LNV beyond dim-5 Weinberg Operator

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Breaking Lepton Number in High Energy Direct Searches

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

CSIC Consejo Superior de Investigaciones Científicas

ASTROPARTICLES Astroparticles and High Energy Physics Group

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

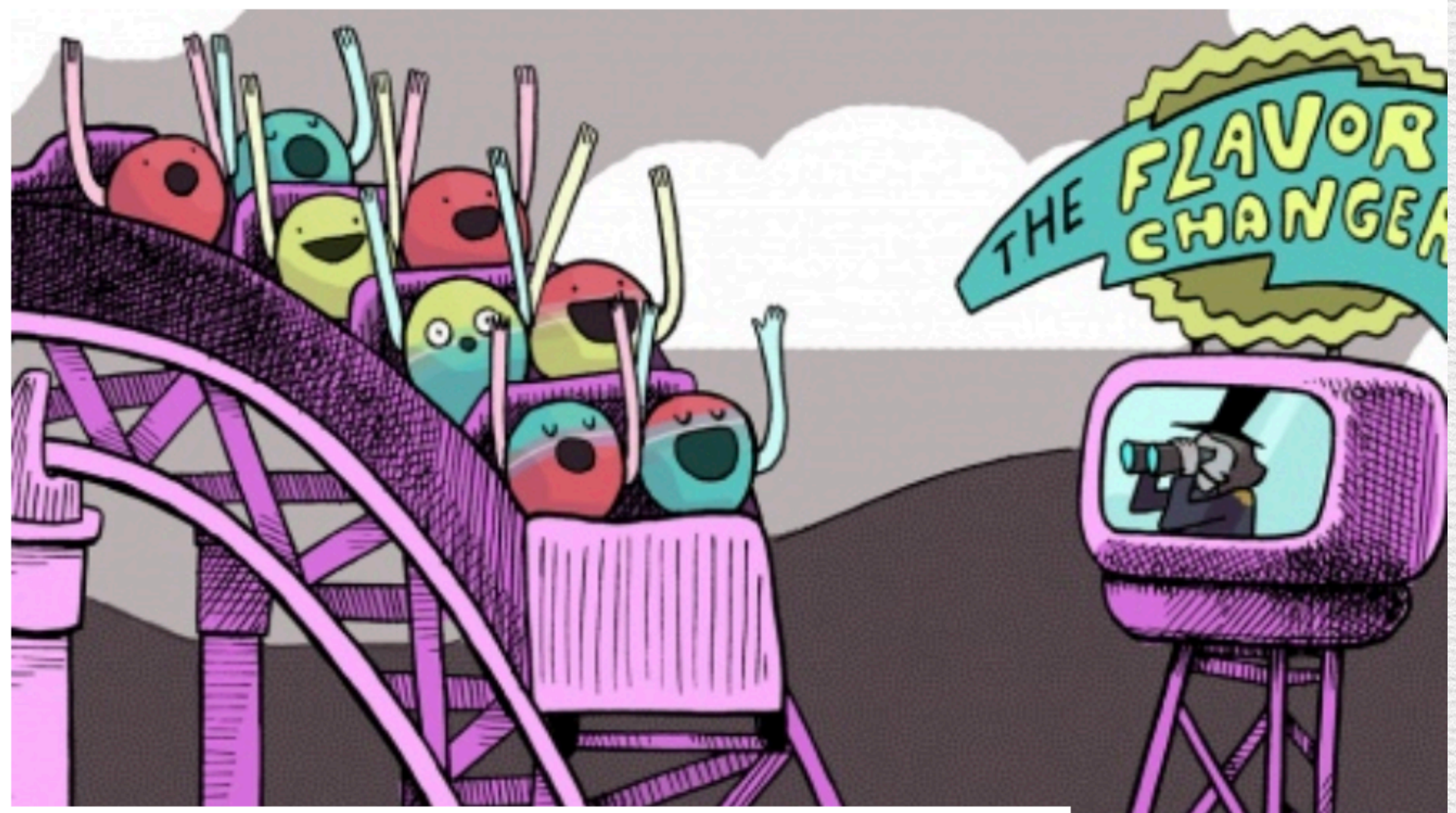
GENERALITAT VALENCIANA Conselleria d'Educació, Universitats i Ocupació

Very rich literature on the topic!

