

Closing in on Lepton Number Violating dimension-7 SMEFT Operators

Chandan Hati

In collaboration with
Kåre Fridell, Lukáš Gráf, and Julia Harz

Based on arXiv: 2303.XXXX (to appear soon!)



Neutrino masses and Lepton Number Violation

The only laboratory evidence of BSM physics so far:

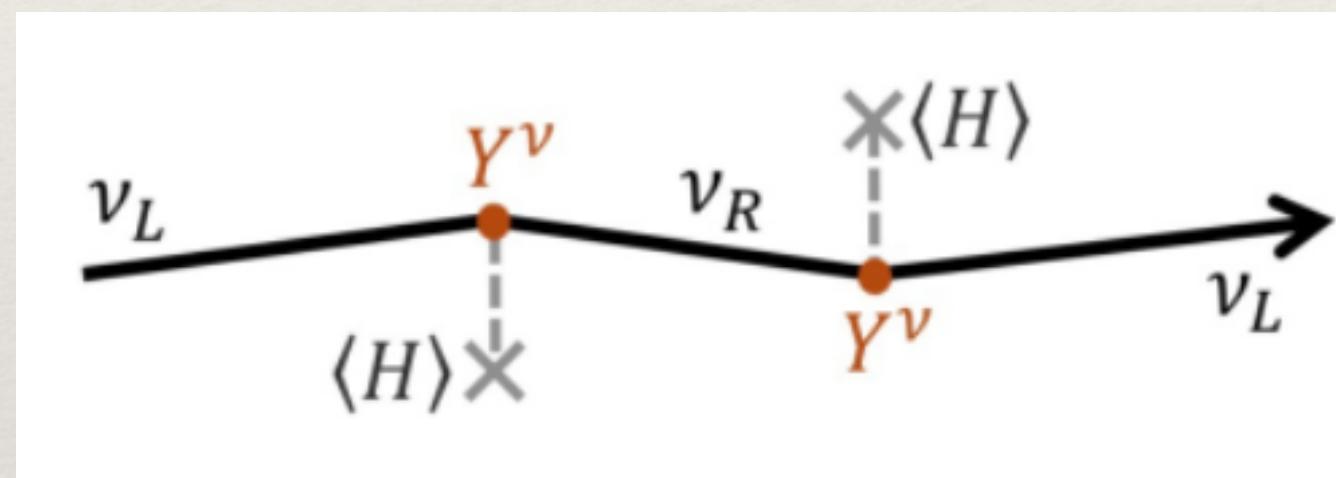
Neutrino oscillations => Neutrino masses

Purely SM:

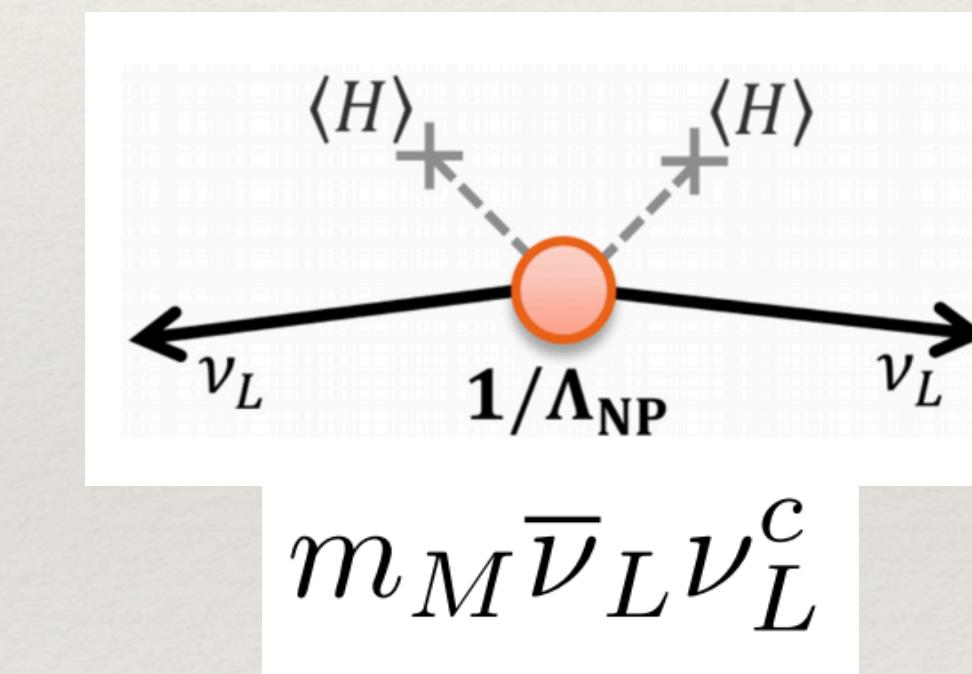
- strictly massless neutrinos
- conservation of lepton number and flavours



Two possibilities for neutrino masses:



vs.



Dirac: like other fermions, but tiny
Yukawa couplings $\sim 10^{-12}$ “finetuning”?

Majorana: needs only left-handed neutrinos
 $\nu = \nu^c$: Lepton Number Violation!

Phenomenologically very interesting!

Simple UV completion: seesaw mechanisms

How to probe the neutrino mass mechanisms?

Numerous possibilities of realising the Majorana neutrino masses

e.g. type I, II, III seesaw, low-scale seesaw, radiative models, Left-Right Symmetric Model, ++

High-scale: $10^{(10-15)}$ GeV

theoretically natural $Y_\nu \lesssim \mathcal{O}(1)$ + unification

Vanilla high-scale leptogenesis

New states decoupled: hard to test!

Low-scale: KeV - tens of TeV

small Y_ν / approximate LNC/ loop suppression

Leptogenesis via resonant/oscillation

New states within experimental reach

How to probe so many different neutrino mass model possibilities?

Effective Field Theory approach provides a robust option



Model Independent



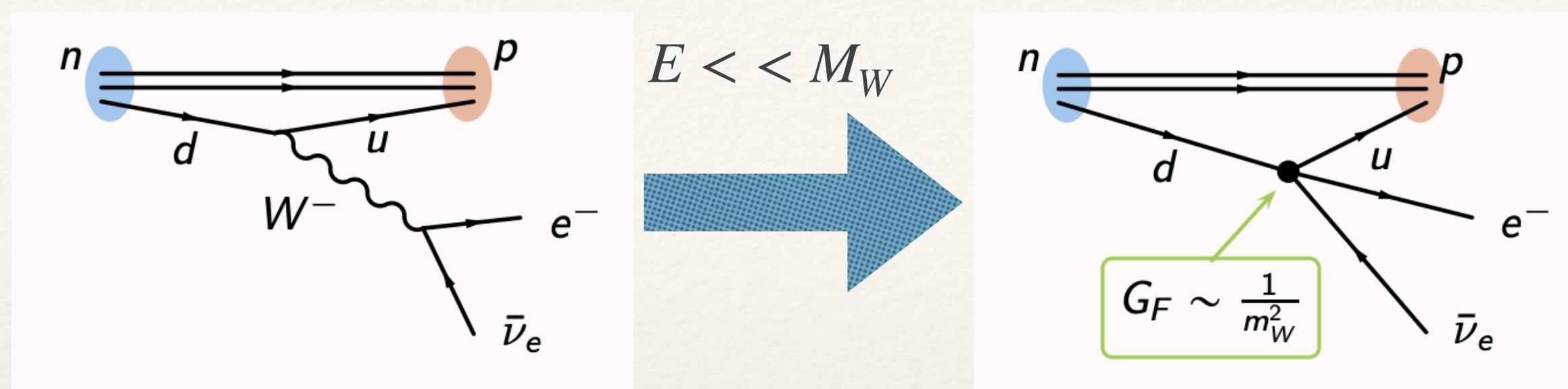
Direct NP signatures

e.g. Resonant NP production:
simplified model approach

Effective Field Theory (EFT)

