Effective Field Theory approach to Lepton Number Violation

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very rich literature!

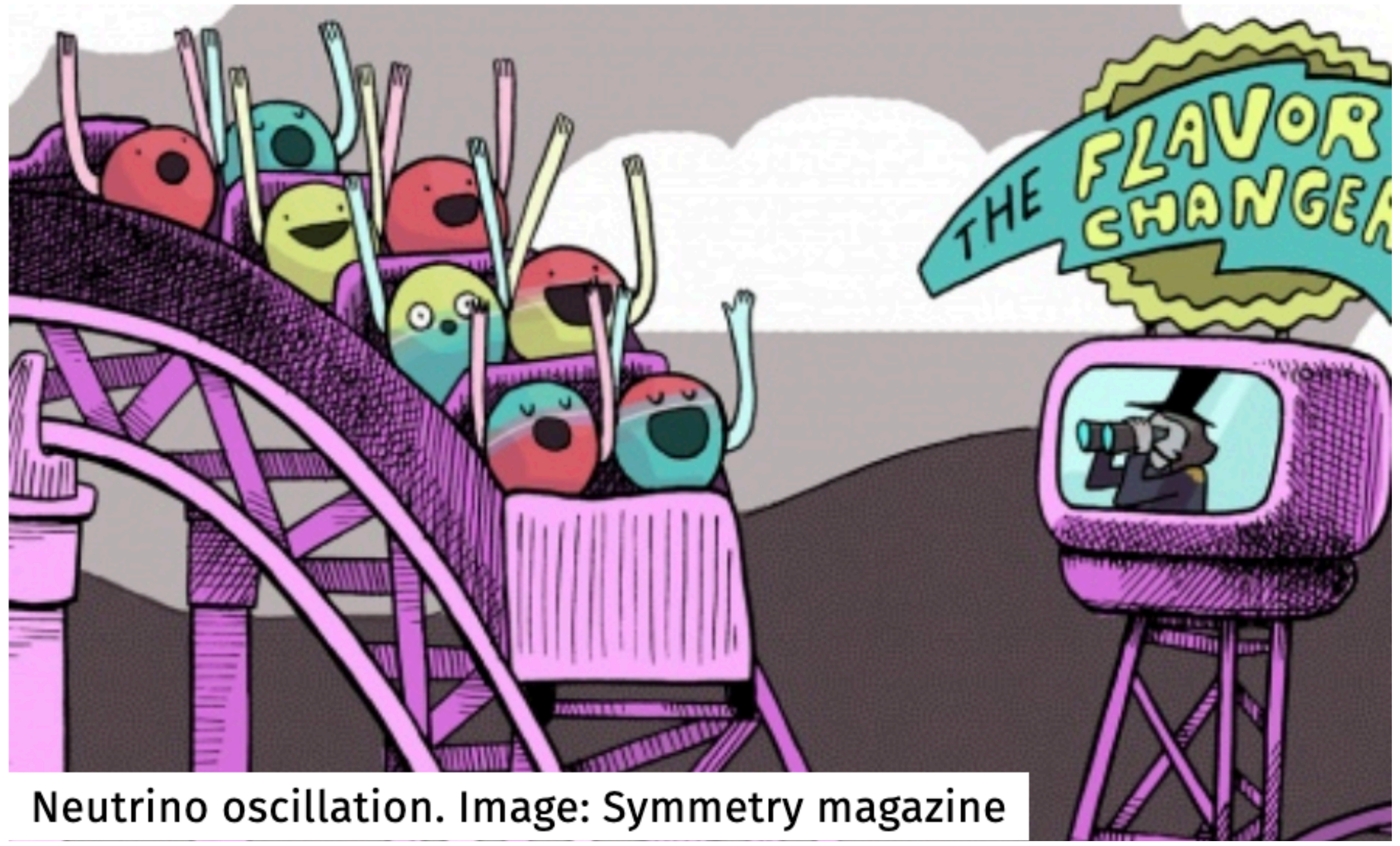
more than four decades of exploration and counting!

highly eccentric and biased take in this talk!

suggestions are very welcome!

Why Lepton Number Violation?

The only laboratory evidence of BSM physics : **Neutrino Oscillations**



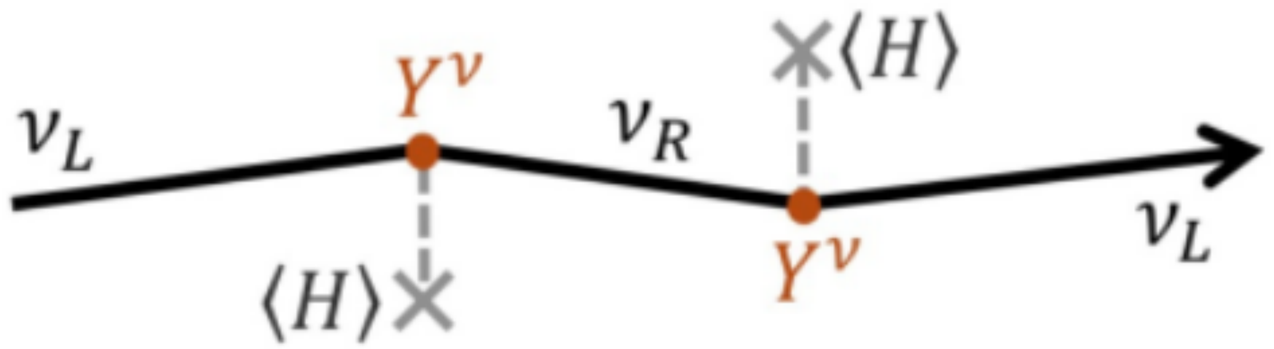
Neutrino oscillation. Image: Symmetry magazine

Purely SM:

- strictly massless neutrinos
- conservation of lepton number and flavours

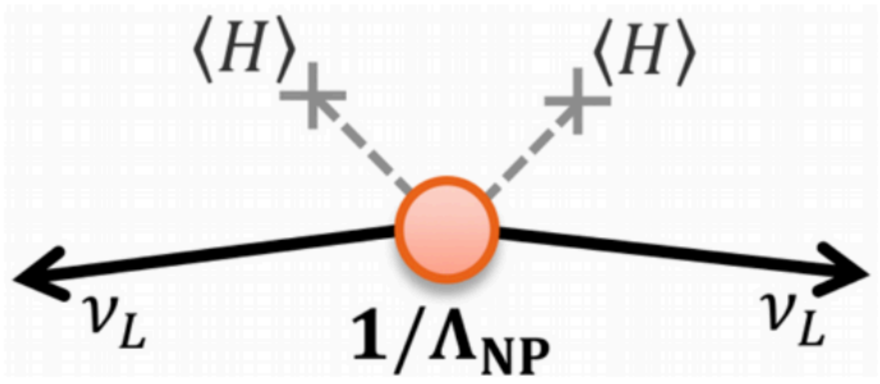
See talks by
Srubabati Goswami
Frank Deppisch

Two possibilities for neutrino masses:



$$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$$

VS.



$$m_M \overline{\nu}_L \nu_L^c$$

Dirac: like other fermions,

but tiny Yukawa couplings ~10^{-12}

finetuning, symmetry, ...?

Majorana: $\nu = \nu^c$: **Lepton Number Violation!**

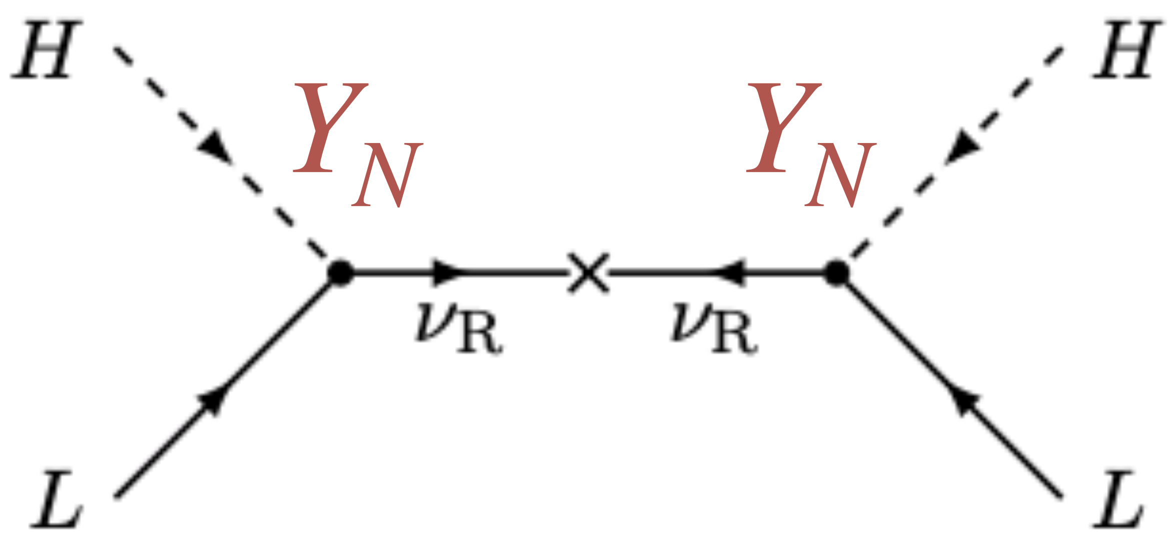
Phenomenologically very interesting!

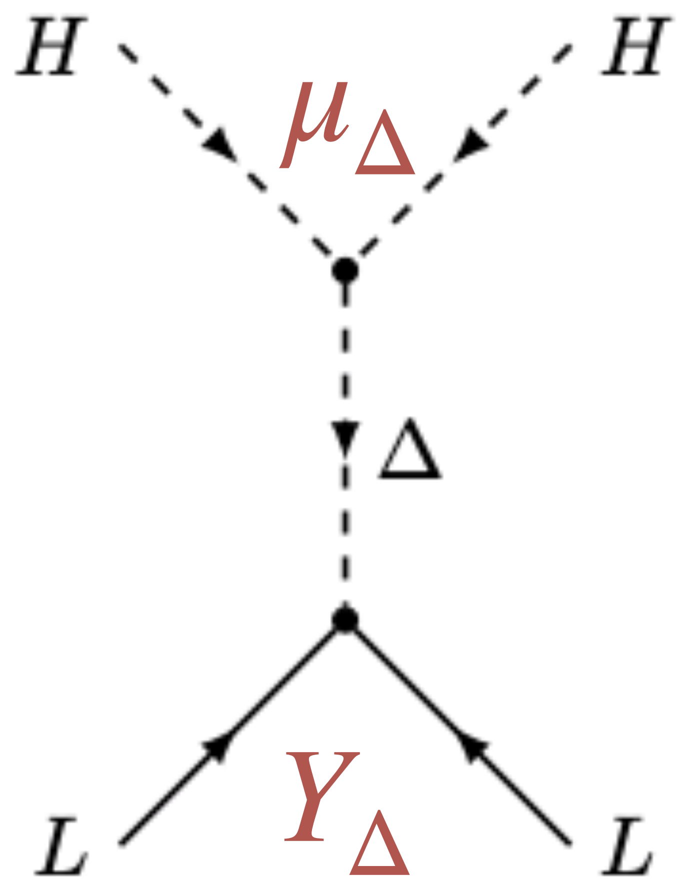
Connection to Leptogenesis?

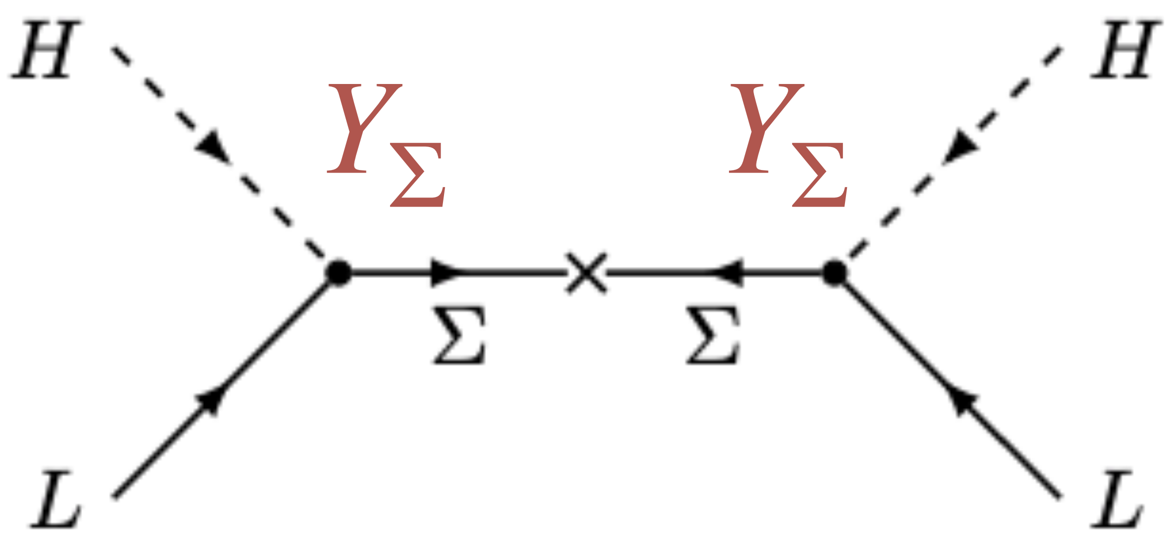
Minimal neutrino mass models

Minimal possibilities for Majorana mass-> Tree-level dimension-5:

Seesaw: type-I type-II type-III







$$m_\nu = Y_N^T \frac{v^2}{M_N} Y_N \qquad m_\nu = Y_\Delta \frac{v^2}{M_\Delta^2} \mu_\Delta \qquad m_\nu = Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

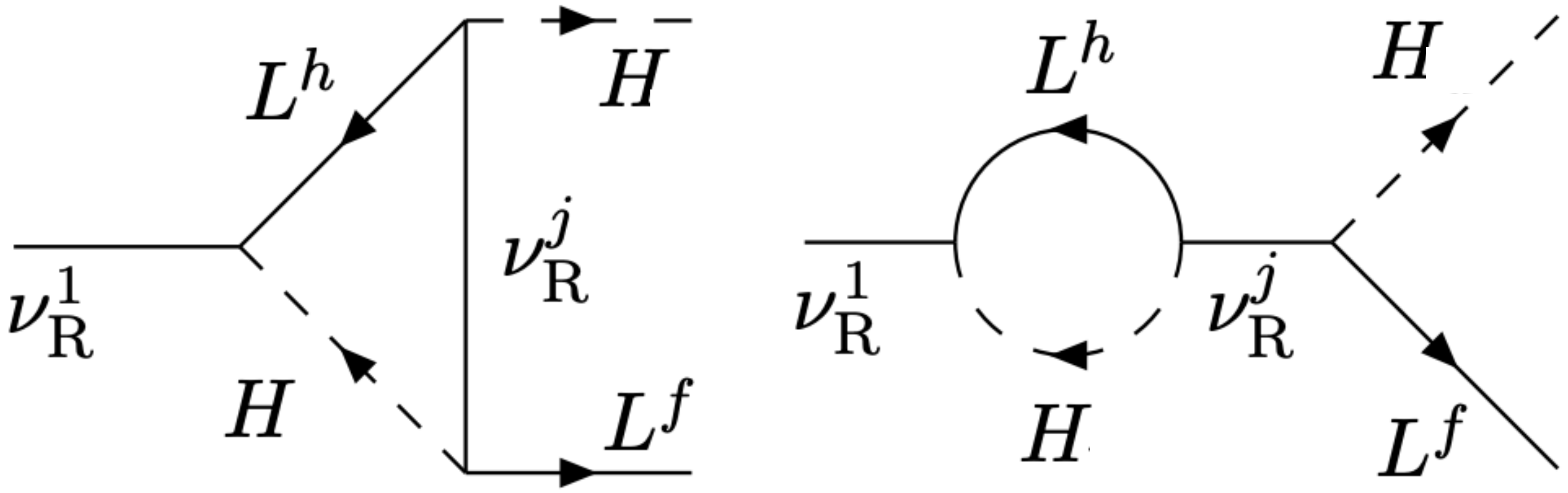
Minkowski; Gell-Mann, Ramond, Slansky;Mohapatra,Senjanovic; Schechter, Valle; Ma, Sarkar; Magg, Wetterich; Cheng, Li; Lazarides, Shafi; Foot,Lew, Joshi; Hambye, Lin, Notari, Papucci, Strumia; Bajc, nemevsek, Senjanovic; Dorsner, Fileviez-Perez ++

Bonus: gateway to explain baryon asymmetry of the Universe

Shakarov's conditions => Leptogenesis

Fukugida,Yanagida

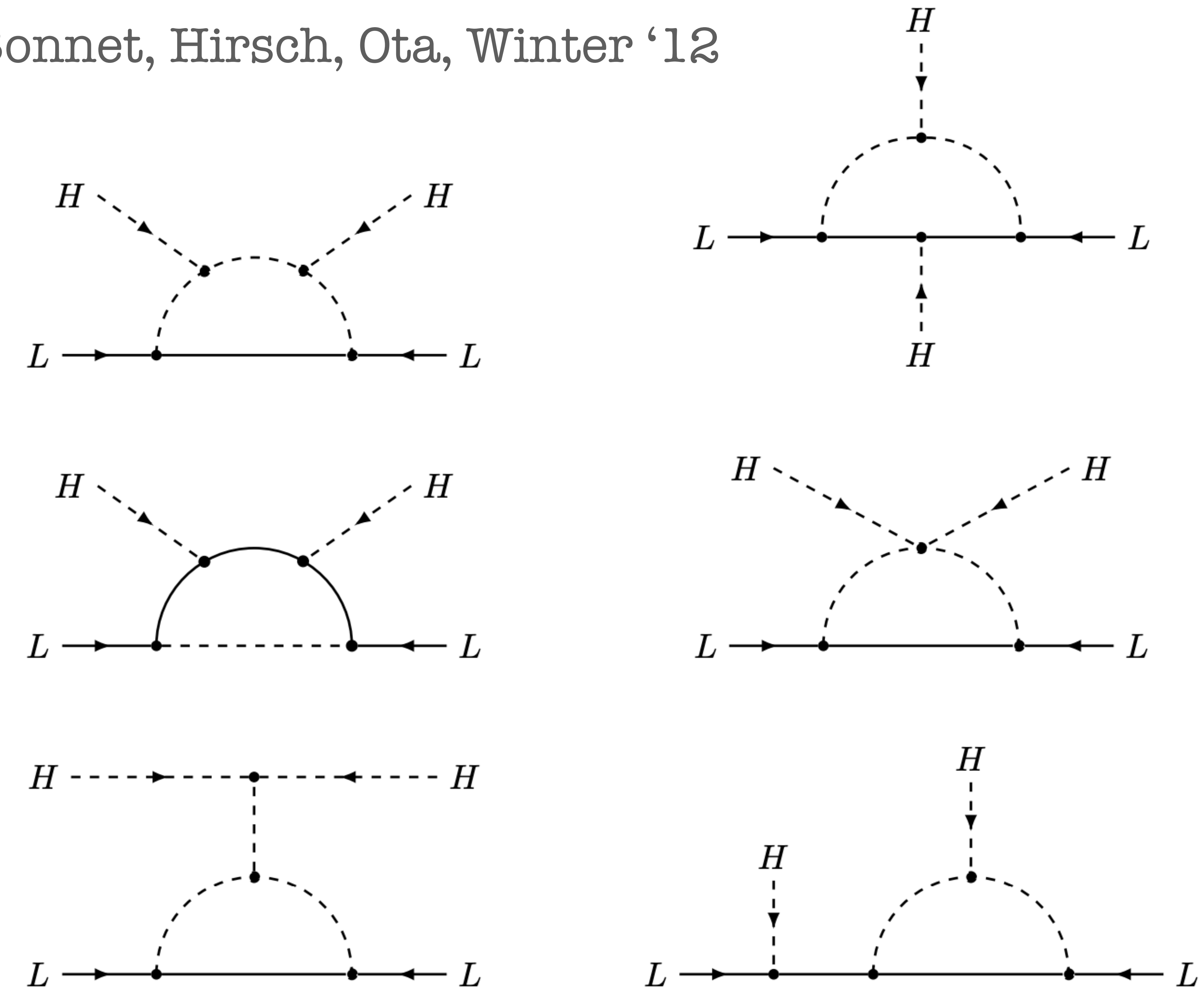
Liu, Segré; Flanz, Paschos, Sarkar; Covi, Roulet,Vissani; Pilaftsis



