# Sterile Neutrinos as a Window to New Physics

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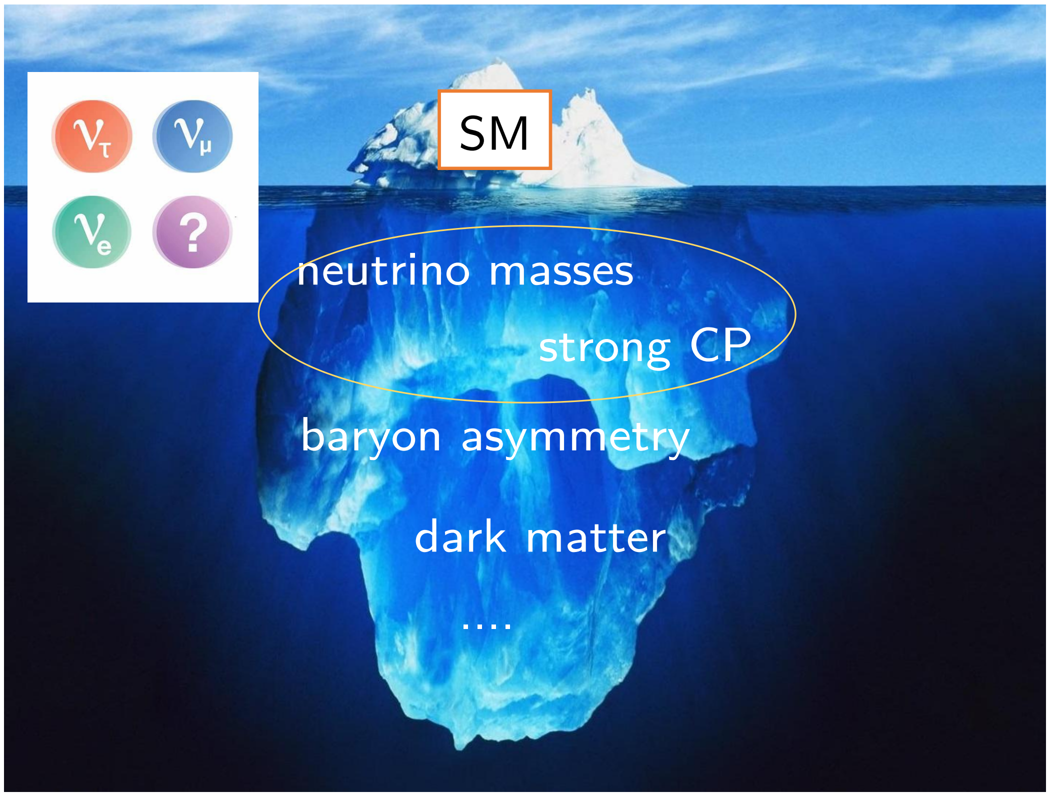
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

2024年5月8日

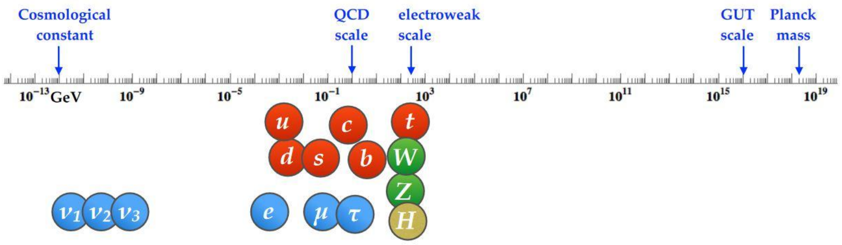
# Tail of new physics

- Massive neutrinos

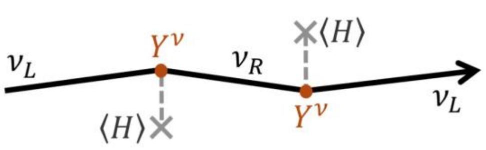


# Neutrino masses

- How do neutrinos get tiny masses?



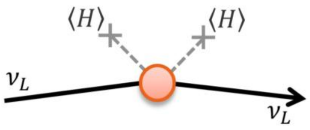

Dirac mass:




$$\mathcal{L}_D = -(Y^\nu \bar{L} H \nu_R + \text{h.c.})$$

very small coupling

Majorana mass:



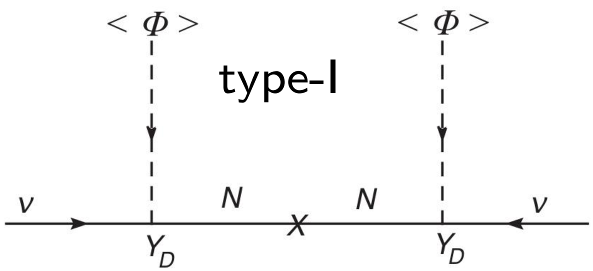

$$\mathcal{L}_M = \frac{C_5}{\Lambda}(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) + \text{h.c.}$$

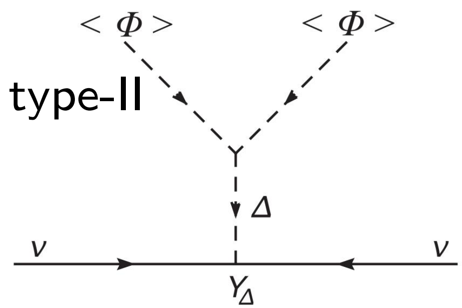
(very) large scale

*a la* eg. type-I, II, III seesaw

# Neutrino masses

Seesaw mechanisms:




$$-M_D M_N^{-1} M_D^T$$

$$Y_\Delta \frac{\mu v^2}{M_\Delta^2}$$

(1) How do right-handed neutrinos interact with the SM?

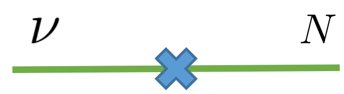
(2) How do right-handed neutrinos get Majorana mass $M_N$?

# Neutrino masses

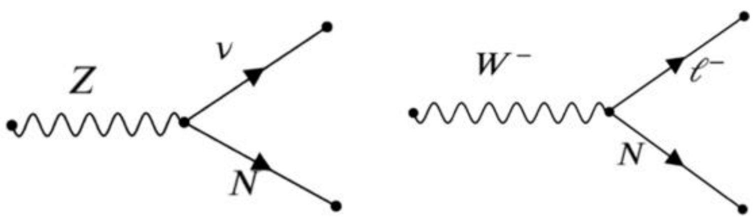
(1) From flavor basis to mass basis, heavy neutrinos interact with the SM

$$\begin{pmatrix} \nu \\ N \end{pmatrix} \to \begin{pmatrix} 1 & \Theta^\dagger \\ -\Theta & 1 \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

active-sterile mixing:




$$\Theta = \frac{1}{M_N} M_D \ll 1$$

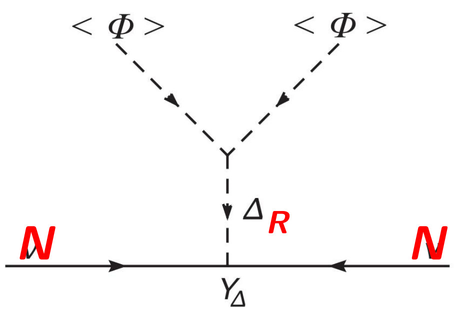


# Neutrino masses

(2) Dynamical origin of right-handed neutrino mass

The Majorana mass of $\nu_R$ may have non-trivial dynamical origin, for instance, $M_R = h_\Delta \langle \Delta_R \rangle$, where $\Delta_R$ is the $SU(2)_R$ Higgs triplet in the L-R symmetric models or $M_R = h_\phi \langle \sigma \rangle$, where $\sigma$ is the gauge singlet. It can originate from condensate of new strongly interacting sector.

**Alexei Yu. Smirnov, 2401.09999**



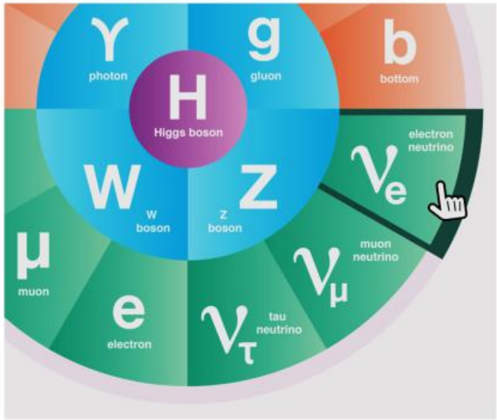

Spontaneous symmetry breaking above the electroweak scale:

$$M_N = Y_{\Delta_R} \langle \Delta_R \rangle$$

# Neutrino masses

Open questions in neutrino physics:

- Normal or Inverted (sign of $\Delta m^2_{31}$?)
- Leptonic CP Violation ($\delta$ = ?)
- Octant of $\theta_{23}$ (> or < 45°?)
- Absolute Neutrino Masses ($m_{\rm lightest} = 0$?)
- Majorana or Dirac Nature ($\nu = \nu^C$ ?)
- Majorana CP-Violating Phases (how?)