Classic example: Fermi theory for beta decays

UV: Electroweak Interaction

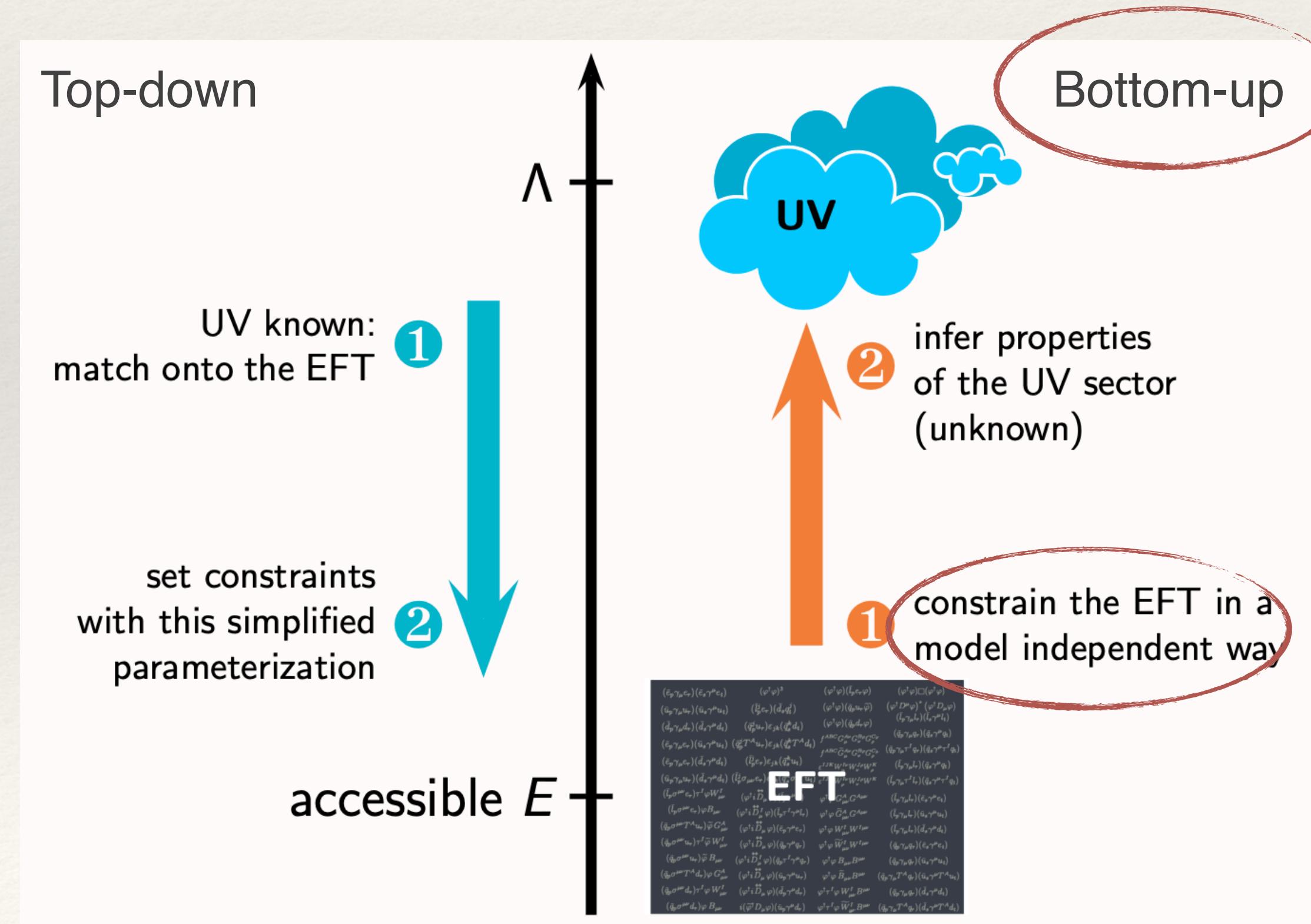


EFT: Fermi interaction

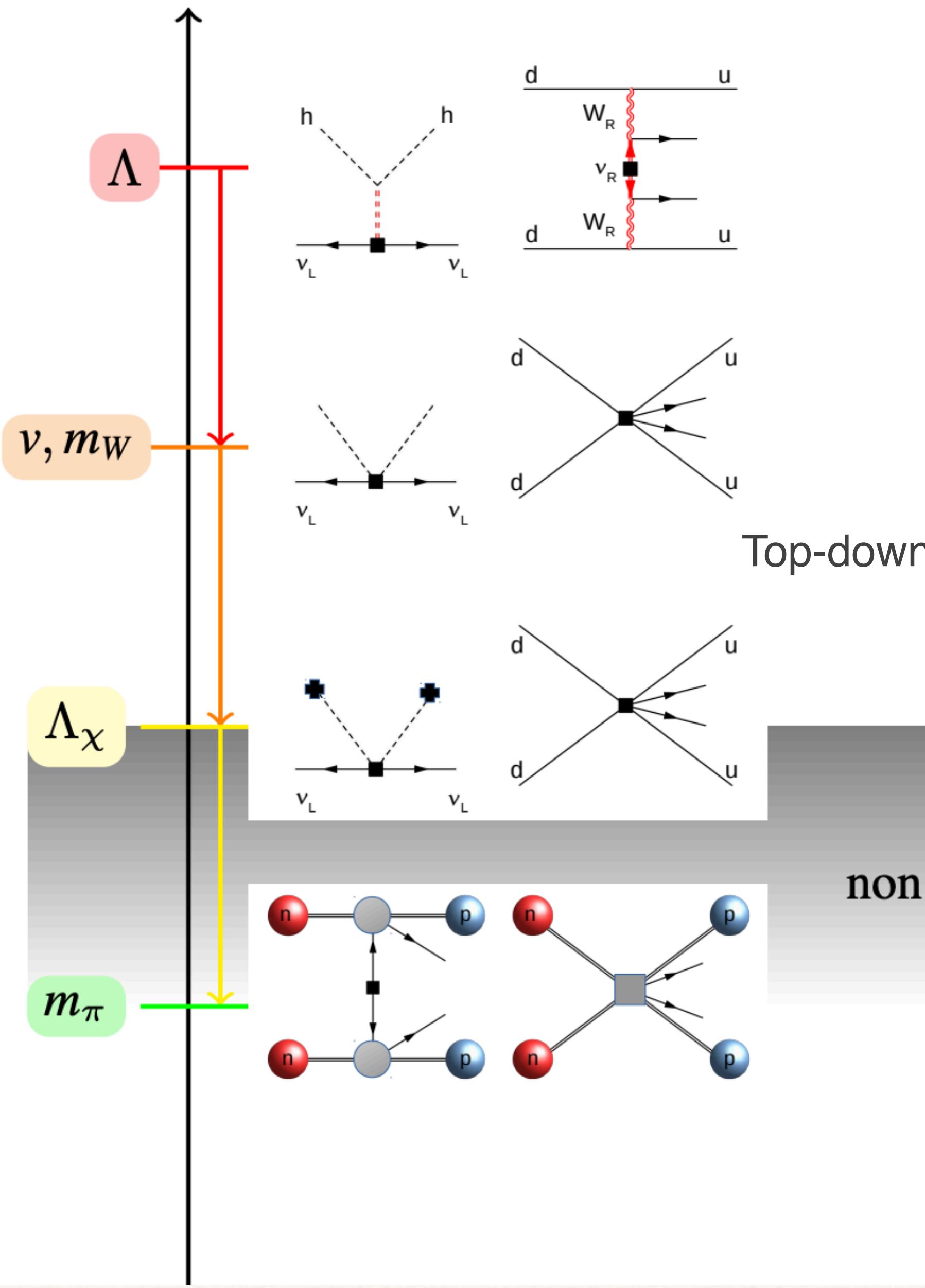
Decoupling theorem

Appelquist,Carrazzone PRD'75

No on-shell production of heavy state



Effective Field Theory (EFT)



Mereghetti NDM'22

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \dots$$

new physics $\Lambda \gg v$

$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

C_i free parameters (Wilson coefficients)

\mathcal{O}_i invariant operators that form a complete, non redundant basis

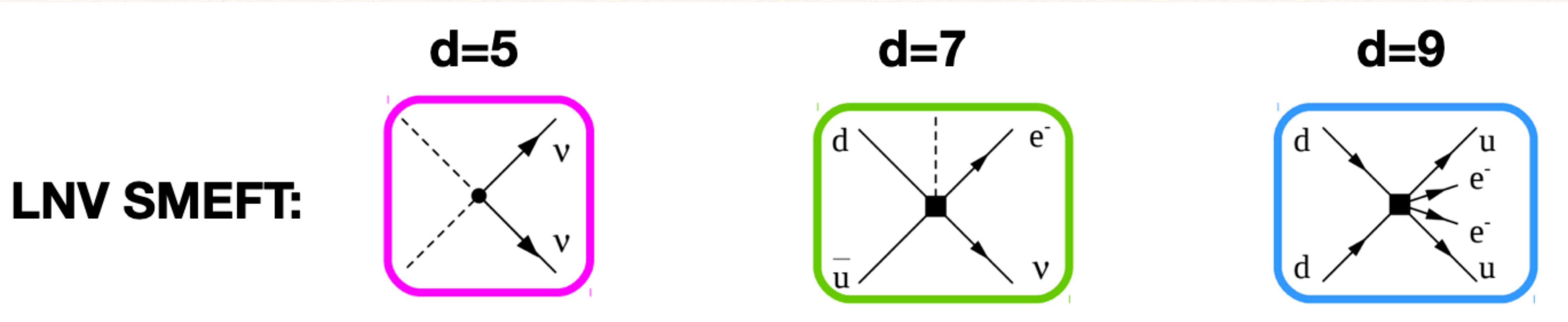
SMEFT operators

$SU(3)_c \times U(1)_{\text{em}}$ operators

non perturbative QCD

Chiral Effective Theory

Lepton Number Violation and SMEFT



Weinberg operator

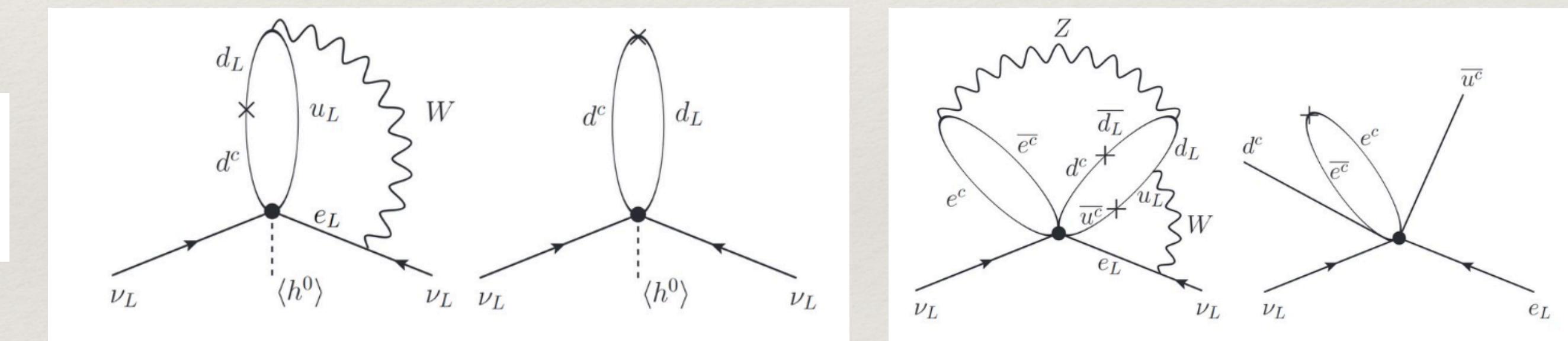
Weinberg '79

Babu and Leung '01
de Gouvea and Jenkins '08
Lehman '14

M. Graesser '16
Y. Liao and X. D. Ma '20

Neutrino mass:

$$\frac{1}{\Lambda} \varepsilon_{ij} \varepsilon_{mn} L_i^T C L_m H_j H_n \rightarrow \frac{v^2}{\Lambda} \nu_L^T C \nu_L$$