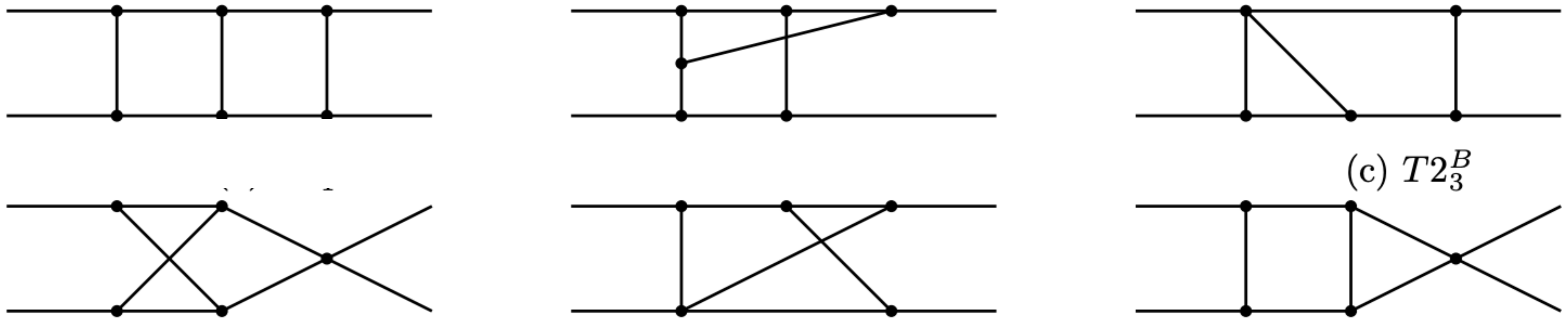
Loop neutrino mass models

One-loop@ dimension-5:

Bonnet, Hirsch, Ota, Winter '12

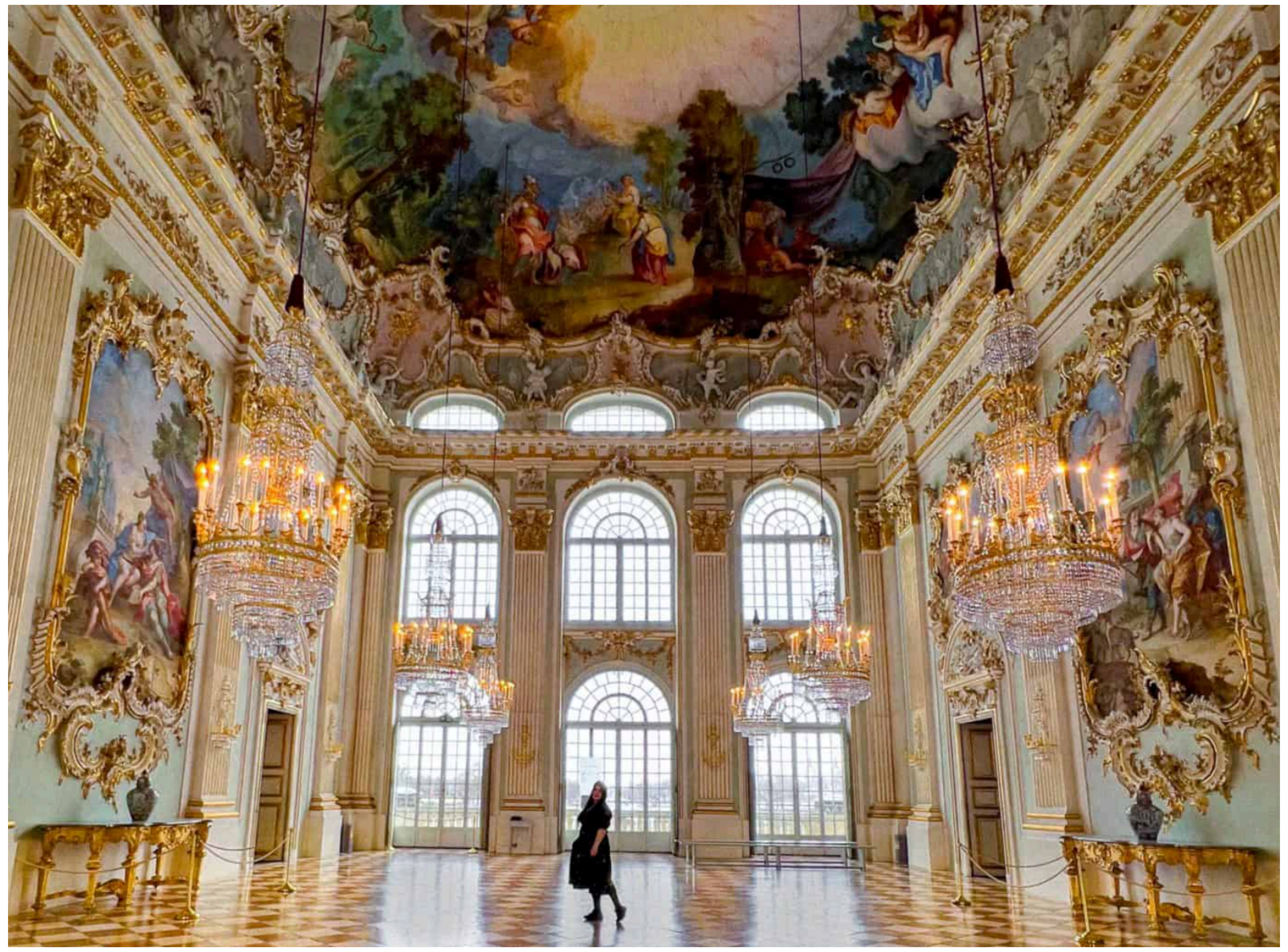


Two-loop@ dimension-5:



Aristizabal Sierra, Degee, Dorame, Hirsch ' 14

Things can seem pretty baroque from here!



Review by: Cai, Herrero-García, Schmidt, Vicente, Volkas

How to probe neutrino mass mechanisms?

Too many possibilities of realising the Majorana neutrino masses

type I, II, III seesaw, low-scale seesaws, n-loop radiative models, Left-Right Symmetric Model, 3-3-1 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 "dim by dim" provides a robust option

Model Independent ✅

❌ **Direct NP signatures**

e.g. Resonant NP production: simplified model approach

Effective Field Theory Approach

An EFT is the set of all allowed local operators with mass dimension less than some maximum one

$$\mathcal{L} = \sum_i c_i \, O_i \qquad [O_i] = d_i \qquad \longrightarrow \qquad c_i \sim \frac{1}{\Lambda^{d_i - 4}}$$

We need an infinite # of operators to absorb all the divergences for d>4 => non-renormalisable

Nature decouples!

Decoupling theorem

Appelquist,Carrazzone ++

$$\mathscr{L}_{\text{full}} = \mathscr{L}_{\text{light}}(g_i) + \frac{1}{2}[(\partial_\mu \Phi_H)^2 - M^2\Phi_H^2] + \mathscr{L}_{\Phi-\text{light}}(g_i, h_i)$$

for $|p_i| \ll M$

$$G^{(n)}(p_1, \ldots p_n) \sim C(g_i, h_i, M)\, \tilde{G}^{(n)}(p_1, \ldots . p_n)(1 + \mathcal{O}\left(\frac{1}{M}\right))$$

$$\mathscr{L}_{\text{eff}} = \tilde{\mathscr{L}}_{\text{light}}[\tilde{g}_i(g_i, h_i, M)]$$

(i) there are no "+ve" powers of M, except in "$\log$"s

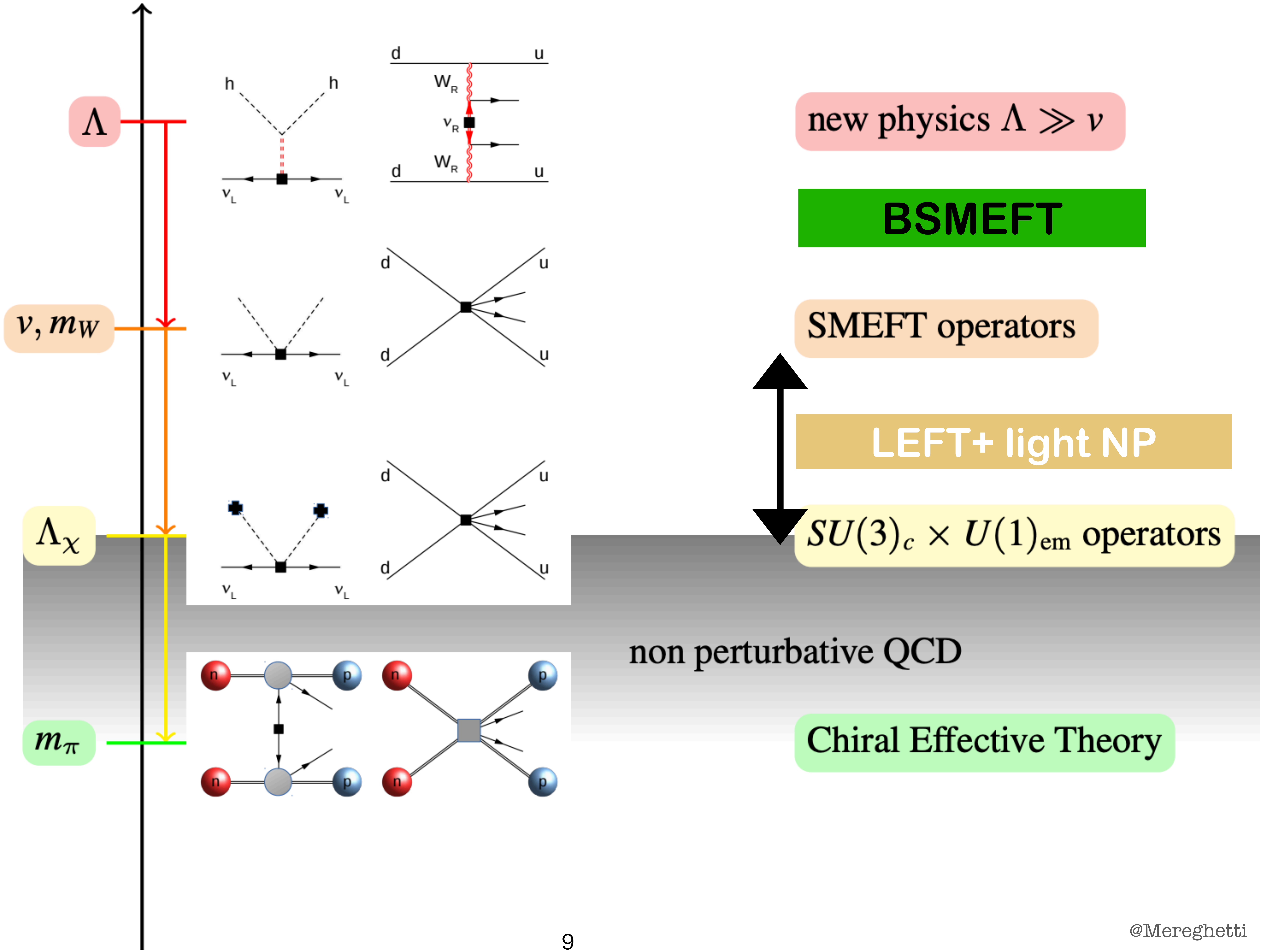
(ii) $\log M$ can be absorbed into $\tilde{g}$ and C

If $M = gv$ then EFT breaks down for:

v or $g \to \infty$ with $M \to \infty$

Connecting EFTs to Experiments

Some popular EFTs for BSM Phenomenology

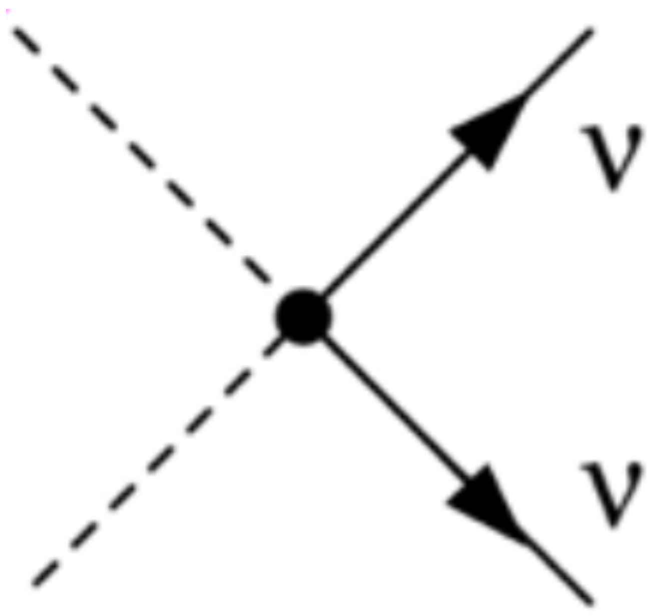


@Mereghetti

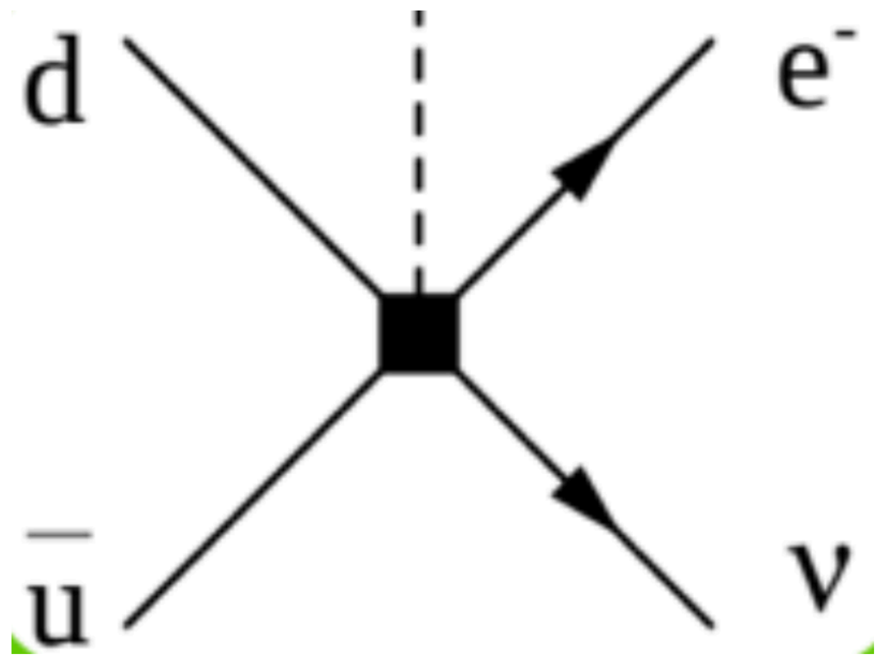
LNV and SMEFT

d=5 **d=7** **d=9**

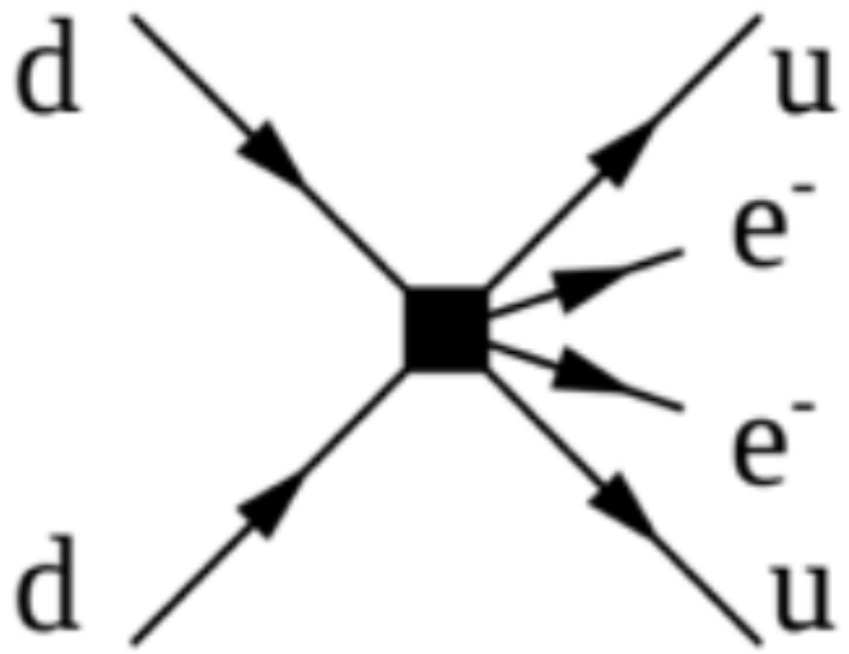
LNV SMEFT:



Weinberg ‘79



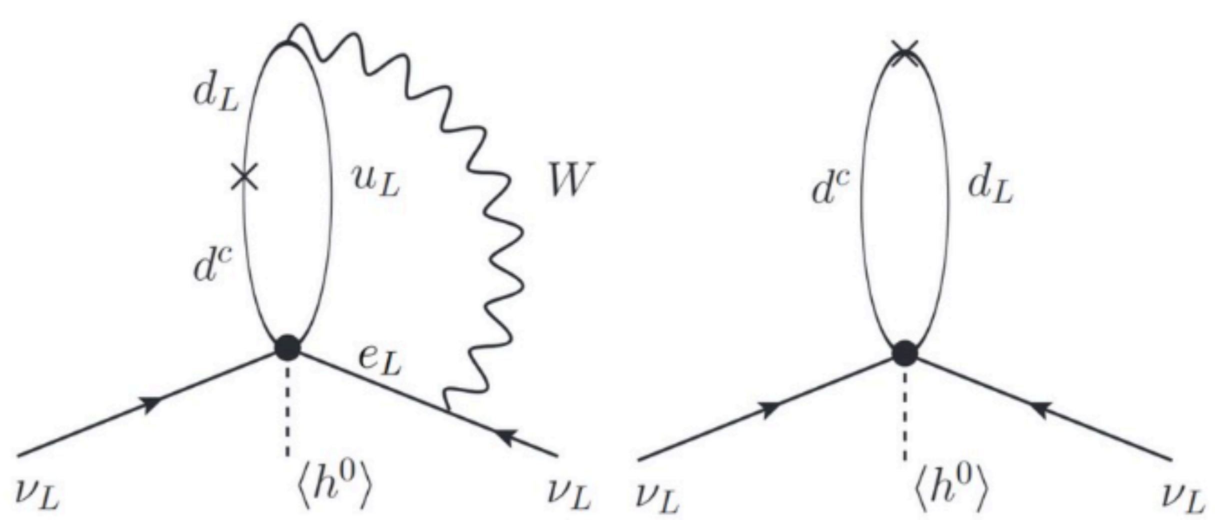
Babu and Leung ‘01
de Gouvea and Jenkins ‘08
Lehman ‘14

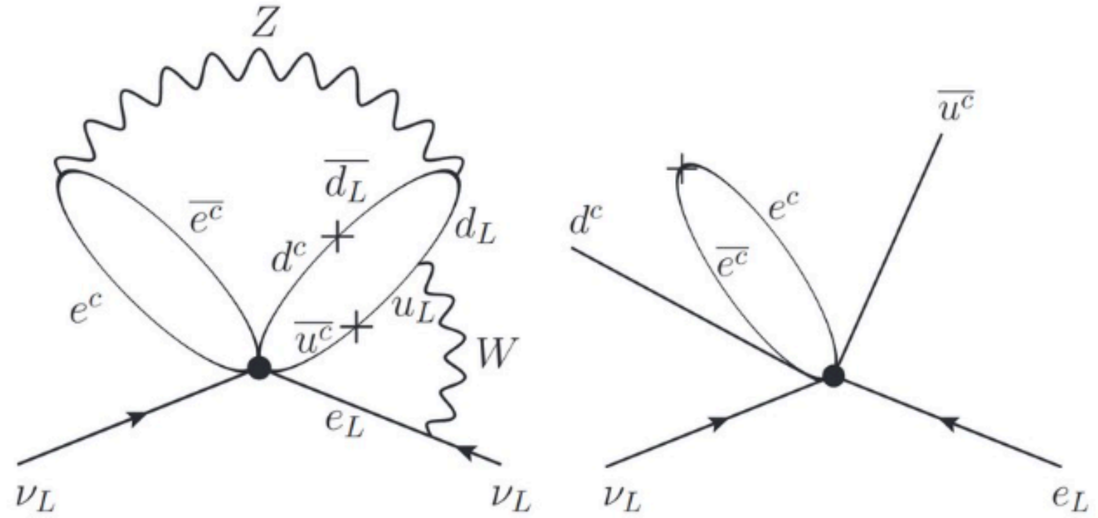


M. Graesser ‘16
Y. Liao and X. D. Ma ‘20

Neutrino mass:

