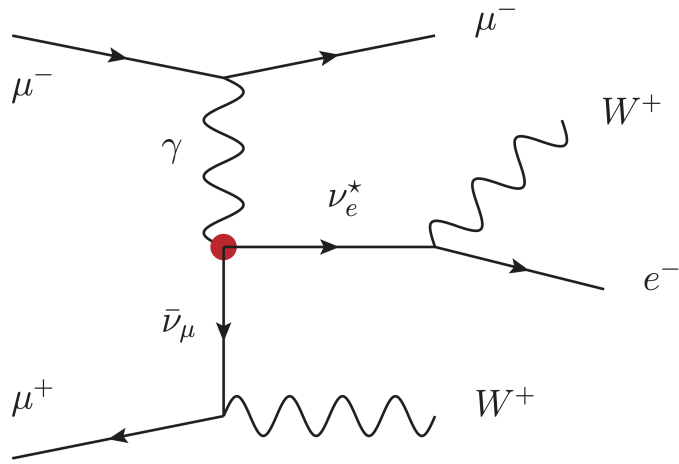
Peculiar LNV process

Background at a very low level: few ab

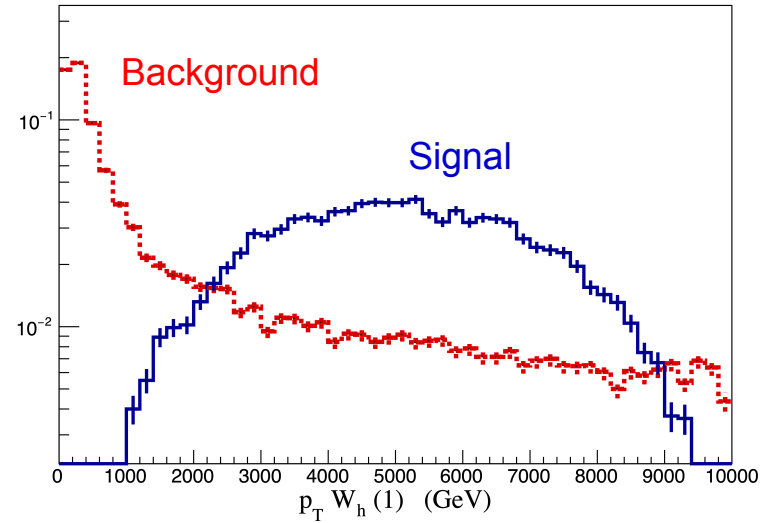
(mainly from $llW_h W_h$ events with misidentified lepton charges and flavours, and from $W_{lep} W_{lep} W_h W_h$)



Neutrino TMM at a Muon Collider



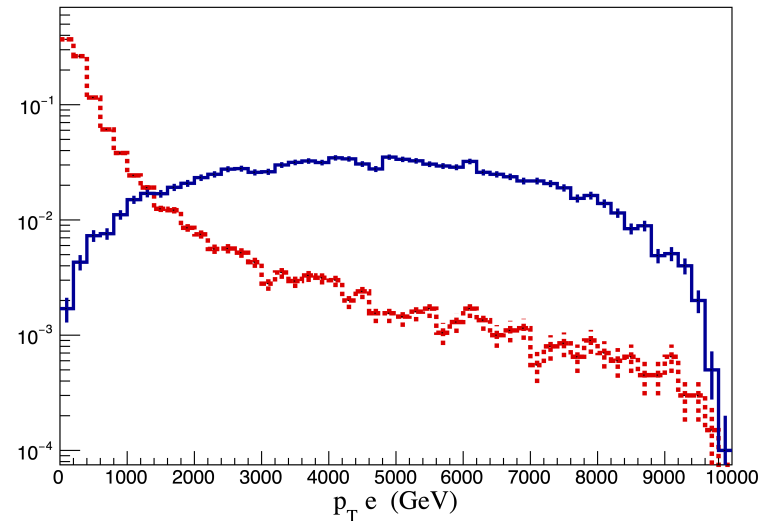
Peculiar kinematics for the signal



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

2 σ sensitivities

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

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

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

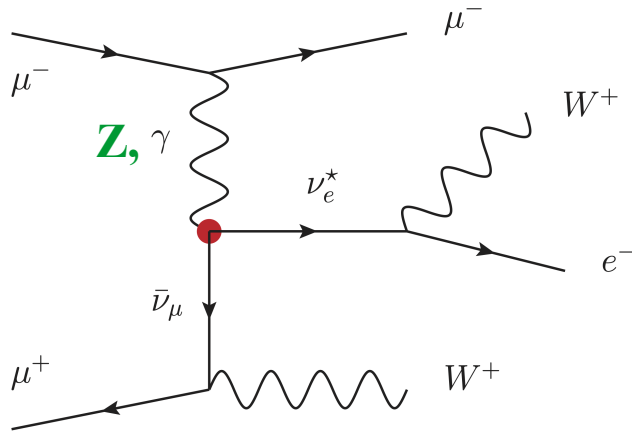
~20-30 TeV Muon Collider competitive with laboratory experiments,

