Probing Lepton-Number-Violating New Physics at Colliders

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Lepton number

Conserved quantum number in the SM:

- In 1953, Konopinski and Mahmoud introduced the concept of lepton number, which must be conserved in reactions
- In 1959, Pontecorvo proposed that the lepton numbers of electrons and muons should be treated separately, which sucessfully explained the absence of $\mu \to e\gamma$ in experiments he conducted

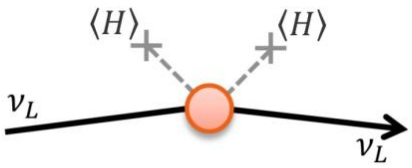
Lepton	Conserved Quantity	Lepton Number
e^-	L_e	+1
ν_e		+1
μ^-	L_μ	+1
ν_μ		+1
τ^-	L_τ	+1
ν_τ		+1

Anti-Lepton	Conserved Quantity	Lepton Number
e^+	L_e	-1
$\bar{\nu}_e$		-1
μ^+	L_μ	-1
$\bar{\nu}_\mu$		-1
τ^+	L_τ	-1
$\bar{\nu}_\tau$		-1

L_e, L_μ and L_τ are each conserved quantities

Lepton number violation

- Majorana neutrino mass

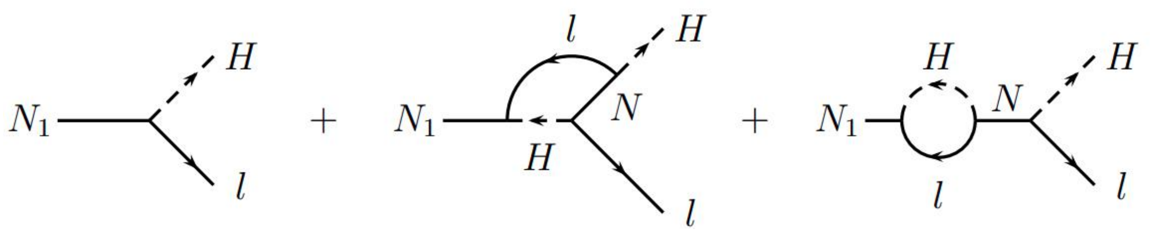


$$\mathcal{L}_M = \frac{C_5}{\Lambda}\left(\bar{L}^c\tilde{H}^*\right)\left(\tilde{H}^\dagger L\right) + \text{ h.c.} \qquad \Delta L = 2$$

$d = 5$ Weinberg operator **S. Weinberg 1979**

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

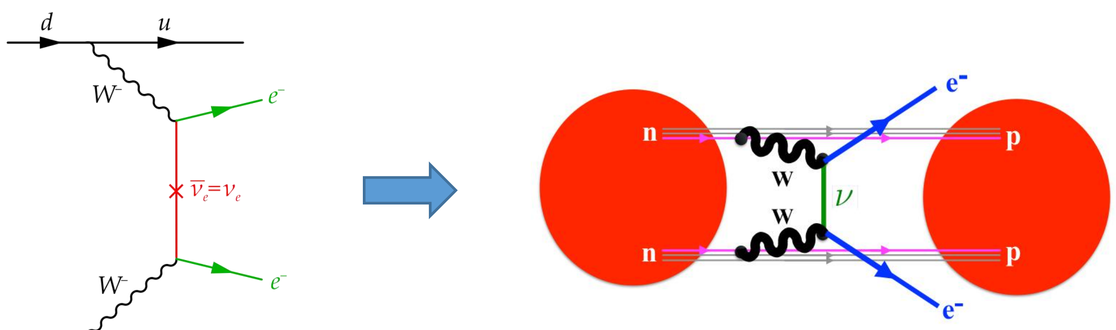
- Baryon Asymmetry in the Universe via leptogenesis



Fukugita, Yanagida, 1986

Neutrinoless double beta decay

$0\nu\beta\beta$ decay and Majorana nature of neutrinos



M. Goeppert-Mayer, Phys.Rev. 48 (1935) 512
W.H. Furry, Phys. Rev. 56 (1939) 1184

- Global experimental efforts: KamLAND-Zen, PandaX, CDEX, ...
- Current limit: $T^{0\nu}_{1/2}(\mathrm{Xe}) > 3.8 \times 10^{26}$ year **KamLAND-Zen, 2406.11438**
- Future prospects: $T^{0\nu}_{1/2} \gtrsim 10^{28}$ year **M. Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002**

Neutrinoless double beta decay

The most sensitive low-energy probe to date

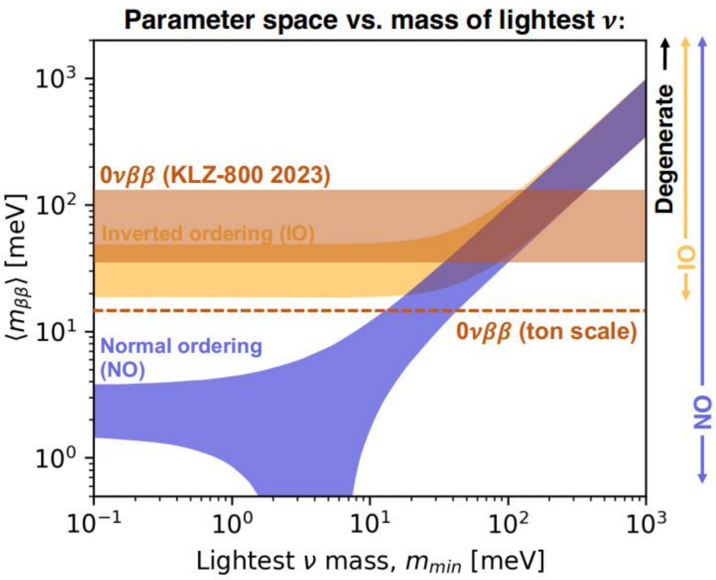
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} M_{0\nu}^2 \langle m_{\beta\beta} \rangle^2$$

$G_{0\nu}$:	phase space factor
$M_{0\nu}$:	nuclear matrix element
$\langle m_{\beta\beta} \rangle$:	effective Majorana mass

In standard mechanism:

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

neutrino oscillation data as inputs



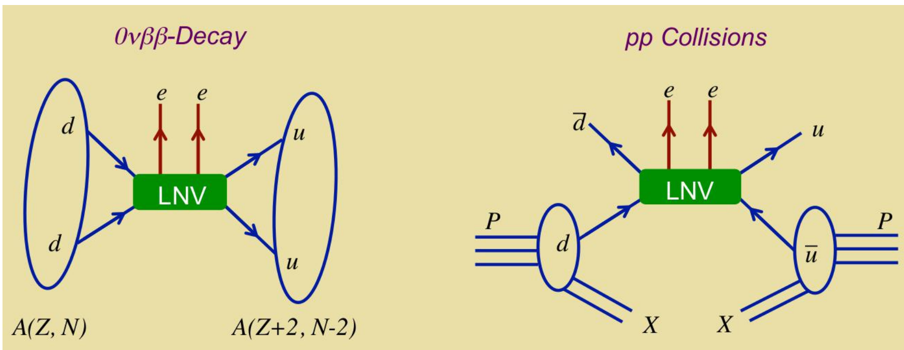
C. Adams, et a., 2212.11099

Collider opportunities

- $0\nu\beta\beta$ decay would undoubtedly imply the Majorana nature of neutrinos, irrespective of the origins of $\Delta L = 2$ LNV interations