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

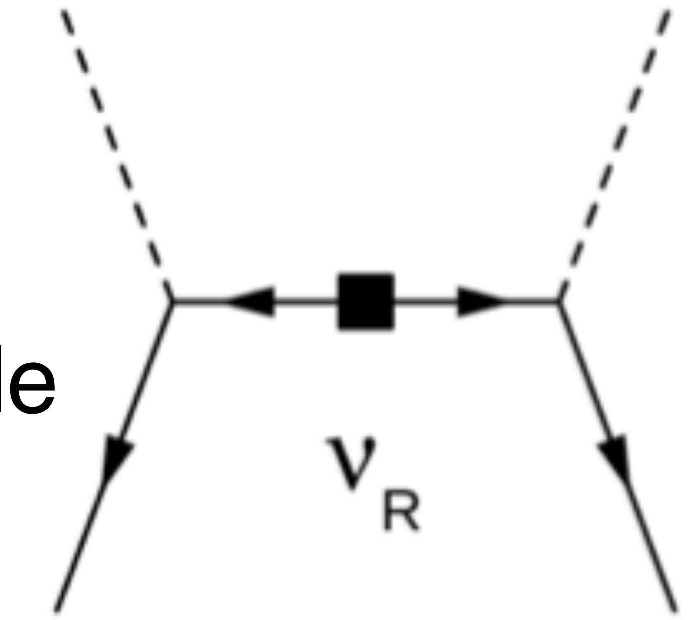


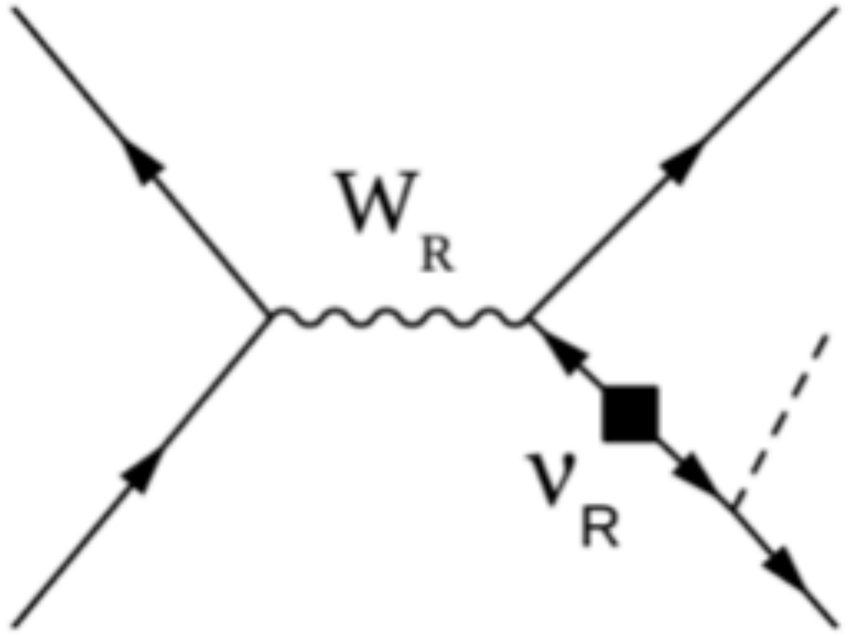


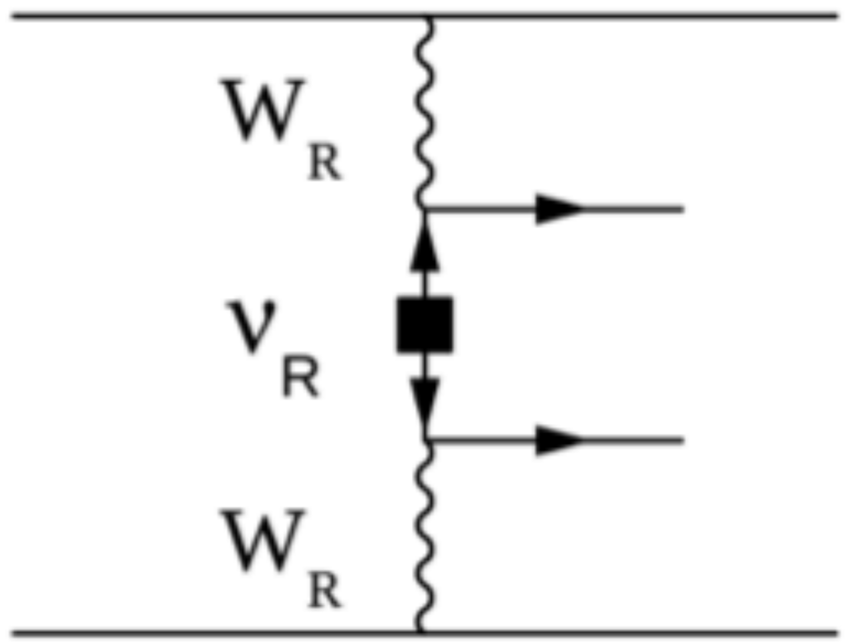
UV example:

LRSM: (L<->R) at high scale

Mohapatra and Pati ‘75
Senjanovic and Mohapatra ‘75







LNV dimension-7 SMEFT operators

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

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

First systematic analysis:

Lehman '14

-> 20 independent operators

13 conserving B but ΔL = 2

7 violating both ΔB = –ΔL = –1

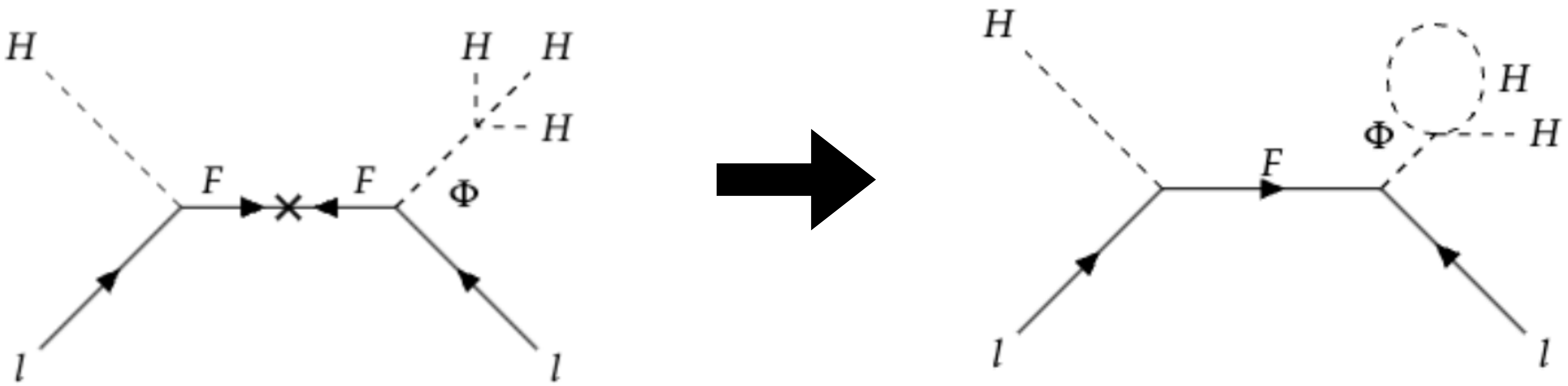
Further reduced in

Liao, Ma '17

18 = 12+6 (indept. structures)

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

Why dimension-7 SMEFT operators?



$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^{i} L_r^m\right)H^jH^n\left(H^\dagger H\right)$

Matching dimension-7 SMEFT operators with LEFT operators

Bottom-up recipe:

Experimental observable

↓

Constraints on LEFT

(Single operator dominance)

↓

Constraints on SMEFT

(Using matching relations)

↓

UV theory

! Highly simplified !

! No correlations and cancellations !

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

Fridell, Graf, Harz, **CH** '23

LNV and Neutrinoless double beta decay

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

Cirigliano, Dekens, de Vries, Graesser, Mereghetti '18

Graf, Deppisch, Iachello, Kotila '18++

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

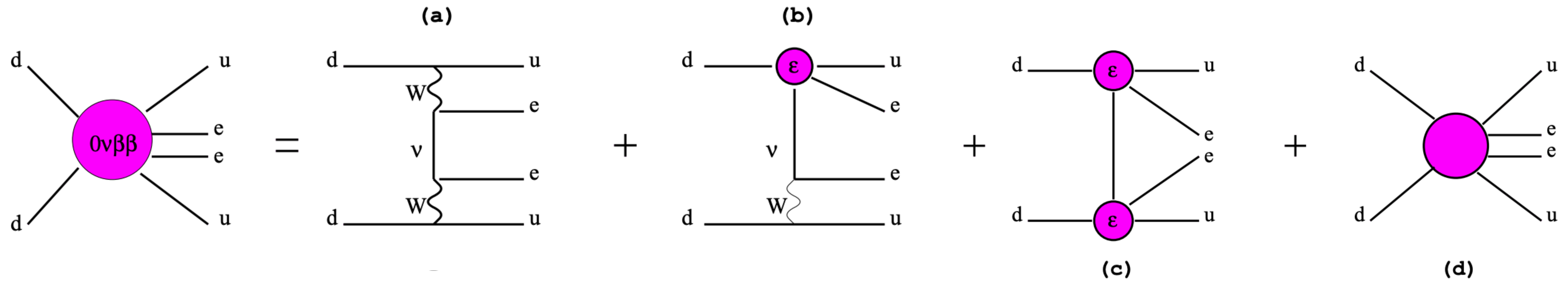
Effective mass $$\langle m_{\beta\beta}\rangle = \left|U^2_{ei}\,m_i\right|$$

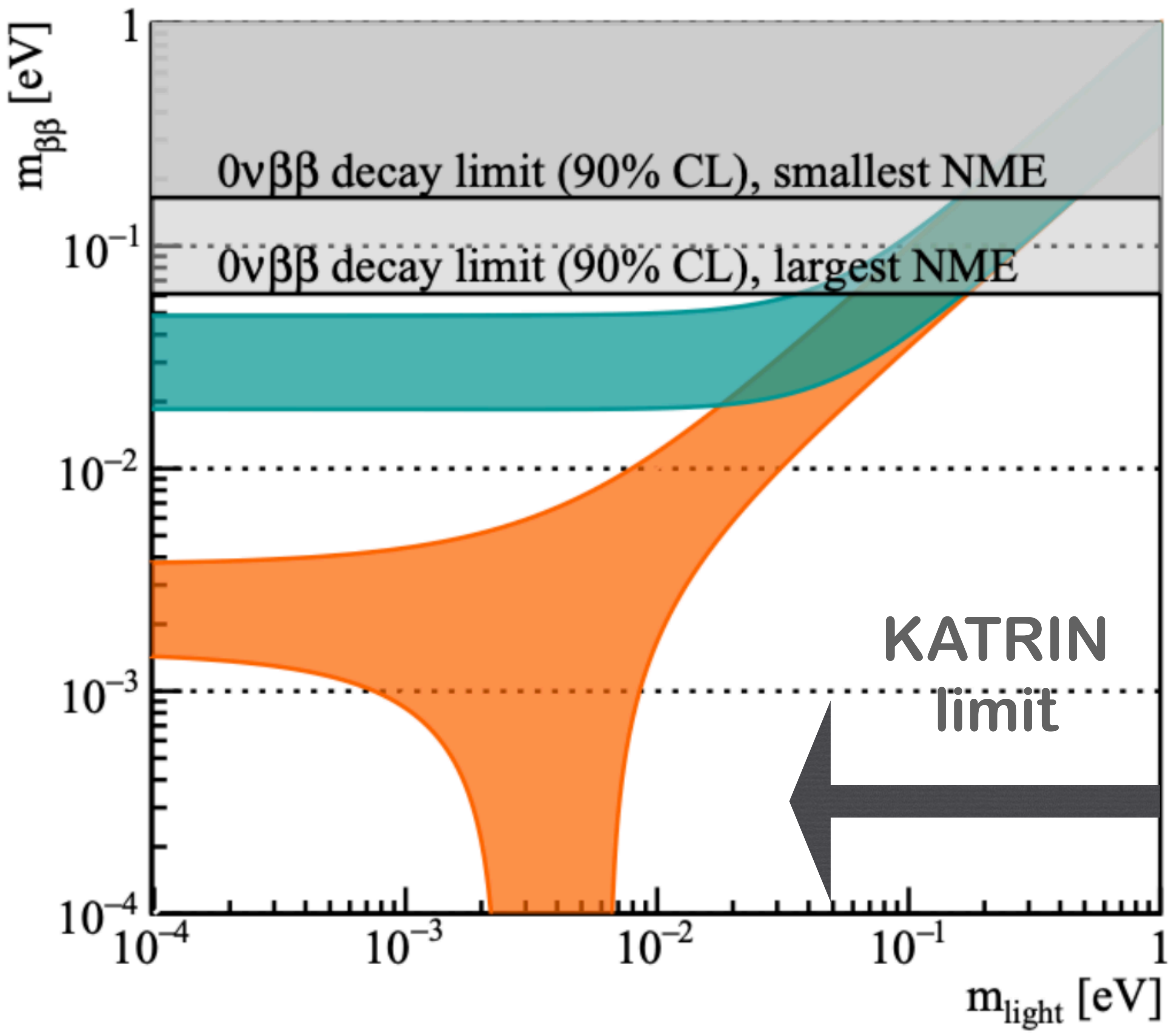
Many experiments: KamLAND-Zen, LEGEND, CUORE, NEMO-3, ...

Main source of uncertainty: Nuclear Matrix elements!

- **Many body problem: isotope and operator dependent**
- **Different nuclear models**

See talk by Frank Deppisch



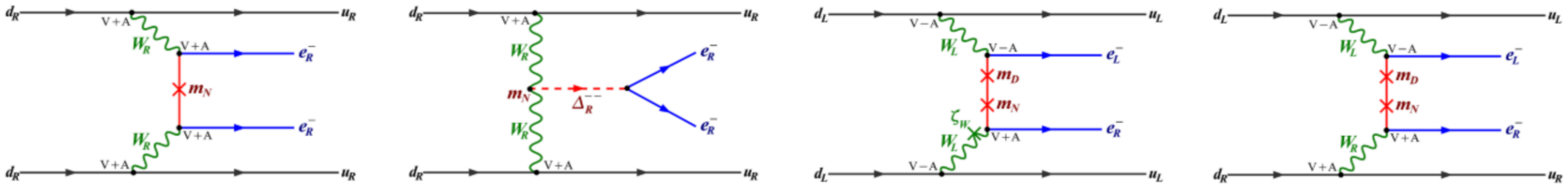


Rev. Mod. Phys. 95, 025002 (2023)

Neutrinoless double beta decay

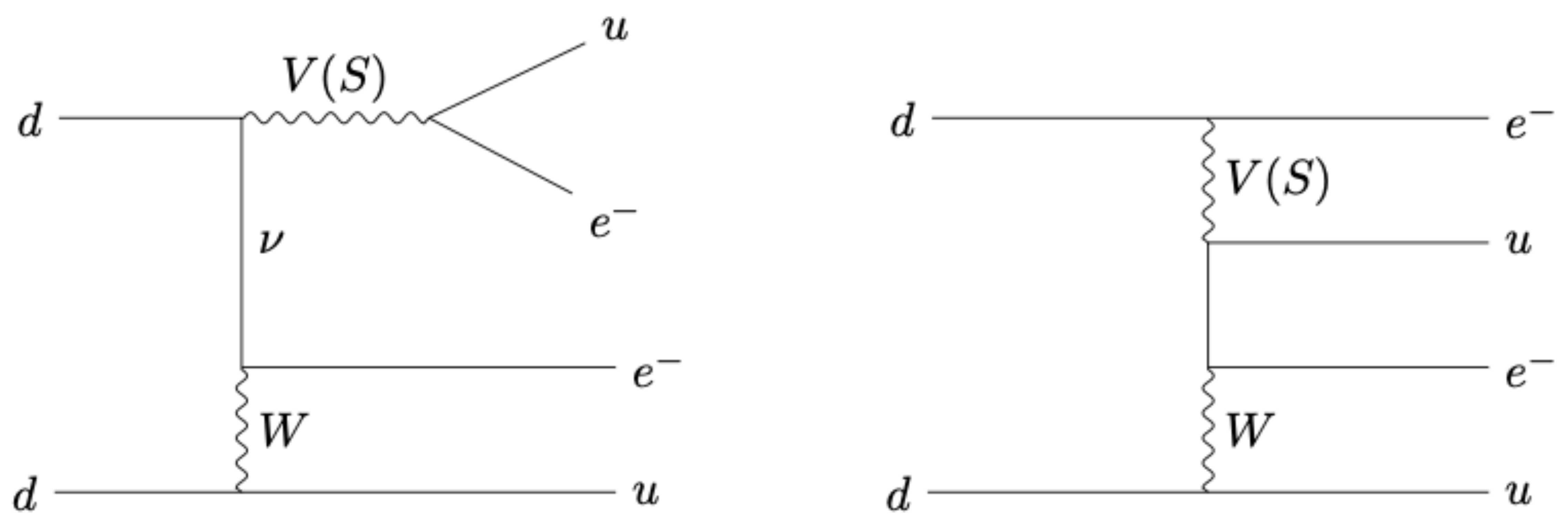
Many new physics scenarios can be responsible:

Left-Right Symmetric Model : $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$



Deppisch, Hirsch, Päs ‘12

scalar and vector Leptoquarks:



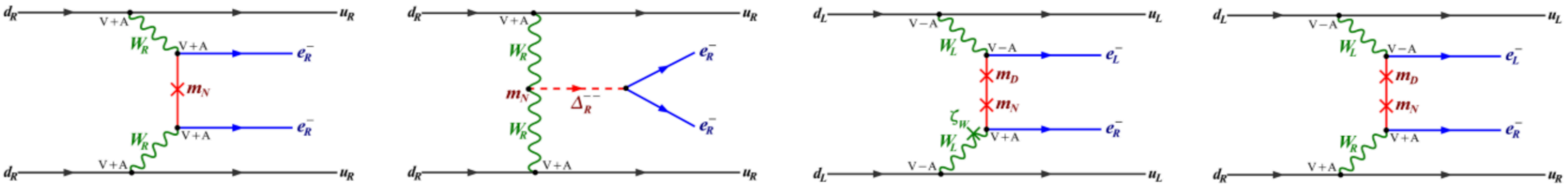
EFT approach helps!

