Phenomenology of LNV in SMEFT at dimension 7

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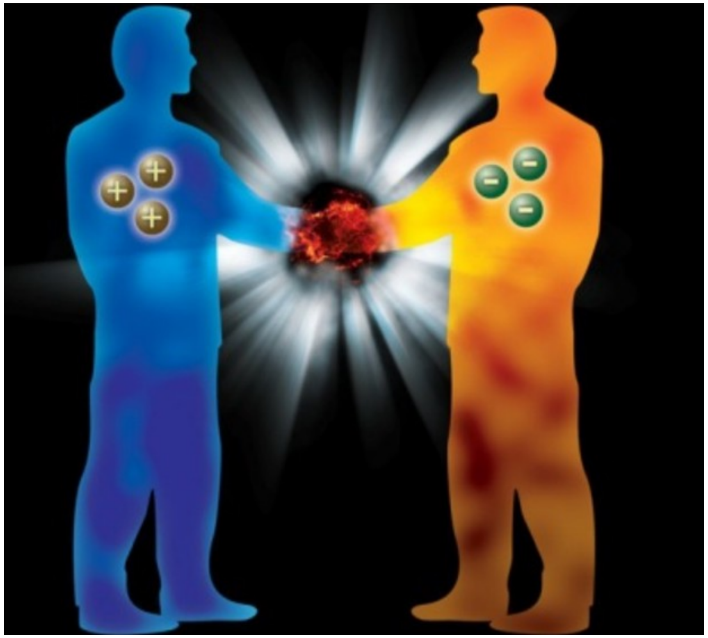
University of Ioannina

Evidence of New Physics

The Standard Model (SM) is a very successful theory, but it is known to be imcomplete by several different observations.

Baryon asymmetry



Evidence from CMB, BBN.

Neutrino masses

Evidence from neutrino oscillations.

Neutrino masses and LNV

One possibility: Dirac mass $\nu_L \neq \nu_R^c$

Very small neutrino masses imply very small Yukawa couplings: $y_\nu \sim 10^{-12}$

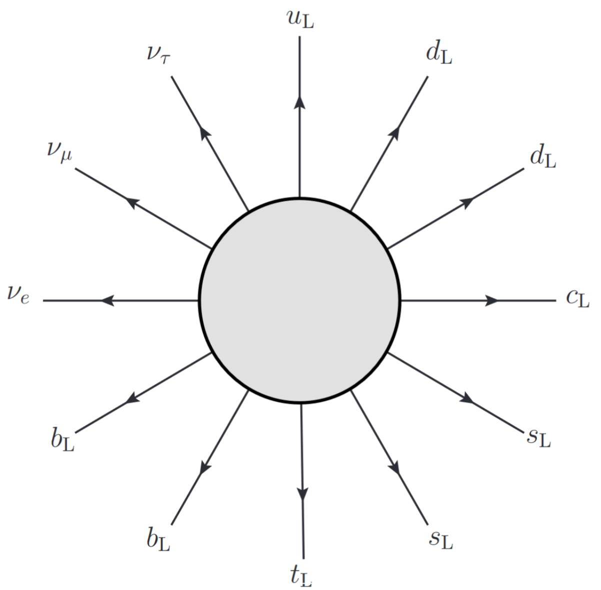
Well motivated scenario: Majorana mass $\nu_L = \nu_R^c$

Neutrino Majorana mass implies **Lepton Number Violation (LNV)**

LNV is related to the matter/antimatter asymmetry:

A lepton asymmetry can be converted into a baryon asymmetry via sphaleron transitions (part of the SM)

$$\text{Majorana neutrino mass: } \Delta L = 2$$
$$\text{Sphalerons: } \Delta L = -\Delta B = 3$$



Can LNV be studied in a model-independent way?

SM Effective field theory

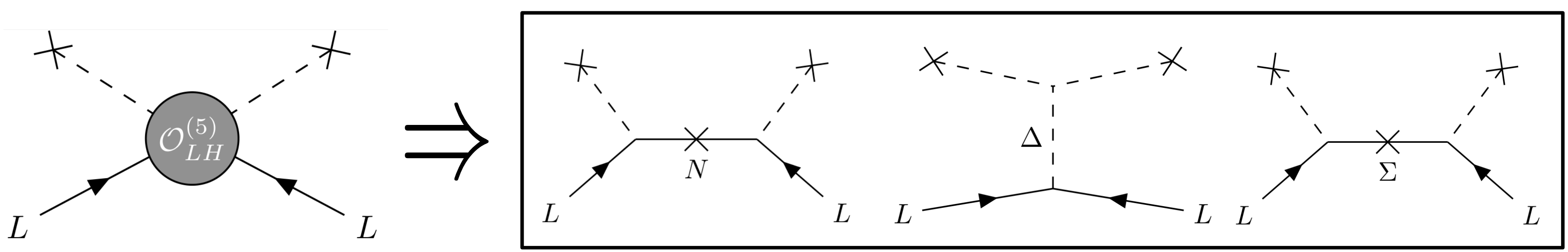
$$\mathcal{L}_{\rm EFT} = \sum_i C_i \mathcal{O}_i + \text{h.c.} \quad \text{Wilson coefficient: } C_i \propto \frac{1}{\Lambda^{(D-4)}},\ \Lambda = \text{New Physics (NP) scale}$$

LNV only occurs at odd mass dimension

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

All SMEFT operators up to mass dimension 11 have been classified (excluding derivatives) Babu, Leung (2001), de Gouvêa, Jenkins (2007), Deppisch et. al. (2018)

Lowest dimension for ΔL = 2 LNV: The dimension-5 operator $\mathcal{O}_{LH}^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$