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

- Complementary searches:



credit: M. Ramsey-Musolf

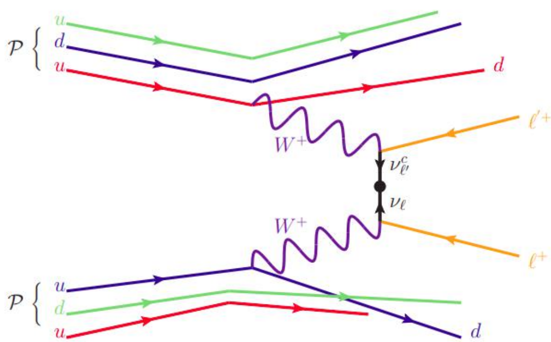
  - smoking-gun signature $e^{\pm}e^{\pm}jj$, low SM backgrounds
  - enhanced cross section from kinematics (resonance, VBS)
  - more options of lepton flavors

VBS = vector boson scattering

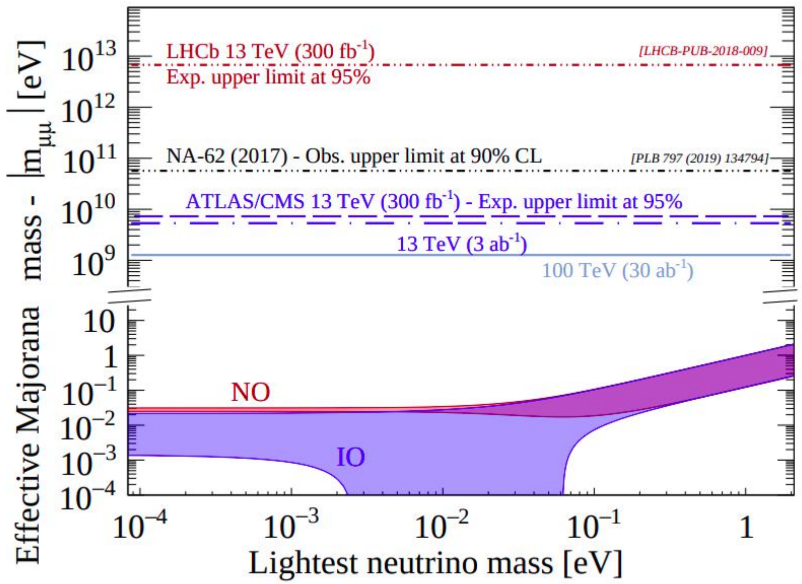
LHC searches

- Probing Weinberg operator

VBS:



$$\sim G_F^2 \frac{m_\nu^{\ell\ell}}{q^2}$$



LHC Run 2

CMS : $|m_{\mu\mu}| \leq 10.8$ GeV **CMS, 2206.08956 (PRL)**

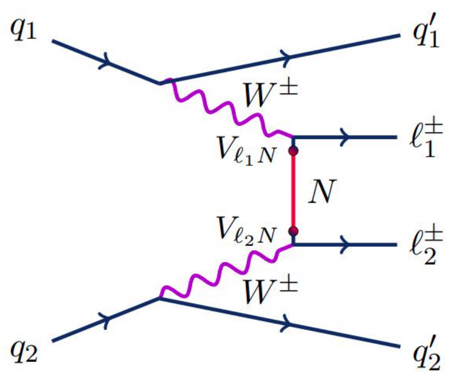
ATLAS : $|m_{\mu\mu}| \leq 16.7$ GeV **ATLAS, 2305.14931 (EPJC)**

low sensitivity due to large q^2

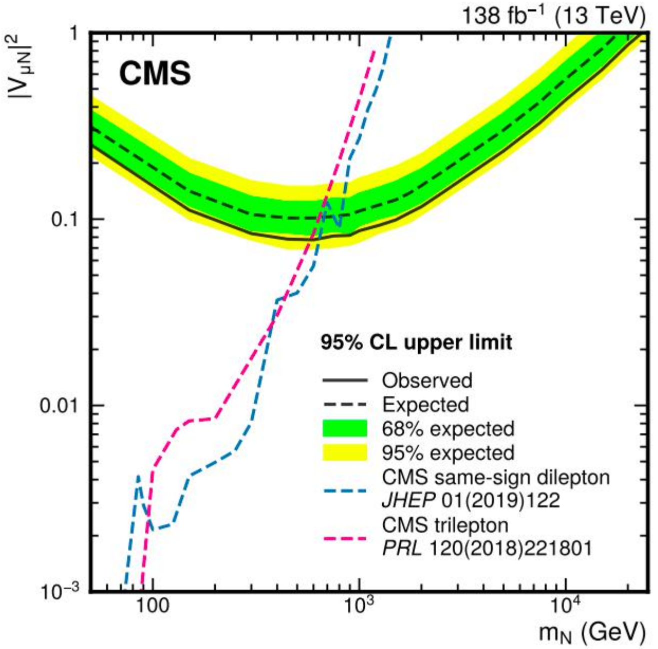
LHC searches

- Searching for sterile neutrino

VBS:



$$\sim G_F^2 \frac{m_N^{\ell\ell}}{q^2}$$



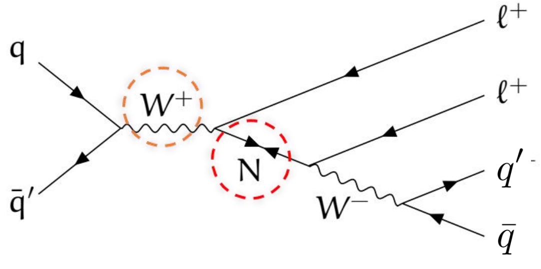
increased sensitivity due to large m_N

CMS, 2206.08956 (PRL)

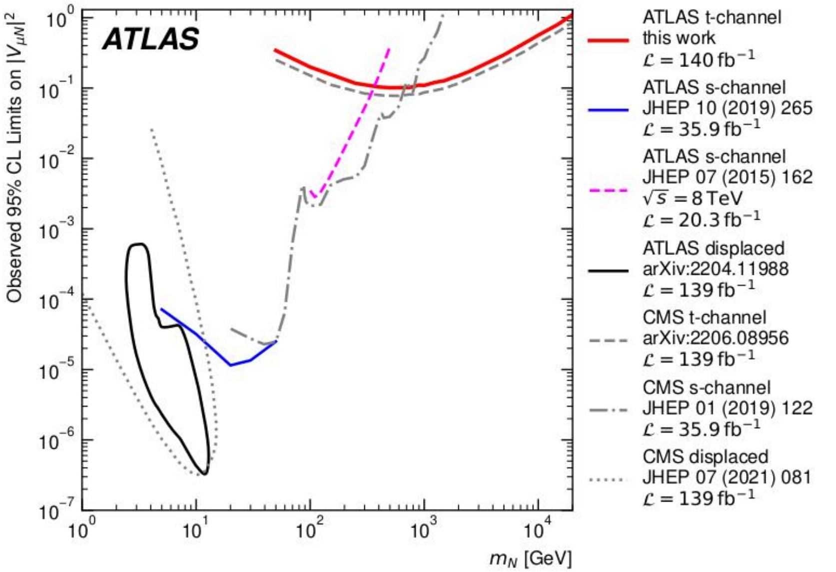
LHC searches

- Searching for sterile neutrino

Resonance:

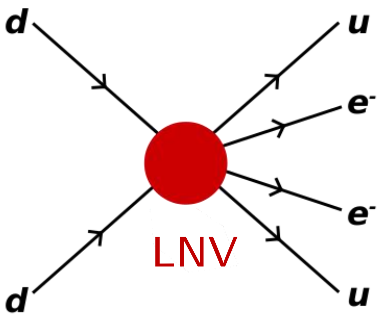


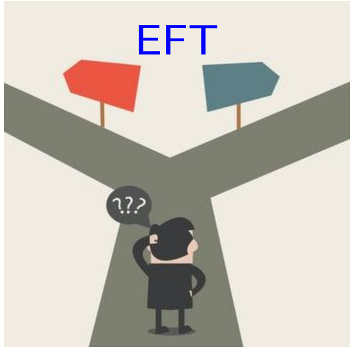
increased sensitivity for $m_N < m_W$



PoS LHCP2024 (2025) 032

EFT approach to LNV





LNV interactions

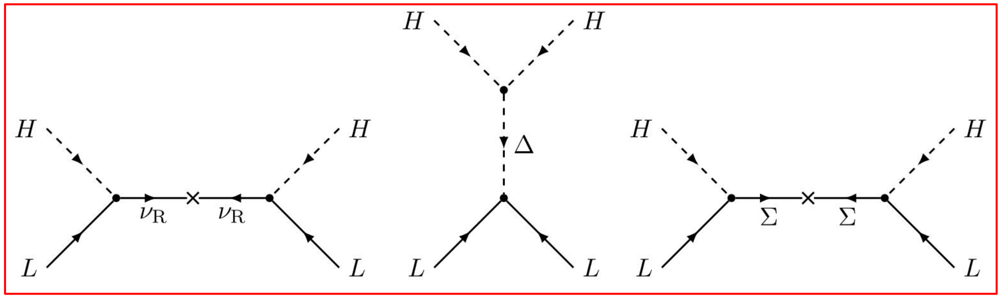
- LNV interactions have odd mass dimension

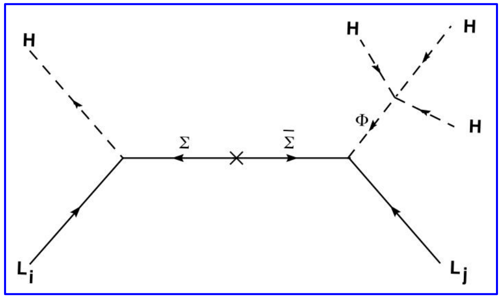
$$d \text{ is even} \longleftrightarrow |\Delta B - \Delta L| = 0, 4, 8, 12, \ldots$$
$$d \text{ is odd} \longleftrightarrow |\Delta B - \Delta L| = 2, 6, 10, 14, \ldots$$

A. Kobach, 1604.05726 (PLB)

- Neutrino masses: $(\Delta B, \Delta L) = (0, \pm 2)$

$d = 5$ Weinberg operator: $(LH)(LH)$ $d = 7$ operator: $LLHH(H^\dagger H)$





Minkowski, 1977; Konetschny, Kummer, 1977; Foot, Lew, He, Joshi, 1989

Babu, Nandi, Tavartkiladze, 0905.2710 (PRD)

$d = 7$ SMEFT

Operators with $(\Delta B, \Delta L) = (0, \pm 2)$

Type	$\mathcal{O}$	Operator	
$\Psi^2 H^4$	$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i L_r^m)H^j H^n (H^\dagger H)$	m_ν
$\Psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i \gamma_\mu e_r)H^j (H^m iD^\mu H^n)$	
$\Psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i D_\mu L_r^j)(H^m D^\mu H^n)$	two D^μ
	$\mathcal{O}_{LHD2}^{pr}$	$\epsilon_{im}\epsilon_{jn}(\overline{L_p^c}^i D_\mu L_r^j)(H^m D^\mu H^n)$	
$\Psi^2 H^2 X$	$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i \sigma_{\mu\nu} L_r^m)H^j H^n B^{\mu\nu}$	
	$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^c}^i \sigma_{\mu\nu} L_r^m)H^j H^n W^{I\mu\nu}$	
$\Psi^4 D$	$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}(\overline{d_p}\gamma_\mu u_r)(\overline{L_s^c}^i iD^\mu L_t^j)$	one D^μ
$\Psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_p}L_r^i)(\overline{L_s^c}^j L_t^m)H^n$	
	$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}(\overline{d_p}L_r^i)(\overline{u_s^c}e_t)H^j$	
	$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_p}L_r^i)(\overline{Q_s^c}^j L_t^m)H^n$	
	$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_p}L_r^i)(\overline{Q_s^c}^j L_t^m)H^n$	
	$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}(\overline{Q_p}u_r)(\overline{L_s^c}L_t^i)H^j$	

L. Lehman, 1410.4193 (PRD);
Y. Liao and X.-D. Ma, 1607.07309 (JHEP)

$d = 9$ SMEFT

Operators with $(\Delta B, \Delta L) = (0, \pm 2)$

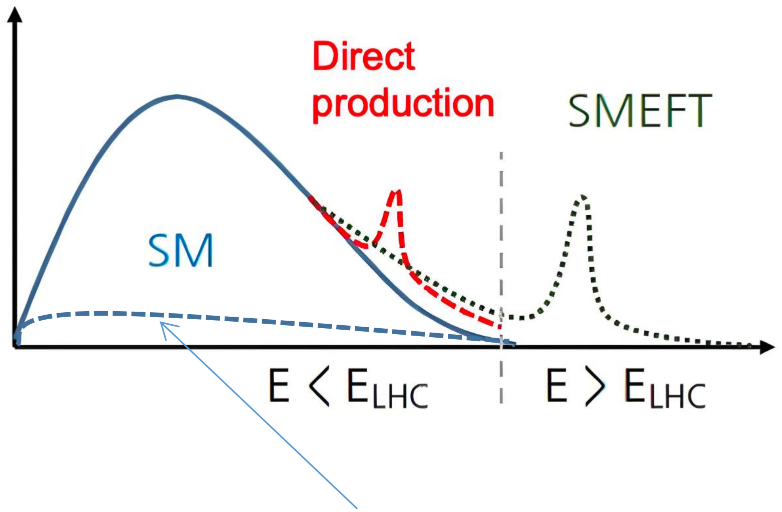
$L^2 H^4 H^{*2}$	$\mathcal{O}_{LLH^6} = \epsilon_{ik}\epsilon_{jl}(\overline{L^{\mathrm{C},i}} L^j) H^k H^l (H^\dagger H)^2$	m_ν
$e^2 H^4 D^2$	$\mathcal{O}_{eeH^4D^2} = \epsilon_{ij}\epsilon_{kl}(\overline{e^{\mathrm{C}}} e)(H^i D_\mu H^j)(H^k D^\mu H^l)$	
$L^2 H^3 H^* D^2$	$\mathcal{O}_{LLH^4D^21} = \epsilon_{ik}\epsilon_{jl}(H^\dagger D_\mu H)(\overline{L^{\mathrm{C},i}} D^\mu L^j) H^k H^l$	
	$\mathcal{O}_{LLH^4D^22} = \epsilon_{ik}\epsilon_{jl}(H^\dagger D_\mu H)(\overline{L^{\mathrm{C},i}} L^j) H^k D^\mu H^l$	
	$\mathcal{O}_{LLH^4D^23} = \epsilon_{ik}\epsilon_{jl}(H^\dagger H)(\overline{D_\mu L^{\mathrm{C},i}} D^\mu L^j) H^k H^l$	two D^μ
	$\mathcal{O}_{LLH^4D^24} = \epsilon_{ik}\epsilon_{jl}(H^\dagger H)(\overline{L^{\mathrm{C},i}} D_\mu L^j) D^\mu H^k H^l$	
	$\mathcal{O}_{LLH^4D^25} = \epsilon_{ik}\epsilon_{jl}(H^\dagger H)(\overline{L^{\mathrm{C},i}} D_\mu L^j) H^k D^\mu H^l$	
	$\mathcal{O}_{LLH^4D^26} = \epsilon_{ik}\epsilon_{jl}(H^\dagger D_\mu H)(\overline{L^{\mathrm{C},i}} i\sigma^{\mu\nu} L^j) D_\nu H^k H^l$	
$ud^* L^2 H H^* D$	$\mathcal{O}_{dLuLH^2D1} = \epsilon_{ij}(\bar{d} L^i)(\overline{u^{\mathrm{C}}} \gamma_\mu L^j)(H^\dagger i D^\mu H)$	
	$\mathcal{O}_{dLuLH^2D2} = \epsilon_{ik}\epsilon_{jl}(\bar{d} L^i)(\overline{u^{\mathrm{C}}} \gamma_\mu L^j) \tilde{H}^k i D^\mu H^l$	
	$\mathcal{O}_{dLuLH^2D3} = \epsilon_{ij}(\bar{d} L^i)(\overline{u^{\mathrm{C}}} \gamma_\mu L^j)[(i D^\mu H)^\dagger H]$	one D^μ
	$\mathcal{O}_{dLuLH^2D4} = \epsilon_{ik}\epsilon_{jl}(\bar{d} L^i)(\overline{u^{\mathrm{C}}} \gamma_\mu L^j)(i D^\mu \tilde{H})^k H^l$	
	$\mathcal{O}_{duLLH^2D} = \epsilon_{ik}\epsilon_{jl}(\bar{d} \gamma_\mu u)(\overline{L^{\mathrm{C},i}} i D_\mu L^j) \tilde{H}^k H^l$	