- Extra Neutrino Species
- Exotic Neutrino Interactions
- Various LNV & LFV Processes
- Leptonic Unitarity Violation

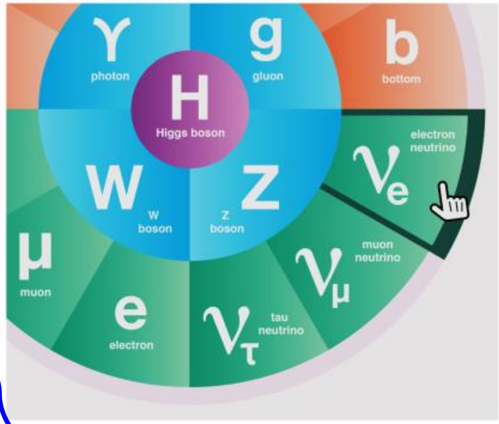
- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM and/or BAU

credit: Shun Zhou

# Neutrino masses

At least three steps are necessary:

- Normal or Inverted (sign of $\Delta m^2_{31}$?)
- Leptonic CP Violation ($\delta$ = ?)
- Octant of $\theta_{23}$ (> or < 45°?)
- Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)
- Majorana or Dirac Nature ($\nu=\nu^C$ ?)
- Majorana CP-Violating Phases (how?)




- Extra Neutrino Species
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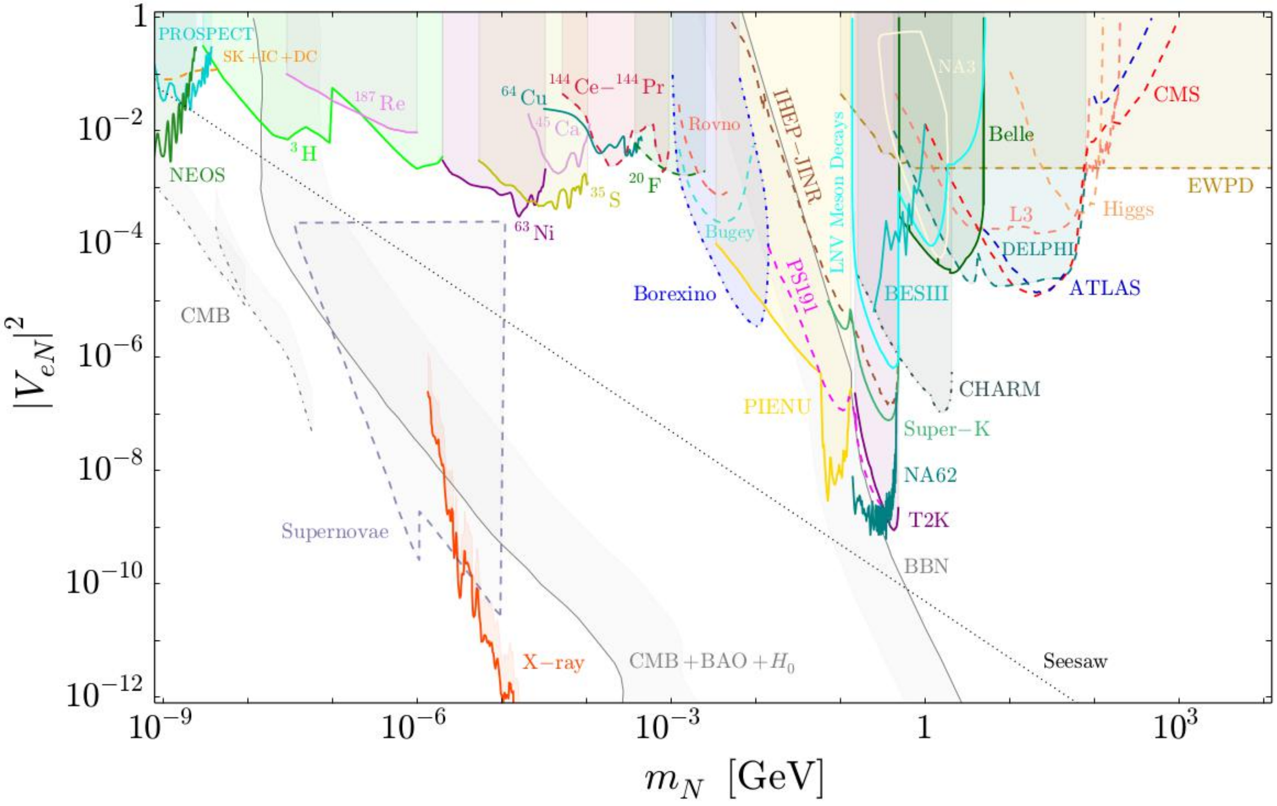
# Sterile neutrino phase space

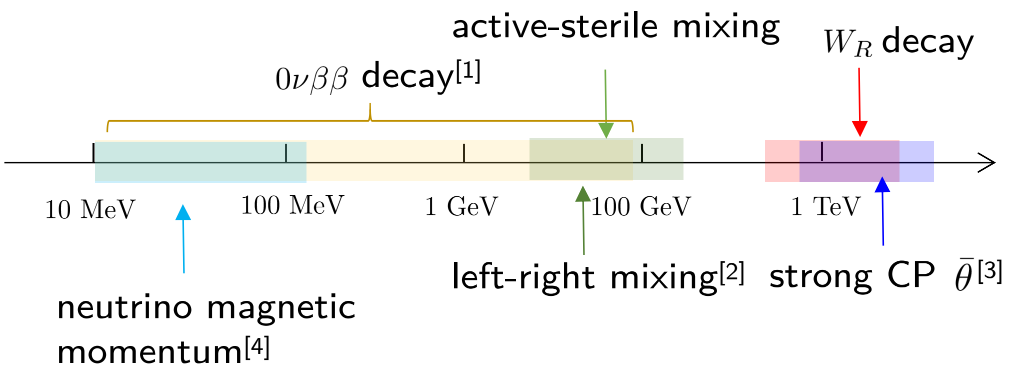
Diverse searches




**Bolton, Deppisch, Bhupal Dev, 1912.03058 (JHEP)**

# Sterile neutrino phase space

Mass ranges from MeV to TeV




[1] GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL);
de Vries, GL, Ramsey-Musolf, Vasquez, 2209.03031 (JHEP)

[2] GL, Ramsey-Musolf, Vasquez, 2202.01789 (PRD)

[3] GL, Ding-Yi Luo, Xiang Zhao, 2404.16740

[4] work in progress

UV completion: left-right symmetric model, inverse/double seesaw

this talk

# Left-Right Symmetric Model

The minimal LRSM:

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Doublets:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$$

**Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165**

Bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$

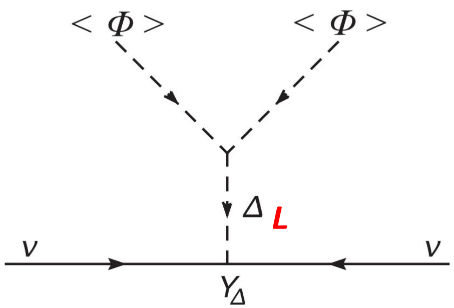
Triplets:

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

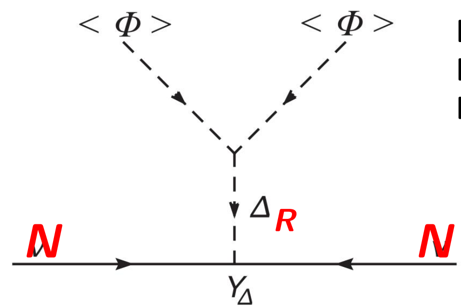
$$\Rightarrow \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

# Left-Right Symmetric Model

Left-right symmetry




$$M_L = Y_{\Delta_L} \langle \Delta_L \rangle$$



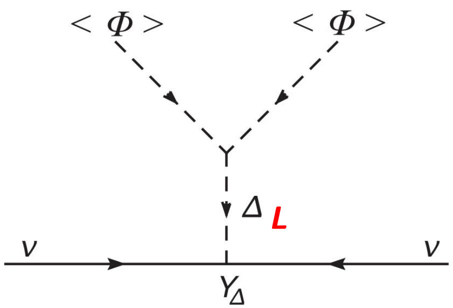

$$M_N = Y_{\Delta_R} \langle \Delta_R \rangle$$

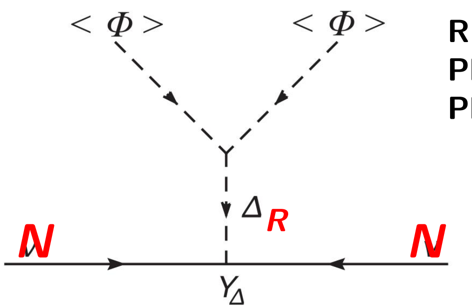
**R. Mohapatra, G. Senjanovic,**
**Phys.Rev.Lett. 44 (1980) 912,**
**Phys.Rev.D 23 (1981) 165**

$$\mathcal{P} : \begin{cases} Y_\Phi = Y_\Phi^\dagger, \\ Y_{\Delta_{L,R}} = Y_{\Delta_{R,L}}, \end{cases} \qquad \mathcal{C} : \begin{cases} Y_\Phi = Y_\Phi^T, \\ Y_{\Delta_{L,R}} = Y^*_{\Delta_{R,L}}. \end{cases}$$