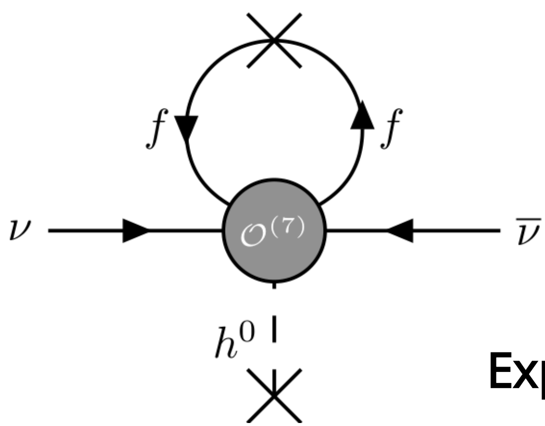
LNV at dimension-7

Second-most simple realization: LNV at dimension-7

e.g. Lehman (2014), Liao, Ma (2019)

Type	$\mathcal{O}$	Operator
Ψ^2H^4	$\mathcal{O}^{pr}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{ci}_p}L^m_r)H^jH^n(H^\dagger H)$
Ψ^2H^3D	$\mathcal{O}^{pr}_{LeHD}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{ci}_p}\gamma_\mu e_r)H^j(H^m iD^\mu H^n)$
$\Psi^2H^2D^2$	$\mathcal{O}^{pr}_{LHD1}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L^{ci}_p}D_\mu L^j_r)(H^m D^\mu H^n)$
	$\mathcal{O}^{pr}_{LHD2}$	$\epsilon_{im}\epsilon_{jn}(\overline{L^{ci}_p}D_\mu L^j_r)(H^m D^\mu H^n)$
Ψ^2H^2X	$\mathcal{O}^{pr}_{LHB}$	$g\epsilon_{ij}\epsilon_{mn}(\overline{L^{ci}_p}\sigma_{\mu\nu}L^m_r)H^jH^nB^{\mu\nu}$
	$\mathcal{O}^{pr}_{LHW}$	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L^{ci}_p}\sigma_{\mu\nu}L^m_r)H^jH^nW^{I\mu\nu}$
Ψ^4D	$\mathcal{O}^{prst}_{\bar{d}uLLD}$	$\epsilon_{ij}(\overline{d_p}\gamma_\mu u_r)(\overline{L^{ci}_s}iD^\mu L^j_t)$
Ψ^4H	$\mathcal{O}^{prst}_{\bar{e}LLLH}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_p}L^i_r)(\overline{L^{cj}_s}L^m_t)H^n$
	$\mathcal{O}^{prst}_{\bar{d}LueH}$	$\epsilon_{ij}(\overline{d_p}L^i_r)(\overline{u^c_s}e_t)H^j$
	$\mathcal{O}^{prst}_{\bar{d}LQLH1}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_p}L^i_r)(\overline{Q^{cj}_s}L^m_t)H^n$
	$\mathcal{O}^{prst}_{\bar{d}LQLH2}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_p}L^i_r)(\overline{Q^{cj}_s}L^m_t)H^n$
	$\mathcal{O}^{prst}_{\bar{Q}uLLH}$	$\epsilon_{ij}(\overline{Q_p}u_r)(\overline{L^c_s}L^i_t)H^j$

- 12 operators instead of one
- Phenomenologically rich: can be UV-completed by 26 different fields in 56 different combinations
- Can lead to radiative neutrino mass



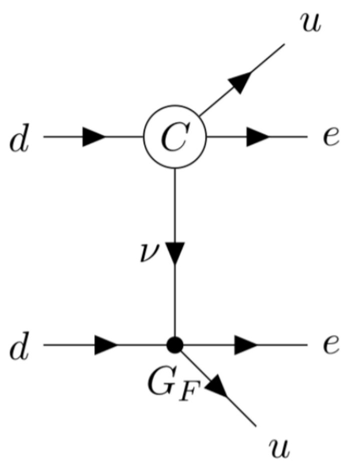
Experimental probes of dimension-7 LNV?

Neutrinoless double beta decay

Neutrinoless double beta decay (0νββ):

+Most sensitive probe of LNV

-Only sensitive to electron flavour

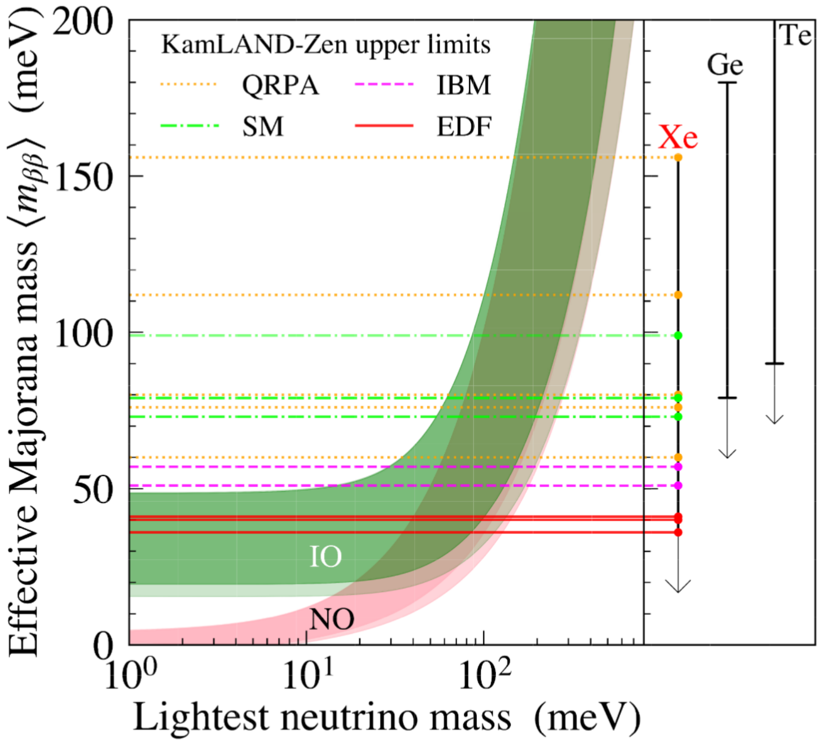


e.g. Cirigliano et. al. (2017)