- imcomplete list here
- 384 for one generation

H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu, Y.-H. Zheng, 2007.07899 (PRD)
Y. Liao, X.-D. Ma, 2007.08125 (JHEP)

EFTs at the LHC

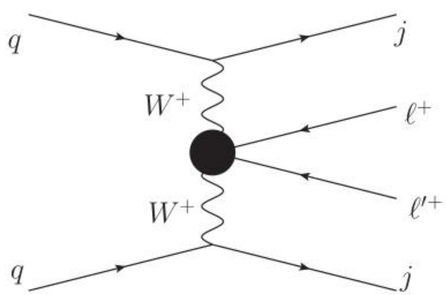
SMEFT paradigm:



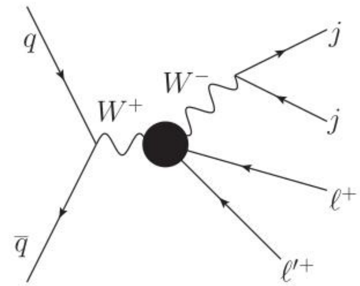
For the searches for LNV signals, there is almost no SM background

EFTs at the LHC

Operators with two covariant derivatives

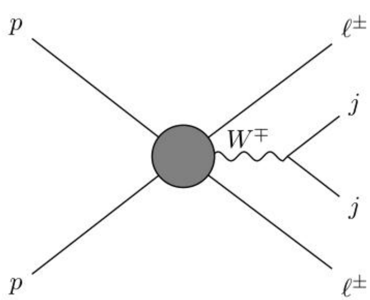


$d = 7,\ 9$

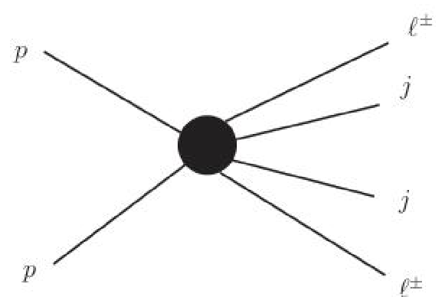


$d = 7,\ 9$

Operators with one or zero covariant derivative



$d = 7,\ 9$



$d = 9$

EFTs at the LHC

Operators with two covariant derivatives:

$$\left.\begin{aligned} &\frac{C^{(7)}_{\ell\ell'}}{\Lambda^3_{\rm LNV}}\left(\overline{\tilde{L}_\ell} D_\mu L_{\ell'}\right)\left(\tilde{H}^\dagger D^\mu H\right) + \text{H.c.} \\ &\frac{C^{(9)}_{\ell\ell'}}{\Lambda^5_{\rm LNV}}\overline{\ell^c_R}\ell'_R\left(\tilde{H}^\dagger D_\mu H\right)^2 \end{aligned}\right\} \quad \overline{\ell^c_R}\ell'_R W^+_\mu W^{+\mu}$$

At the HL-LHC,

M. Aoki, K. Enomoto, S. Kanemura, 2002.12265 (PRD)

- $pp \to \mu^+\mu^+ jj$

$$\Lambda^{(7)}_{\rm LNV} \gtrsim 1.8\ \text{TeV}, \quad \Lambda^{(9)}_{\rm LNV} \gtrsim 0.71\ \text{TeV}$$

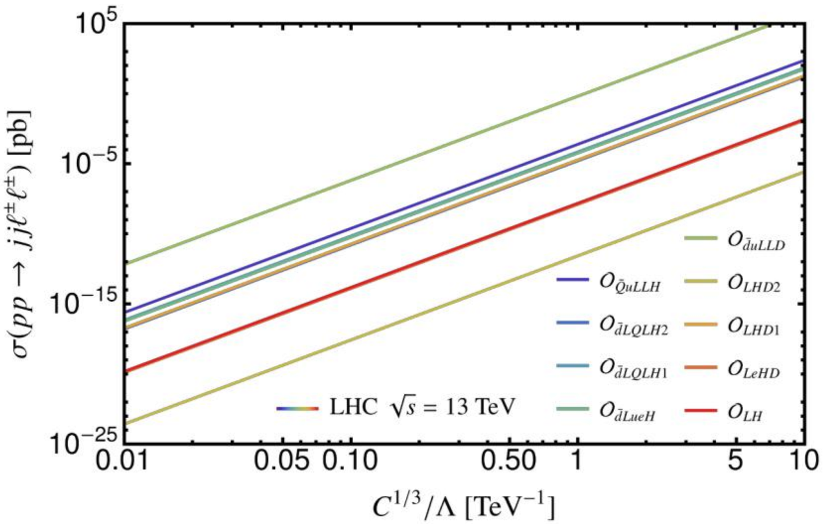
- $pp \to e^+\mu^+ jj$

$$\Lambda^{(7)}_{\rm LNV} \gtrsim 2.3\ \text{TeV}, \quad \Lambda^{(9)}_{\rm LNV} \gtrsim 0.82\ \text{TeV}$$

EFTs at the LHC

Operators with one covariant derivatives:

$$\mathcal{O}_{\bar{d}uLLD}^{prst} = \epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^c} i D^\mu L_t^j\right)$$

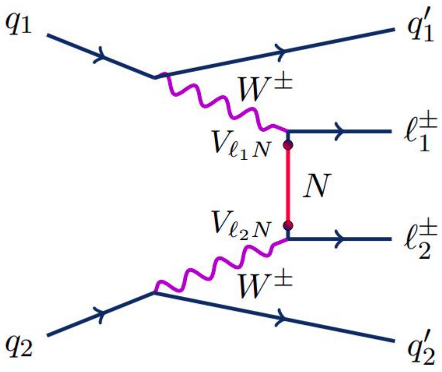


Operator	$\sigma(pp \to \mu^\pm\mu^\pm jj)$ (pb)		Λ_{LNV}	$\Lambda_{\text{LNV}}^{\text{future}}$
	LHC	FCC	[TeV]	[TeV]
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.4	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.90	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	1.1	4.3
$\mathcal{O}_{\bar{d}LueH}$	5.7×10^{-5}	0.035	1.1	4.5
$\mathcal{O}_{\bar{d}uLLD}$	0.64	210	5.0	19
$\mathcal{O}_{LHD2}$	2.7×10^{-12}	1.7×10^{-10}	0.075^*	0.18
$\mathcal{O}_{LHD1}$	1.9×10^{-5}	0.061	1.1	4.9
$\mathcal{O}_{LeHD}$	1.2×10^{-8}	3.1×10^{-8}	0.21^*	0.44
$\mathcal{O}_{LH}$	1.5×10^{-8}	2.0×10^{-6}	0.35^*	0.87

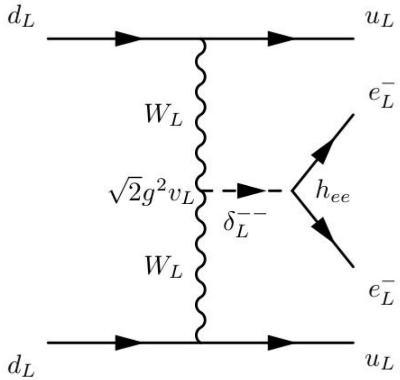
K. Fridell, L. Gráf, J. Harz, C. Hati, 2306.08709 (JHEP)