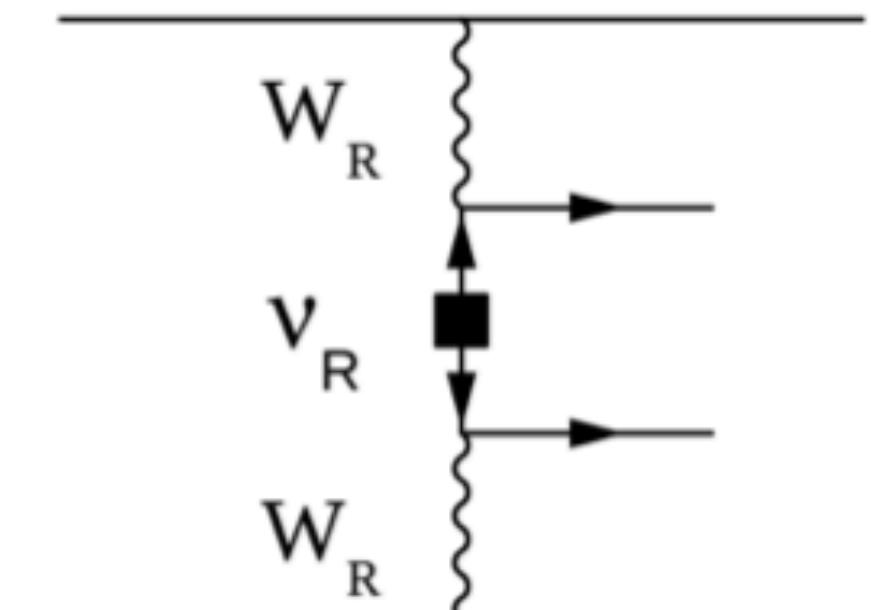
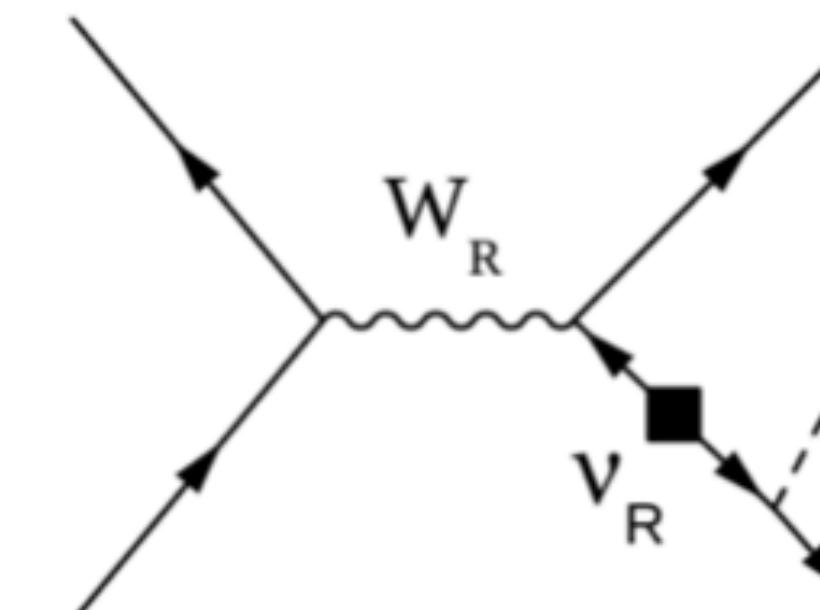
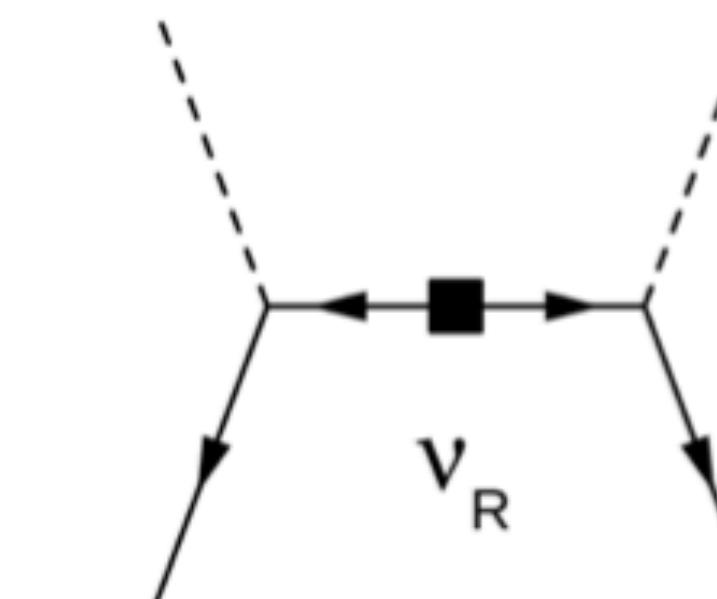


UV example:

LRSM

Mohapatra and Pati '75

Senjanovic and Mohapatra '75



Lepton Number Violating dimension-7 SMEFT operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + C_5 \mathcal{O}_5 + \sum_i C_7^i \mathcal{O}_7^i + \sum_i C_9^i \mathcal{O}_9^i + \dots$$

dim-7: 12 Independent operator with $\Delta L = 2$

First systematic analysis:

Lehman PRD'14-> 20 independent operators

13 conserving B but $\Delta L = 2$

7 violating both $\Delta B = -\Delta L = -1$

Further reduced in Liao, Ma JHEP'17

18 = 12+6 (indep. structures)

Sterile neutrino extensions:

Bhattacharya-Wudka '15

Liao-Ma '17

Why dim-7 SMEFT operators interesting?

Type	\mathcal{O}	Operator
$\Psi^2 H^4$	\mathcal{O}_{LH}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i L_r^m) H^j H^n (H^\dagger H)$
$\Psi^2 H^3 D$	\mathcal{O}_{LeHD}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i \gamma_\mu e_r) H^j (H^m i D^\mu H^n)$
$\Psi^2 H^2 D^2$	\mathcal{O}_{LHD1}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i D_\mu L_r^j) (H^m D^\mu H^n)$
	\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}	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^c}^i \sigma_{\mu\nu} L_r^m) H^j H^n W^{I\mu\nu}$
$\Psi^4 D$	$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}(\overline{d_p} \gamma_\mu u_r) (\overline{L_s^c}^i i D^\mu L_t^j)$
$\Psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_p} L_r^i) (\overline{L_s^c}^j L_t^m) H^n$
	$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}(\overline{d_p} L_r^i) (\overline{u_s^c} e_t) H^j$
	$\mathcal{O}_{\bar{d}QLLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_p} L_r^i) (\overline{Q_s^c}^j L_t^m) H^n$
	$\mathcal{O}_{\bar{d}QLLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_p} L_r^i) (\overline{Q_s^c}^j L_t^m) H^n$
	$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}(\overline{Q_p} u_r) (\overline{L_s^c} L_t^i) H^j$

Matching dimension-7 SMEFT operators with dim-6 LEFT operators

Bottom-up recipe:

Experimental observable

↓
Constraints on LEFT
(Single operator dominance)

↓
Constraints on SMEFT
(Using matching relations)

↓
UV theory

Highly simplified

Ignores correlations and cancellations

O	Operator	Matching
$O_{e\nu;LL}^{S,prst}$	$(\overline{e}_{Rp} e_{Lr})(\overline{\nu}_s^c \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{e\nu;LL}^{S,prst} = -\frac{\sqrt{2}v}{8} (2C_{\bar{e}LLLH}^{prst} + C_{\bar{e}LLLH}^{psrt} + s \leftrightarrow t)$
$O_{e\nu;RL}^{S,prst}$	$(\overline{e}_{Lp} e_{Rr})(\overline{\nu}_s^c \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{e\nu;RL}^{S,prst} = -\frac{\sqrt{2}v}{2} (C_{LeHD}^{sr} \delta^{tp} + C_{LeHD}^{tr} \delta^{sp})$
$O_{e\nu;LL}^{T,prst}$	$(\overline{e}_{Rp} \sigma_{\mu\nu} e_{Lr})(\overline{\nu}_s^c \sigma^{\mu\nu} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{e\nu;LL}^{T,prst} = +\frac{\sqrt{2}v}{32} (C_{\bar{e}LLLH}^{psrt} - C_{\bar{e}LLLH}^{ptrs})$
$O_{d\nu;LL}^{S,prst}$	$(\overline{d}_{Rp} d_{Lr})(\overline{\nu}_s^c \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{d\nu;LL}^{S,prst} = -\frac{\sqrt{2}v}{8} V_{xr} (C_{\bar{d}LQLH1}^{ptxs} + C_{\bar{d}LQLH1}^{psxt})$
$O_{d\nu;LL}^{T,prst}$	$(\overline{d}_{Rp} \sigma_{\mu\nu} d_{Lr})(\overline{\nu}_s^c \sigma^{\mu\nu} \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{d\nu;LL}^{T,prst} = -\frac{\sqrt{2}v}{32} V_{xr} (C_{\bar{d}LQLH1}^{ptxs} - C_{\bar{d}LQLH1}^{psxt})$
$O_{u\nu;RL}^{S,prst}$	$(\overline{u}_{Lp} u_{Rr})(\overline{\nu}_s^c \nu_t)$	$\frac{4G_F}{\sqrt{2}} c_{u\nu;RL}^{S,prst} = +\frac{\sqrt{2}v}{4} (C_{\bar{Q}uLLH}^{prst} + C_{\bar{Q}uLLH}^{ptrs})$
$O_{du\nu e;LL}^{S,prst}$	$(\overline{d}_{Rp} u_{Lr})(\overline{\nu}_s^c e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c_{du\nu e;LL}^{S,prst} = +\frac{\sqrt{2}v}{8} (2C_{\bar{d}LQLH1}^{ptrs} + C_{\bar{d}LQLH2}^{ptrs} - C_{\bar{d}LQLH2}^{psrt})$
$O_{du\nu e;RL}^{S,prst}$	$(\overline{d}_{Lp} u_{Rr})(\overline{\nu}_s^c e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c_{du\nu e;RL}^{S,prst} = +\frac{\sqrt{2}v}{2} V_{xp}^* C_{\bar{Q}uLLH}^{xrts}$
$O_{du\nu e;LL}^{T,prst}$	$(\overline{d}_{Rp} \sigma_{\mu\nu} u_{Lr})(\overline{\nu}_s^c \sigma^{\mu\nu} e_{Lt})$	$\frac{4G_F}{\sqrt{2}} c_{du\nu e;LL}^{T,prst} = +\frac{\sqrt{2}v}{32} (2C_{\bar{d}LQLH1}^{ptrs} + C_{\bar{d}LQLH2}^{ptrs} + C_{\bar{d}LQLH2}^{psrt})$
$O_{du\nu e;LR}^{V,prst}$	$(\overline{d}_{Lp} \gamma_\mu u_{Lr})(\overline{\nu}_s^c \gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}} c_{du\nu e;LR}^{V,prst} = +\frac{\sqrt{2}v}{2} V_{rp}^* C_{LeHD}^{st}$
$O_{du\nu e;RR}^{V,prst}$	$(\overline{d}_{Rp} \gamma_\mu u_{Rr})(\overline{\nu}_s^c \gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}} c_{du\nu e;RR}^{V,prst} = +\frac{\sqrt{2}v}{4} C_{\bar{d}LueH}^{psrt}$
$O_{d\nu;RL}^{S,prst}$	$(\overline{d}_{Lp} d_{Rr})(\overline{\nu}_s^c \nu_t)$	Not induced by $d = 7 \Delta L = 2$ SMEFT operators
$O_{u\nu;LL}^{S,prst}$	$(\overline{u}_{Rp} u_{Lr})(\overline{\nu}_s^c \nu_t)$	
$O_{u\nu;LL}^{T,prst}$	$(\overline{u}_{Rp} \sigma_{\mu\nu} u_{Lr})(\overline{\nu}_s^c \sigma^{\mu\nu} \nu_t)$	

Neutrinoless double beta decay

$$(A, Z) \rightarrow (A, Z + 2) + 2 e^- + Q_{\beta\beta}$$

Half life $T_{1/2}^{0\nu} = (G |\mathcal{M}|^2 \langle m_{\beta\beta} \rangle)^{-1} \simeq 10^{27-28} \left(\frac{0.01 \text{ eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{ y}$

Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)
Graf, Deppisch, Iachello, Kotila (2018)++

Effective mass

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

Current best experimental limit:

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \text{ yr} \quad \langle m_{\beta\beta} \rangle < 36 - 156 \text{ meV}$$

Other NP possibilities from distributions:

Majoron emission $0\nu\beta\beta J$

Cepedello, Deppisch, Gonzalez, CH, Hirsch PRL'19
Brune, Päs PRD'19

Exotic $2\nu\beta\beta$

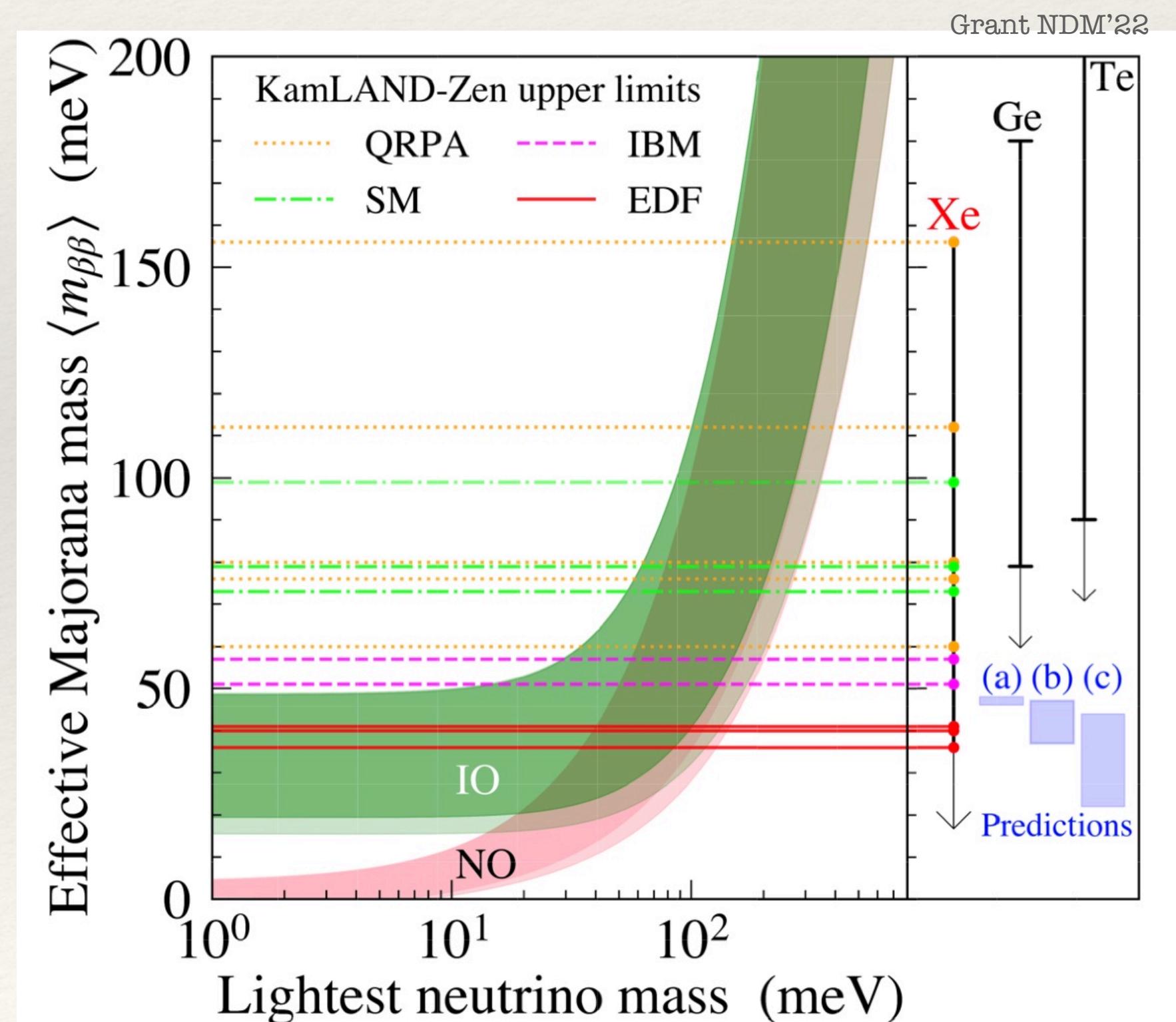
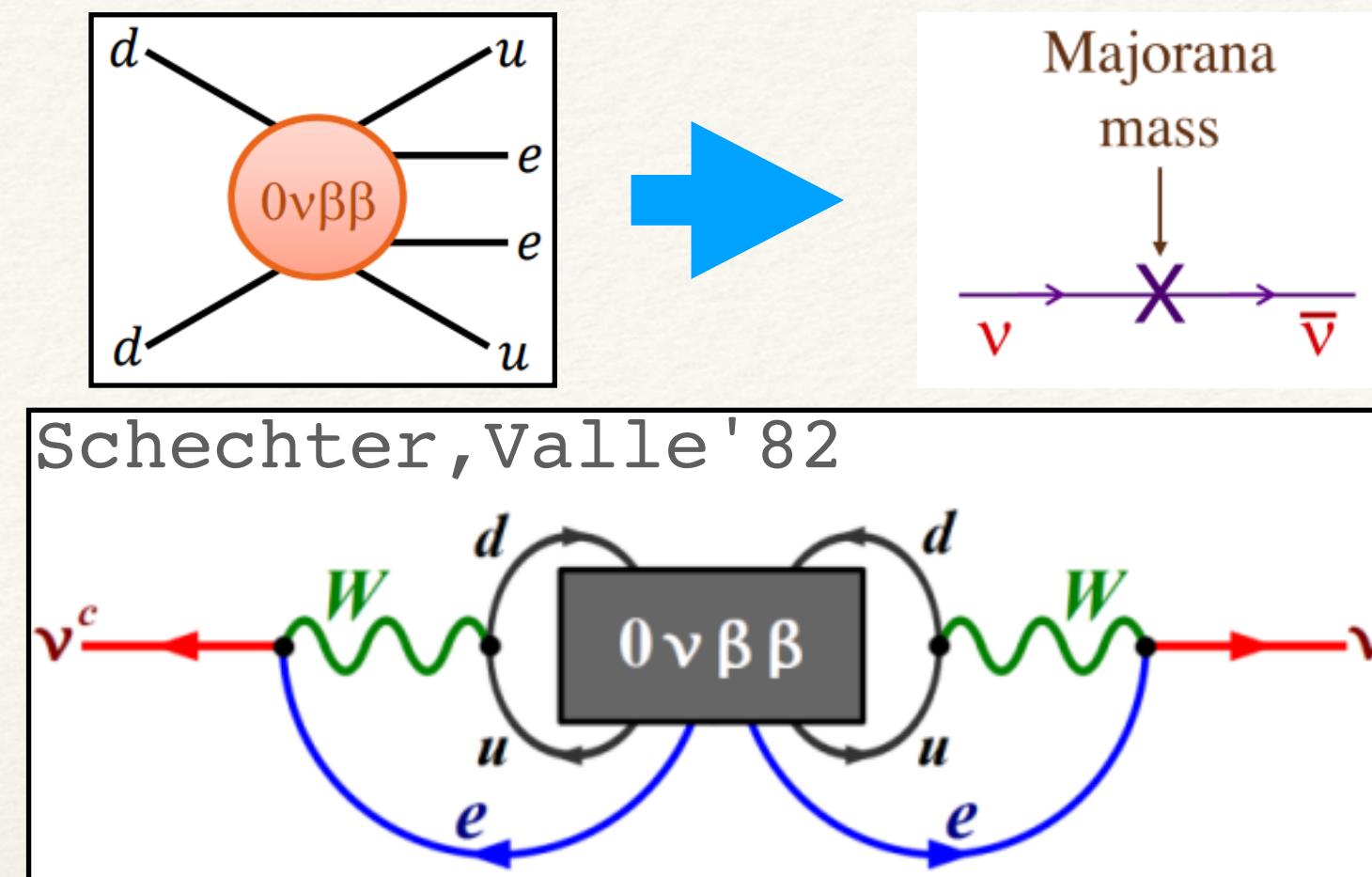
Deppisch, Graf, Simkovic PRL'20;
Deppisch, Graf, Rodejohan, Xu PRD RC'20 ++

Connection to baryogenesis:

Deppisch, Graf, Harz, Huang (2018)

Deppisch, Harz, Huang, Hirsch, Päs (2015)++

$0\nu\beta\beta$ is usually the most sensitive probe of LNV



LNV dim-7 SMEFT @Neutrinoless double beta decay

\mathcal{O}	Operator
\mathcal{O}_{LH}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i L_r^m) H^j H^n (H^\dagger H)$
\mathcal{O}_{LeHD}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i \gamma_\mu e_r) H^j (H^m i D^\mu H^n)$
\mathcal{O}_{LHD1}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i D_\mu L_r^j) (H^m D^\mu H^n)$
\mathcal{O}_{LHD2}^{pr}	$\epsilon_{im}\epsilon_{jn}(\overline{L_p^c}^i D_\mu L_r^j) (H^m D^\mu H^n)$
\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}	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^c}^i \sigma_{\mu\nu} L_r^m) H^j H^n W^{I\mu\nu}$
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}(\overline{d}_p \gamma_\mu u_r) (\overline{L_s^c}^i i D^\mu L_t^j)$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e}_p L_r^i) (\overline{L_s^c}^j L_t^m) H^n$
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}(\overline{d}_p L_r^i) (\overline{u}_s^c e_t) H^j$
$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d}_p L_r^i) (\overline{Q}_s^c{}^j L_t^m) H^n$
$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}(\overline{d}_p L_r^i) (\overline{Q}_s^c{}^j L_t^m) H^n$
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}(\overline{Q}_p u_r) (\overline{L}_s^c L_t^i) H^j$