Dimension-7 LNV operators give rise to long-range contributions to 0νββ decay

Currently most stringent limit:

$$T_{1/2}^{^{136}\mathrm{Xe}} \leq 2.3 \times 10^{26} \text{ yrs, } 90\% \text{ C.L.}$$



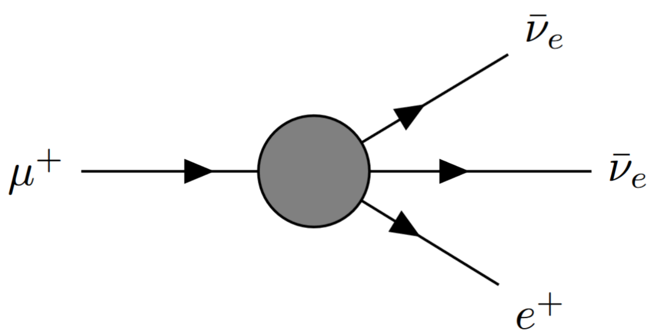
KamLAND-Zen collaboration (2022)

The muon sector

LNV μ decay: $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_\mu$

+ Includes the μ flavour

- Probes only a single operator



e.g. Cirigliano et. al. (2017)

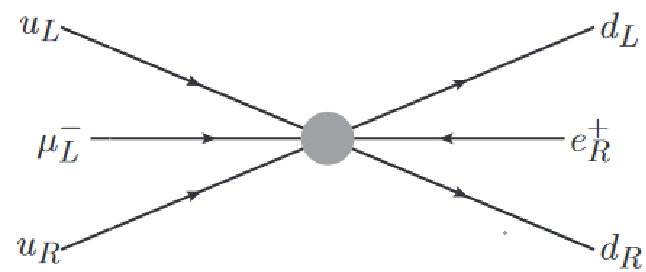
$$\mathrm{BR}(\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_\mu) \lesssim 0.9 \times 10^{-3}$$

KARMEN collaboration (2003)

μ^- to e^+ conversion

+ Includes the μ flavour

- Dimension-9



e.g. Berryman, de Gouvêa, Kelly, Kobach (2017)

$$R^{\mathrm{Ti}}_{\mu^- e^+} \equiv \frac{\Gamma\left(\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca}\right)}{\Gamma\left(\mu^- + \mathrm{Ti} \to \nu_\mu + \mathrm{Sc}\right)} < 1.7 \times 10^{-12}$$

SINDRUM II collaboration (1998)

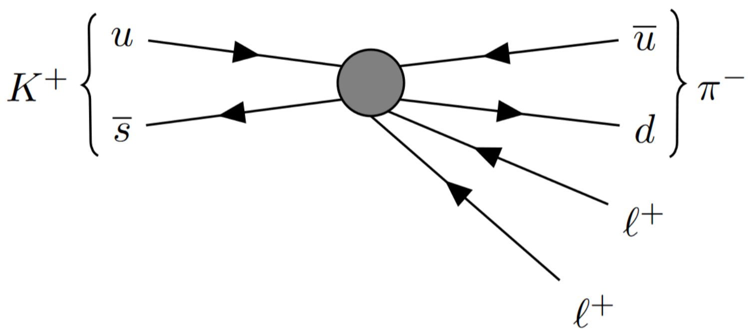
LNV in meson decays (e.g. kaons)

Double charged lepton final state

+Guaranteed LNV

-Dimension-9

e.g. Chun, Das, Mandal, Mitra, Sinha (2019)



Muons or electrons in the final state

$$\mathrm{BR}(K^+ \to \pi^- \mu^+ \mu^+) \leq 4.2 \times 10^{-11}\,,\ 90\%\ \mathrm{C.L.}$$

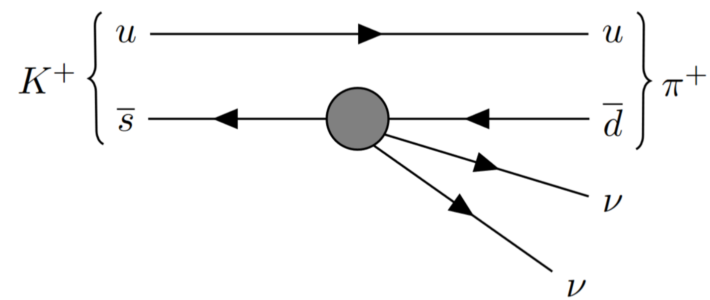
NA62 collaboration (2019)

Two-neutrino final state (rare)

+Dimension-7

-LNV not guaranteed

e.g. Li, Ma, Schmidt (2019)
Deppisch, KF, Harz (2020)



Cannot determine flavour of neutrinos

Experiment:

$$\mathrm{BR}(K^+ \to \pi^- \nu\bar{\nu}) = (10.6^{+4.9}_{-4.3}) \times 10^{-11}\,,\ 68\%\ \mathrm{C.L.}$$

NA62 collaboration (2021)

SM expectation:

$$\mathrm{BR}(K^+ \to \pi^- \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

Buras et. al. (2015)

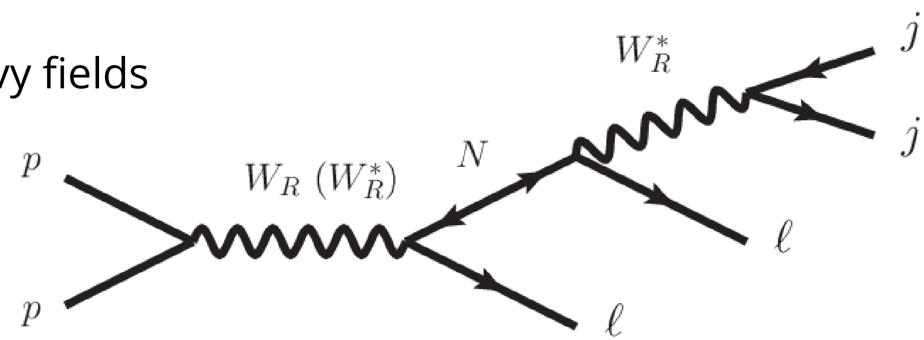
LNV at the LHC

Keung-Senjanović process: leads to LNV at **dimension-9** when integrating out the heavy fields