RPV SUSY, Extra Dimensions, ++

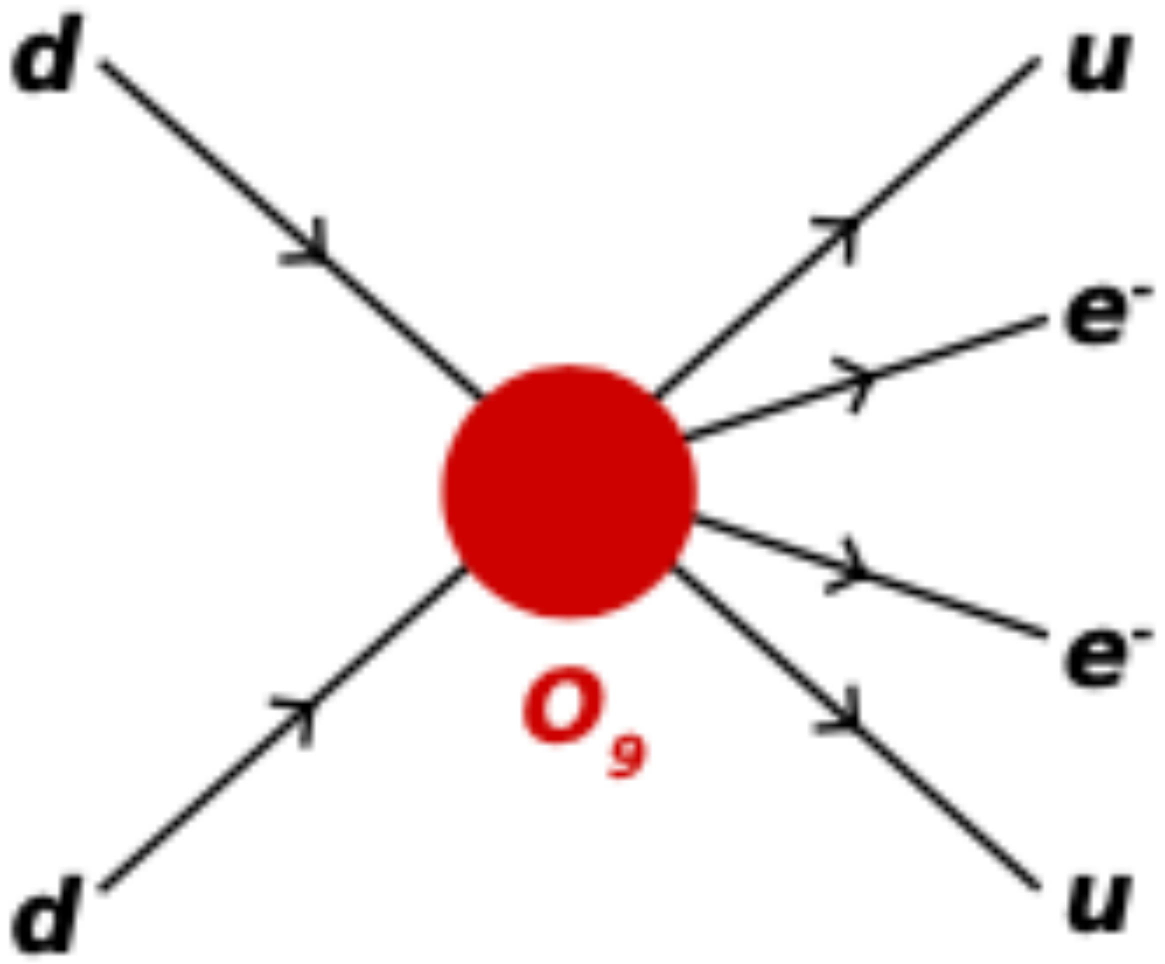
Neutrinoless double beta decay

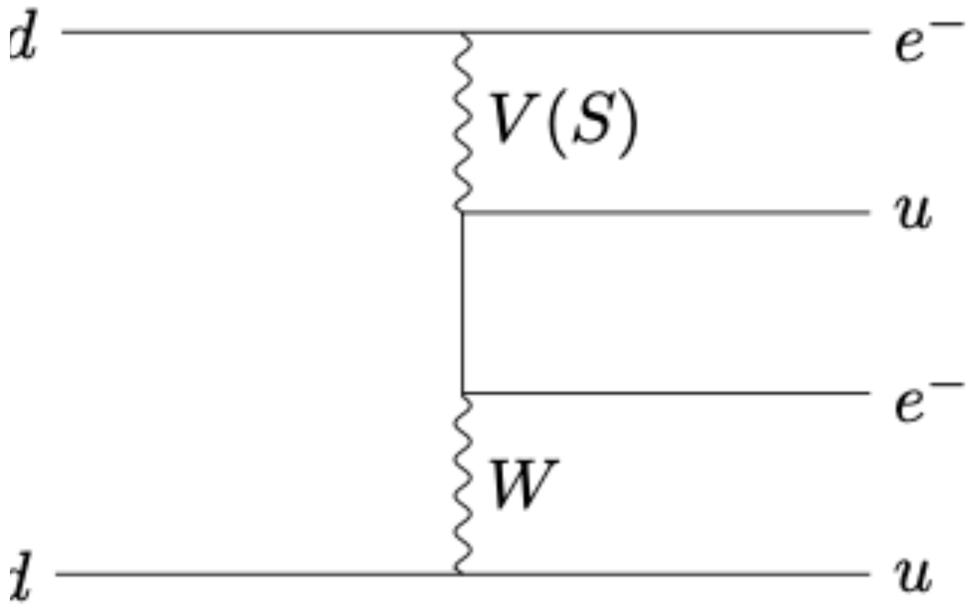
Many new physics scenarios can be responsible:

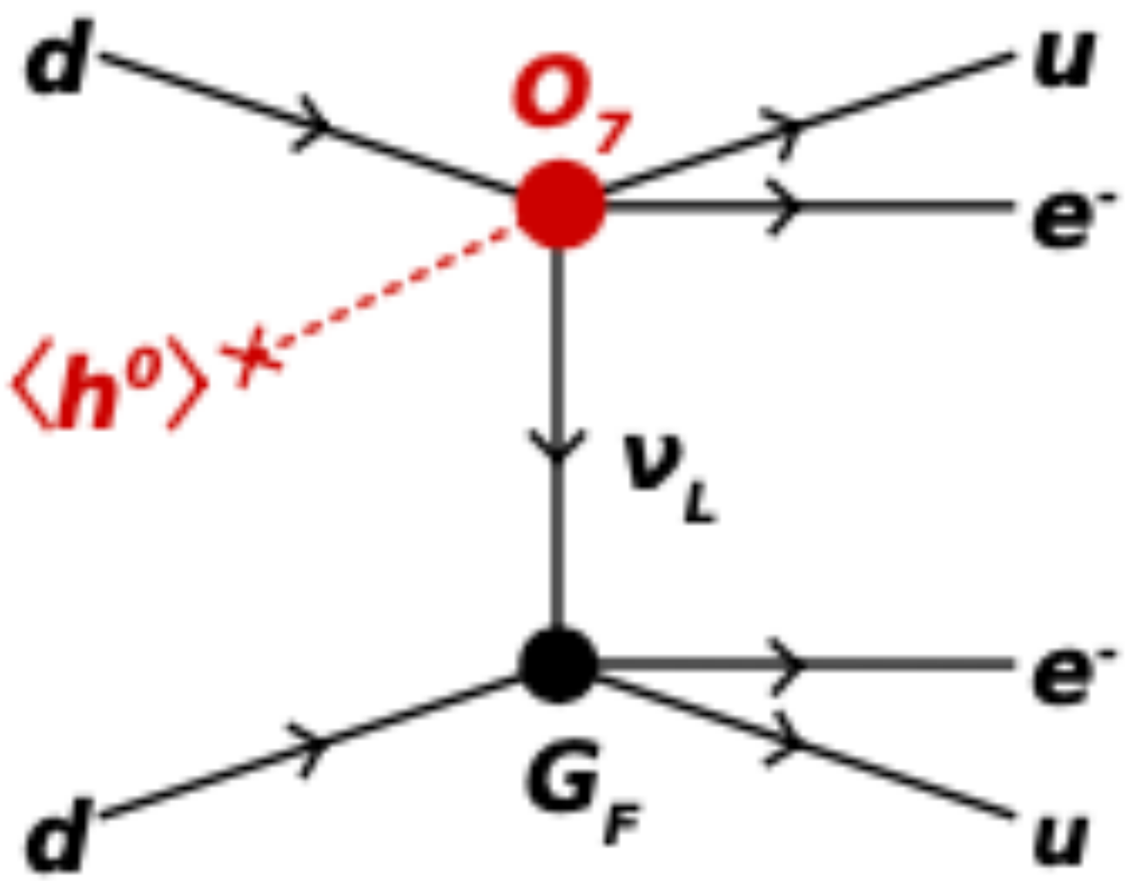
Left-Right Symmetric Model : $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$



Deppisch, Hirsch, Päs ‘12







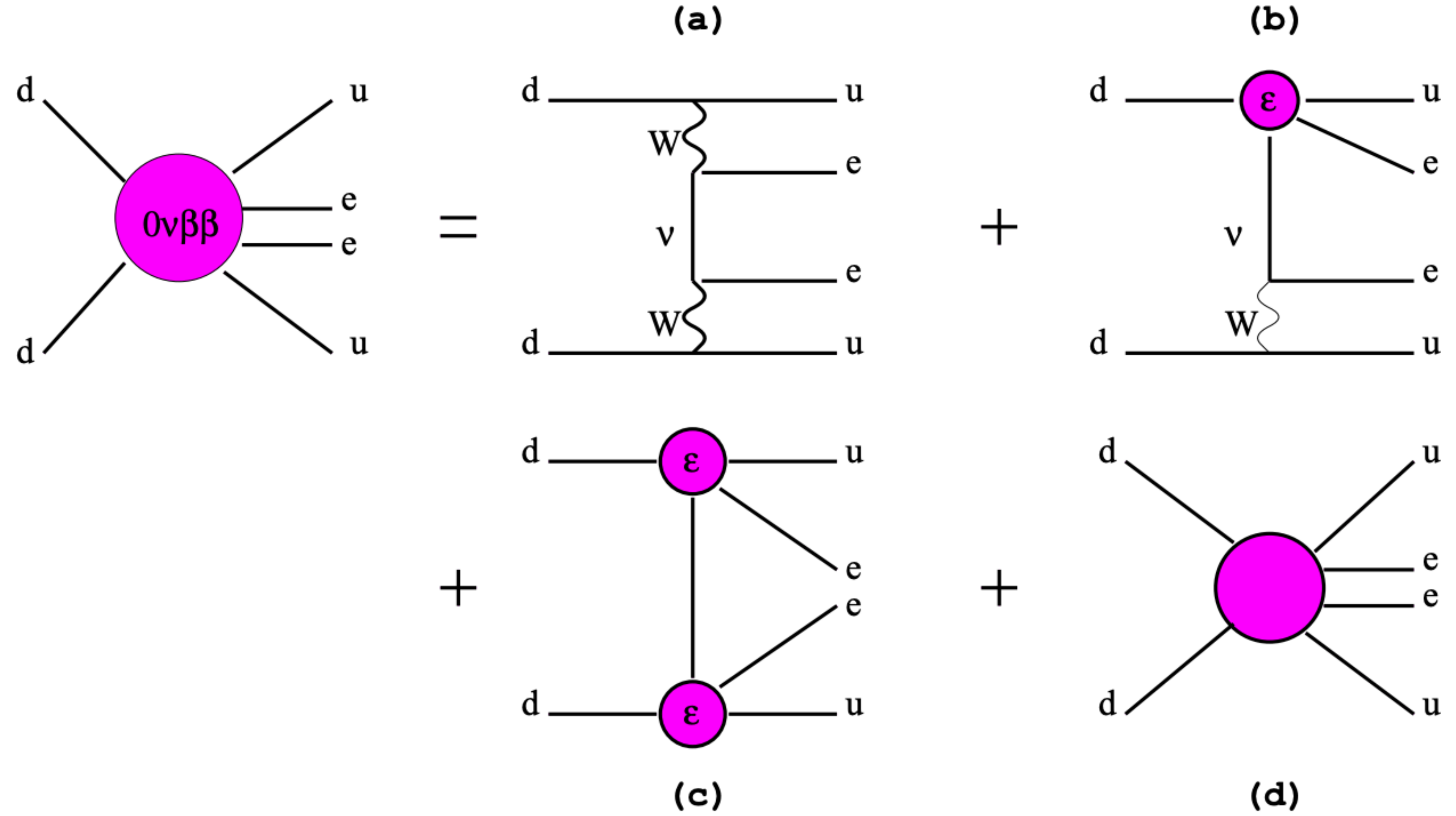
Neutrinoless double beta decay: EFT approach

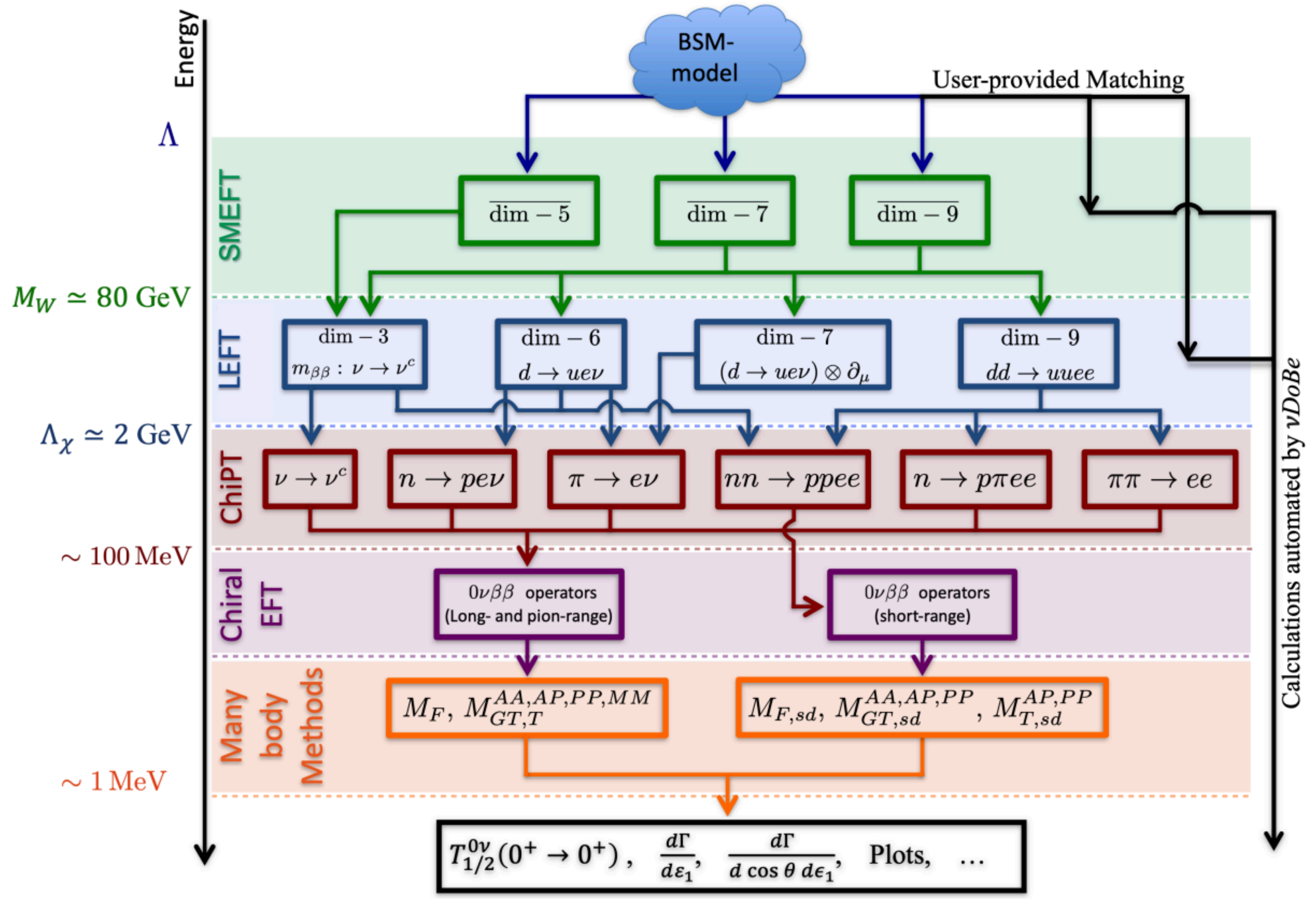
Start from SMEFT and match to LEFT:

$$\mathcal{L}_{\Delta L=2}^{\mathrm{LEFT}(d=6)} = \frac{4G_F}{\sqrt{2}}\Big[c^V_{du\nu e;LR}(\overline{d_L}\gamma_\mu u_L)(\overline{\nu^c}\gamma^\mu e_R) + c^V_{du\nu e;RR}(\overline{d_R}\gamma_\mu u_R)(\overline{\nu^c}\gamma^\mu e_R)$$
$$+c^S_{du\nu e;LL}(\overline{d_R}u_L)(\overline{\nu^c}e_L) + c^S_{du\nu e;RL}(\overline{d_L}u_R)(\overline{\nu^c}e_L)$$
$$+c^T_{du\nu e;LL}(\overline{d_R}\sigma_{\mu\nu}u_L)(\overline{\nu^c}\sigma^{\mu\nu}e_L)\Big] + \mathrm{h.c.},$$

$$\mathcal{L}_{\Delta L=2}^{\mathrm{LEFT}(d=7)} = \frac{4G_F}{\sqrt{2}v}\Big[c^{(7)V}_{du\nu e;LL}\,(\overline{d_L}\gamma^\mu u_L)\,(\overline{\nu^c_L}\overleftrightarrow{D}_\mu e_L) + c^{(7)V}_{du\nu e;RL}\,(\overline{d_R}\gamma^\mu u_R)\,(\overline{\nu^c_L}\overleftrightarrow{D}_\mu e_L)\Big] + \mathrm{h.c.}.$$

$$\mathcal{L}_{\Delta L=2}^{\mathrm{LEFT}(d=9)} = \frac{8G_F^2}{v}\bar{e}_{L,i}C\bar{e}^T_{L,j}\Big\{c^{(9);ij}_{V;LL}\,\bar{u}_L\gamma^\mu d_L\,\bar{u}_L\gamma_\mu d_L + c^{(9);ij}_{V;LR}\,\bar{u}_L\gamma^\mu d_L\,\bar{u}_R\gamma_\mu d_R$$
$$+\,c^{(9);ij}_{V';LR}\,\bar{u}^\alpha_L\gamma^\mu d^\beta_L\,\bar{u}^\beta_R\gamma_\mu d^\alpha_R\Big\} + \mathrm{h.c.}\ .$$





Automatization possibilities! Scholer, de Vries, Graf '23

Multiple isotopes and correlations

Possibility to distinguish different mechanisms and operators

LNV dim-7 SMEFT @Neutrinoless double beta decay

Fridell, Graf, Harz, **CH** JHEP '24

$\mathcal{O}$	Operator
$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}L_r^m\right)H^jH^n\left(H^\dagger H\right)$
$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}\gamma_\mu e_r\right)H^j\left(H^m iD^\mu H^n\right)$
$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\mathcal{O}_{LHD2}^{pr}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{L_p^{ci}}D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{ci}}\sigma_{\mu\nu}L_r^m\right)H^jH^nB^{\mu\nu}$
$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L_p^{ci}}\sigma_{\mu\nu}L_r^m\right)H^jH^nW^{I\mu\nu}$
$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^{ci}}iD^\mu L_t^j\right)$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p}L_r^i\right)\left(\overline{L_s^{cj}}L_t^m\right)H^n$
$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}L_r^i\right)\left(\overline{u_s^c}e_t\right)H^j$
$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$
$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$
$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}\left(\overline{Q_p}u_r\right)\left(\overline{L_s^c}L_t^i\right)H^j$