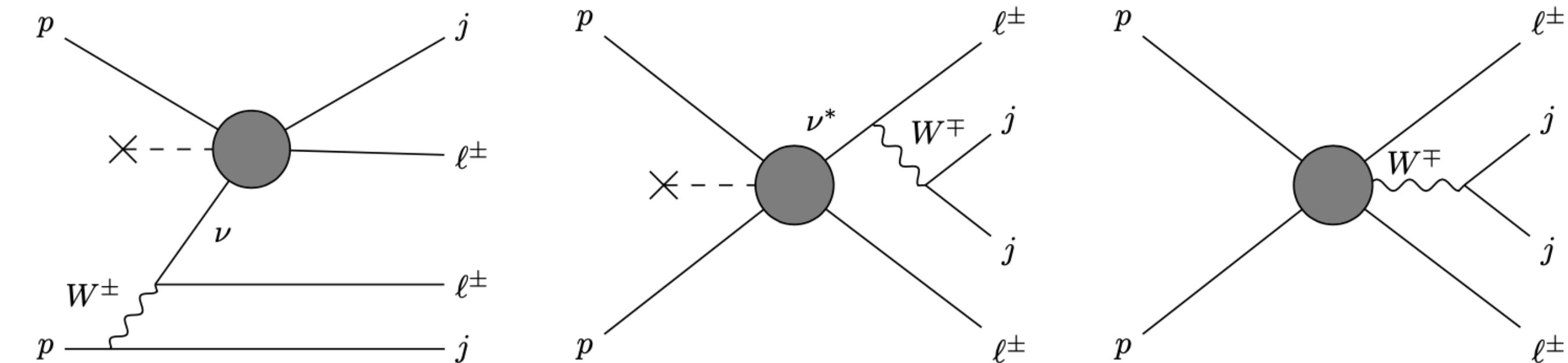
LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV $^{-3}$]	Λ_{NP} [TeV]
$c_{du\nu e;LL}^S$	$1.86 \cdot 10^{-10}$	$C_{\bar{d}LQLH1}$	$7.06 \cdot 10^{-8}$	242
$c_{du\nu e;RL}^S$	$1.86 \cdot 10^{-10}$	$C_{\bar{Q}uLLH}$	$3.62 \cdot 10^{-8}$	302
$c_{du\nu e;LR}^V$	$8.20 \cdot 10^{-10}$	C_{LeHD}	$1.55 \cdot 10^{-7}$	186
$c_{du\nu e;RR}^V$	$5.93 \cdot 10^{-8}$	$C_{\bar{d}LueH}$	$1.12 \cdot 10^{-5}$	44.7
$c_{du\nu e;LL}^T$	$4.51 \cdot 10^{-10}$	$C_{\bar{d}LQLH1}$	$6.83 \cdot 10^{-7}$	114
		$C_{\bar{d}LQLH2}$	$3.41 \cdot 10^{-7}$	143
$c_{du\nu e;LL}^{(7)V}$	$9.87 \cdot 10^{-6}$	C_{LHD1}	$1.36 \cdot 10^{-3}$	9.03
		C_{LHD2}	$2.71 \cdot 10^{-3}$	7.17
		C_{LHW}	$3.39 \cdot 10^{-4}$	14.3
$c_{du\nu e;RL}^{(7)V}$	$9.87 \cdot 10^{-6}$	$C_{\bar{d}uLLD}$	$1.32 \cdot 10^{-3}$	9.11
$c_{V;LL}^{(9);ij}$	$1.40 \cdot 10^{-5}$	C_{LHD1}	$9.91 \cdot 10^{-4}$	10.0
$c_{V;LR}^{(9);ij}$	$2.66 \cdot 10^{-8}$	C_{LHW}	$2.48 \cdot 10^{-4}$	15.9
		$C_{\bar{d}uLLD}$	$1.83 \cdot 10^{-6}$	81.7

Sensitive to 1st gen: What if LNV small in 1st gen but large for others?

LNV dim-7 SMEFT at LHC and FCC

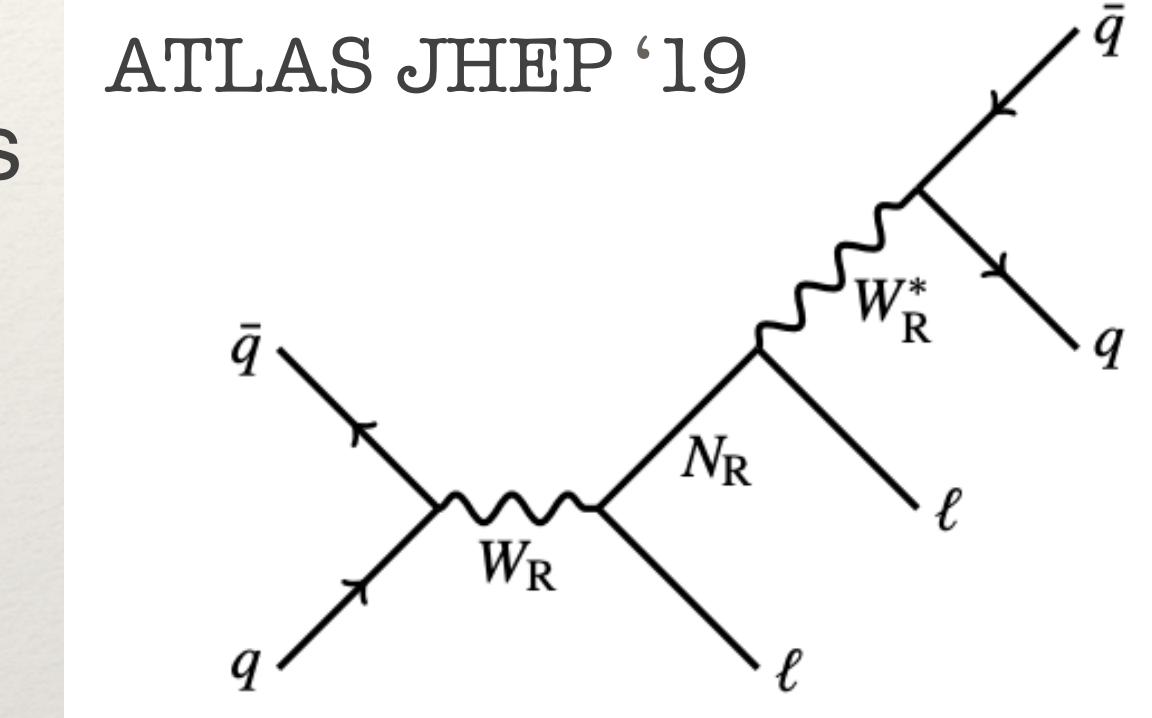
Our main mode of interest:

$$pp \rightarrow \ell^\pm \ell^\pm jj + X$$



Operator	$\sigma(pp \rightarrow \mu^\pm \mu^\pm jj + X)$ (pb)		Λ_{LNV}	$\Lambda_{\text{LNV}}^{\text{future}}$
	LHC	FCC	[TeV]	[TeV]
$\mathcal{O}_{\bar{Q}uLLH}$	4.2×10^{-5}	0.14	0.80	5.6
$\mathcal{O}_{\bar{d}LQLH2}$	1.4×10^{-5}	0.015	0.66	3.8
$\mathcal{O}_{\bar{d}LQLH1}$	1.5×10^{-5}	0.041	0.67	4.6
$\mathcal{O}_{\bar{d}LueH}$	1.5×10^{-5}	0.058	0.67	4.9
$\mathcal{O}_{\bar{d}uLLD}$	0.010	1.5×10^3	2.0	26
\mathcal{O}_{LDH2}	1.1×10^{-8}	1.1×10^{-5}	0.20*	1.2
\mathcal{O}_{LDH1}	4.3×10^{-7}	3.4×10^{-3}	0.37	3.0
\mathcal{O}_{LeHD}	6.8×10^{-9}	5.6×10^{-8}	0.13*	0.48
\mathcal{O}_{LH}	6.4×10^{-9}	1.8×10^{-6}	0.19*	0.86

Recasting of the search for
Keung–Senjanović (KS) process
By ATLAS



$\mathcal{O}_{eLLLH}, \mathcal{O}_{LHW}, \mathcal{O}_{LHB}$ can not give this signal at tree level

Similar philosophy to the analysis for dimension -5 LNV:

Fuks, Neundorf, Peters, Ruiz, Saimpert '21
CMS'22

Major Caveats: resonant production; Validity of EFT

Graesser, Li, Ramsey-Musolf, Shen, Quiroga '22

Validity of the EFT approach for LNV Collider searches

Expansion of heavy mediator propagator

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

For collider searches Q can be quite high

$$Q = \sqrt{x_1 x_2} \sqrt{s}$$

Avg. momentum exchange:

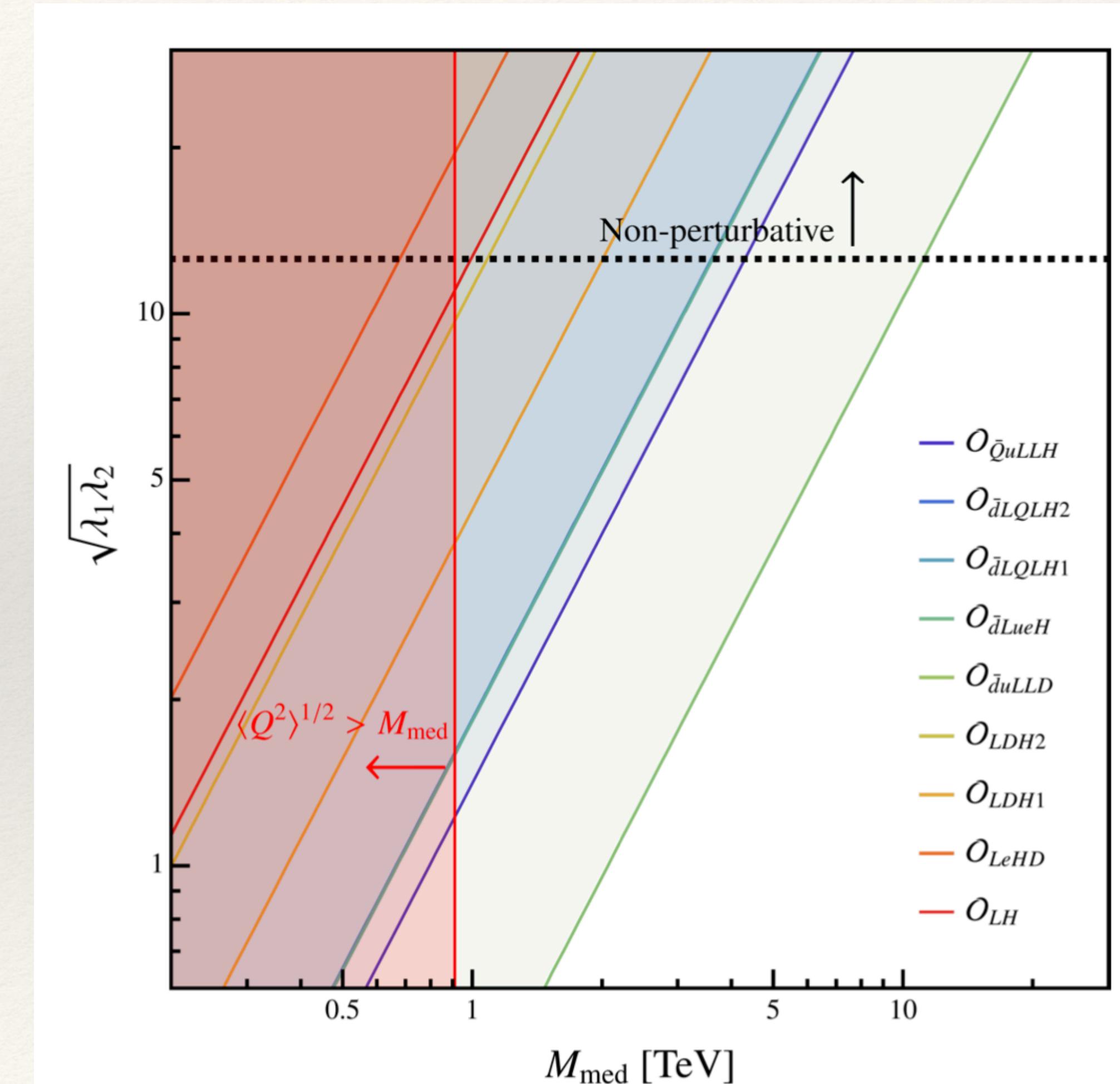
$$\langle Q^2 \rangle = \frac{\sum_{q_1=u,c} \sum_{q_2=d,s} \int dx_1 dx_2 (f_{q_1}(x_1) f_{\bar{q}_2}(x_2) + f_{q_1}(x_2) f_{\bar{q}_2}(x_1)) \Theta(Q - Q_0) Q^2}{\sum_{q_1=u,c} \sum_{q_2=d,s} \int dx_1 dx_2 (f_{q_1}(x_1) f_{\bar{q}_2}(x_2) + f_{q_1}(x_2) f_{\bar{q}_2}(x_1)) \Theta(Q - Q_0)}$$