Probes $5\ \mathrm{GeV} \gtrsim m_N \gtrsim 50\ \mathrm{GeV}$

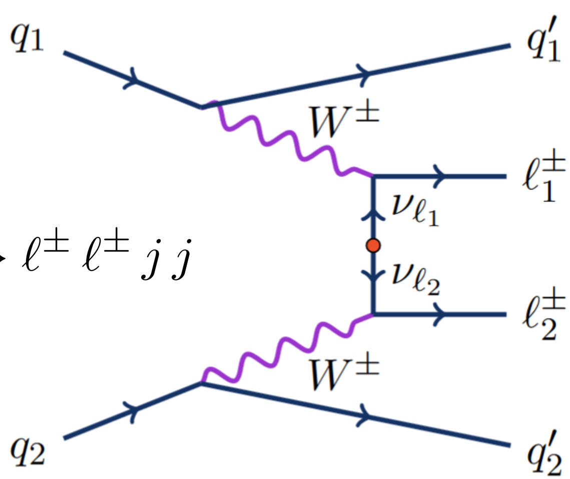
for couplings $|U_{e/\mu}| \gtrsim 10^{-5}$

ATLAS collaboration (2019) + ...



$p\,p \to \ell^\pm\,\ell^\pm\,j\,j$

Keung, Senjanovic (1983)



$p\,p \to \ell^\pm\,\ell^\pm\,j\,j$

Fuks et. al. (2021)

Possible to probe the **dimension-5** Weinberg operator at colliders in vector boson fusion

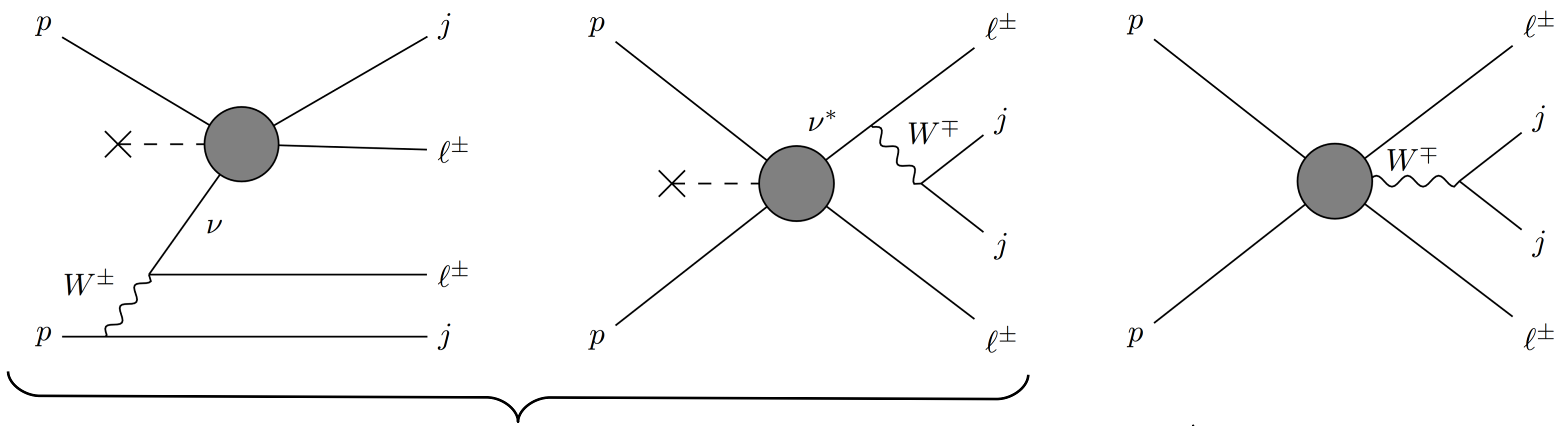
$$m_{\mu\mu} < 10.8\ \mathrm{GeV\ at\ 95\%\ C.L.}$$

$$m_{\ell\ell'} = \frac{C_{\ell\ell'} v^2}{\Lambda}$$

CMS collaboration (2022)

Dimension-7 LNV at the LHC

Nine out of the twelve dimension-7 ΔL=2 LNV operators lead to $p\,p \to \ell^{\pm}\,\ell^{\pm}\,j\,j$



$$\mathcal{O}^{prst}_{\bar{Q}uLLH} = \epsilon_{ij}\overline{Q_p}u_r\overline{L^c_s}L^i_t H^j$$

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

Leads to the same signal as for dimension-9 processes: we can use existing LHC results and compare with EFT cross section obtained using MadGraph5_aMC@NLO

Alwall et. al. (2014)