UV completions at the LHC

UVs for operators with *two* derivatives:

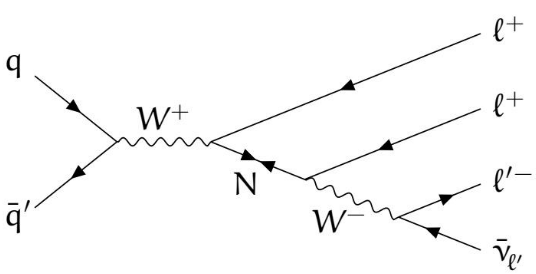


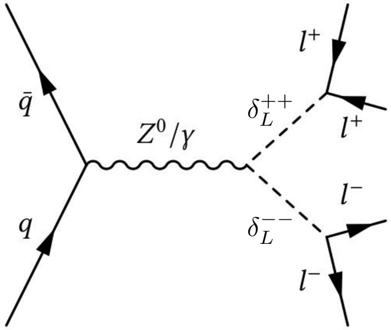
type-I seesaw



type-II seesaw

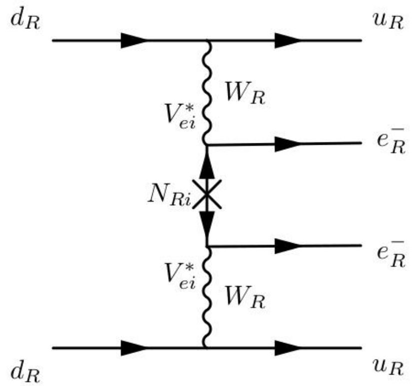
New channels:

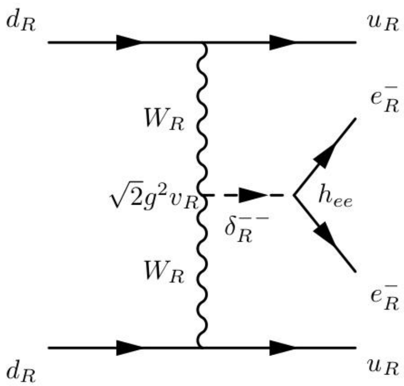




UV completions at the LHC

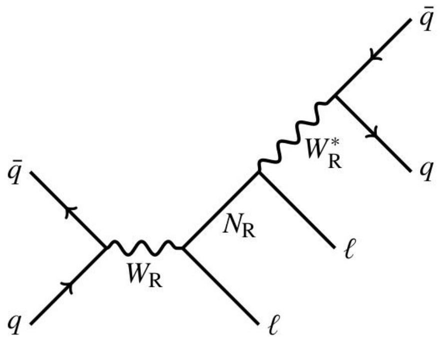
UVs for operators with *zero* derivative:

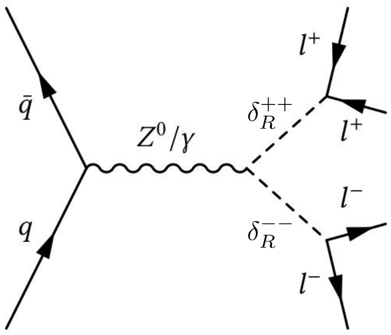




left-right symmetric models

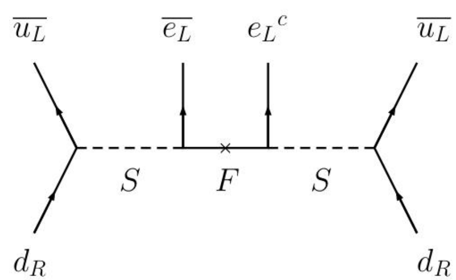
New channels:

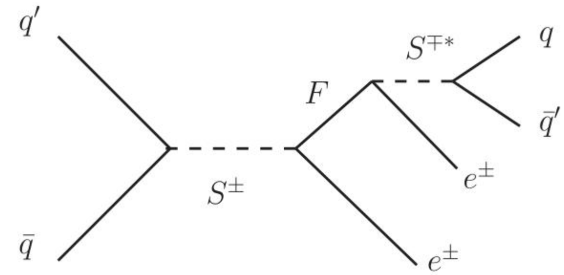




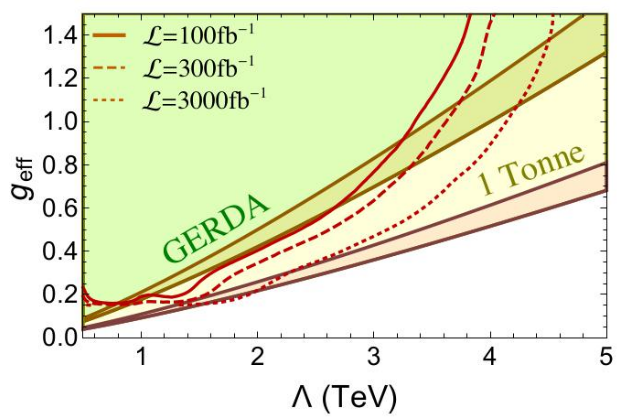
UV completions at the LHC

UVs for operators with *zero* derivative:

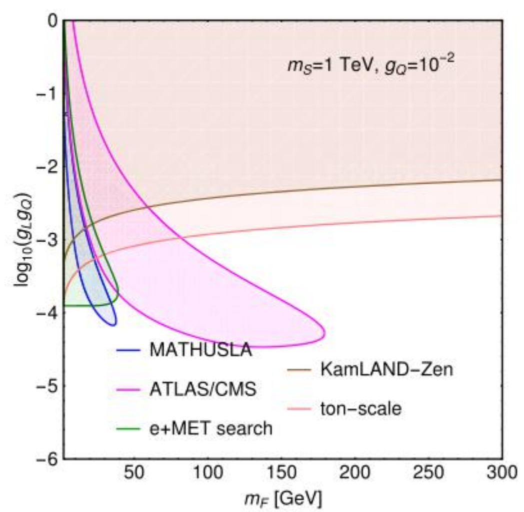




template: SUSY



T. Peng, M. J. Ramsey-Musolf, P. Winslow, 1508.04444 (PRD)



GL, M. J. Ramsey-Musolf, S. Su, J. C. Vasquez, 2109.08172 (PRD)

UV completions at the LHC

UVs for $d = 7$ operator with *one* derivative:

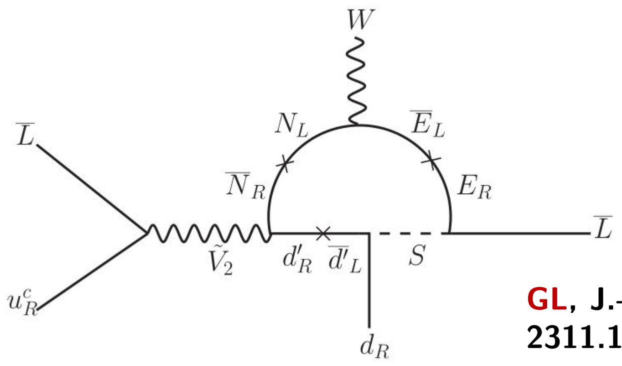
$$\mathcal{O}^{prst}_{\bar{d}uLLD} = \epsilon_{ij} \left(\overline{d_p}\gamma_\mu u_r\right) \left(\overline{L^c_s} i D^\mu L^j_t\right)$$