$Q_0 \rightarrow$ Min final state invariant mass

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

For dim-7 SMEFT

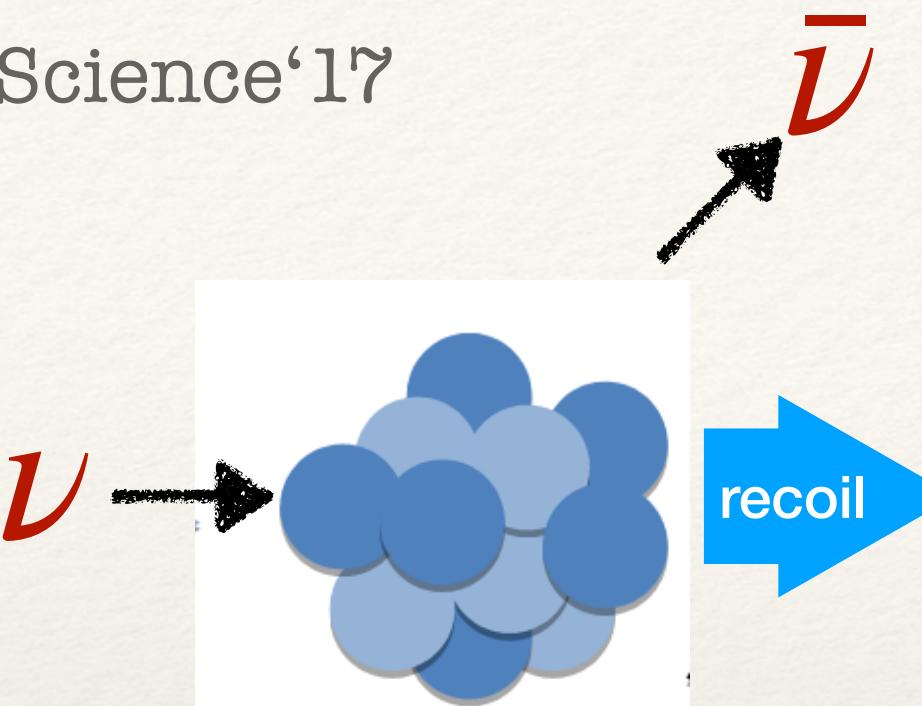
$\Lambda < Q_{\text{tr}} \implies$ large λ such that $M_{\text{med}} > Q_{\text{tr}}$



Neutral Current LNV @CE ν NS experiments

First observation: Akimov et al. Science'17

Neutrino scatters elastically from entire nucleus
 $E_\nu \lesssim \frac{hc}{R_N} \sim \mathcal{O}(10 \text{ MeV})$



Changed Current LNV NSI @LBL Oscillation experiments

Production charge blind
 Detection sensitive to outgoing lepton charge

$$R_{\alpha\beta} \equiv \frac{N_{\ell_\beta^+}}{N_{\ell_\beta^-}} = \frac{\Gamma_{\nu_\alpha \rightarrow \bar{\nu}_\beta} + \Gamma_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta}}{\Gamma_{\nu_\alpha \rightarrow \nu_\beta} + \Gamma_{\bar{\nu}_\alpha \rightarrow \nu_\beta}}$$

$$S_{\mu\mu} \approx \frac{\int dE_q \sum_{\rho,\sigma} \frac{d\Gamma_{\nu_\mu}}{dE_q} \cdot P_{\nu_\mu \rightarrow \bar{\nu}_\mu}^{(\rho,\sigma)} \cdot \sigma_{\bar{\nu}_\mu}}{\int dE_q \sum_{\rho,\sigma} \frac{d\Gamma_{\nu_\mu}}{dE_q} \cdot P_{\nu_\mu \rightarrow \nu_\mu}^{(\rho,\sigma)} \cdot \sigma_{\nu_\mu}} \lesssim 0.026$$

Bolton, Deppisch PRD'19

Current Bound				
LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Experiment
$c_{d\nu;LL(LR)}^{S,11\mu\mu}$	0.030	11.3	0.4	COHERENT
$c_{d\nu;LL}^{T,11st}$	0.178	540.2	0.1	COHERENT
Future Sensitivity				
$c_{d\nu;LL(LR)}^{S,11\alpha\alpha}$	0.008	3.0	0.7	Ge
$c_{d\nu;LL}^{T,11st}$	0.062	186.9	0.2	Ge

LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV $^{-3}$]	Λ_{NP} [TeV]	Experiment
$c_{du\nu e;LR}^{V,11ee(e\mu)}$	0.017	$C_{LeHD}^{ee(e\mu)}$	3.2	0.7	KamLAND
$c_{du\nu e;RR}^{V,11ee(e\mu)}$	0.017	$C_{\bar{d}LueH}^{1e1e(1e1\mu)}$	6.4	0.5	KamLAND
$c_{du\nu e;LR}^{V,11e\tau}$	0.015	$C_{LeHD}^{ee(e\tau)}$	2.8	0.7	KamLAND
$c_{du\nu e;RR}^{V,11e\tau}$	0.015	$C_{\bar{d}LueH}^{1e1\tau}$	5.7	0.6	KamLAND
$c_{du\nu e;LR}^{V,11\mu e}$	0.22 – 3.47	$C_{LeHD}^{\mu e}$	41.7-658.1	0.1-0.3	MINOS
$c_{du\nu e;RR}^{V,11\mu e}$	0.22 – 3.47	$C_{\bar{d}LueH}^{1\mu 1e}$	83.4-1316.2	0.1-0.2	MINOS
$c_{du\nu e;LR}^{V,11\mu\mu}$	0.16 – 0.63	$C_{LeHD}^{\mu\mu}$	30.3-119.5	0.2-0.3	MINOS
$c_{du\nu e;RR}^{V,11\mu\mu}$	0.16 – 0.63	$C_{\bar{d}LueH}^{1\mu 1\mu}$	60.7-239.0	0.2-0.3	MINOS
$c_{du\nu e;LR}^{V,11\mu\tau}$	0.16 – 0.71	$C_{LeHD}^{\mu\tau}$	30.3-134.7	0.2-0.3	MINOS
$c_{du\nu e;RR}^{V,11\mu\tau}$	0.16 – 0.71	$C_{\bar{d}LueH}^{1\mu 1\tau}$	60.7-269.31	0.2-0.3	MINOS

LNV dim-7 SMEFT @ Rare meson and τ decays

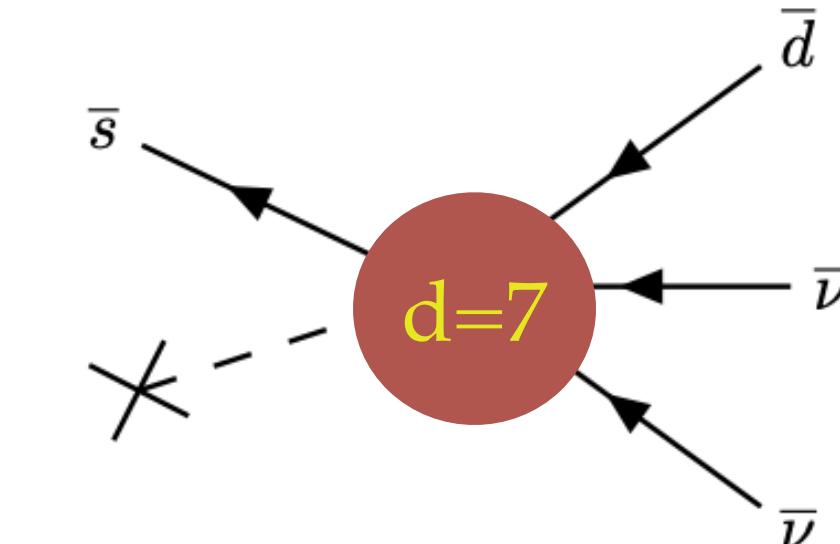
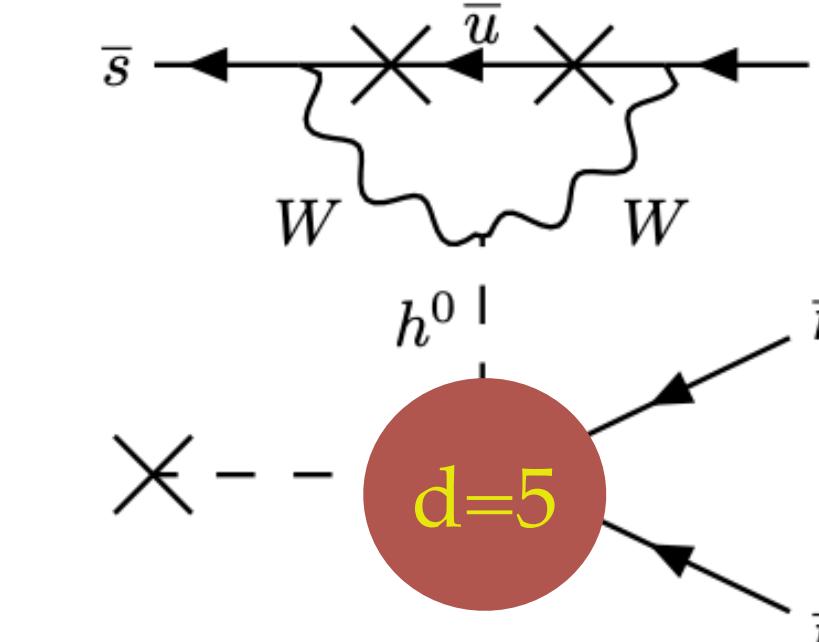
Very weak constraints from

$$\tau^\pm \rightarrow \ell_\alpha^\mp P_i^\pm P_j^\pm \quad K^+ \rightarrow \pi^- \ell^+ \ell^+$$

$$M \rightarrow M' \nu \bar{\nu}$$

Well discussed in literature
in the context of dim-7 SMEFT

Li, Ma, Schmidt PRD '20
Deppisch, Fridell, Harz JHEP '20
Felkl, Li, Schmidt JHEP '21