J. High Energ. Phys. (2019) 2019: 16
DOI: 10.1007/JHEP01(2019)016

CERN-EP-2018-199
13th November 2019

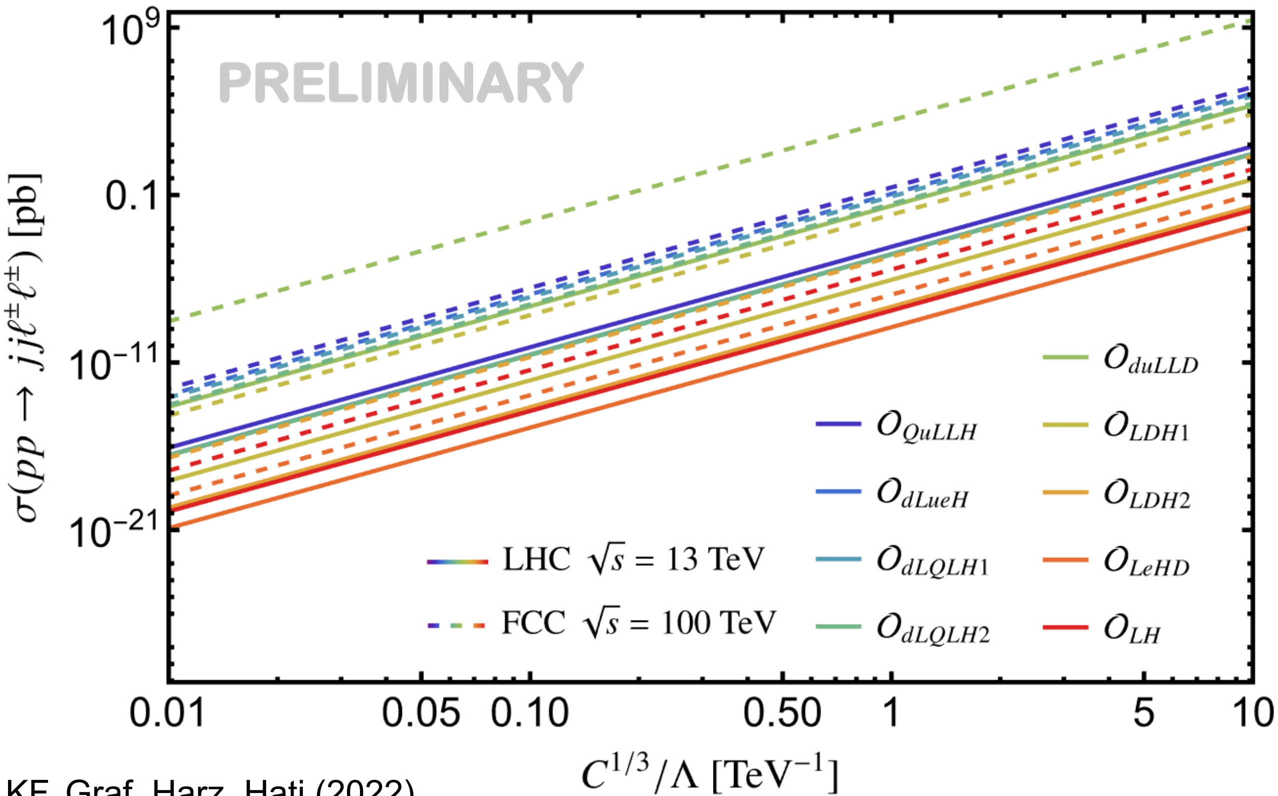
Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets at $\sqrt{s}$ = 13 TeV with the ATLAS detector

⇒ No events in 36.1 fb^{-1} of data.

⇓

Leads to constranints on Λ_{LNV}

LHC results for dimension-7



KF, Graf, Harz, Hati (2022)

LNV scales in TeV

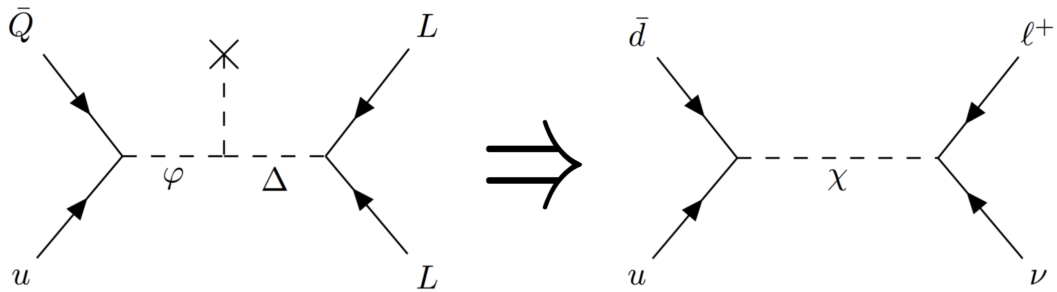
Operator	Λ_{LNV}	$\Lambda_{\text{LNV}}^{\text{future}}$
$\mathcal{O}_{\bar{d}LueH}$	0.72	5.1
$\mathcal{O}_{\bar{d}LQLH1}$	0.71	4.8
$\mathcal{O}_{\bar{d}LQLH2}$	0.71	4.1
$\mathcal{O}_{\bar{Q}uLLH}$	0.85	6.0
$\mathcal{O}_{LDH1}$	0.40	3.2
$\mathcal{O}_{LDH2}$	0.22	1.2
$\mathcal{O}_{LeHD}$	0.13	0.51
$\mathcal{O}_{\bar{d}uLLD}$	2.2	28
$\mathcal{O}_{LH}$	0.20	0.91

Constraints at 95% C.L.

LNV scales ~$\mathcal{O}$(1 TeV) are constrained by same-sign dilepton plus dijet searches at the LHC