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



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

$$(O_W)_{\alpha\beta}|_v = -gv^2 (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [s_w A_{\mu\nu} + c_w Z_{\mu\nu} + ig(W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+)]$$

$$-\frac{gv^2}{\sqrt{2}} (\bar{\nu}_\alpha^c \sigma^{\mu\nu} \ell_\beta + \bar{\ell}_\alpha^c \sigma^{\mu\nu} \nu_\beta) [W_{\mu\nu}^+ + igW_\mu^+ (s_w A_\nu + c_w Z_\nu) - igW_\nu^+ (s_w A_\mu + c_w Z_\mu)]$$

2 σ sensitivities for a completely \mathbf{O}_B -generated TMM

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

2 σ sensitivities for a completely \mathbf{O}_W -generated TMM

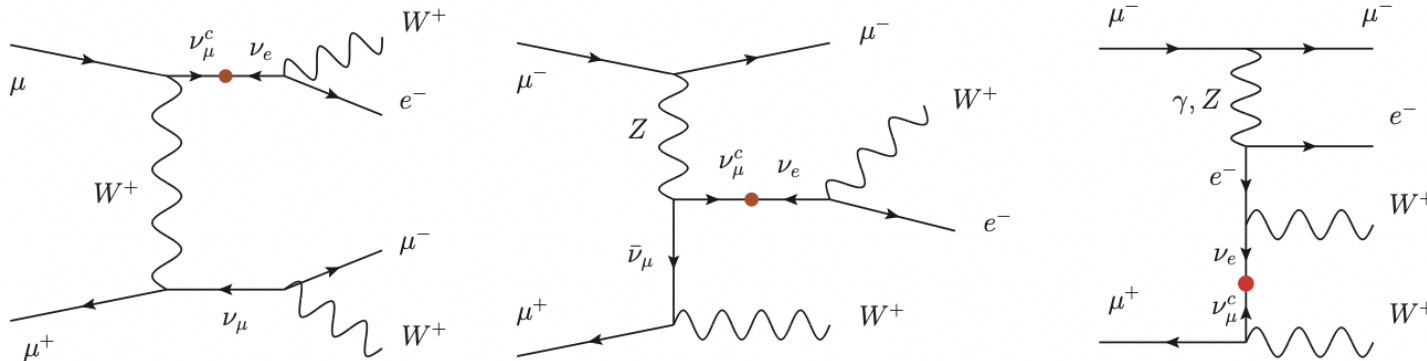
| $\sqrt{s} =$ | 3 TeV | 10 TeV | 20 TeV | 30 TeV | 50 TeV |
|------------------------------|---------------------|----------------------|----------------------|----------------------|----------------------|
| $\frac{ \mu_{e\mu} }{\mu_B}$ | $2.6 \cdot 10^{-9}$ | $8.6 \cdot 10^{-11}$ | $1.2 \cdot 10^{-11}$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

LNV test at a muon collider: The Weinberg operator

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

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

also sensitive to the Weinberg operator (Majorana neutrino masses)



2 σ sensitivities:

| $\sqrt{s} =$ | 3 TeV | 10 TeV | 20 TeV | 30 TeV | 50 TeV |
|----------------|---------|---------|----------|---------|--------|
| $ m_{e\mu} $ | 110 MeV | 3.2 MeV | 0.50 MeV | 140 KeV | 36 KeV |
| $ m_{\mu\mu} $ | 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 few $\bullet 10^{-12} \mu_B$
- We estimate for the first time the collider sensitivity to electron-muon neutrino TMMs:

A LNV signature $\mu^+ \mu^- \rightarrow e^\pm \mu^\pm + W_h^\mp W_h^\mp$

at a future muon collider would provide an important complementary probe for TMMs. A muon collider with a collision energy of $\sim 20\text{-}30$ TeV would be competitive with the latest astrophysical observation and laboratory experiments. Contrary to these 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.