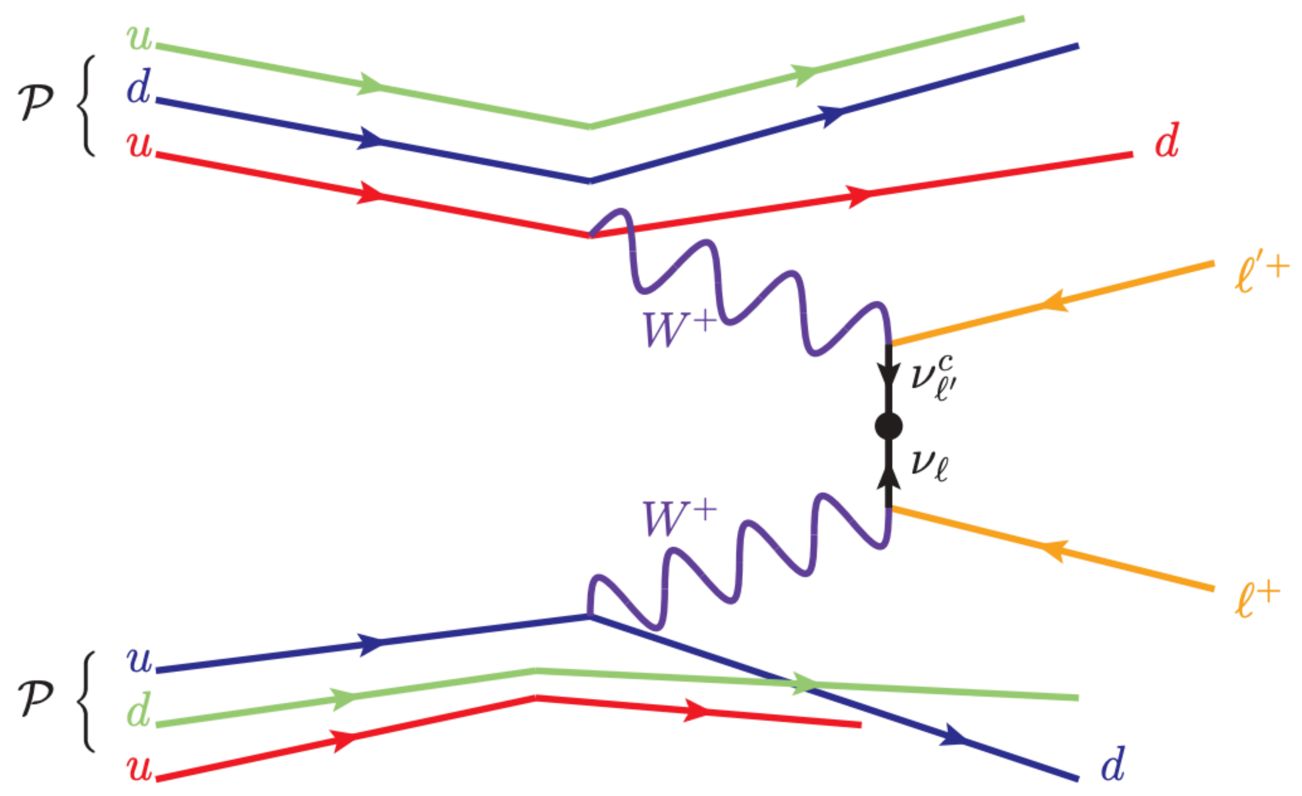
Assumption:

single LEFT operator dominance*

LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV^{-3}]	$\Lambda_{\rm NP}$ [TeV]
$c^S_{du\nu e;LL}$	$1.86\cdot10^{-10}$	$C_{\bar{d}LQLH1}$	$7.06\cdot10^{-8}$	242
$c^S_{du\nu e;RL}$	$1.86\cdot10^{-10}$	$C_{\bar{Q}uLLH}$	$3.62\cdot10^{-8}$	302
$c^V_{du\nu e;LR}$	$8.20\cdot10^{-10}$	C_{LeHD}	$1.55\cdot10^{-7}$	186
$c^V_{du\nu e;RR}$	$5.93\cdot10^{-8}$	$C_{\bar{d}LueH}$	$1.12\cdot10^{-5}$	44.7
$c^T_{du\nu e;LL}$	$4.51\cdot10^{-10}$	$C_{\bar{d}LQLH1}$	$6.83\cdot10^{-7}$	114
		$C_{\bar{d}LQLH2}$	$3.41\cdot10^{-7}$	143
$c^{(7)V}_{du\nu e;LL}$	$9.87\cdot10^{-6}$	C_{LHD1}	$1.36\cdot10^{-3}$	9.03
		C_{LHD2}	$2.71\cdot10^{-3}$	7.17
		C_{LHW}	$3.39\cdot10^{-4}$	14.3
$c^{(7)V}_{du\nu e;RL}$	$9.87\cdot10^{-6}$	$C_{\bar{d}uLLD}$	$1.32\cdot10^{-3}$	9.11
$c^{(9);ij}_{V;LL}$	$1.40\cdot10^{-5}$	C_{LHD1}	$9.91\cdot10^{-4}$	10.0
		C_{LHW}	$2.48\cdot10^{-4}$	15.9
$c^{(9);ij}_{V;LR}$	$2.66\cdot10^{-8}$	$C_{\bar{d}uLLD}$	$1.83\cdot10^{-6}$	81.7

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

LNV SMEFT at Colliders



Dim-5: Weinberg operator

13 TeV LHC : $\Lambda \lesssim 8.3\ (11)$ TeV

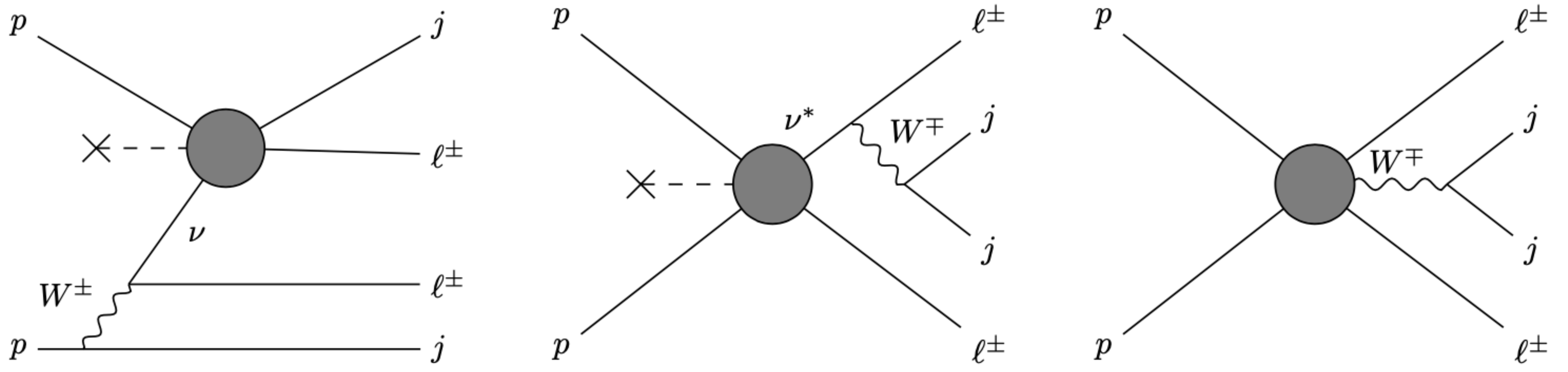
100TeV FCC : $\Lambda \lesssim 48$ TeV

Fuks, Neundorf, Peters, Ruiz, Saimpert '21

Dim-7: comprehensively for the first time Fridell, Graf, Harz, **CH** JHEP '24

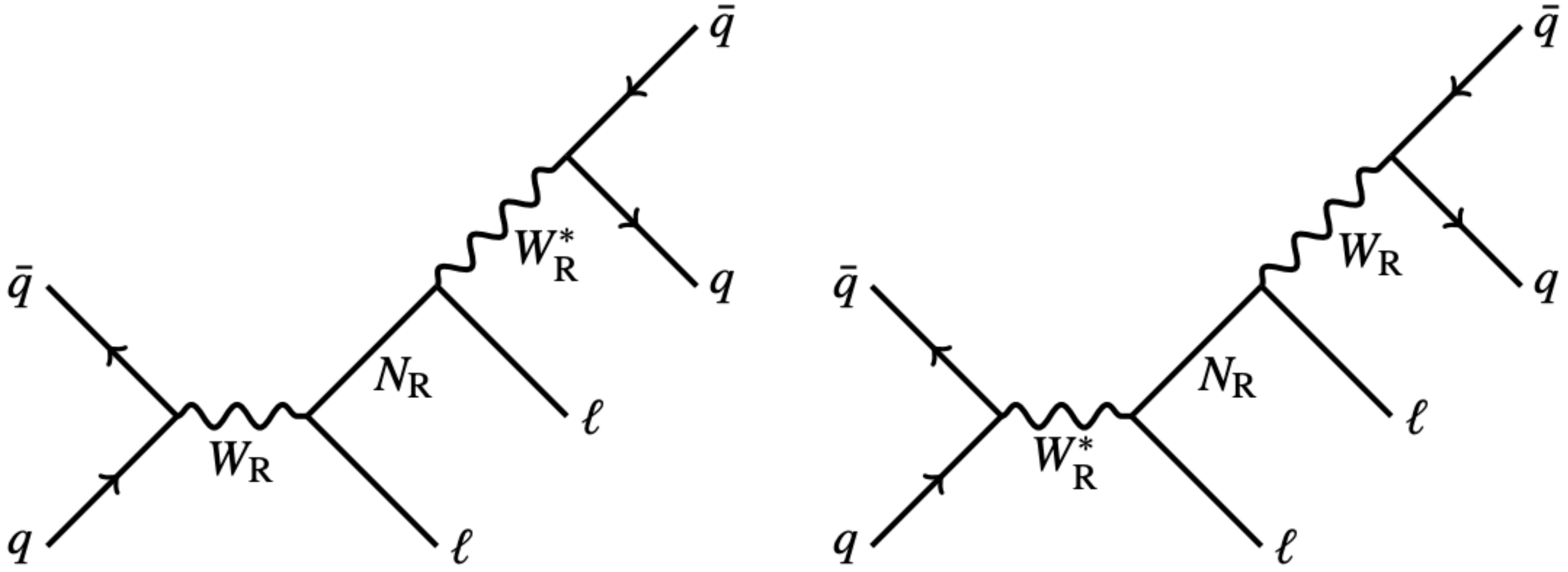
our main mode of interest:

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



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

ATLAS EPJC '23



$\mathcal{O}_{eLLLH}$, $\mathcal{O}_{LHW}$, $\mathcal{O}_{LHB}$ no signal at tree level

LNV dim-7 SMEFT at LHC and FCC

LNV operators using FeynRule

↓

LO cross sections with MadGraph5_aMC@NLO using the basic generator level cuts

↓

Hadronisation by Pythia8

↓

Detector simulation by Delphes3: selection cuts

Cuts for $pp \to \mu^\pm\mu^\pm jj$ at $\sqrt{s} = 13$ TeV	
Object selection cuts	
$p_T^{\mu^{1(2)}} > 25$ GeV	$p_T^{j^{1(2)}} > 20$ GeV
$\lvert\eta^{\mu^{1(2)}}\rvert < 2.5$	$\lvert\eta^{j^{1(2)}}\rvert < 2.5$
Track-to-vertex association cuts	
$\lvert z_0 \sin\theta\rvert < 5$ mm	$\lvert d_0\rvert < 1$ µm
Signal region cuts	
$p_T^{\mu^{\text{leading}}} > 40$ GeV	$p_T^{j^{1(2)}} > 100$ GeV
$H_T > 400$ GeV	$\Delta R_{\mu\mu} < 3.9$ GeV
$m_{\mu^1\mu^2} > 400$ GeV	$m_{j^1 j^2} > 110$ GeV

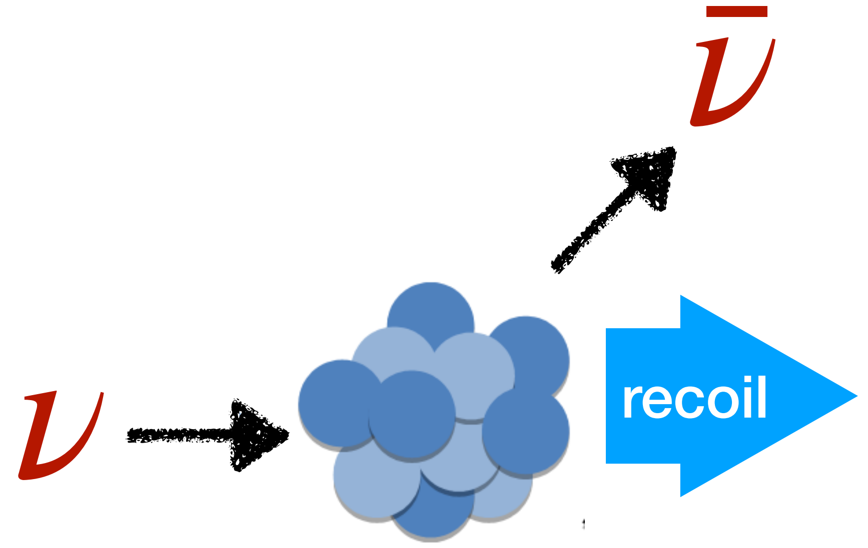
Operator	$\sigma(pp \to \mu^\pm\mu^\pm jj)$ (pb) LHC	FCC	Λ_{LNV} [TeV]	$\Lambda_{\text{LNV}}^{\text{future}}$ [TeV]
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.4	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.90	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	1.1	4.3
$\mathcal{O}_{\bar{d}LueH}$	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

Major Caveats:

Fridell, Graf, Harz, **CH** JHEP '24

(i) validity of EFT (ii) resonant production

Many more observables!

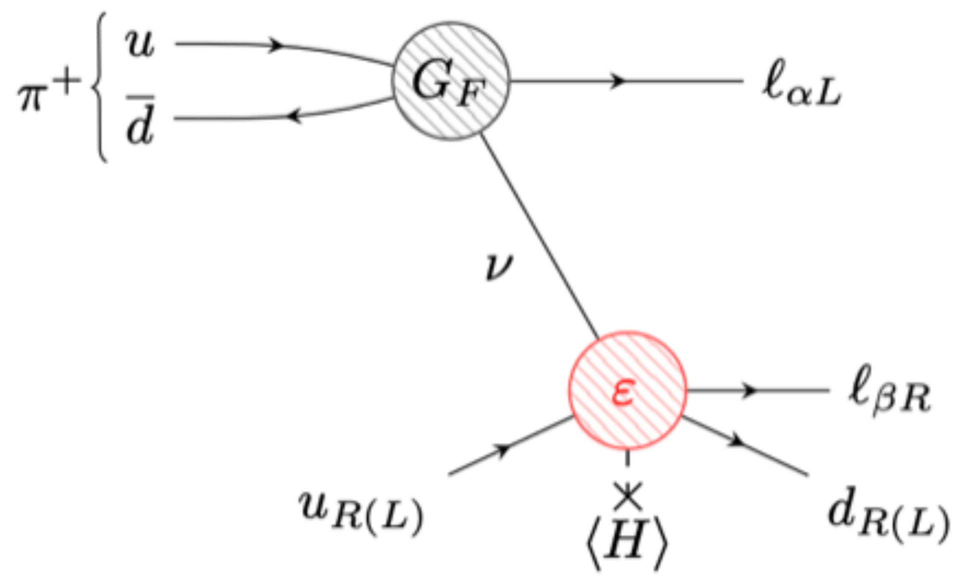


Neutral Current LNV@ low energy

Lindner, Rodejohann, Xu;
Aristizabal Sierra, De Romeri, Rojas; ++

Changed Current LNV NSI @ LBL Oscillation experiments

Bolton, Deppisch'19



Rare meson and τ decays $M \to M' \nu \nu$

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

$\mathcal{O}_{\bar{e}LLLH}$ @ leptonic μ^+ decay $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_\mu$

B. Armbruster et al PRL '03

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

Berryman, de Gouvêa et al '16

Neutrino magnetic moment

Solar: Borexino

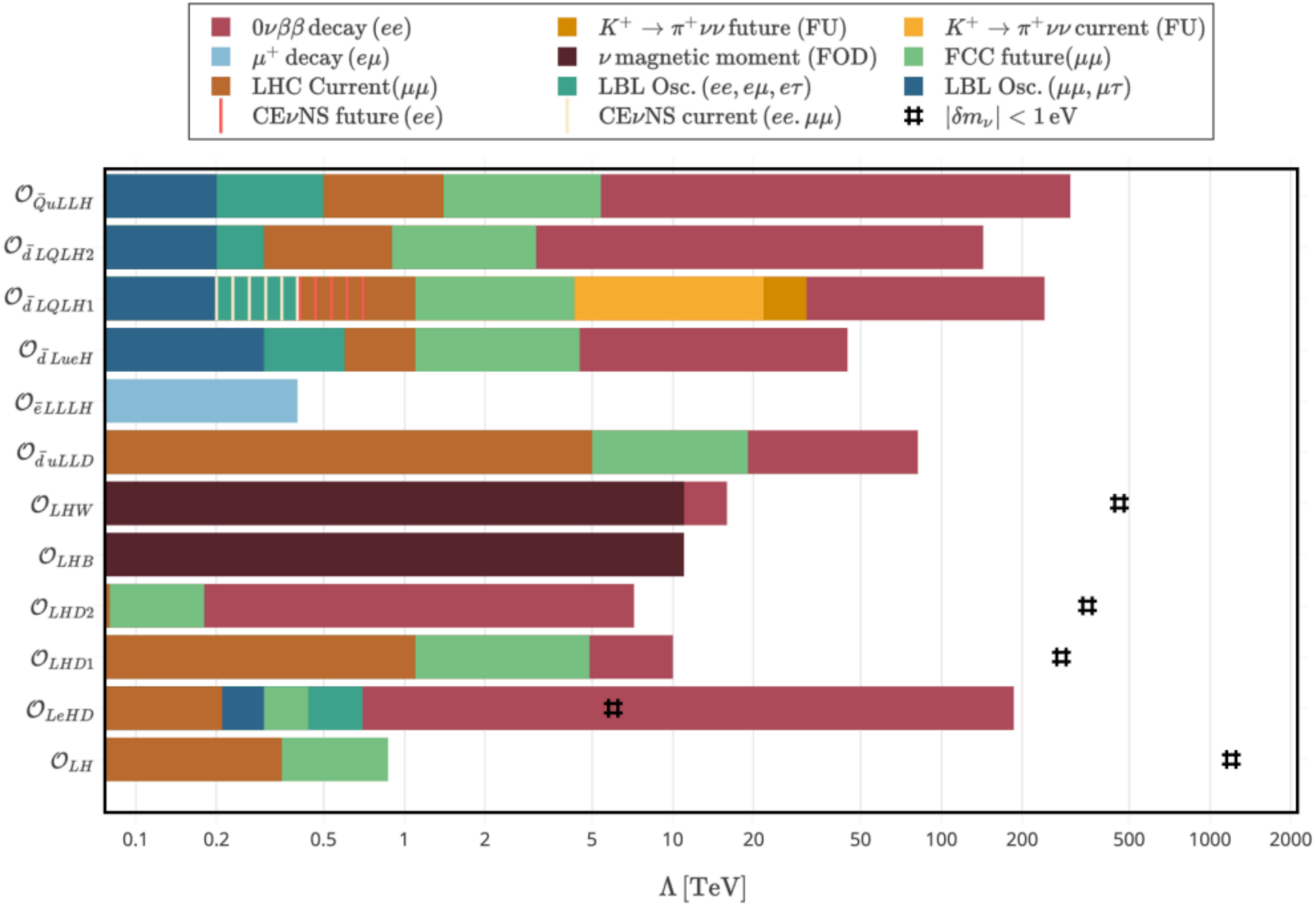
Reactor: GEMMA, TEXONO, CONUS

Accelerator: LSND, DUNE

See also talk by Sudip Jana

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

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



Fridell, Graf, Harz, **CH** JHEP '24

Tree level UV completions of the SMEFT operators

Operator “expansion” gives: tree-level UV completions

Henning, Lu, Murayama ’14
Gargalionis, Volkas ‘20

$$\mathcal{O}_{\bar{Q}uLLH} = \epsilon_{ij}(\overline{Q}u)(\overline{L^c}L^i)H^j \quad \rightarrow \quad \epsilon_{ij}\overline{Q}^k u L^k L^i H^j \quad (\chi_1,\ \phi_1,\ \psi_1,\ \omega_1)$$

$$\mathcal{O}_{\bar{Q}uLLH} \rightarrow \epsilon_{ij}{\chi_1}^k L^k L^i H^j \; (\chi_2,\chi_3,\chi_4) \;/\; \epsilon_{ij}{\psi_1}^k u L^i H^j \; (\psi_2,\psi_3,\psi_4) \;/\; \epsilon_{ij}{\phi_1}^k u L^k H^j \; (\phi_2,\phi_3,\phi_4) \;/\; \epsilon_{ij}{\omega_1}^k u L^k L^i \; (\omega_2,\omega_3,\omega_4)$$

$\chi_1 \sim S(1,2,1/2)$	$\psi_1 \sim V(\bar{3},1,-2/3)$	$\phi_1 \sim V(\bar{3},3,-2/3)$	$\omega_1 \sim F_L(\bar{3},3,1/3)$
$\chi_2 \sim F_R(1,1,0)$	$\psi_2 \sim F_R(1,1,0)$	$\phi_2 \sim F_R(1,3,0)$	$\omega_2 \sim S(1,3,1)$
$\chi_3 \sim F_R(1,3,0)$	$\psi_3 \sim F_L(\bar{3},2,-7/6)$	$\phi_3 \sim F_L(\bar{3},2,-7/6)$	$\omega_3 \sim V(\bar{3},2,-1/6)$
$\chi_4 \sim S(1,3,1)$	$\psi_4 \sim V(\bar{3},2,-1/6)$	$\phi_4 \sim V(\bar{3},2,-1/6)$	$\omega_4 \sim V(\bar{3},2,-1/6)$

These can be used to check which operators are generated by which types of models

Exhaustive list with scalar, vector, fermion NP: Fridell, Graf, Harz, **CH to appear soon!**

Loop neutrino masses: a subtlety

what if the two new physics fields are hierarchical in mass?