For FCC the constraints could reach ~$\mathcal{O}$(few TeV) up to ~30 TeV

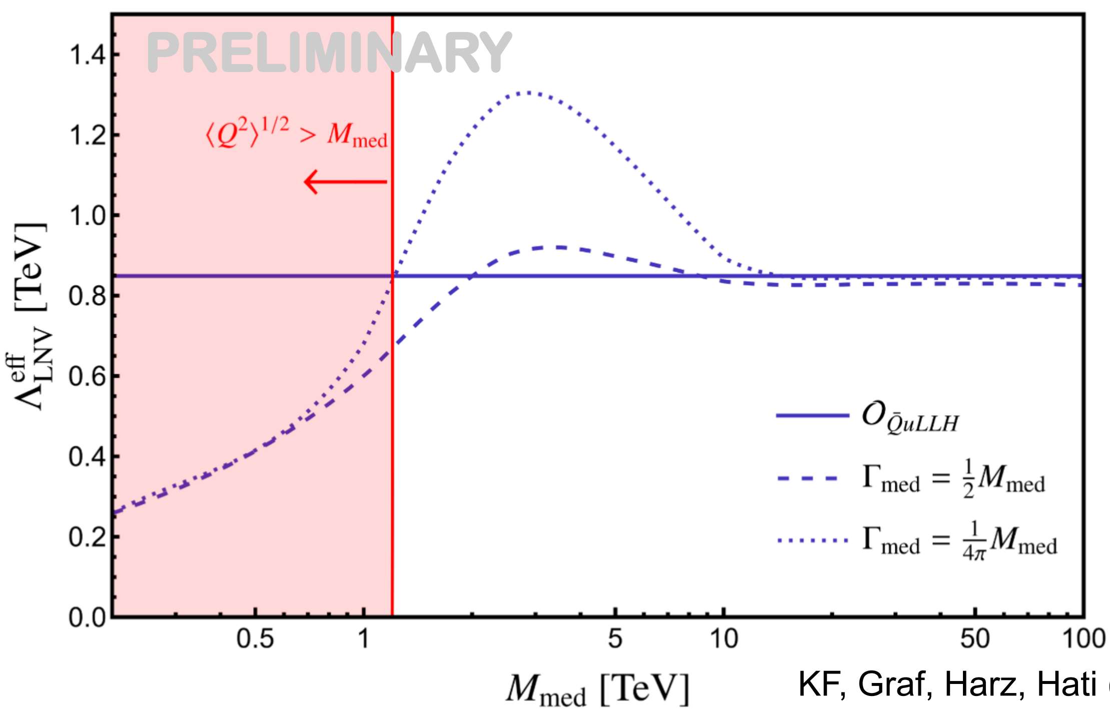
EFT vs simplified model



We can compare the EFT approach with a simplified model example to see how well it performs

$$\mathcal{O}_{\bar{Q}uLLH} = \epsilon_{ij}\overline{Q}u\overline{L^c}L^iH^j$$

$$\mathcal{L} \supset \lambda_1 \bar{d}_L u_R \chi^* + \lambda_2 \bar{e}^c_L \nu_L \chi + \text{h.c.}$$



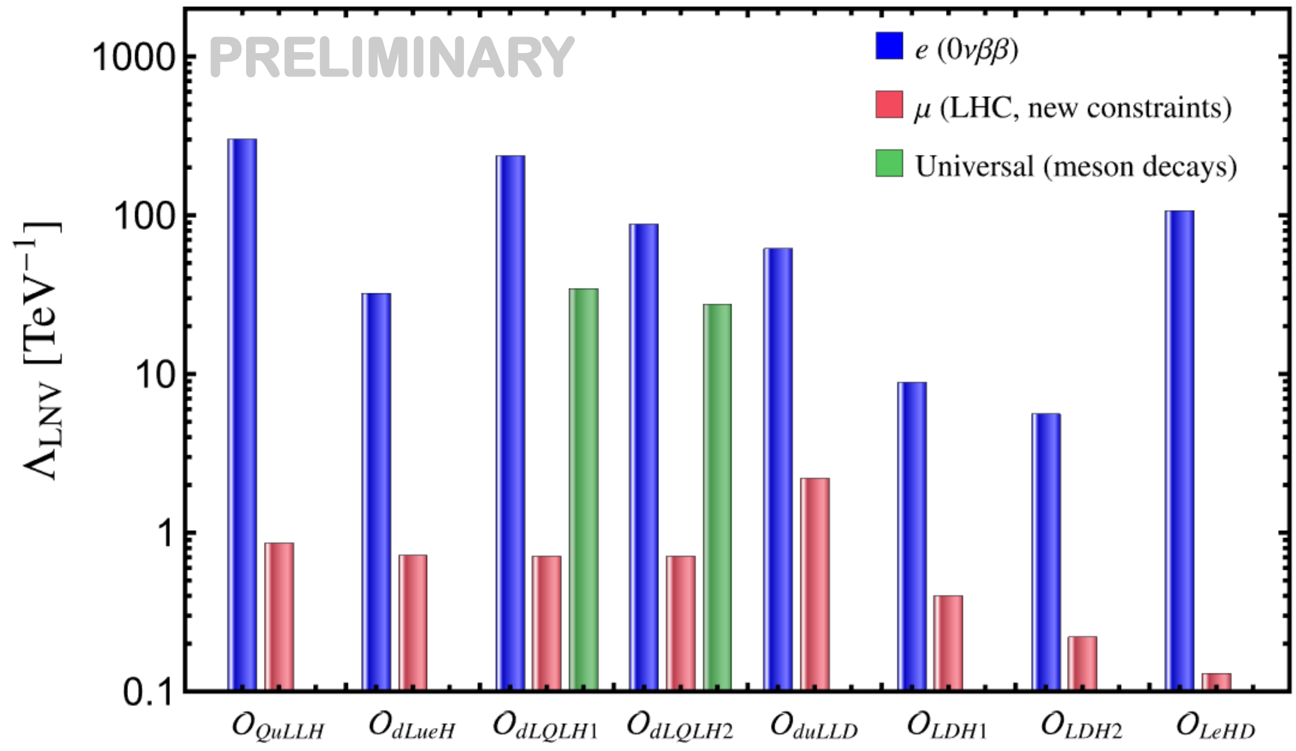
KF, Graf, Harz, Hati (2022)

Using the relation

$$\frac{\lambda_1\lambda_2}{M^2_{\mathrm{med}}} = \frac{v}{(\Lambda^{\mathrm{eff}}_{\mathrm{LNV}})^3}$$

we naively expect the same cross section for the simplified model and EFT operator

Comparison of different probes



KF, Graf, Harz, Hati (2022)

The red bars constitute new constraints on dimension-7 operators using LHC results

We see that LHC offers the most effective way to probe the μ flavour content of dimension-7 ΔL= 2 SMEFT operators

Conclusion

- Neutrino masses may violate lepton number via a Majorana mass term, which in turn could be connected to the baryon asymmetry via leptogenesis.
- Dimension-7 LNV operators offer the second simplest solution to realize LNV mechanisms on an effective level.
- We find that the most stringent μ-sector constraints on the scale of LNV in many dimension-7 operators come from collider searches.