# Left-Right Symmetric Model

Left-right symmetry




**R. Mohapatra, G. Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165**

$$M_L = Y_{\Delta_L} \langle \Delta_L \rangle \qquad M_N = Y_{\Delta_R} \langle \Delta_R \rangle$$

seesaw relation (type I+II):

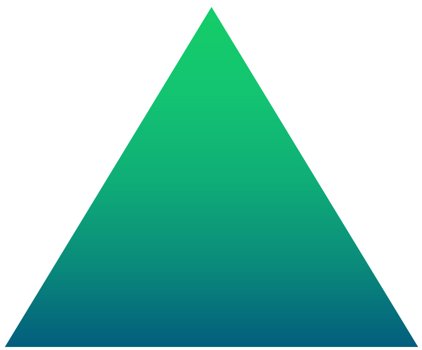
$$M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

type-II $\quad$ type-I

# Left-Right Symmetric Model

Key to the problems:

neutrino masses



parity restoration

strong CP problem

$U(1)_{em}$

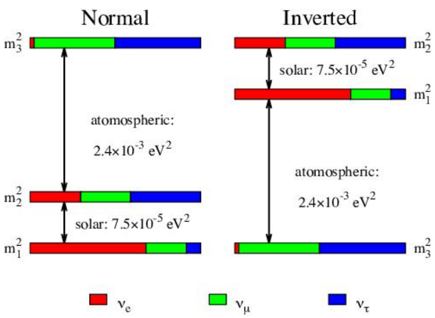
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

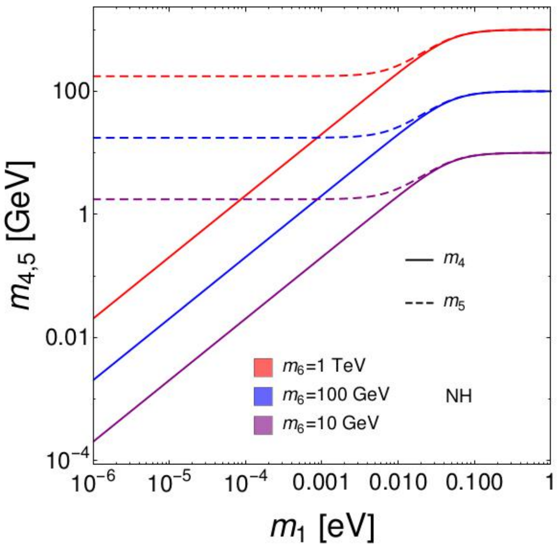
$E$

# Left-Right Symmetric Model

Mass correlation

$$M_\nu = M_L = \frac{v_L}{v_R} M_N \qquad v_{L,R} \equiv \langle \Delta_{L,R} \rangle \qquad \text{type-II seesaw}$$




**de Vries, GL, Ramsey-Musolf, Vasquez, 2209.03031 (JHEP)**

# Left-Right Symmetric Model

Physical parameters as input

- In type-I seesaw models:

$$M_D = i\sqrt{m_N}O\sqrt{m_\nu}V_L^\dagger$$

Casas-Ibarra parameterization

- In the minimal LRSM for the case of

charge conjugation:

$$M_D = V_L^* m_N \sqrt{\frac{v_L}{v_R} - \frac{m_\nu}{m_N}V_L^\dagger}$$

$$V_R = V_L^*$$

**Nemevsek, Senjanovic, Tello, 1211.2837 (PRL)**

parity:

$$M_D = V_L m_N \sqrt{\frac{v_L}{v_R} - \frac{m_\nu}{m_N}V_L^\dagger}$$

$$V_R = V_L$$

**Senjanovic, Tello, 1612.05503 (PRL)**

# Left-Right Symmetric Model

P not PQ: no QCD $\theta$ term due to parity (axionless solution)

$$\delta\mathcal{L}_{\rm QCD} = \theta\frac{g_s^2}{32\pi^2}G\tilde{G}$$

**Mohapatra, Senjanovic 1978**
**Babu, Mohapatra 1989**

Strong CP problem: $\bar{\theta}^{\rm exp} \lesssim 10^{-10}$

$$\bar{\theta} = \arg\det\left(M_u M_d\right)$$

$$\bar{\theta} \simeq s_\alpha t_{2\beta} m_t / \left(2m_b\right)$$

tree-level, from CP violation in quark sector

For quark Yukawa interaction $\bar{Q}_L Y_Q \Phi Q_R$ ,

$$Q_L \leftrightarrow Q_R \quad \Phi \leftrightarrow \Phi^\dagger \quad Y_Q \leftrightarrow Y_Q^\dagger$$

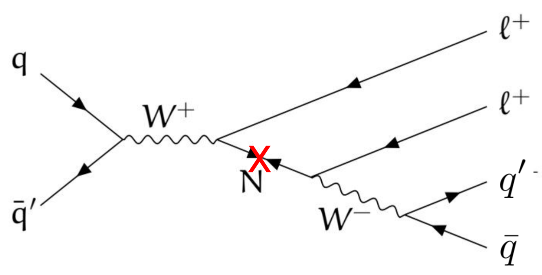
**A. Maiezza and M. Nemevšek, 1407.3678 (PRD)**

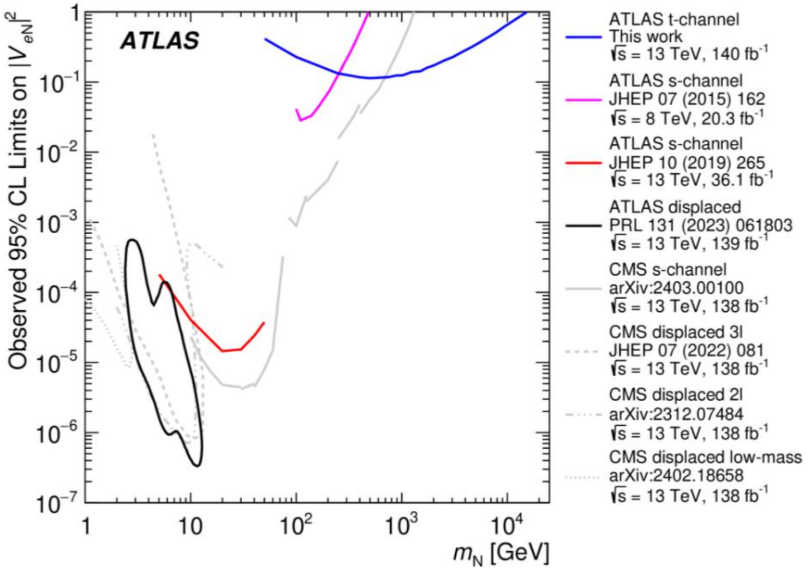
Quark mass matrix $M_Q = Y_Q \langle\Phi\rangle$ is generally complex

$$\langle\Phi\rangle = v\,\mathrm{diag}\left(c_\beta, -s_\beta e^{-i\alpha}\right)$$

# Direct searches at the LHC

via active-sterile mixing



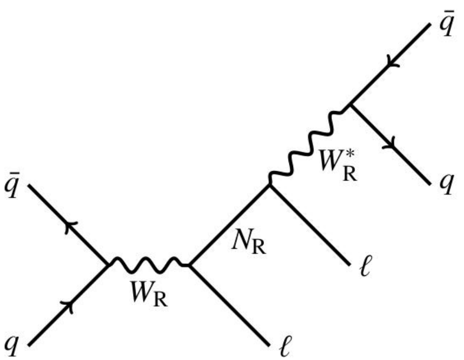

- active-sterile mixing $\Theta$
- sensitive to light $N$

**Holly Pacey @Moriond (2024)**

$$V_{eN} \sim \Theta$$

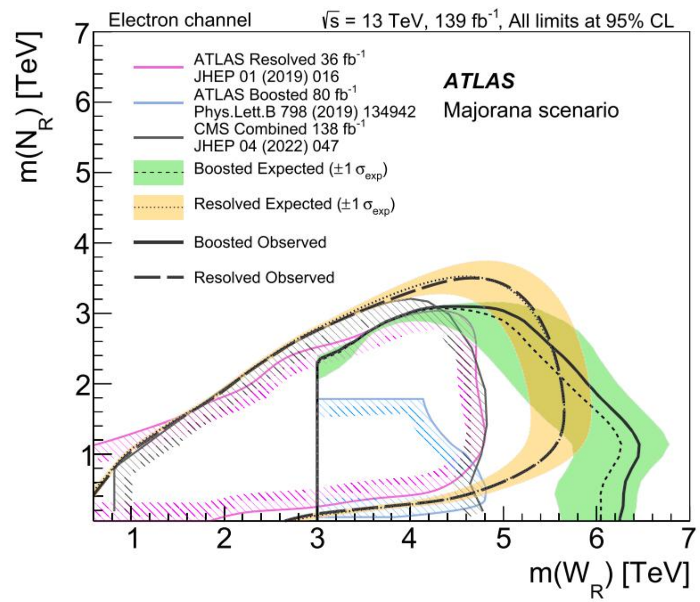
# Direct searches at the LHC

w/ right-handed charged current




Keung-Senjanovic process

- suppression by $W_R$ mass
- sensitive to heavy $N$

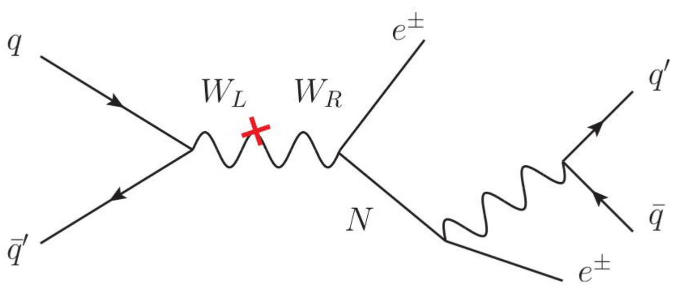



**2304.09553 (EPJC)**

# Direct searches at the LHC

via left-right mixing (proposal)