$m_{\tilde{R}_2} > m_{S_1}$

full model gives the light neutrino mass

$$m_\nu \propto \frac{3v\sin 2\theta}{32\pi^2}\log\frac{m^2_{\tilde{R}_2}+m^2_{S_1}+\sqrt{(m^2_{\tilde{R}_2}-m^2_{S_1})^2+\mu^2v^2}}{m^2_{\tilde{R}_2}+m^2_{S_1}-\sqrt{(m^2_{\tilde{R}_2}-m^2_{S_1})^2+\mu^2v^2}}$$

Babu, Dev, Jana, Thapa '19

EFT cutoff regularization based estimate

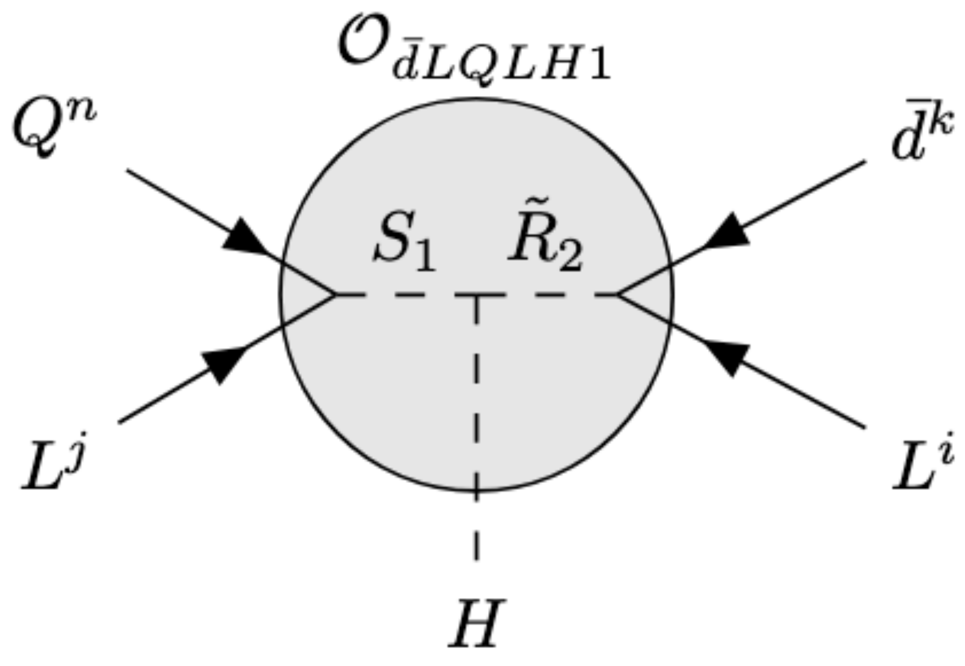
$$m_\nu \propto \frac{1}{16\pi^2}\frac{v^2}{\Lambda}$$

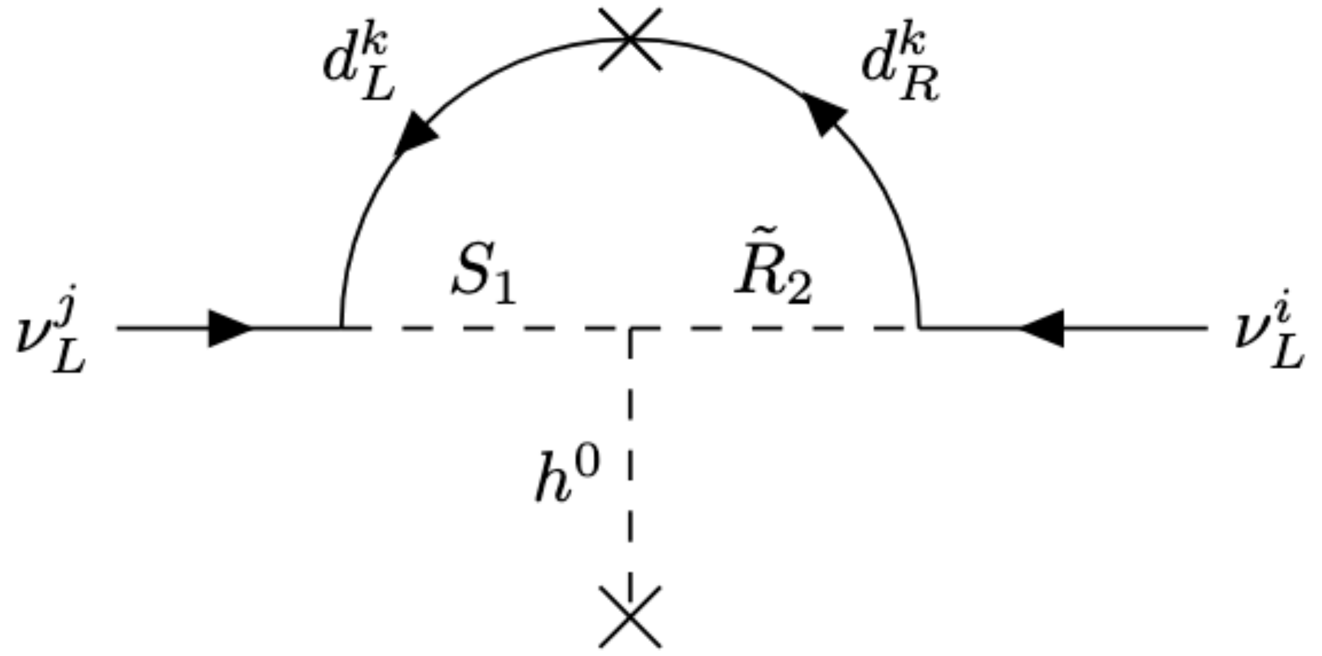
de Gouvea, Jenkins '07

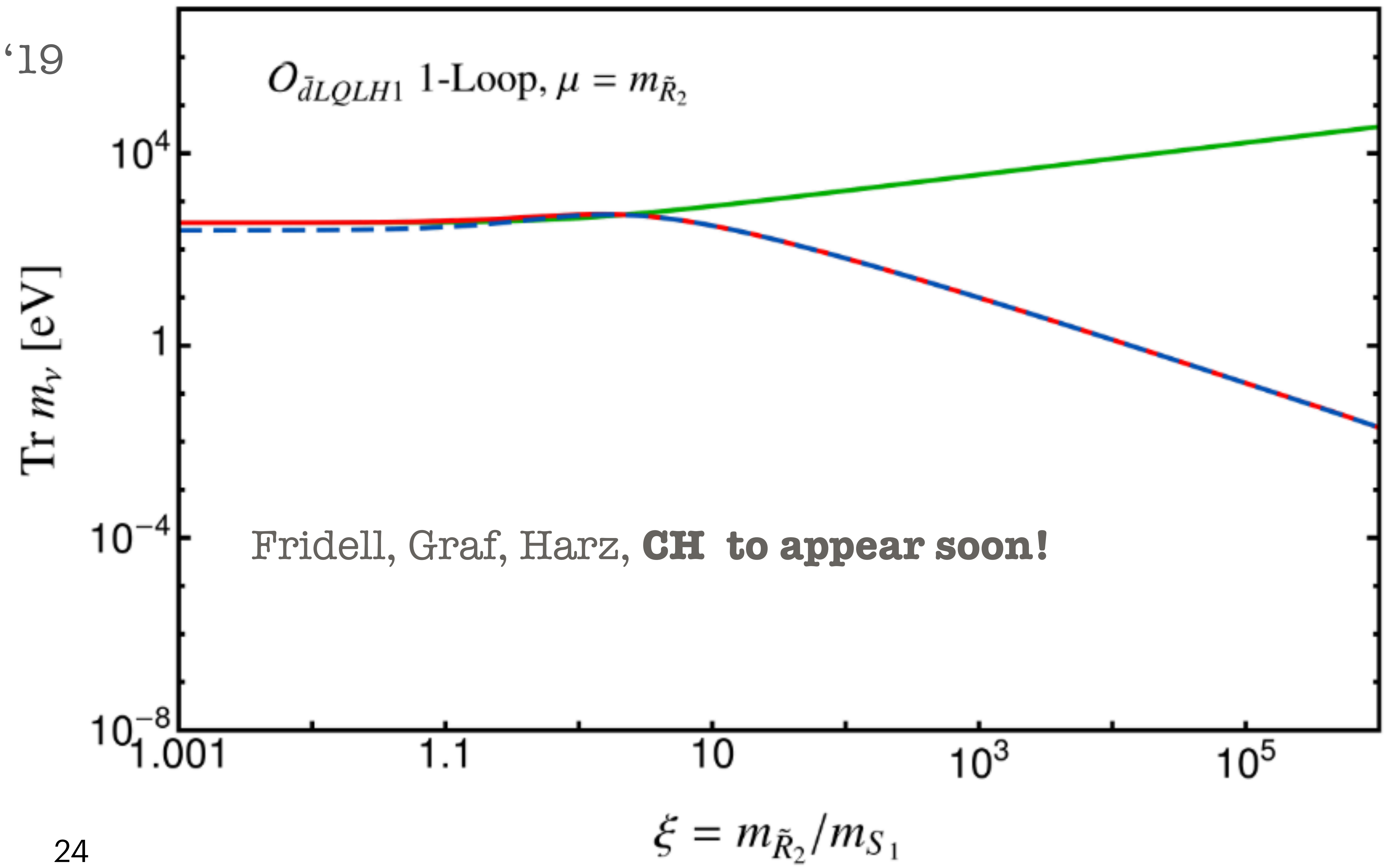
$$I^{\rm full} = c_m\,\mu^{2\varepsilon}\int\frac{d^dk}{(2\pi)^d}\frac{1}{k^2}\frac{1}{k^2-m^2_{S_1}}\frac{1}{k^2-m^2_{\tilde{R}_2}}$$

Multi-scale approach with method of regions=>

a more reliable way to "estimate" loop masses







Light neutrino masses and "naturalness"

Tree level contribution from $\mathcal{O}_{LH}$: $(\delta m_\nu)_{ij} = -\frac{v}{2}\left(v^3 \mathcal{C}_{LH,ij}\right)$

RG running $\Lambda \to M_W$

$$\mathcal{O}_{LHD1}\,;\mathcal{O}_{LHD2}\,;\mathcal{O}_{LeHD}\,;\mathcal{O}_{LHW} \longrightarrow \mathcal{O}_{LH}$$

$$(\delta m_\nu)_{ij} < 1\,\mathrm{eV} \implies C_{LH}:\ \Lambda > 1200\,\mathrm{TeV}$$

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

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

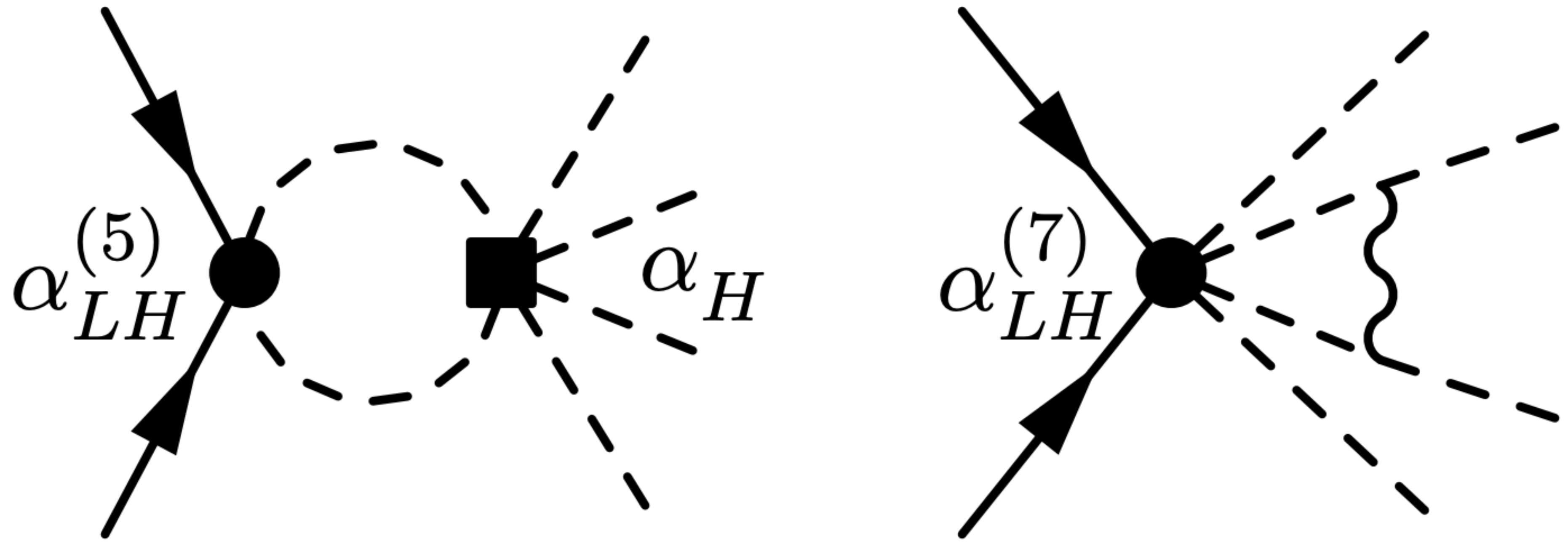
RGE improved EFT provides a cumbersome but robust approach

$$\mu\frac{\mathrm{d}C_5}{\mathrm{d}\mu} = \gamma^{(5,5)}C_5 + \hat{\gamma}^{(5,5)}C_5C_5C_5 + \gamma_i^{(5,6)}C_5C_6^i + \gamma_i^{(5,7)}C_7^i$$

$$\mu\frac{\mathrm{d}C_7^i}{\mathrm{d}\mu} = \gamma_{ij}^{(7,7)}C_7^j + \gamma_i^{(7,5)}C_5C_5C_5 + \gamma_{ij}^{(7,6)}C_5C_6^j$$

Leading log for neutrino masses:

Chala, Titov '21, di Zhang ++



Concluding Remarks

EFTs provide robust frameworks to parametrize and constrain BSM physics

In the absence of any direct experimental signals provides a systematic approach

The new physics scale hierarchy requires a more careful approach

Light-NP-EFTs and BSMEFTs promise rich landscapes of LNV BSM Physics:

stay tuned for long lived LNV EFT action: Patrick Bolton Wednesday Oct 16, 2024, 2:30 PM

Backup slides

Validity of the EFT approach for LNV Collider searches

Expansion of heavy mediator propagator

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

Fridell, Graf, Harz, **CH** JHEP '24

For collider searches Q can be quite high

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

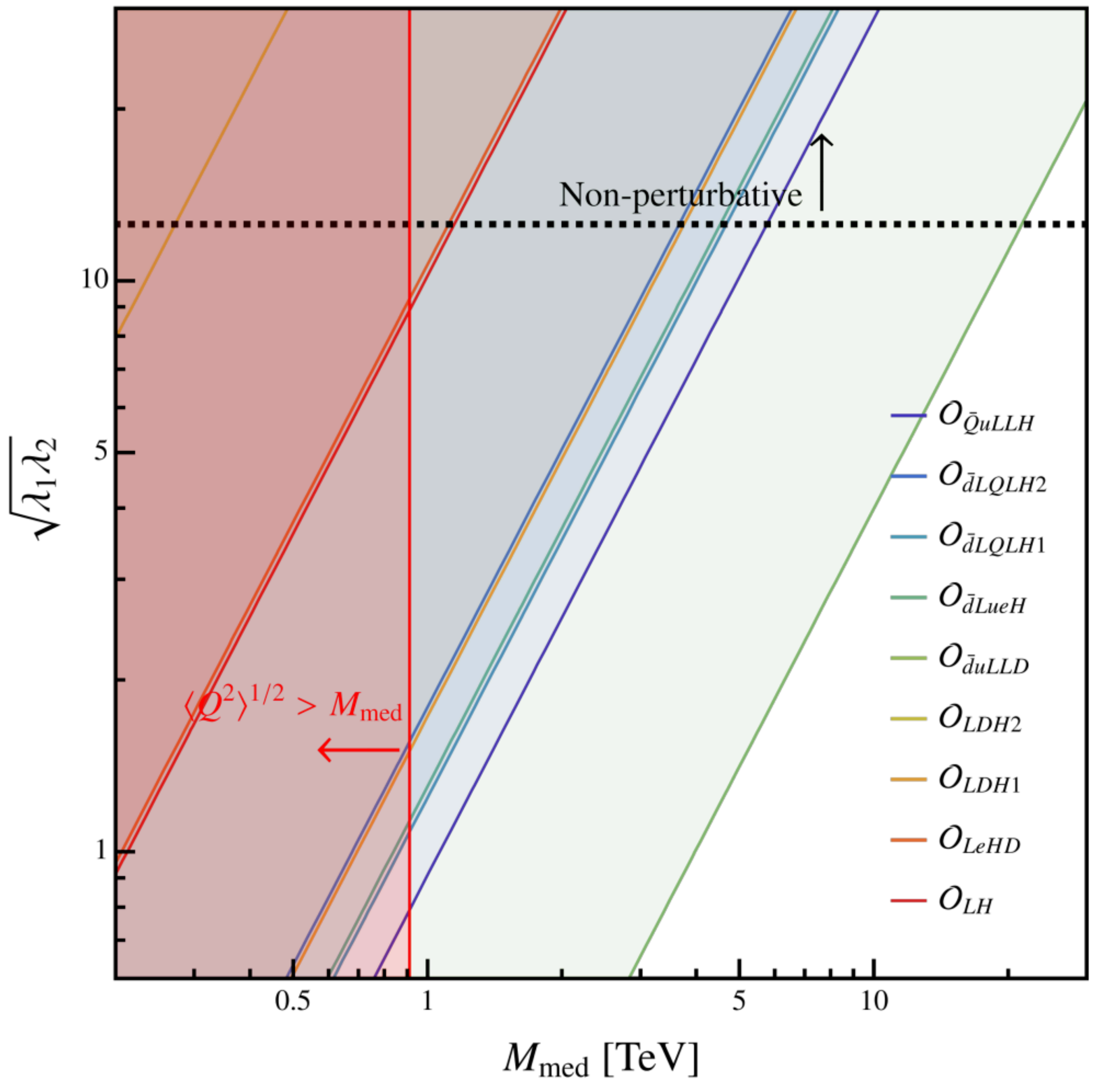
Avg. momentum exchange:

$$\langle Q^2 \rangle = \frac{\sum_{q1=u,c}\sum_{q2=d,s}\int dx_1 dx_2 \left(f_{q_1}(x_1) f_{\bar{q}_2}(x_2) + f_{q_1}(x_2) f_{\bar{q}_2}(x_1)\right)\Theta(Q - Q_0) Q^2}{\sum_{q1=u,c}\sum_{q2=d,s}\int dx_1 dx_2 \left(f_{q_1}(x_1) f_{\bar{q}_2}(x_2) + f_{q_1}(x_2) f_{\bar{q}_2}(x_1)\right)\Theta(Q - Q_0)}$$

$Q_0 \rightarrow$ Min final state invariant mass : controls avg. mom. exc.