Thank you

Backup slides

Limitations on the EFT approach

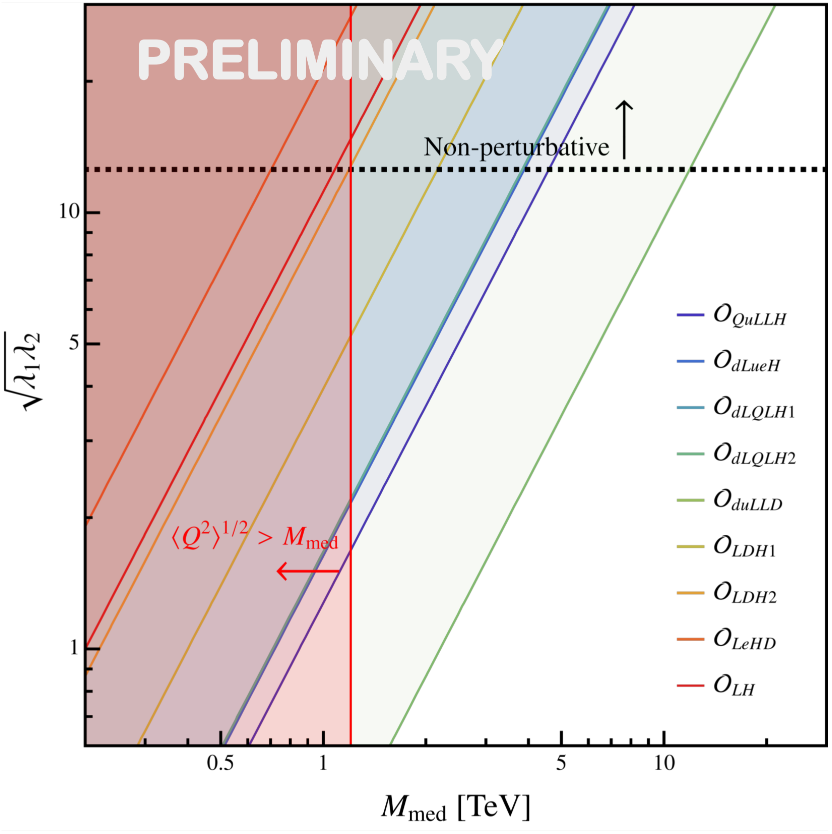
EFTs are only valid for $M_{\mathrm{med}}^2 > Q^2$

$$\frac{1}{Q^2 - M_{\mathrm{med}}^2} = -\frac{1}{M_{\mathrm{med}}^2}\left[1 + \frac{Q^2}{M_{\mathrm{med}}^2} + \mathcal{O}\left(\frac{Q^4}{M_{\mathrm{med}}^4}\right)\right]$$

We can compare effective mediator mass with the average momentum transfer to get an idea of the validity range

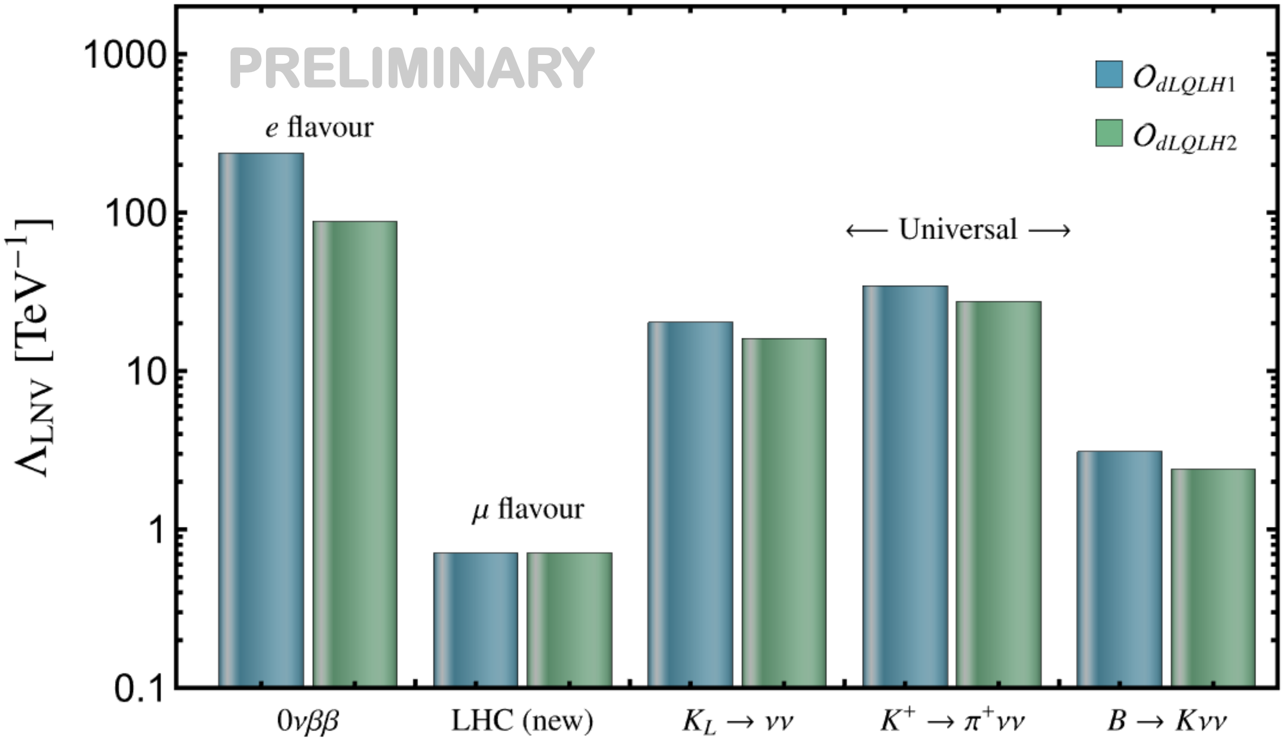
$$\Lambda_{\mathrm{LNV}} = M_{\mathrm{med}}/(\lambda_1\lambda_2)^{1/3}$$

$$\langle Q^2 \rangle = \frac{\sum_{q\bar{q}} \int (\mathrm{PDF} \times \mathrm{PDF})\, Q^2}{\sum_{q\bar{q}} \int (\mathrm{PDF} \times \mathrm{PDF})}$$