residual of left-right symmetry




constraint: $\zeta = \frac{M_W^2}{M_{W_R}^2} \sin(2\beta) \lesssim 10^{-4}$

$$\langle \Phi \rangle = v \, \mathrm{diag}\left(c_\beta, -s_\beta e^{-i\alpha}\right)$$

estimate: $|V_{eN}|^2 \to \zeta$

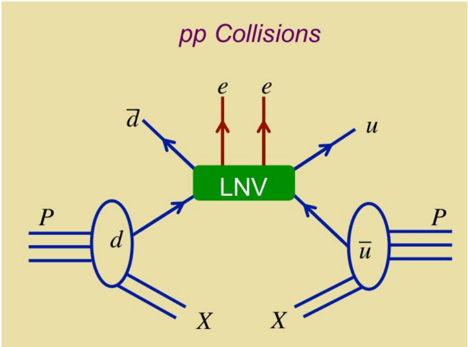
- left-right mixing $\zeta$
- sensitive to light $N$

Sensitivity comparable to Keung-Senjanovic process for $|V_{eN}|^2 \sim \zeta \sim 10^{-4}$

**GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2202.01789 (PRD)**

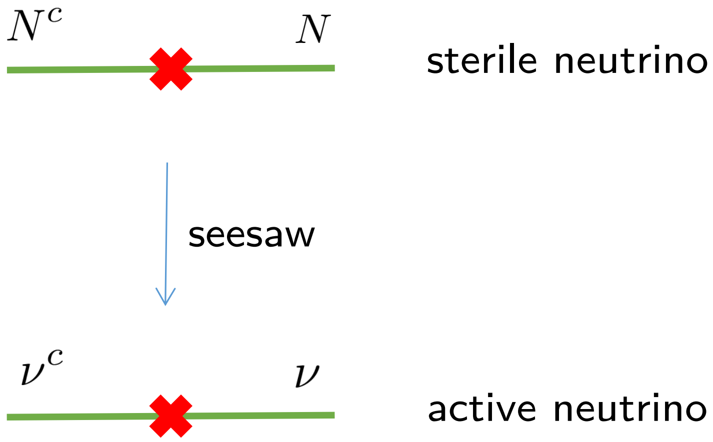
# Direct searches at the LHC

In order to assess the Majorana nature of neutrinos, same-sign dilepton final state is selected




Lepton Number Violation

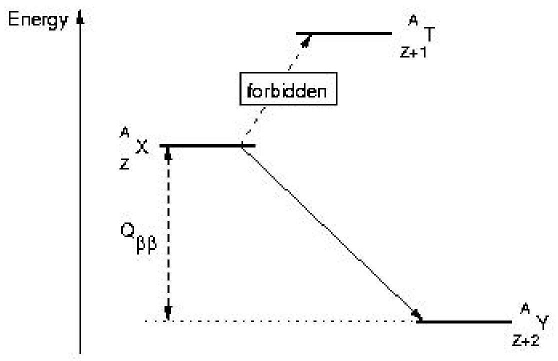
$$L_e : \quad 0 \to \pm 2$$

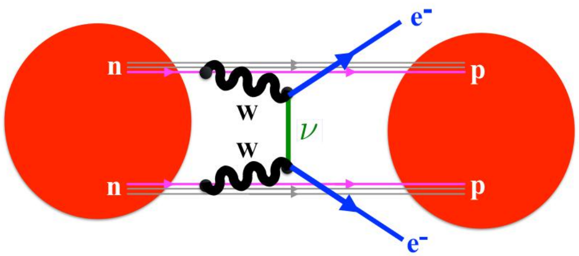


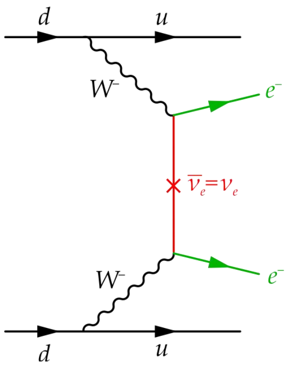

complementary to neutrinoless double beta decay

# Neutrinoless double beta decay

An observation of $0\nu\beta\beta$ decay undoubtedly implies the Majorana nature of neutrinos




nuclear level: $(A, Z) \to (A, Z + 2) + e^- + e^-$

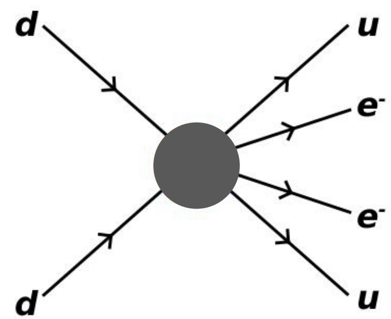
nucleon level: $nn \to ppe^-e^-$

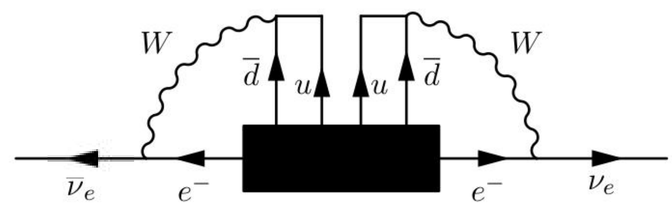
quark level: $dd \to uue^-e^-$

$0\nu\beta\beta$ decay is a low-energy process

# Neutrinoless double beta decay

An observation of $0\nu\beta\beta$ decay undoubtedly implies the Majorana nature of neutrinos

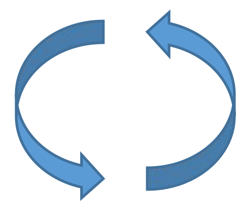



**Schechter, Valle, Phys.Rev. D25 (1982) 774**

various $\Delta L = 2$
LNV interactions

$\nu = \nu^c$

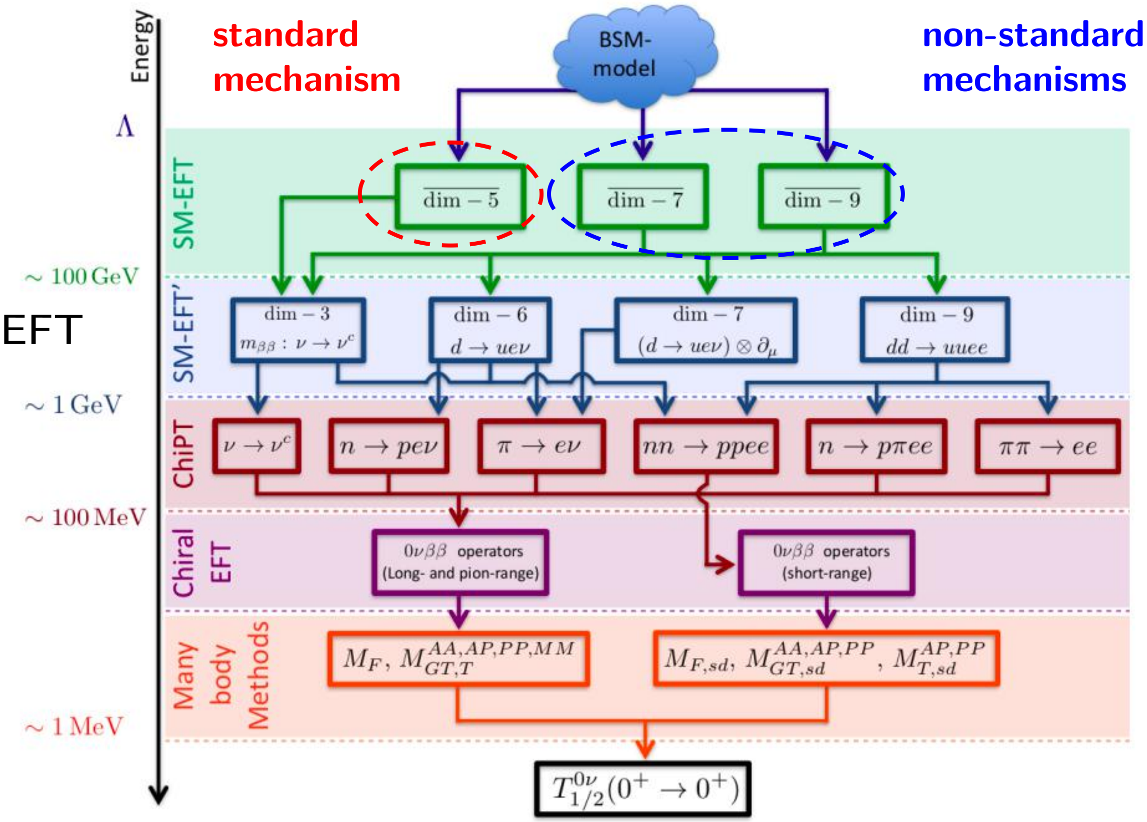


$0\nu\beta\beta$ decay

# Neutrinoless double beta decay

Effective field theory approach:

or LEFT



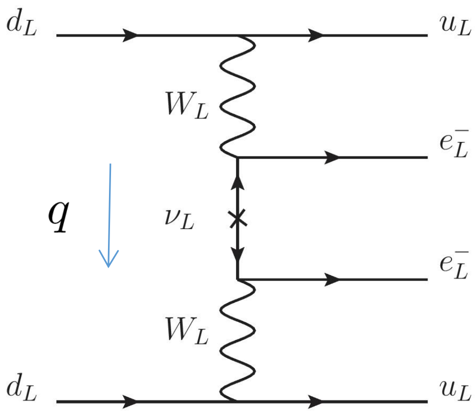

$\mathcal{L}(u, d, \nu, e)$

$\mathcal{L}(N, \pi, \nu, e)$

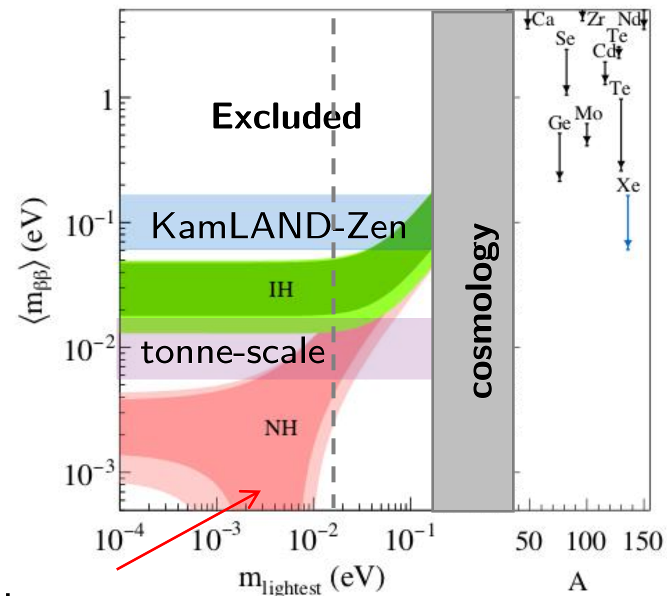
V. Cirigliano et al., 2203.12169, Snowmass 2021

# Neutrinoless double beta decay

Standard mechanism:




$$-q^2 \sim (200\ \mathrm{MeV})^2$$




nightmare region

**Phys.Rev.Lett. 130 (2023) 5, 051801**

$$P_L \frac{\not{q} + m_i}{q^2 - m_i^2} P_L = P_L \frac{m_i}{q^2 - m_i^2} P_L$$

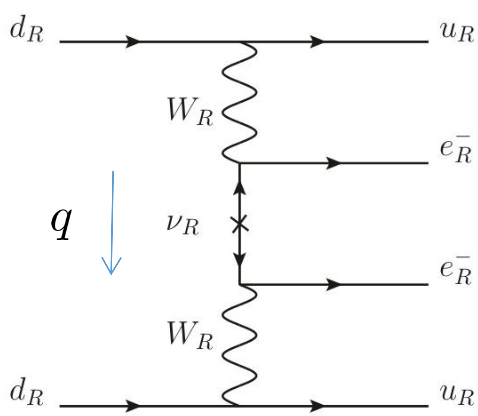
$$m_i^2 \ll -q^2$$

$$\longrightarrow \quad P_L \frac{m_i}{q^2} P_L$$

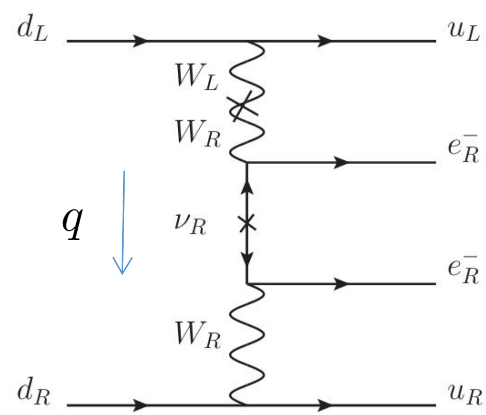
$$\langle m_{\beta\beta} \rangle = |\sum_i m_i U_{ei}^2|$$

# Neutrinoless double beta decay

Non-standard mechanisms:




$$-q^2 \sim (200\ \mathrm{MeV})^2$$




$$-q^2 \sim (200\ \mathrm{MeV})^2$$

**Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165**
**Doi et al., Prog.Theor.Phys. 66 (1981) 1739**
**Tello et al., Phys.Rev.Lett. 106 (2011) 151801; S.-F. Ge, M. Lindner, S. Patra, 1508.07286 (JHEP); Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004**
**and many others**

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**G. Prezeau, M. Ramsey-Musolf, P. Vogel, Phys.Rev.D 68 (2003)**
**V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, E. Mereghetti 1806.02780 (JHEP)**
**GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL)**
**J. de Vries, GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2209.03031 (JHEP)**

# Neutrinoless double beta decay

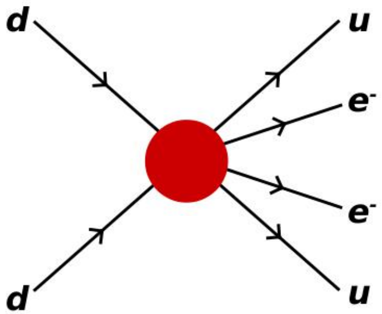
Non-standard mechanisms:

sterile neutrino mass dependence

$$P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

$$\xrightarrow{m_i^2 \ll -q^2} \quad P_R \frac{m_i}{q^2} P_R$$

$$\xrightarrow{m_i^2 \gg -q^2} \quad -P_R \frac{1}{m_i} P_R$$




$$m_i \sim M_{W_R} \sim \Lambda$$

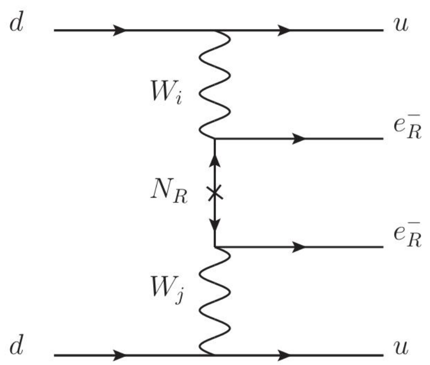
$$\sim c/\Lambda^5$$

$$\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee}/p^2} = c(\frac{3.3 \text{ TeV}}{\Lambda})^5 \frac{0.1 \text{ eV}}{m_\nu^{ee}}$$

# Neutrinoless double beta decay

Non-standard mechanisms:

left-right mixing and chiral enhancement




$(i,j) = (R,R) \qquad \bar{u}_R \gamma_\mu d_R \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_1' \bar{e}_R e_R^c$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \left( \frac{M_W}{M_{W_R}} \right)^4 p^0$$

$(i,j) = (1,2) \qquad \bar{u}_L \gamma_\mu d_L \bar{u}_R \gamma_\mu d_R \bar{e}_R e_R^c \sim O_4 \bar{e}_R e_R^c$

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{1}{m_N} \sin 2\beta \left( \frac{M_W}{M_{W_R}} \right)^4 \Lambda_\chi^2 p^{-2}$$

**G. Prezeau, M. Ramsey-Musolf, P. Vogel, Phys.Rev.D 68 (2003)**

*backup slides*

# Neutrinoless double beta decay

Non-standard mechanisms:

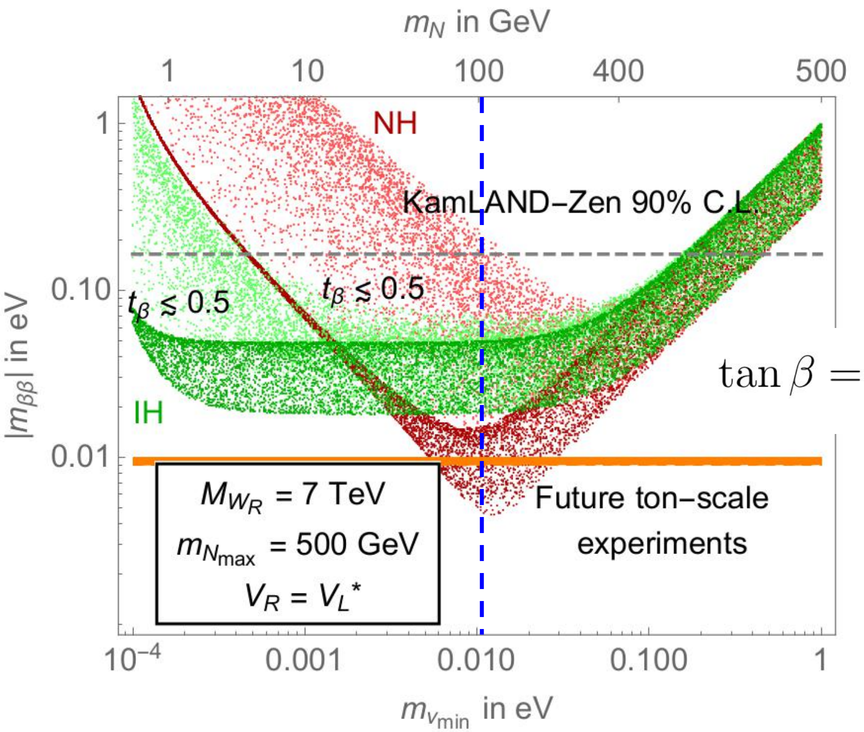
$$P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

$$\xrightarrow{m_i^2 \gg -q^2} \quad -P_R \frac{1}{m_i} P_R$$

type-II seesaw dominance:

$$m_4 = \frac{m_1}{m_3} m_{N_{\max}} \qquad m_{N_{\max}} \equiv m_6$$

$$m_N \simeq 200\ \mathrm{GeV} \cdot \frac{m_1}{0.01\ \mathrm{eV}} \cdot \frac{m_{N_{\max}}}{1\ \mathrm{TeV}}$$




$$\tan\beta = \frac{v_2}{v_1}$$

**GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2009.01257 (PRL)**

# Neutrinoless double beta decay

Non-standard mechanisms:

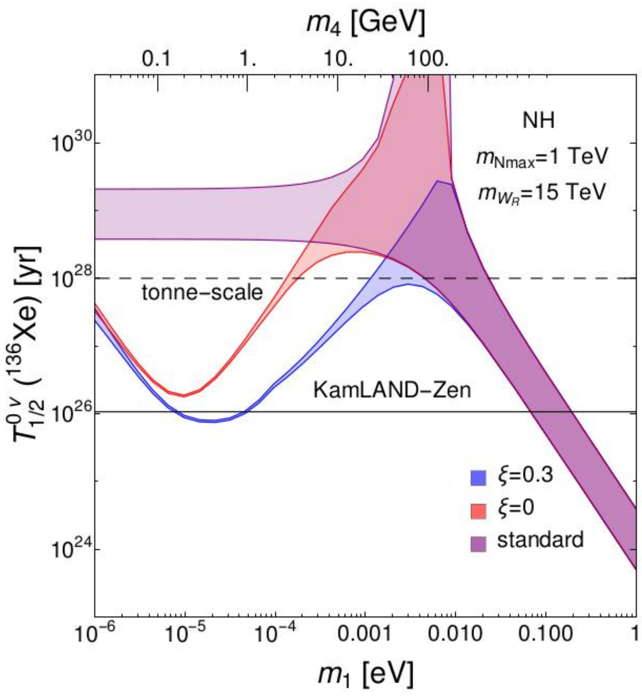
$$P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_R = P_R \frac{m_i}{q^2 - m_i^2} P_R$$

$$m_i^2 \ll -q^2 \quad \longrightarrow \quad P_R \frac{m_i}{q^2} P_R$$

type-II seesaw dominance:

$$m_4 = \frac{m_1}{m_3} m_{N_{\rm max}} \qquad m_{N_{\rm max}} \equiv m_6$$

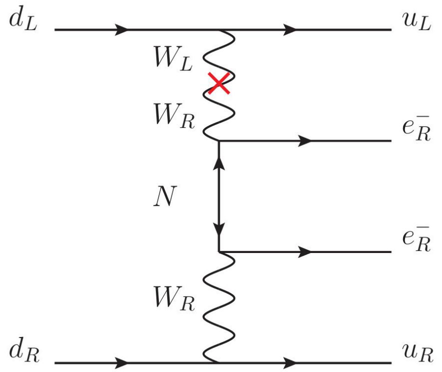
$$m_N \simeq 200 \text{ GeV} \cdot \frac{m_1}{0.01 \text{ eV}} \cdot \frac{m_{N_{\rm max}}}{1 \text{ TeV}}$$

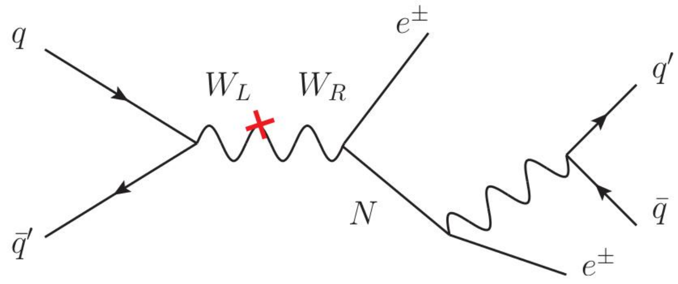



**J. de Vries, GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2209.03031 (JHEP)**

# Interplay with LHC searches

w/ left-right mixing

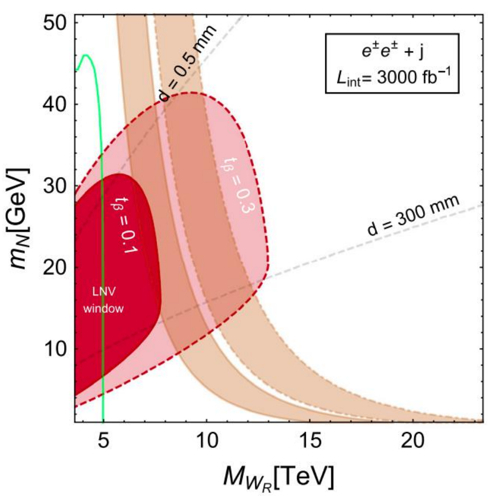



decay length of *N*:

$$d_{LR} \simeq \frac{1.2b}{1+\sin^2(2\beta)}\left(\frac{10\mathrm{GeV}}{m_N}\right)^5\left(\frac{M_{W_R}}{10\mathrm{TeV}}\right)^4 [m]$$

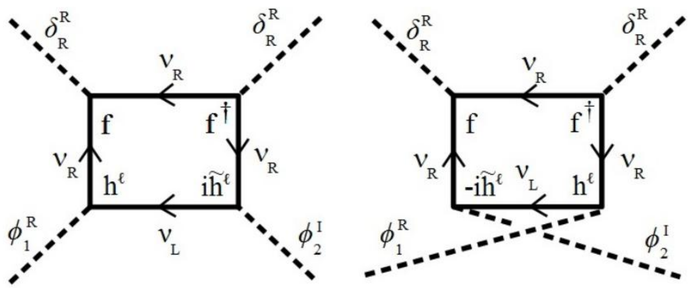
long-lived particle




**GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2202.01789 (PRD)**

# Connection to strong CP problem

$\bar{\theta}$ can be generated from leptonic CP violation with sterile neutrino in the loop




**R. Kuchimanchi, 1408.6382 (PRD)**

$$V \supset \left[\alpha_2 \,\mathrm{Tr}\left(\Delta_R^\dagger \Delta_R\right) + \text{ h.c. }\right] \mathrm{Tr}(\tilde{\Phi}\Phi)$$

At one-loop level:

$$\bar{\theta}_{\text{loop}} \simeq \frac{1}{16\pi^2} \frac{m_t}{m_b} \frac{1}{v_R^2 v^2} \,\mathrm{Im}\,\mathrm{Tr}\left(M_N^T M_N^* \left[M_D, M_\ell\right]\right) \ln \frac{M_{Pl}}{v_R}$$

$$M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

Upper bound on sterile neutrino mass

$$\bar{\theta}_{\text{loop}} \propto M_N^{5/2}$$

**G. Senjanovic and V. Tello, 2004.04036 (IJMPA)**

# Connection to strong CP problem

In the minimal LRSM with parity, if $V_R = V_L$

$$M_D = V_L m_N \sqrt{\frac{v_L}{v_R} - \frac{m_\nu}{m_N}} V_L^\dagger$$

Senjanovic estimated

$$M_N \lesssim 500 \text{ GeV} \qquad \text{for } M_{W_R} \simeq 10 \text{ TeV}$$

But...