Current Bound				
LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Observable
$c_{d\nu;LL}^{S,ds\gamma\gamma}$	1.3×10^{-6}	4.8×10^{-4}	12.8	$K_L \rightarrow \nu \bar{\nu}$
$c_{d\nu;LL}^{S,ds\gamma\gamma}$	2.5×10^{-7}	9.6×10^{-5}	21.8	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
$c_{d\nu;LL}^{S,ds\gamma\gamma}$	2.6×10^{-7}	9.9×10^{-5}	21.6	$K^0 \rightarrow \pi^0 \nu \bar{\nu}$

Future Sensitivity				
LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Observable
$c_{d\nu;LL}^{S,ds\gamma\gamma}$	8.4×10^{-8}	3.2×10^{-5}	31.5	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
$c_{d\nu;LL}^{S,ds\gamma\gamma}$	1.4×10^{-7}	5.2×10^{-5}	26.8	$K^0 \rightarrow \pi^0 \nu \bar{\nu}$

Assumptions:

1. single LEFT operator dominance
2. Lepton flavour universality

Current Bound				
LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Observable
$c_{d\nu;LL}^{S,sb\gamma\gamma}$	3.6×10^{-4}	0.14	1.9	$B \rightarrow K^{(*)} \nu \bar{\nu}$
$c_{d\nu;LL}^{S,sb\gamma\delta}$	2.7×10^{-4}	0.21	1.7	$B \rightarrow K^{(*)} \nu \bar{\nu}$
$c_{d\nu;LL}^{T,sb\gamma\delta}$	0.6×10^{-4}	0.18	1.75	$B \rightarrow K^* \nu \bar{\nu}$

Future Sensitivity (50 ab $^{-1}$)				
LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Observable
$c_{d\nu;LL}^{S,sb\gamma\gamma}$	0.6×10^{-4}	0.02	3.5	$B \rightarrow K \nu \bar{\nu}$
$c_{d\nu;LL}^{S,sb\gamma\delta}$	0.6×10^{-4}	0.05	2.8	$B \rightarrow K \nu \bar{\nu}$
$c_{d\nu;LL}^{T,sb\gamma\delta}$	0.3×10^{-4}	0.08	2.3	$B \rightarrow K^* \nu \bar{\nu}$

Dipole type of contributions can be present but suppressed
Charged Kaon decays @NA62 provide the best limits

$\mathcal{O}_{\bar{e}LLLH}$ and leptonic μ^+ decay

$\mathcal{O}_{\bar{e}LLLH}$ doesn't contribute to $0\nu\beta\beta$ decay at tree level

After the EW symmetry breaking
at the LEFT level:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} \left\{ c_{e\nu;LL}^{S,\mu ee\mu} (\bar{\mu}_R e_L) (\bar{\nu}_e^c \nu_\mu) + c_{e\nu;LL}^{S,e\mu e\mu} (\bar{e}_R \mu_L) (\bar{\nu}_e^c \nu_\mu) \right. \\ \left. + c_{e\nu;LL}^{T,\mu ee\mu} (\bar{\mu}_R \sigma_{\mu\nu} e_L) (\bar{\nu}_e^c \sigma^{\mu\nu} \nu_\mu) + c_{e\nu;LL}^{T,e\mu e\mu} (\bar{e}_R \sigma_{\mu\nu} \mu_L) (\bar{\nu}_e^c \sigma^{\mu\nu} \nu_\mu) \right\} + \text{h.c.}$$

Only $c_{e\nu;LL}^{S(T),\mu ee\mu}$ can mediate the experimentally searched $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$

CC process $p \bar{\nu}_e \rightarrow e^+ n$ was used to identify $\bar{\nu}_e$

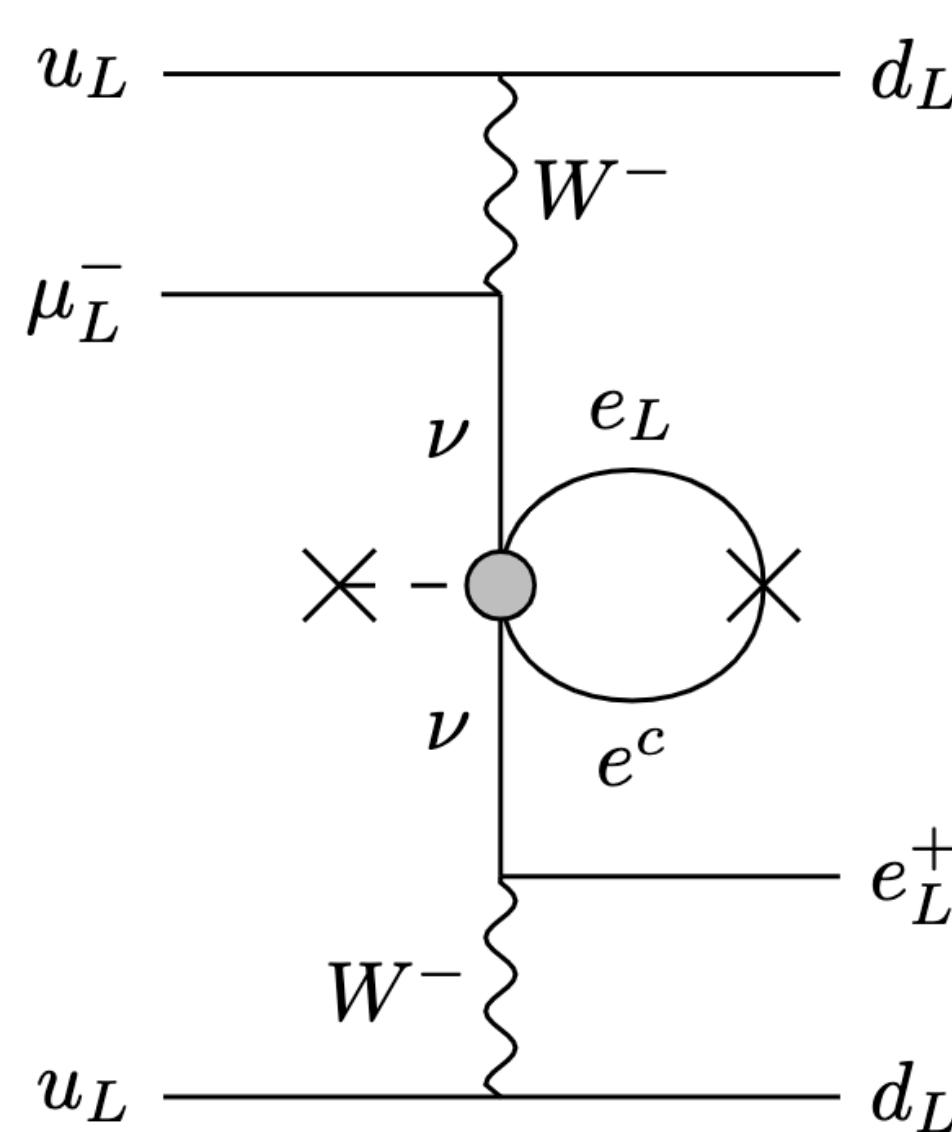
B. Armbruster et al RRL '03

Current Bound				
LEFT Wilson		$C_{\bar{e}LLLH}$ [TeV $^{-3}$]	Λ_{NP} [TeV]	Observable
Coefficient	Value			
$c_{e\nu;LL}^{S,\mu ee\mu}$	0.06	15.2	0.4	$\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu, \tilde{\rho} = 0.75$
$c_{e\nu;LL}^{T,\mu ee\mu}$	0.04	121.6	0.2	$\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu, \tilde{\rho} = 0.25$

LNV ($\mu^- - e^+$) conversion

$\mathcal{O}_{\bar{e}LLLH}$

$$R_{\mu^- e^+} \equiv \frac{\Gamma(\mu^- + N \rightarrow e^+ + N')}{\Gamma(\mu^- + N \rightarrow \nu_\mu + N'')}$$



Best limits: SINDRUM II ; Future: Mu2e and COMET P-I

$$\frac{|g_{e\mu}|^2 \left(\frac{G_F}{\sqrt{2}}\right)^4 \left(\frac{1}{q^2}\right)^2 \left(\frac{y_\tau v \Lambda^2}{16\pi^2}\right)^2 v^2 \left(\frac{1}{\Lambda^3}\right)^2 Q^8 |\psi_{100}(0)|^2}{\left(\frac{G_F}{\sqrt{2}}\right)^2 Q^2 |\psi_{100}(0)|^2}$$

Berryman, de Gouvea et al PRD '16

For $\Lambda \sim 1$ TeV $R_{\mu^- e^+} \sim 10^{-24}$

Small contributions for
dim-7 SMEFT

Neutrino magnetic moment

$$\mathcal{L}_M \supset \frac{1}{2} \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \end{pmatrix} \sigma_{\mu\nu} \begin{pmatrix} 0 & \mu_{12} & \mu_{13} \\ -\mu_{12} & 0 & \mu_{23} \\ -\mu_{13} & -\mu_{23} & 0 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} F^{\mu\nu} + \text{h.c.}$$

$$c_{\nu\nu F}^{5\gamma}/e \equiv \mu_{ij} = \frac{1}{2v} \left(v^3 C_{LHB}^{ij} - v^3 \frac{C_{LHW}^{ij} - C_{LHW}^{ji}}{2} \right)$$

Solar: Borexino

Reactor: GEMMA, TEXONO, CONUS

Accelerator: LSND, DUNE

$$|\mathcal{C}_{LHB}^{ij} - \mathcal{C}_{LHW}^{ij}|_{i \neq j} \lesssim \frac{10^{-11}}{4m_e v^2}$$

$\Lambda > 10$ TeV

Competitive with $0\nu\beta\beta$

Correction to neutrino mass and “naturalness”