It must originate from a UV-completion containing a fermion mediator:

$$\mathcal{L}^{\Psi}_{\text{eff}} = \frac{\partial \mathcal{L}^{\text{int}}_{\Psi}}{\partial \bar{\Psi}} \left(\frac{1}{m^2_\Psi} + \frac{D^2 + \frac{1}{2} X_{\mu\nu}\sigma^{\mu\nu}}{m^4_\Psi} + \ldots \right) (i\not{D} + m_\Psi) \frac{\partial \mathcal{L}^{\text{int}}_{\Psi}}{\partial \Psi}$$

K. Fridell, L. Gráf, J. Harz, C. Hati, 2412.14268 (JHEP)

- No tree-level UV completion
- Example for one-loop UV completion:



GL, J.-H. Yu, X. Zhao, 2311.10079 (PRD)

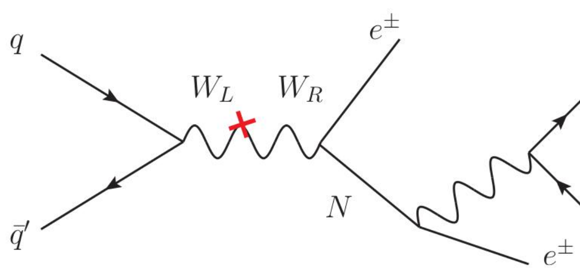
UV completions at the LHC

UVs for $d = 9$ operator with *one* derivative:

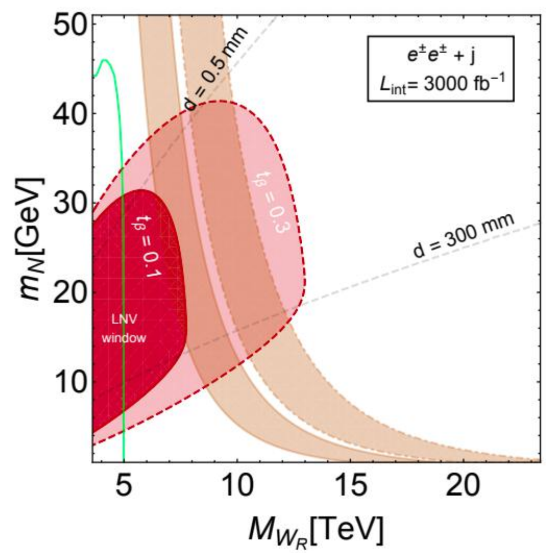
$$\mathcal{O}^{(1)}_{u\bar{d}e^2H^2D} = \epsilon^{ij}\left(\overline{d}^a_t\gamma^\mu e_r\right)(u_{sa}Ce_p)H_jD_\mu H_i$$

H.-L. Li, et al., 2007.07899 (PRD)

$W_L - W_L$ mixing: $$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix}\begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$



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



UV completions at the LHC

UVs for $d = 9$ operator with *one* derivative:

$$\mathcal{O}^{(1)}_{u\bar{d}e^2H^2D} = \epsilon^{ij}\left(\overline{d}^a_t\gamma^\mu e_r\right)(u_{sa}Ce_p)H_jD_\mu H_i$$

H.-L. Li, et al., 2007.07899 (PRD)

Leptoquark model:

$$\mathcal{L} \supset \lambda_{ed}(\bar{d}_R\gamma_\mu e_R)U_1^\mu + \lambda_{u\Psi}\tilde{R}_2^*\bar{u}_R^c\Psi_R + \lambda_{DH}U_1^{\mu\dagger}\tilde{R}_2\epsilon(iD_\mu H) + f_{\Psi e}\bar{\Psi}_L He_R + \text{H.c.}$$

template: SUSY

leptoquarks:

$$\tilde{R}_2 \in (3, 2, 1/6), \quad U_1 \in (3, 1, 2/3)$$

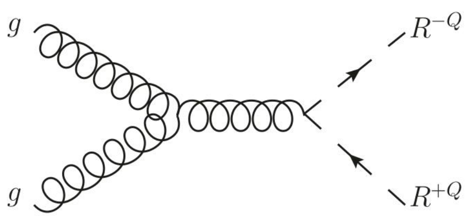
vector-like fermions:

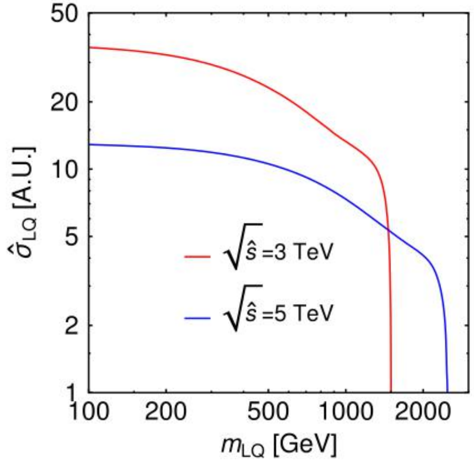
GL, J.-H. Yu, X. Zhao, 2311.10079 (PRD)

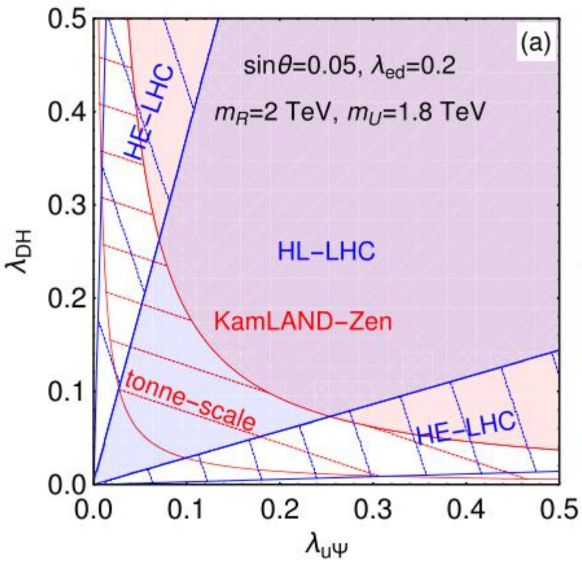
$$\Psi_L = \begin{pmatrix} N_L \\ E_L \end{pmatrix}, \quad \Psi_R = \begin{pmatrix} N_R \\ E_R \end{pmatrix}$$

UV completions at the LHC

Leptoquark pair production





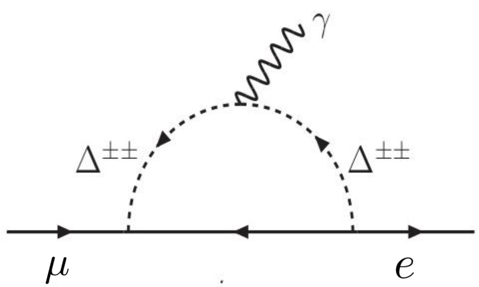


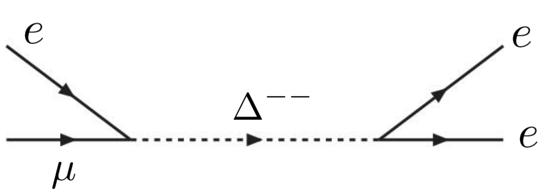
- Sensitive to the leptoquark mass
- LHC searches for TeV scale LNV are complementary to $0\nu\beta\beta$ decay searches

GL, J.-H. Yu, X. Zhao, 2311.10079 (PRD)

A light doubly-charged scalar

Charged lepton flavor violation:





$$\frac{m_{\Delta_L^{\pm\pm}}}{\sqrt{\left|\sum_\ell (f_L)^\dagger_{\mu\ell}(f_L)_{e\ell}\right|}} > 65 \text{ TeV} \qquad \frac{m_{\Delta_L^{\pm\pm}}}{\sqrt{\left|(f_L)^\dagger_{ee}(f_L)_{e\mu}\right|}} > 208 \text{ TeV}$$

In the type-II seesaw model, the Yukawa couplings are correlated with the neutrino masses and mixings:

$$\Delta_L = \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix} \qquad m_\nu = \sqrt{2} f_L v_L = U \hat{m}_\nu U^T$$