For dim-7 SMEFT $$\frac{\lambda_1 \lambda_2}{M_{\rm med}^3} = \frac{1}{(\Lambda_{\rm LNV})^3}$$

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



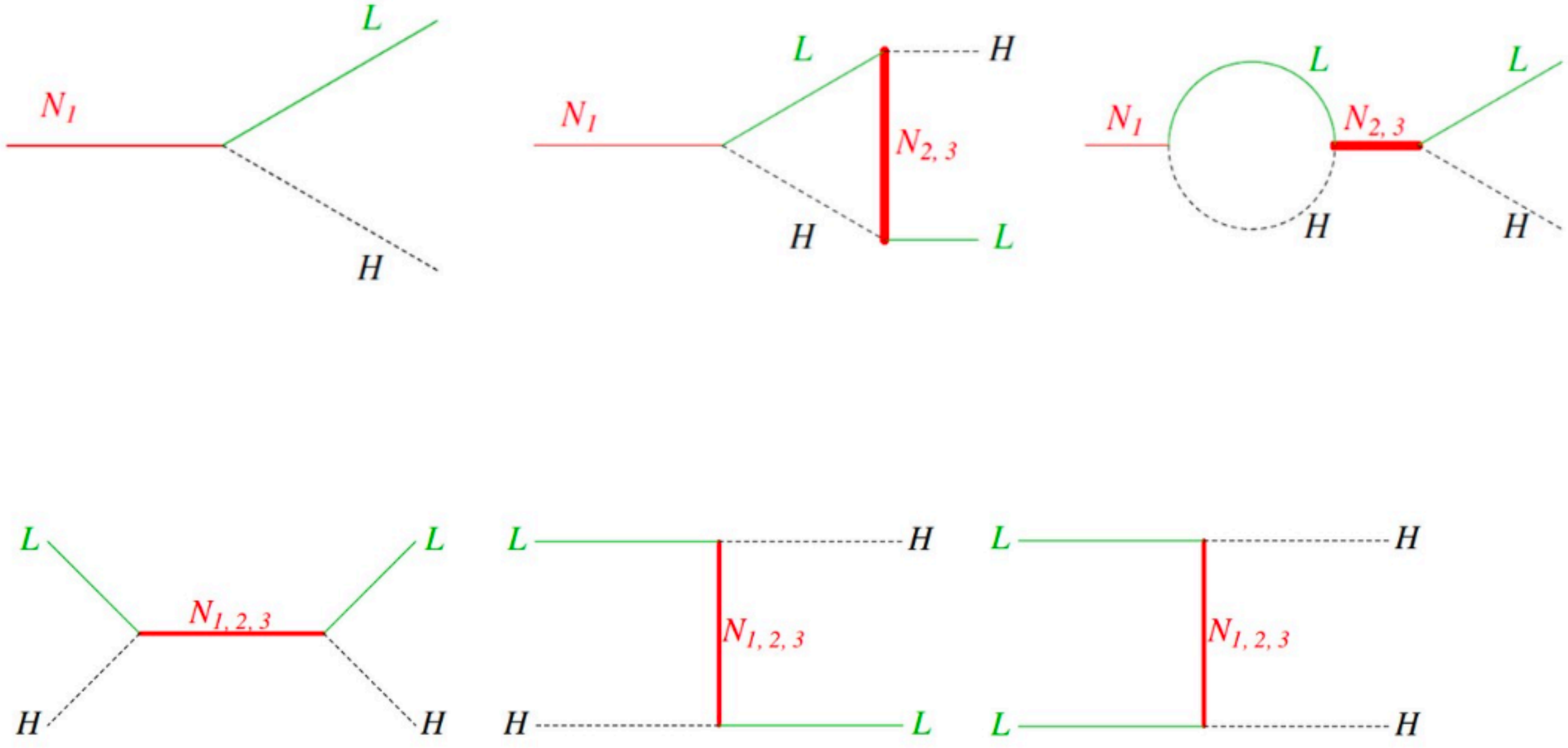
One cosmological “application” of LNV/BNV Effective Field Theory

Baryogenesis/Leptogenesis

In the SM

- baryon number violation
- C and CP violation
- departure from thermal equilibrium

Type-I seesaw leptogenesis



Guidice et al. (2004)

A Simple picture of Washout in EFT Approach

Washout:

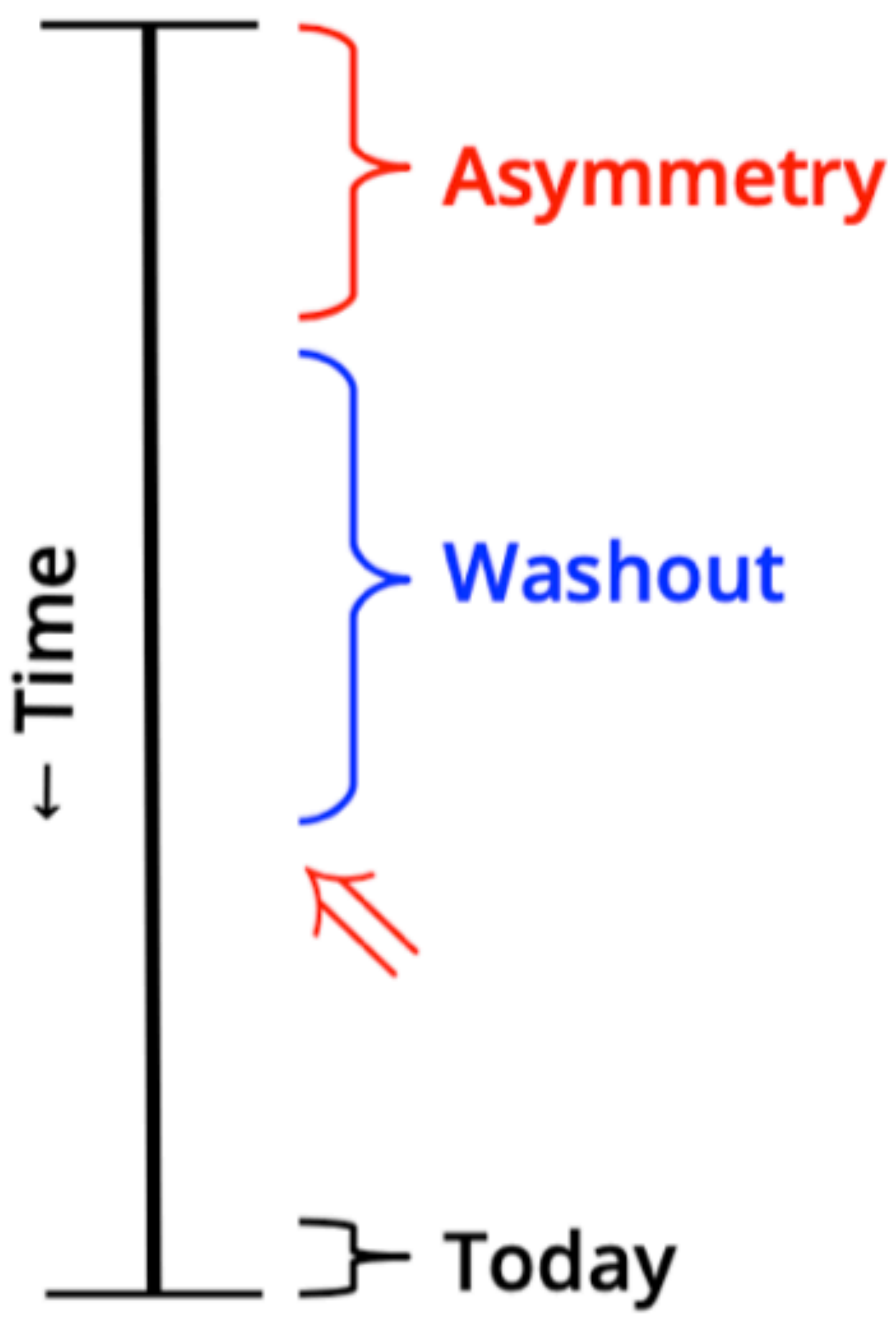
B-L violating processes that can remove (B-L) asymmetry

Generic form

$$zHn_\gamma \frac{d\eta_X}{dz} = -\sum_{a,i,j,\cdots} [Xa\cdots \leftrightarrow ij\cdots],$$

$$[Xa\cdots \leftrightarrow ij\cdots] = \frac{n_X n_a \cdots}{n_X^{eq} n_a^{eq}\cdots}\gamma^{eq}(Xa\cdots \to ij\cdots) - \frac{n_i n_j\cdots}{n_i^{eq} n_j^{eq}\cdots}\gamma^{eq}(ij\cdots \to Xa\cdots),$$

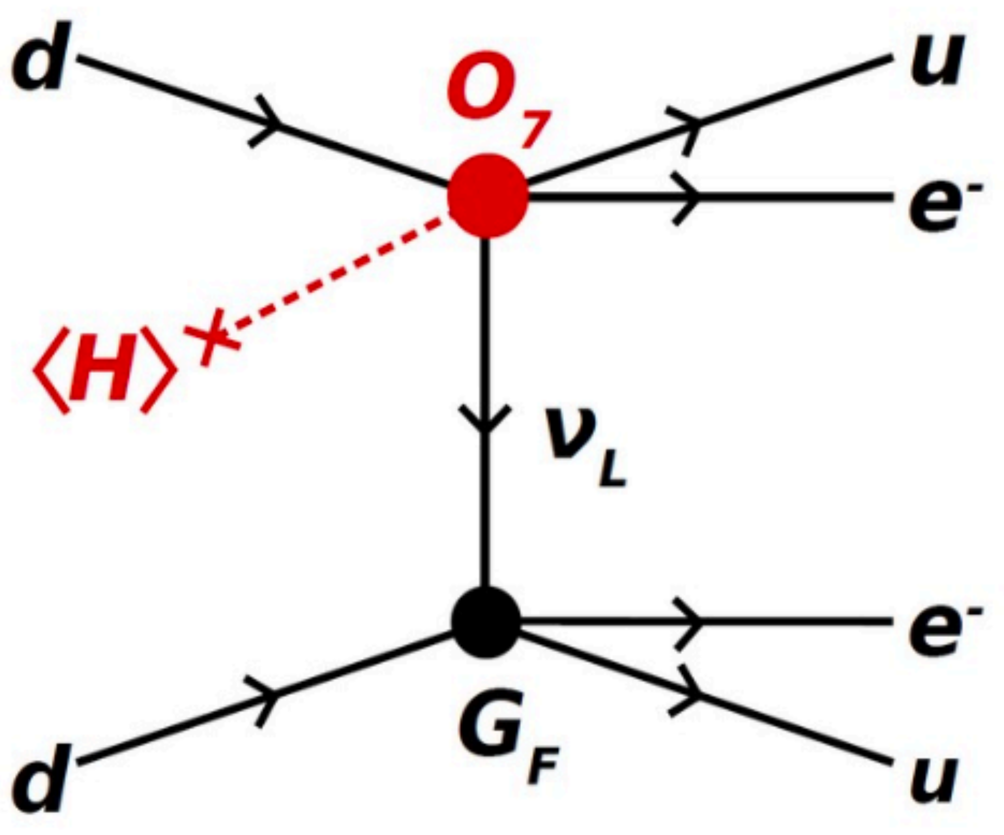
$$\gamma^{eq}(Na\cdots \to ij\cdots) = \int \frac{d^3p_N}{2E_N(2\pi)^3} e^{-\frac{E_N}{T}} \times \prod_{a=1}^{n-1}\left[\int \frac{d^3p_a}{2E_a(2\pi)^3} e^{-\frac{E_a}{T}}\right] \times \prod_{i=1}^{m}\left[\int \frac{d^3p_i}{2E_i(2\pi)^3}\right] \times (2\pi)^4\delta^4\left(p_N + \sum_{a=1}^{n-1} p_a - \sum_{i=1}^{m} p_i\right)|M|^2,$$



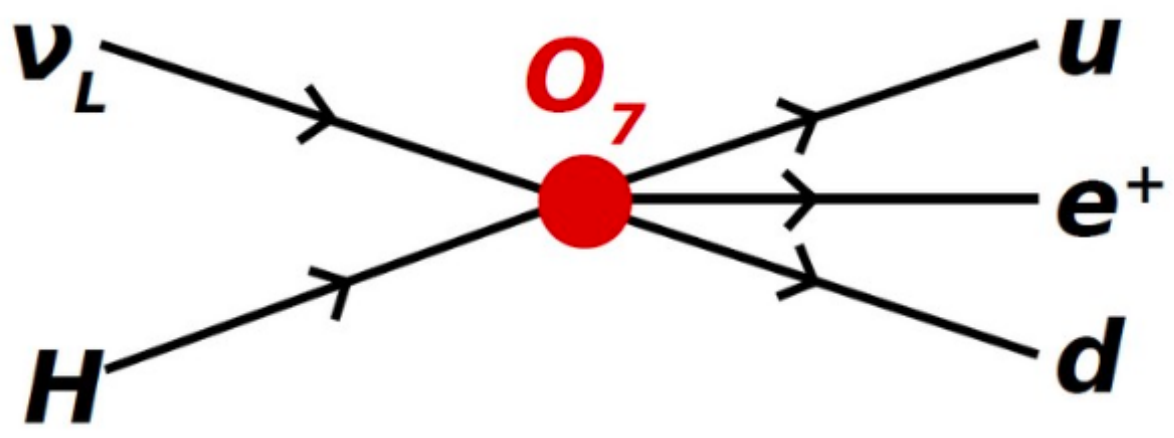
Assume: $|M|^2$ does not depend on the relative motion of particles

$$\gamma^{eq}(Na\cdots \to ij\cdots) = \frac{1}{(2\pi)^3}\int ds\,\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right) dPS^n dPS^m \times |M|^2,$$

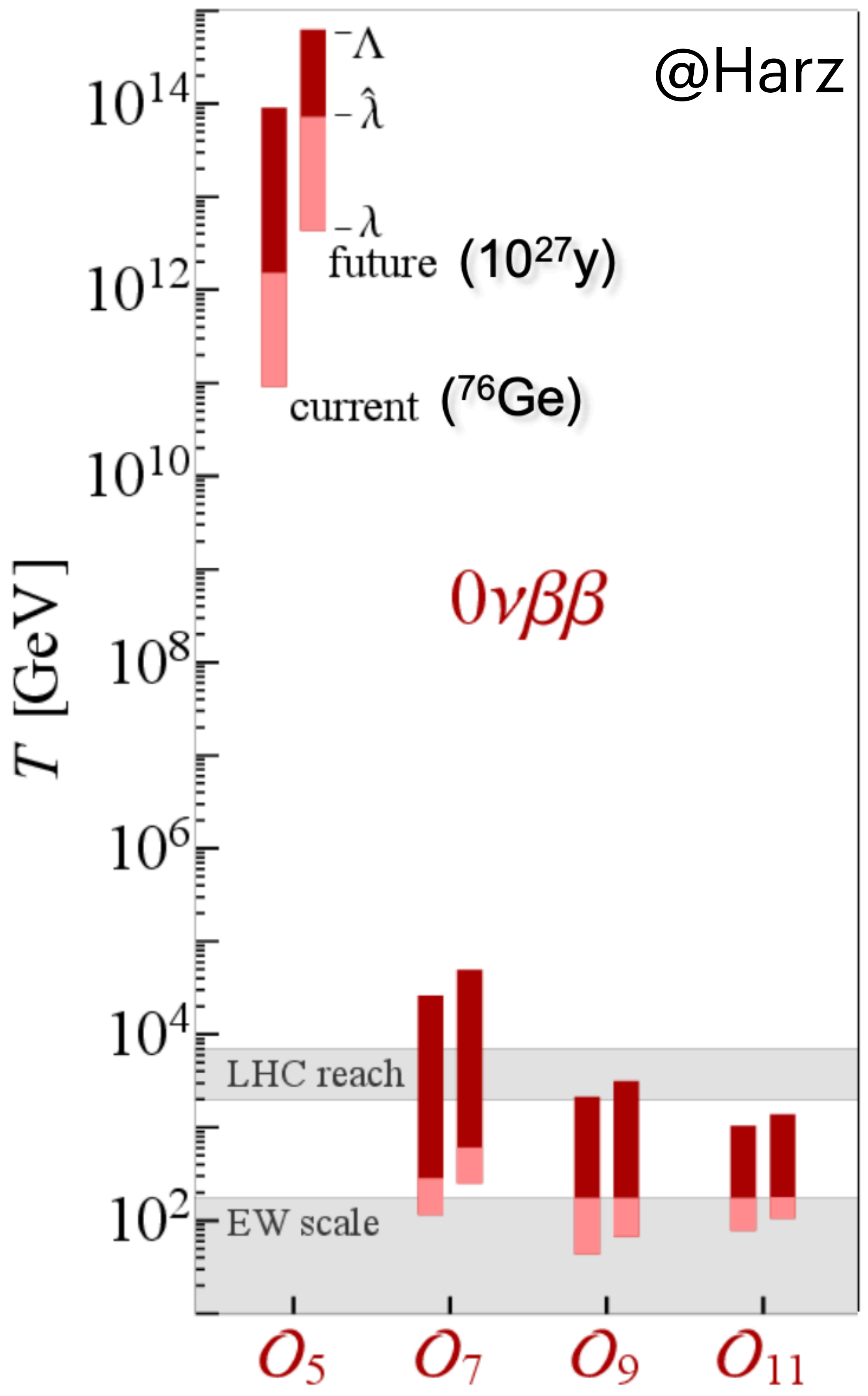
Observation of LNV and baryogensis



$\mathcal{O}$	Operator
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$



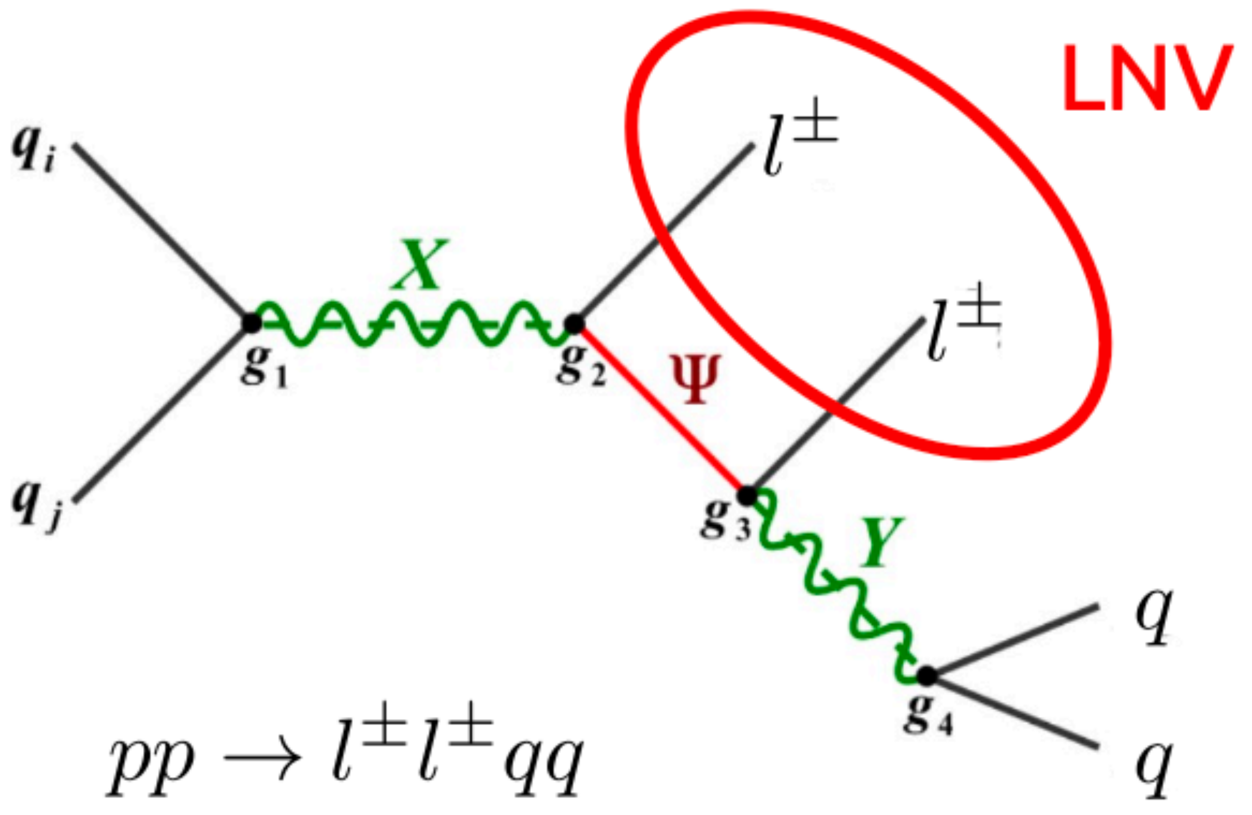
Observed rate at experiment ➡ **New physics scale Λ** ➡ **Washout rate**