KF, Graf, Harz, Hati (2022)

Details of meson decay probes



KF, Graf, Harz, Hati (2022)

Two operators are constrained by rare meson decays: no handle on flavour content since the final state neutrinos are not observed

Li, Ma, Schmidt (2019), Deppisch, KF, Harz (2020)

Operator explosion

"Explode" an operator to find all possible tree-level UV completions using combinatorics

$$\mathcal{O}_{\overline{Q}uLLH} = \epsilon_{ij}(\overline{Q}u)(\overline{L^C}L^i)H^j \quad \rightarrow \quad \epsilon_{ij}\overline{Q}^k u L^k L^i H^j \qquad (\chi_1,\ \phi_1,\ \psi_1,\ \xi_1)$$

$$\mathcal{O}_{\overline{Q}uLLH} \quad \rightarrow \quad \epsilon_{ij}\chi_1{}^k L^k L^i H^j \;(\chi_2,\chi_3,\chi_4) \;\Big/\; \epsilon_{ij}\phi_1{}^k u L^i H^j \;(\psi_2,\psi_3,\psi_4) \;\Big/\; \epsilon_{ij}\psi_1{}^k u L^k H^j \;(\phi_2,\phi_3,\phi_4) \;\Big/\; \epsilon_{ij}\xi_1{}^k u L^k L^i \;(\xi_2,\xi_3,\xi_4)$$

Leads to 4 × 3 =12 models, but not all are unique.

$\chi_1 \sim S(1,2,1/2)$	$\psi_1 \sim V(\overline{3},1,-2/3)$	$\phi_1 \sim V(\overline{3},3,-2/3)$	$\xi_1 \sim F_L(\overline{3},3,1/3)$
$\chi_2 \sim F_R(1,1,0)$	$\psi_2 \sim F_R(1,1,0)$	$\phi_2 \sim F_R(1,3,0)$	$\xi_2 \sim S(1,3,1)$
$\chi_3 \sim F_R(1,3,0)$	$\psi_3 \sim F_L(\overline{3},2,-7/6)$	$\phi_3 \sim F_L(\overline{3},2,-7/6)$	$\xi_3 \sim V(\overline{3},2,-1/6)$
$\chi_4 \sim S(1,3,1)$	$\psi_4 \sim V(\overline{3},2,-1/6)$	$\phi_4 \sim V(\overline{3},2,-1/6)$	$\xi_4 \sim V(\overline{3},2,-1/6)$

Here we find the simplified model that we used as an example earlier

Teaser: neutrino mass

Given all possible tree-level UV-completions of a dimension-7 operator, we can classify them in terms of the neutrino mass topology

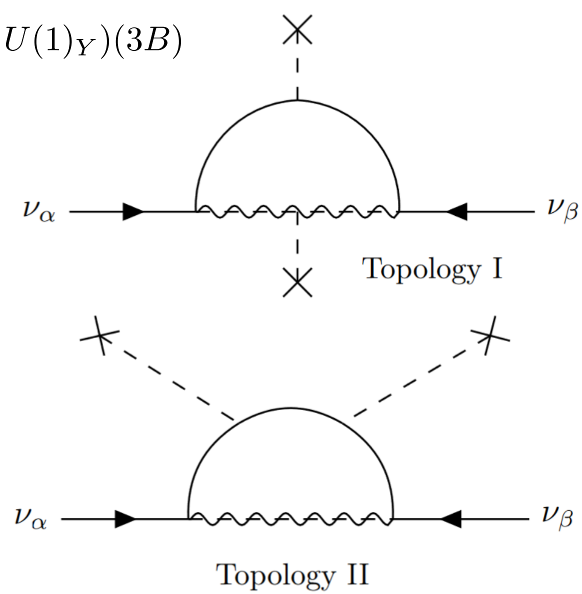
We can then compare with the different EFT LNV constraints to see which mass mechanisms are excluded…. **Look to arXiv:2207:XXXXX**

$\bigcirc$ = Generates the dimension-5 Weinberg operator

$$\mathcal{O}_{\overline{Q}uLLH} = \epsilon_{ij}\left(\overline{Q_p}u_r\right)\left(\overline{L_s^c}L_t^i\right)H^j$$

	Δ	φ	N	Σ	Q_7	$T_1^\dagger$	U_1	$\bar{V}_2^\dagger$	U_3
Δ		I			II	II			
φ			$\bigcirc$	$\bigcirc$					
N							$\bigcirc$	$\bigcirc$	
Σ								$\bigcirc$	$\bigcirc$
Q_7							II		II
$T_1^\dagger$								II	
U_1								I	
$\bar{V}_2^\dagger$									I
U_3									

Field	Rep $(SU(3)_c, SU(2)_L, U(1)_Y)(3B)$
Δ	$S(1,3,1)(0)$
φ	$S(1,2,1/2)(0)$
N	$F(1,1,0)(0)$
Σ	$F(1,3,0)(0)$
Q_7	$F(3,2,7/6)(1)$
T_1	$F(3,3,-1/3)(1)$
U_1	$V(3,1,2/3)(1)$
$\bar{V}_2$	$V(\bar{3},2,-1/6)(-1)$
U_3	$V(3,3,2/3)(1)$



KF, Graf, Harz, Hati (2022)