Δ_L^{++} can be $O(1)$ TeV only if all Yukawa couplings $f_L^{\ell\ell'} \lesssim 10^{-3}$

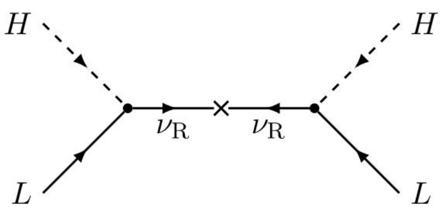
A light doubly-charged scalar

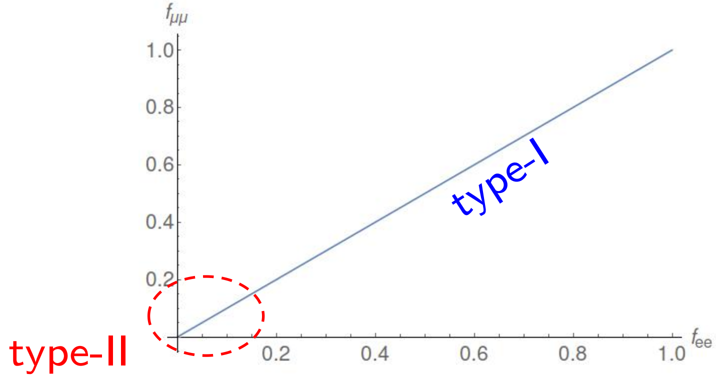
In the minimal left-right symmetric model

$f_L = f_R$ (parity) $\qquad f_L = f_R^\dagger$ (charge conjugation)

- If neutrinos obtain masses via the type-II seesaw mechanism, Δ_R^{++} can be $O(1)$ TeV only if all Yukawa couplings $f_R^{\ell\ell'} \lesssim 10^{-3}$
- If neutrinos obtain masses via the type-I seesaw mechanism, $\Delta_{L,R}^{++}$ can be $O(1)$ TeV if $f_{L,R}$ are diagonal

$$m_\nu = -M_D M_R^{-1} M_D^T, \quad M_R = \sqrt{2} f_R v_R$$





A light doubly-charged scalar

In left-right symmetric model with D-parity breaking

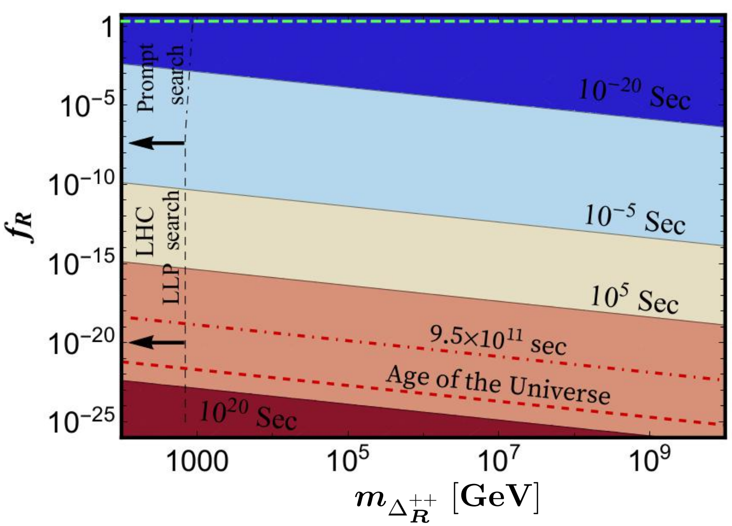
$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes P \to \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$$

mass spectra:

Chang, Mohapatra, Parida, Phys.Rev.Lett. 52 (1984) 1072; Phys.Rev.D 30 (1984) 1052

$$\mu^2_{\Delta_L} = \mu^2_\Delta + M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2$$
$$\mu^2_{\Delta_R} = \mu^2_\Delta - M\langle\eta\rangle + \lambda_2\langle\eta\rangle^2$$

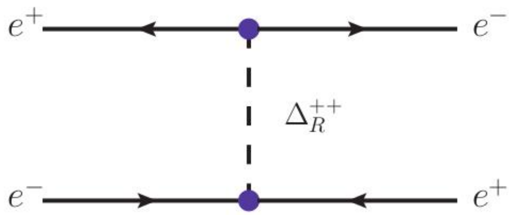
Δ_L^{++} is at the D-parity breaking scale, while Δ_R^{++} can be much lighter, and the Yukawa coupling matrix f_R is arbitrary



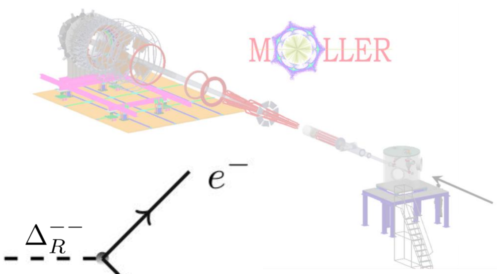
E. Akhmedov, et al., 2401.15145 (PLB)