Tree level contribution from \mathcal{O}_{LH} :

$$(\delta m_\nu)_{ij} = -\frac{v}{2} (v^3 \mathcal{C}_{LH,ij})$$



$$(\delta m_\nu)_{ij} < 1 \text{ eV} \implies$$

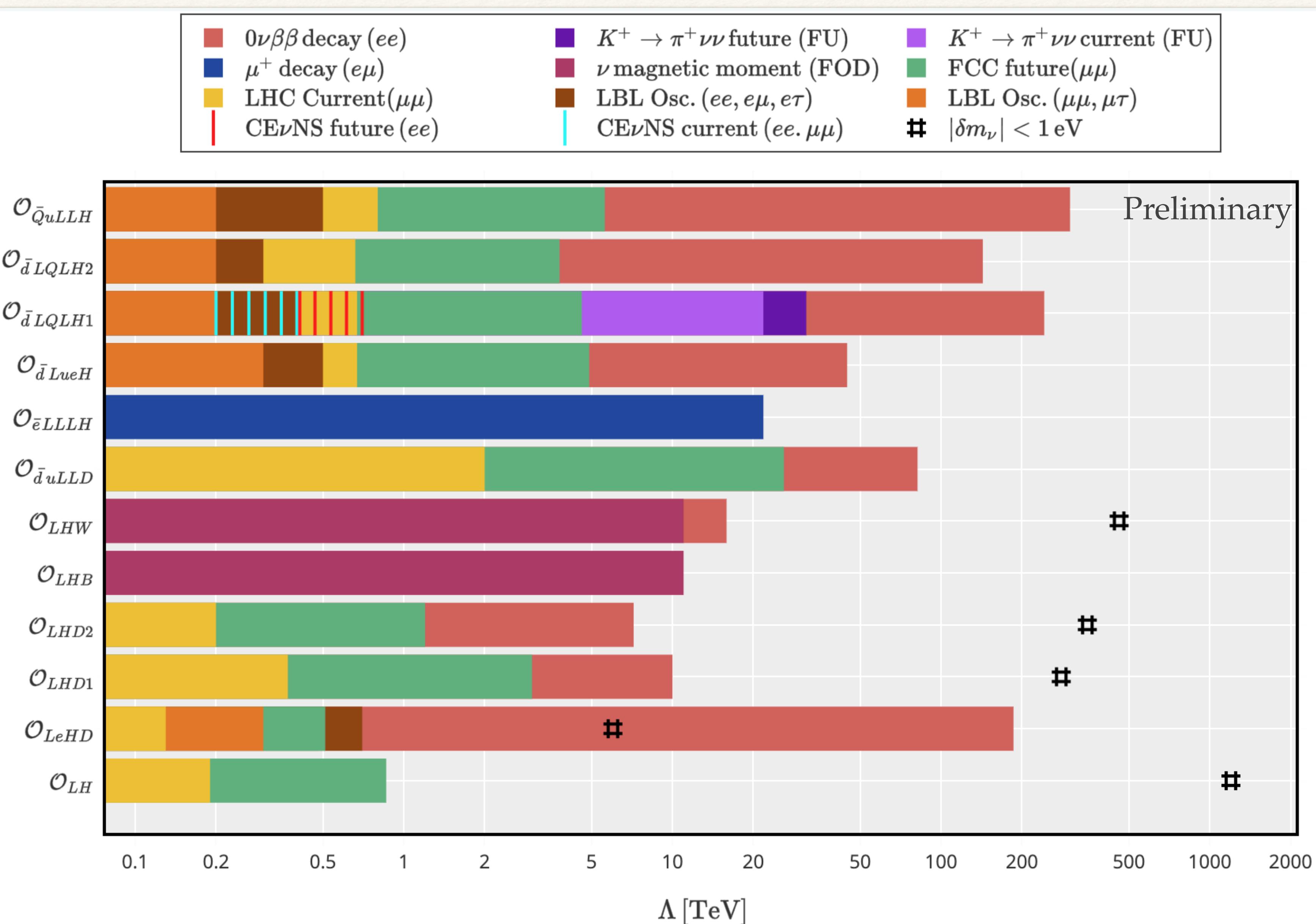
$$C_{LH}: \Lambda > 1200 \text{ TeV}$$

$$C_{LeHD}: \Lambda > 6 \text{ TeV} \quad C_{LHW}: \Lambda > 460 \text{ TeV}$$

$$C_{LHD1}: \Lambda > 280 \text{ TeV} \quad C_{LHD2}: \Lambda > 350 \text{ TeV}$$

Bird's eye view of the constraints on LNV dim-7 SMEFT operators

\mathcal{O}	Operator
\mathcal{O}_{LH}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}{}^i L_r^m) H^j H^n (H^\dagger H)$
\mathcal{O}_{LeHD}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}{}^i \gamma_\mu e_r) H^j (H^m i D^\mu H^n)$
\mathcal{O}_{LHD1}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}{}^i D_\mu L_r^j) (H^m D^\mu H^n)$
\mathcal{O}_{LHD2}^{pr}	$\epsilon_{im}\epsilon_{jn}(\overline{L_p^c}{}^i D_\mu L_r^j) (H^m D^\mu H^n)$
\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}	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^c}{}^i \sigma_{\mu\nu} L_r^m) H^j H^n W^{I\mu\nu}$
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}(\overline{d}_p \gamma_\mu u_r) (\overline{L_s^c}{}^i i D^\mu L_t^j)$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e}_p L_r^i) (\overline{L_s^c}{}^j L_t^m) H^n$
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}(\overline{d}_p L_r^i) (\overline{u}_s^c e_t) H^j$
$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d}_p L_r^i) (\overline{Q}_s^c{}^j L_t^m) H^n$
$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}(\overline{d}_p L_r^i) (\overline{Q}_s^c{}^j L_t^m) H^n$
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}(\overline{Q}_p u_r) (\overline{L}_s^c{}^i L_t^j) H^j$



Summary

Operator	Collider	$0\nu\beta\beta$	LBL Osc.	μ_ν	μ^+ -decay	CE ν NS	Meson decay
\mathcal{O}_{LH}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^{ci}}L_r^m)H^jH^n(H^\dagger H)$	\checkmark	\checkmark	-	-	-	-
\mathcal{O}_{LeHD}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^{ci}}\gamma_\mu e_r)H^j(H^m iD^\mu H^n)$	\checkmark	\checkmark	\checkmark	-	-	-
\mathcal{O}_{LHD1}^{pr}	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^{ci}}D_\mu L_r^j)(H^m D^\mu H^n)$	\checkmark	\checkmark	-	-	-	-
\mathcal{O}_{LHD2}^{pr}	$\epsilon_{im}\epsilon_{jn}(\overline{L_p^{ci}}D_\mu L_r^j)(H^m D^\mu H^n)$	\checkmark	\checkmark	-	-	-	-
\mathcal{O}_{LHB}^{pr}	$g\epsilon_{ij}\epsilon_{mn}(\overline{L_p^{ci}}\sigma_{\mu\nu}L_r^m)H^jH^nB^{\mu\nu}$	-	-	-	\checkmark	-	-
\mathcal{O}_{LHW}^{pr}	$g'\epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^{ci}}\sigma_{\mu\nu}L_r^m)H^jH^nW^{I\mu\nu}$	-	\checkmark	-	\checkmark	-	-
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}(\overline{d_p}\gamma_\mu u_r)(\overline{L_s^{ci}}iD^\mu L_t^j)$	\checkmark	\checkmark	-	-	-	-
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_p}L_r^i)(\overline{L_s^{cj}}L_t^m)H^n$	-	-	-	-	\checkmark	-
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}(\overline{d_p}L_r^i)(\overline{u_s^c}e_t)H^j$	\checkmark	\checkmark	\checkmark	-	-	-
$\mathcal{O}_{\bar{d}QLLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_p}L_r^i)(\overline{Q_s^{cj}}L_t^m)H^n$	\checkmark	\checkmark	\checkmark	-	-	\checkmark
$\mathcal{O}_{\bar{d}QLLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_p}L_r^i)(\overline{Q_s^{cj}}L_t^m)H^n$	\checkmark	\checkmark	\checkmark	-	-	-
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}(\overline{Q_p}u_r)(\overline{L_s^{ci}}L_t^i)H^j$	\checkmark	\checkmark	\checkmark	-	-	-

Outlook:

\mathcal{O} by \mathcal{O} simplified model analysis to compliment EFT results with resonant production@ collider
Comprehensive exploration of ν SMEFT

Thanks a lot for your attention!

Neutral Current LNV@CE ν NS experiments

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{\bar{\nu}^c\nu ff} = \frac{4G_F}{\sqrt{2}} & \left[c_{d\nu;LL}^{S,prst}(\overline{d_{Rp}}d_{Lr})(\overline{\nu_s^c}\nu_t) + c_{d\nu;RL}^{S,prst}(\overline{d_{Lp}}d_{Rr})(\overline{\nu_s^c}\nu_t) + c_{d\nu;LL}^{T,prst}(\overline{d_{Rp}}\sigma_{\mu\nu}d_{Lr})(\overline{\nu_s^c}\sigma^{\mu\nu}\nu_t) \right. \\ & \left. + c_{u\nu;LL}^{S,prst}(\overline{u_{Rp}}u_{Lr})(\overline{\nu_s^c}\nu_t) + c_{u\nu;RL}^{S,prst}(\overline{u_{Lp}}u_{Rr})(\overline{\nu_s^c}\nu_t) + c_{u\nu;LL}^{T,prst}(\overline{u_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu_s^c}\sigma^{\mu\nu}\nu_t) \right]. \end{aligned}$$

Changed Current LNV @LBL Oscillation experiments

$$\begin{aligned} \mathcal{L}_{\text{LEFT}}^{d=6} \supset \frac{4G_F}{\sqrt{2}} & \left[c_{du\nu e;LR}^{V,prst}(\overline{d_{Lp}}\gamma_\mu u_{Lr})(\overline{\nu_s^c}\gamma^\mu e_{Rt}) + c_{du\nu e;RR}^{V,prst}(\overline{d_{Rp}}\gamma_\mu u_{Rr})(\overline{\nu_s^c}\gamma^\mu e_{Rt}) \right] \\ \mathcal{L}_{\text{LEFT}}^{d=6} = \frac{4G_F}{\sqrt{2}} & \left[c_{du\nu e;LL}^{S,prst}(\overline{d_{Rp}}u_{Lr})(\overline{\nu_s^c}e_{Lt}) + c_{du\nu e;RL}^{S,prst}(\overline{d_{Lp}}u_{Rr})(\overline{\nu_s^c}e_{Lt}) \right. \\ & \left. + c_{du\nu e;LL}^{T,prst}(\overline{d_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu_s^c}\sigma^{\mu\nu}e_{Lt}) \right]. \end{aligned}$$

$$\sigma_{\bar{\nu}_\mu p \rightarrow \ell_\beta^+ n}(E_{\bf q}) \backsimeq \sigma_{\nu_\mu n \rightarrow \ell_\beta^- p}(E_{\bf q}) \backsimeq \frac{G_F^2 |V_{ud}|^2}{\pi} \big(g_{\rm V}^2 + 3 g_{\rm A}^2\big) E_{\bf q}^2.$$

$$\sigma_{\bar{\nu}_\mu p \rightarrow \ell_\beta^+ n}(E_{\bf q}) \backsimeq \sigma_{\nu_\mu n \rightarrow \ell_\beta^- p}(E_{\bf q}) \backsimeq \frac{G_F^2 |V_{ud}|^2}{\pi} \big(g_{\rm S}^2\big) E_{\bf q}^2,$$