An additional motivation of our study was to scrutinize the possible connection between light sterile neutrinos and the strong CP problem identified in refs. [37, 38]. To our surprise, we found for certain representative cases, namely $U_R = U^*_{\text{PMNS}}$ and $U_R = \mathbf{1}$ in the type-I dominance of $\mathcal{P}$-symmetric mLRSM, that the loop contributions to $\bar{\theta}$ vanish, in conflict with the statements of refs. [37, 38]. It remains to be seen whether this conclusion applies in general. Recently, ref. [107] also studied other leptonic observables such as $\mu \to eee$,

$$U_{\text{PMNS}} = V_L, \; U_R^* = V_R$$

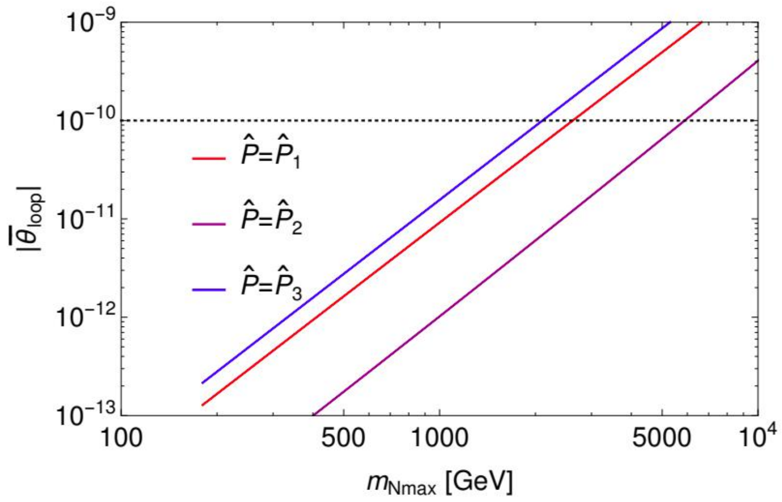
**J. de Vries, GL, M. J. Ramsey-Musolf, J. C. Vasquez, 2209.03031 (JHEP)**

# Connection to strong CP problem

General parameterization of $V_R$:

$$V_R = \hat{P} V_L, \quad \hat{P} \equiv P V_L \sqrt{m_N m_\nu}^{-1} V_L^\dagger$$

The Hermicity of $M_D$ requires that $\hat{P}$ is unitary, and $P$ is symmetric or anti-symmetric




**GL, Ding-Yi Luo, Xiang Zhao, 2404.16740**

$$\hat{P}_1 = i \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \hat{P}_2 = i \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\hat{P}_3 = i \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & -\frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \end{pmatrix}$$

# Connection to strong CP problem

General parameterization of $V_R$:

$$V_R = \hat{P} V_L, \quad \hat{P} \equiv P V_L \sqrt{m_N m_\nu}^{-1} V_L^\dagger$$

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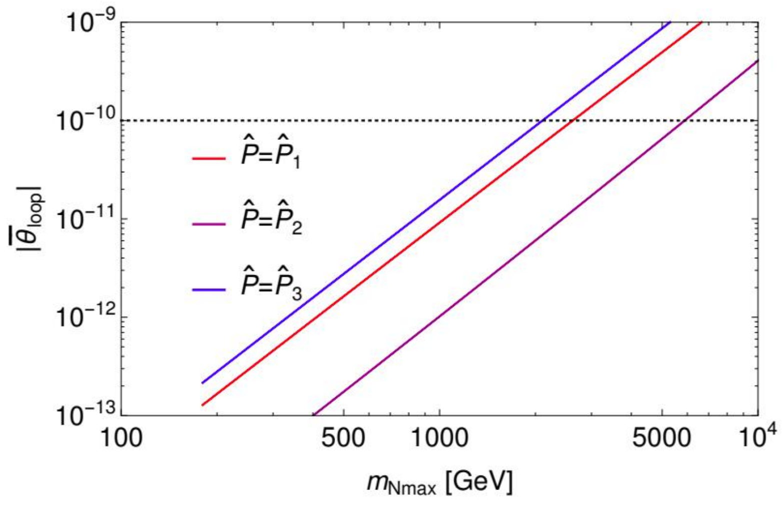



**GL, Ding-Yi Luo, Xiang Zhao, 2404.16740**

$$\hat{P}_1 = i\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \hat{P}_2 = i\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

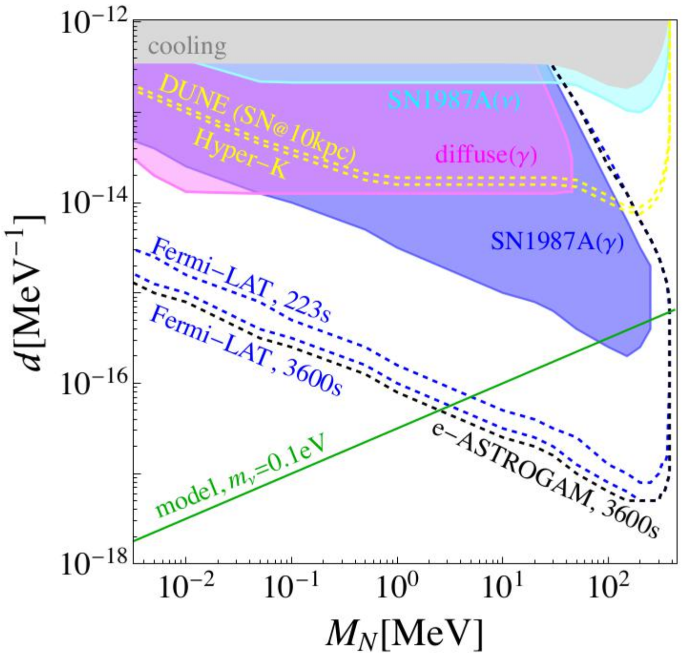
$$\hat{P}_3 = i\begin{pmatrix} \frac{1}{2} & \frac{1}{2} & -\frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \end{pmatrix}$$

BP: $\hat{P} = \hat{P}_1 \qquad m_N = \begin{pmatrix} 2.86\ \text{TeV} & 0 & 0 \\ 0 & 3.32\ \text{GeV} & 0 \\ 0 & 0 & 57.2\ \text{MeV} \end{pmatrix} \qquad \bar{\theta}_{\rm loop} = -1.241335 \times 10^{-10}$

$0\nu\beta\beta$ decay

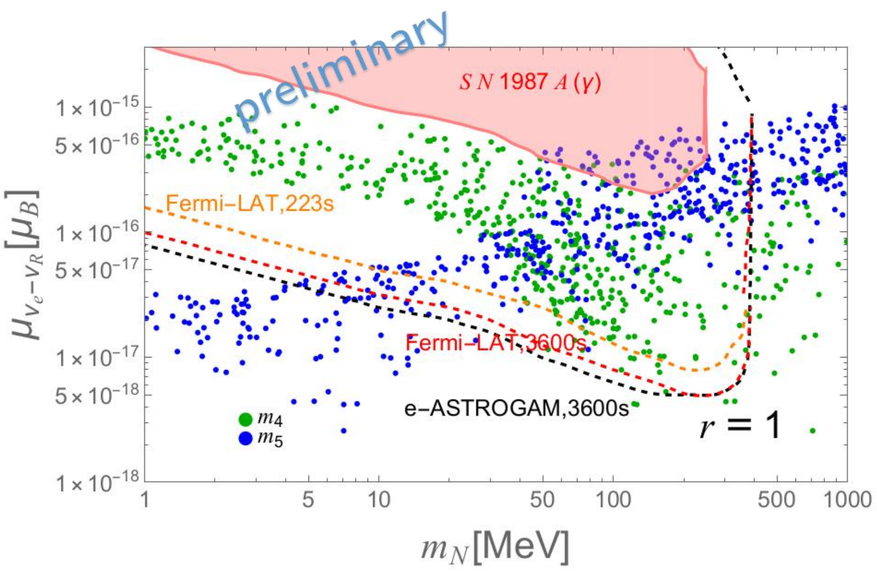
# Connection to neutrino magnetic moement

Active-sterile NMM:




**V. Brdar, A. de Gouvêa, Y.-Y. Li, P. A. N. Machado, 2302.10965 (PRD)**

model independent



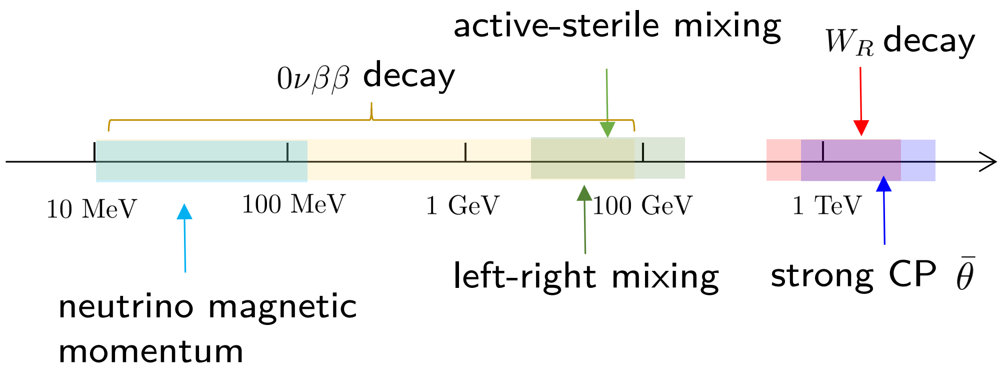

**GL, Xiang Zhao, work in progress**

simplified model: common origins of neutrino masses, NMM and $0\nu\beta\beta$ decay

# Summary

- Sterile neutrinos provide a unique insight into new physics, including the understanding of neutrino masses and connection to strong CP problem.