Deppisch, Graf, Harz, Huang ’18

Deppisch, Harz, Huang, Hirsch, Päs ’15

Harz, Huang, Päs ’15

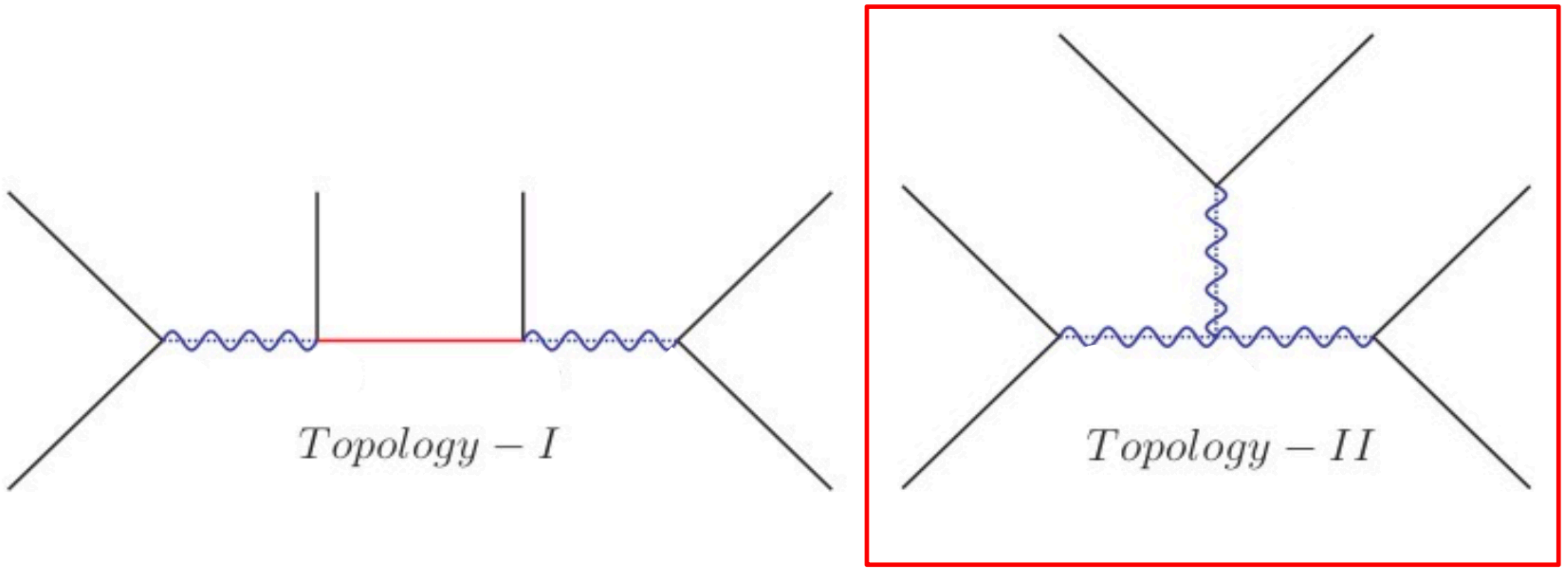


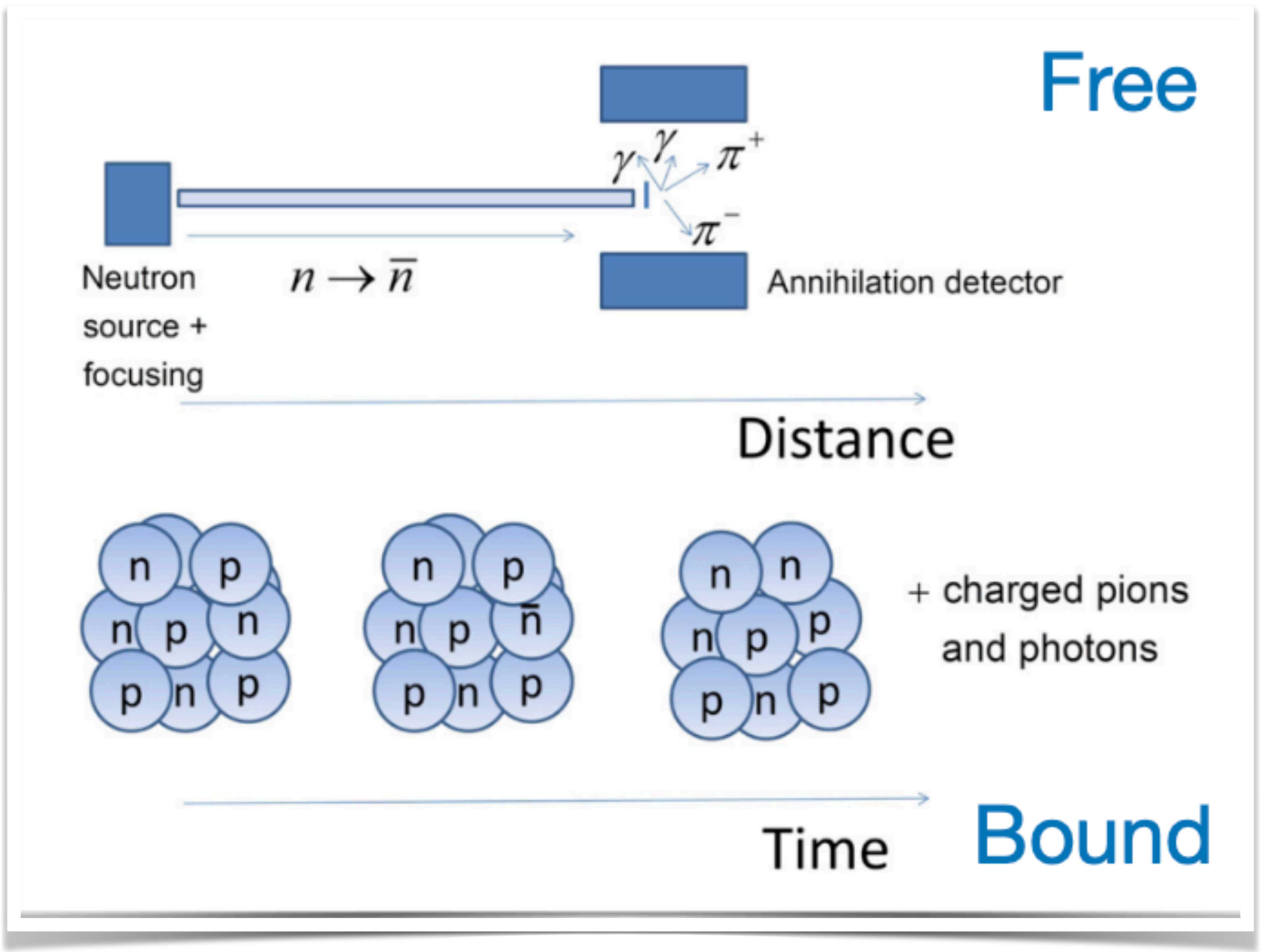
Similar approach for Colliders using resonances

Caveats: penetration of washout in different flavors

Neutron-Antineutron oscillations

Neutron-anti-neutron oscillation can be realized at tree level by dim 9 operators





$$\mathcal{L}^{\bar{n}n}_{\text{WET}} = \sum_i C_i \mathcal{O}_i + \text{h.c.}$$

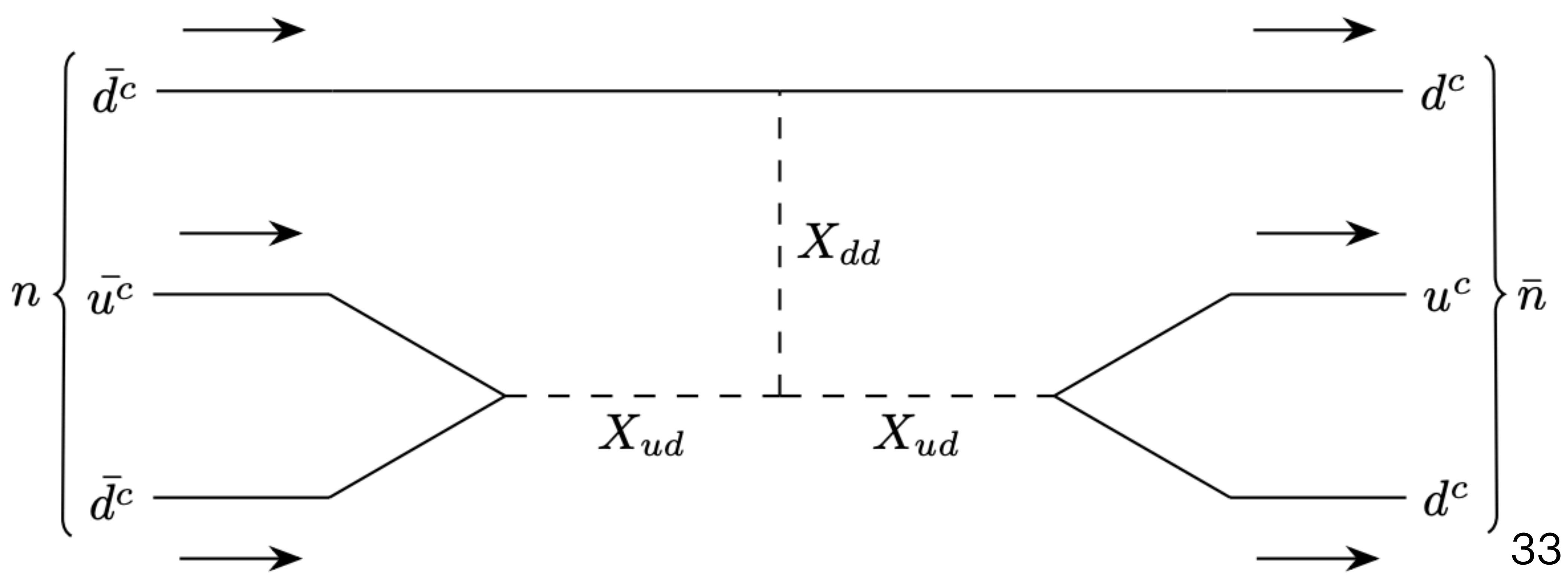
$$\mathcal{O}_1 = (\psi P_R \psi^c)(\psi P_R \psi^c)(\psi P_R \psi^c)$$

$$\tau^{-1}_{n\bar{n}} = \langle \bar{n} | \mathcal{L}^{n\bar{n}}_{\text{WET}} | n \rangle = \left| C_1(\mu) \mathcal{M}_1(\mu) \right|$$

$$\mathcal{M}_i(\mu) = \langle \bar{n} | \mathcal{O}_i(\mu) | n \rangle$$

Rinaldi et al (2019)

Wilson coefficient: $C_i \propto \frac{1}{\Lambda^5}$ Λ = New Physics (NP) scale → encodes all the effects of heavy NP.



Decomposition of 126 multiplet of $SO(10)$

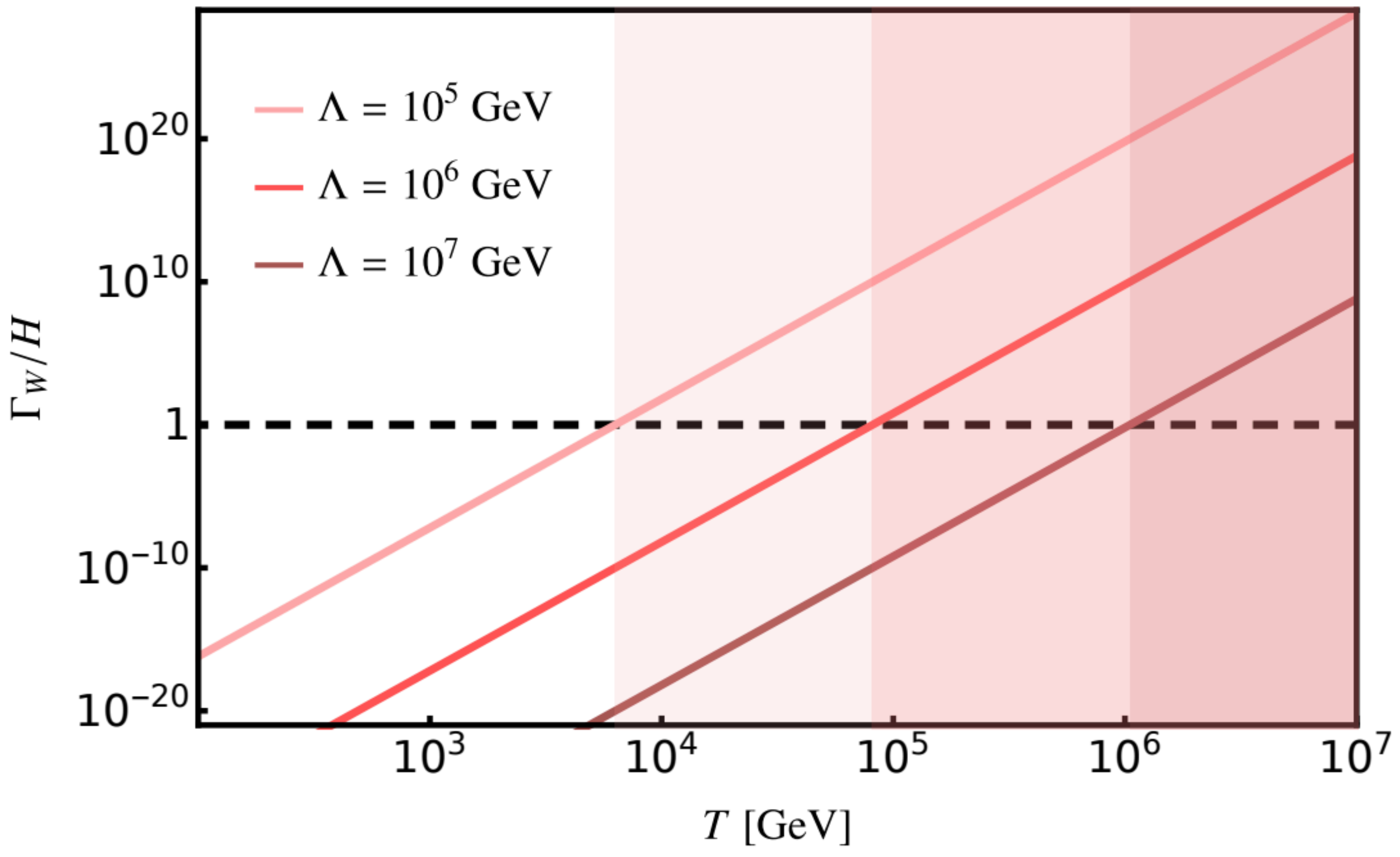
G_{PS}	G_{LR}	G_{SM}
$(\mathbf{1}, \mathbf{3}, \overline{\mathbf{10}})$	$(1,1,3,+2)$	$(\mathbf{1},\mathbf{1},\mathbf{0}) \oplus (1,1,+1) \oplus (1,1,+2)$
	$(\bar{3},1,3,+\frac{2}{3})$	$(\bar{3},1,-\frac{2}{3}) \oplus (\bar{3},1,+\frac{1}{3}) \oplus (\bar{3},1,+\frac{4}{3})$
	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{3},-\frac{\mathbf{2}}{\mathbf{3}})$	$(\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{4}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{1}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},+\frac{\mathbf{2}}{\mathbf{3}})$

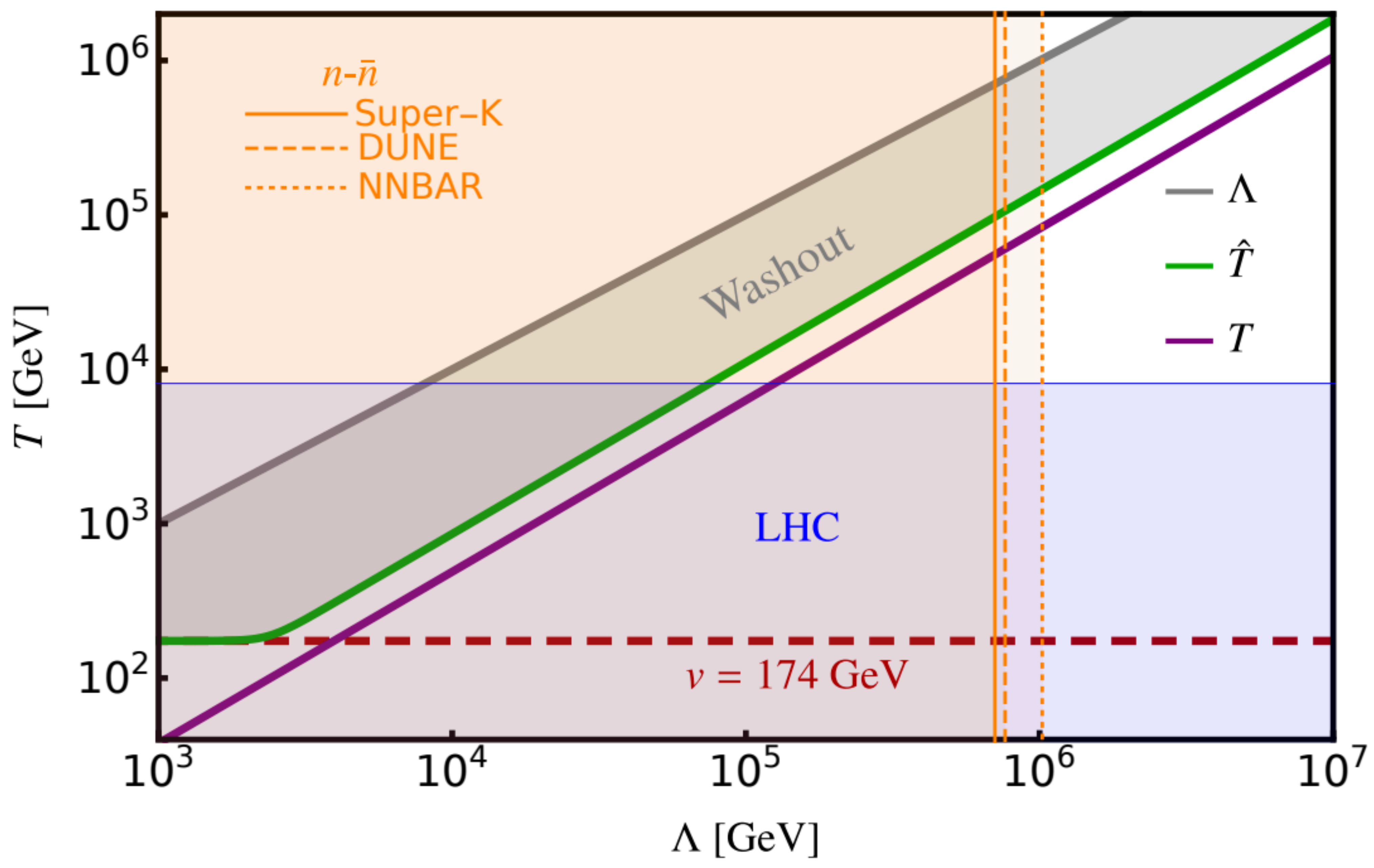
Neutron-Antineutron oscillations

$n - \bar{n}$ operators correspond to washout processes $\Delta B = 2$

Out of equilibrium temperature: $\Gamma \sim H, \quad \Gamma \propto |C_i \mathcal{M}_i|^2 \propto |\frac{1}{\Lambda^5}$

chemical potential relations=> $$zHn_\gamma \frac{d\eta_{\Delta B}}{dz} = -c\frac{T^{14}}{\Lambda^{10}}\eta_{\Delta B}$$





Observed NP scale Λ in $n - \bar{n}$ operator -> the OOE temperature for the washout

Caveats: validity of the EFT treatment e.g. hierarchical NP scales, CPV sources

Fridell, Harz, **CH** JHEP '21