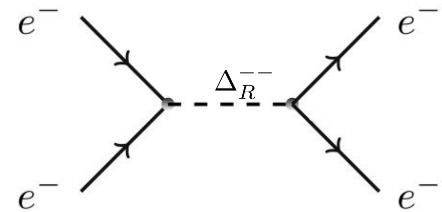
LNV at lepton colliders

- CEPC/FCC-ee, MOLLER

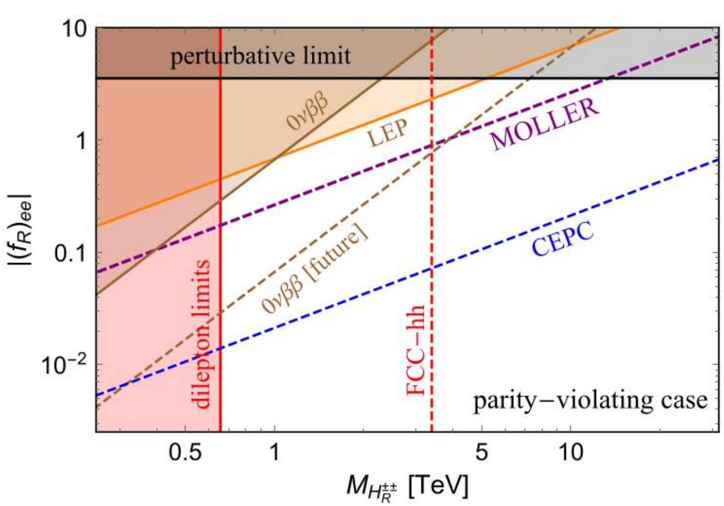


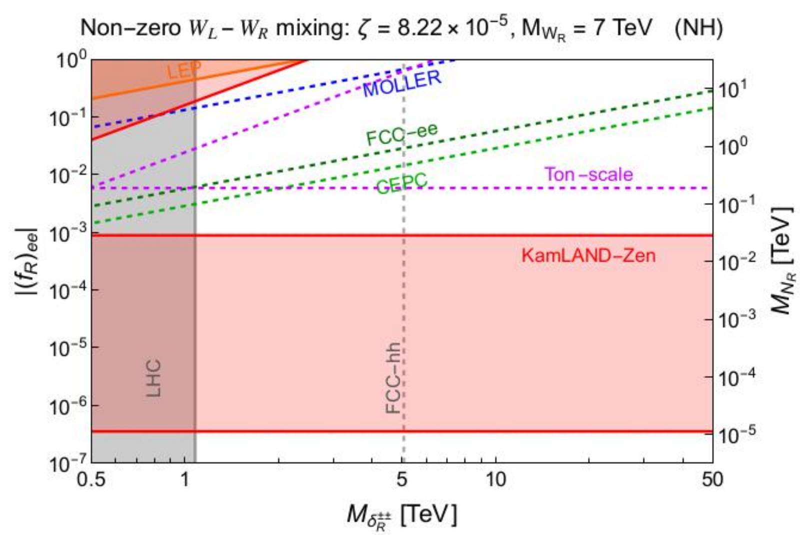
$\sqrt{s} = 246$ GeV





$\sqrt{s} = 11$ GeV





P. S. Bhupal Dev, M. J. Ramsey-Musolf, Y. Zhang, 1806.08499 (PRD)

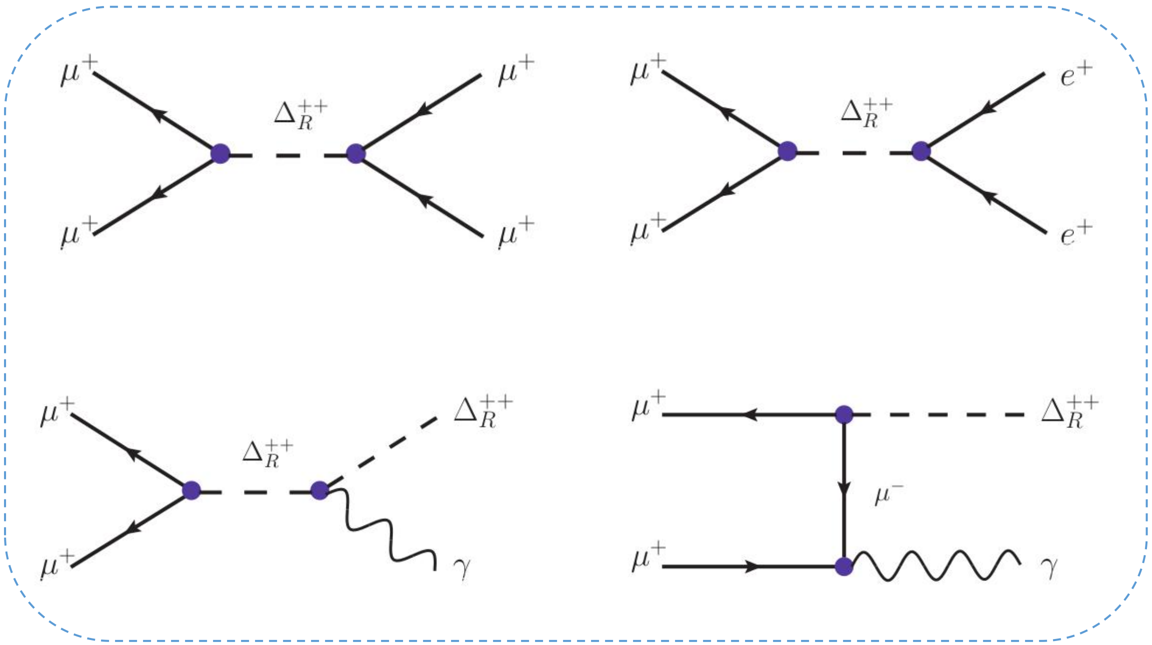
GL, M. J. Ramsey-Musolf, S. Urrutia Quiroga, J. C. Vasquez, 2408.06306

LNV at lepton colliders

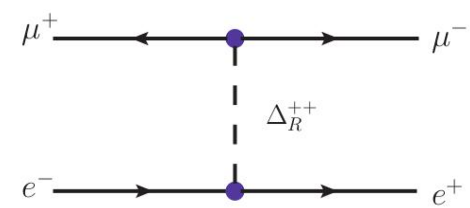
- μTRISTAN

  μ^+ beam obtained from ultra-cold muon technology developed for the muon $g-2$ experiment at J-PARC is accelerated up to 1 TeV

Y. Hamada, et al., Prog. 2201.06664 (PTEP)



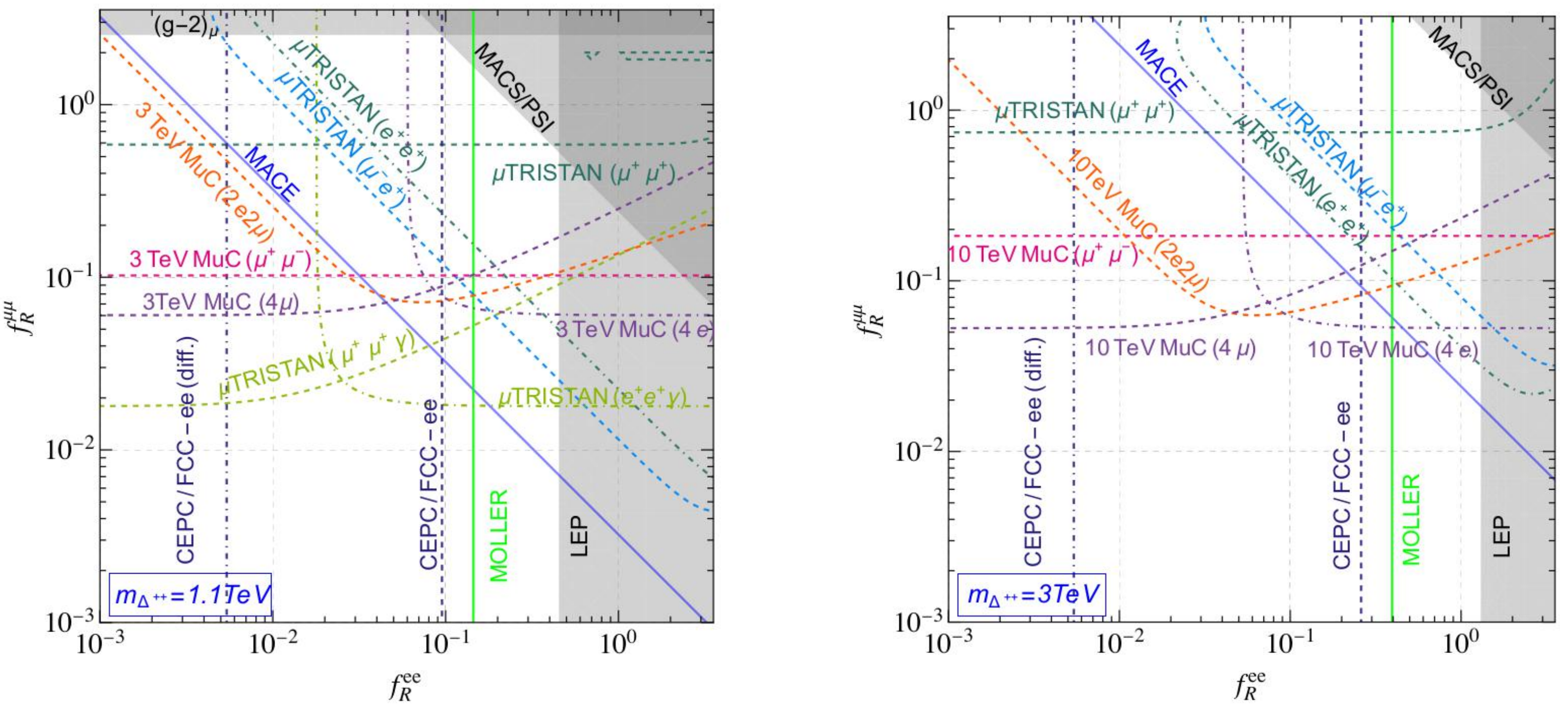
$\sqrt{s} = 2$ TeV



$\sqrt{s} = 346$ GeV

LNV at lepton colliders

Low- and high-energy probes of diagonal couplings



GL, Jin Sun, 2510.xxxxx

Summary

- Colliders provide unique opportunities for probing lepton-number-violating new physics
- EFTs help to identify optimal LNV interactions, which are constructed using covariant derivatives
- UV completions for SMEFT with 0, 1, 2 covariant derivatives are discussed
- We investigate the sensitivity of lepton colliders to a specific LNV scenario: a light doubly-charged scalar

Thank you