- This talk:




- Outlook:
  connections of sterile neutrinos to baryon asymmetry and dark matter

Thanks for your attention!

# backup slides

# Effective field theory approach

Dim-9 LEFT operators: $\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c$

- lepton bilinear

$$\bar{e}\Gamma_3 e^c = \bar{e}_L e^c_L\ , \bar{e}_R e^c_R\ , \bar{e}\gamma_\mu\gamma_5 e^c$$

- quark biliners

**M. L. Graesser, 1606.04549 (JHEP)**

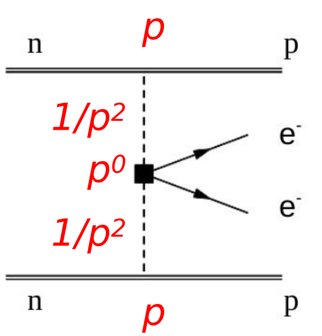
$$O_1 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_L \gamma^\mu \tau^+ q^\beta_L\,, \qquad O'_1 = \bar{q}^\alpha_R \gamma_\mu \tau^+ q^\alpha_R\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_2 = \bar{q}^\alpha_R \tau^+ q^\alpha_L\ \bar{q}^\beta_R \tau^+ q^\beta_L\,, \qquad O'_2 = \bar{q}^\alpha_L \tau^+ q^\alpha_R\ \bar{q}^\beta_L \tau^+ q^\beta_R\,,$$

$$O_3 = \bar{q}^\alpha_R \tau^+ q^\beta_L\ \bar{q}^\beta_R \tau^+ q^\alpha_L\,, \qquad O'_3 = \bar{q}^\alpha_L \tau^+ q^\beta_R\ \bar{q}^\beta_L \tau^+ q^\alpha_R\,,$$

$$O_4 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,,$$

$$O_5 = \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\beta_L\ \bar{q}^\beta_R \gamma^\mu \tau^+ q^\alpha_R\,,$$




$\sim p^{-2}$

$$O^\mu_6 = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L \tau^+ q_R\right)\ , \qquad O^{\mu\prime}_6 = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R \tau^+ q_L\right)\ ,$$

$$O^\mu_7 = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ , \qquad O^{\mu\prime}_7 = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ ,$$

$$O^\mu_8 = \left(\bar{q}_L \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R \tau^+ q_L\right)\ , \qquad O^{\mu\prime}_8 = \left(\bar{q}_R \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L \tau^+ q_R\right)\ ,$$

$$O^\mu_9 = \left(\bar{q}_L t^a \tau^+ \gamma^\mu q_L\right)\left(\bar{q}_R t^a \tau^+ q_L\right)\ , \qquad O^{\mu\prime}_9 = \left(\bar{q}_R t^a \tau^+ \gamma^\mu q_R\right)\left(\bar{q}_L t^a \tau^+ q_R\right)\ ,$$

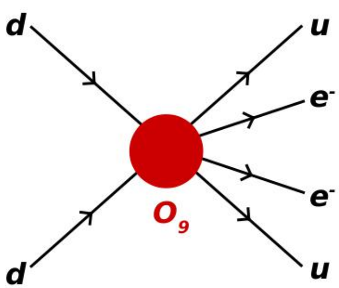
# Effective field theory approach

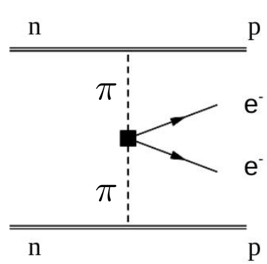
LECs are ordered in powers of $p/\Lambda_\chi$ using chiral effective field theory

$$\bar{u}\Gamma_1 d\ \bar{u}\Gamma_2 d\ \bar{e}\Gamma_3 e^c \quad \Rightarrow \quad \underline{\pi^-\pi^-\bar{e}_R e^c_R} \qquad \left(\bar{p}S\cdot\partial\pi^- n\right)\bar{e}_R e^c_R \qquad (\bar{p}n)(\bar{p}n)\bar{e}_R e^c_R$$

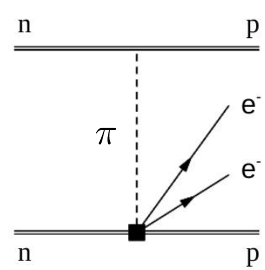
$$\partial_\mu\pi^-\partial^\mu\pi^-\bar{e}_R e^c_R \qquad \left(\bar{p}S\cdot\partial\pi^- n\right)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c \qquad (\bar{p}n)(\bar{p}n)v^\mu\bar{e}\gamma_\mu\gamma_5 e^c$$

**Prezeau, Ramsey-Musolf, Vogel, PRD 68 (2003) 034016** $\quad R\to L$

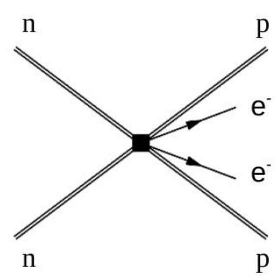



$p^{-2}$, $p^0$




$p^0$

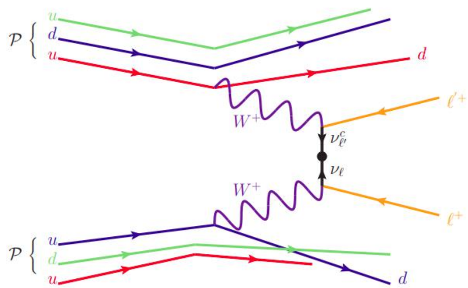



$p^0$

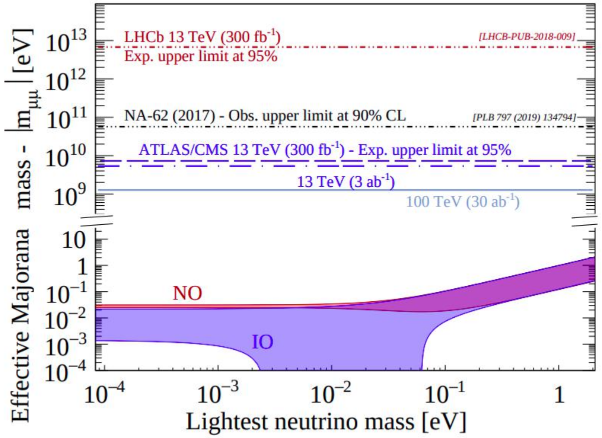
$p^{-2}: \ \dfrac{\Lambda_\chi^2}{p^2} \simeq 25$ chiral enhancement at the amplitude level

# LHC searches

- Searches for LNV at the LHC



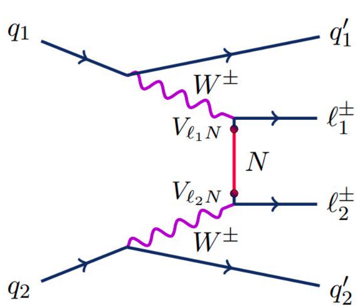
active neutrinos



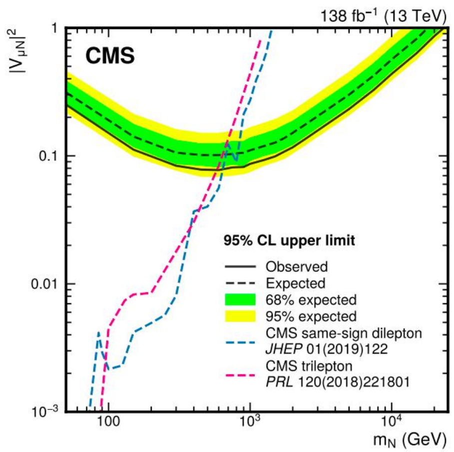

LHC Run 2

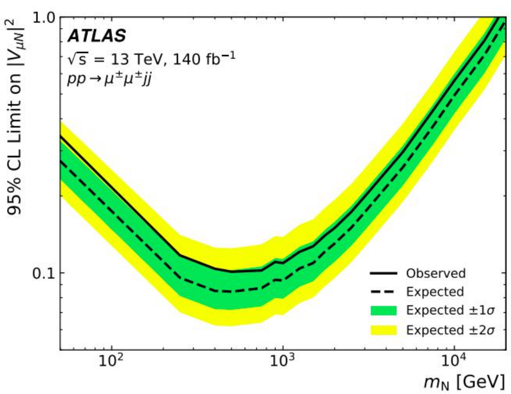
CMS : $|m_{\mu\mu}| \leq 10.8$ GeV

ATLAS : $|m_{\mu\mu}| \leq 16.7$ GeV



sterile neutrino




**CMS, 2206.08956 (PRL)**

**ATLAS, 2305.14931 (EPJC)**