I am sure I have missed many relevant citations

Neutrino masses and Lepton Number Violation

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

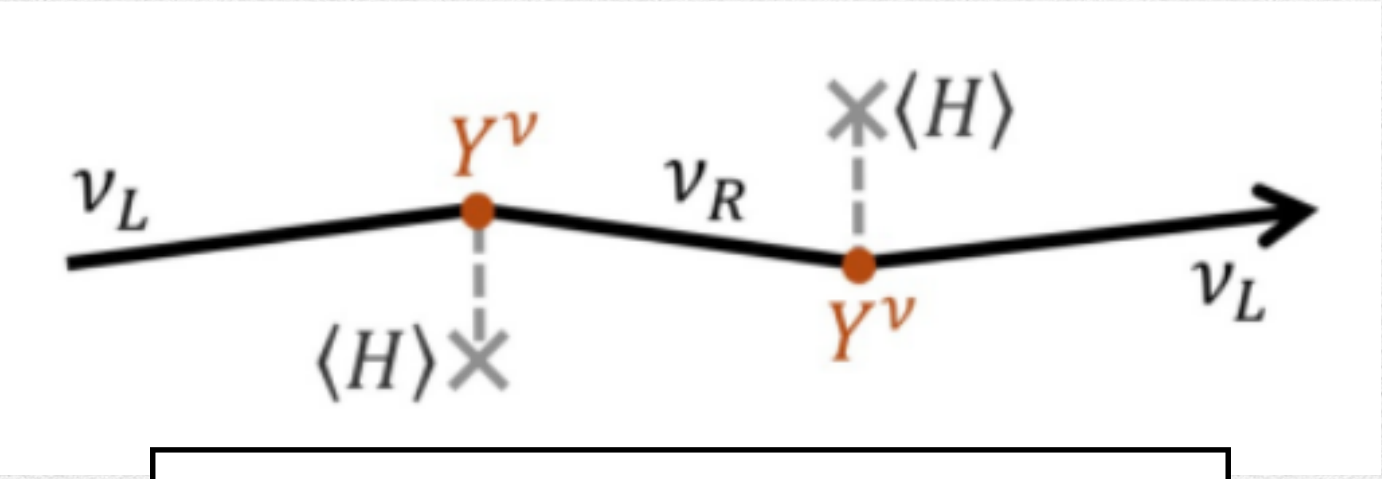


Neutrino oscillation. Image: Symmetry magazine

Purely SM:

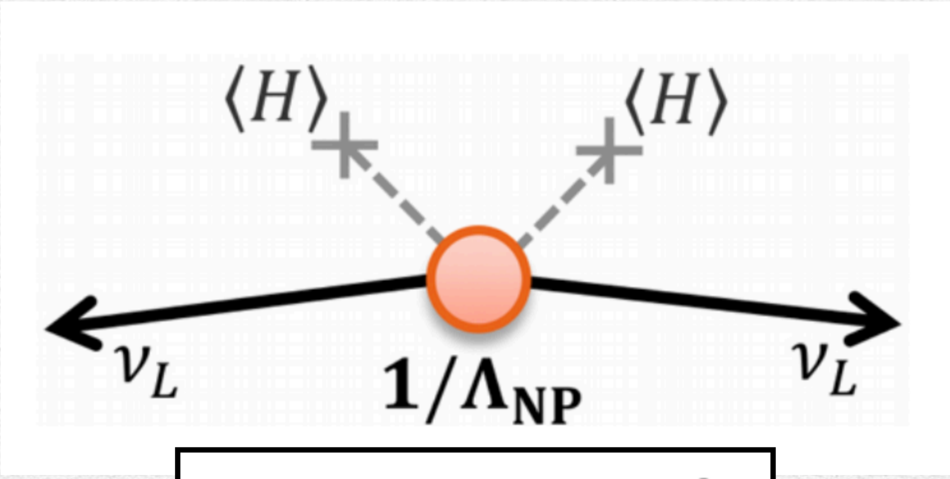
- strictly massless neutrinos
- conservation of lepton number and flavours

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, ...?

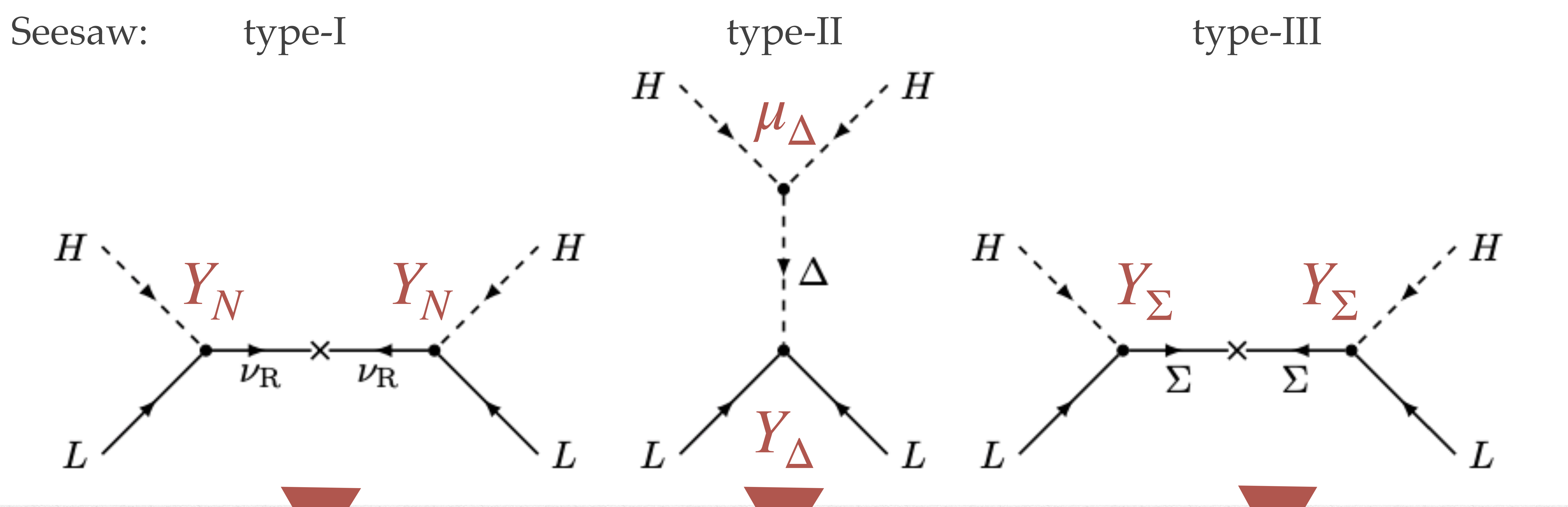
Majorana: $\nu = \nu^c$: **Lepton Number Violation!**

Phenomenologically very interesting!

Connection to Leptogenesis?

Minimal neutrino mass models: "Bauhaus"

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

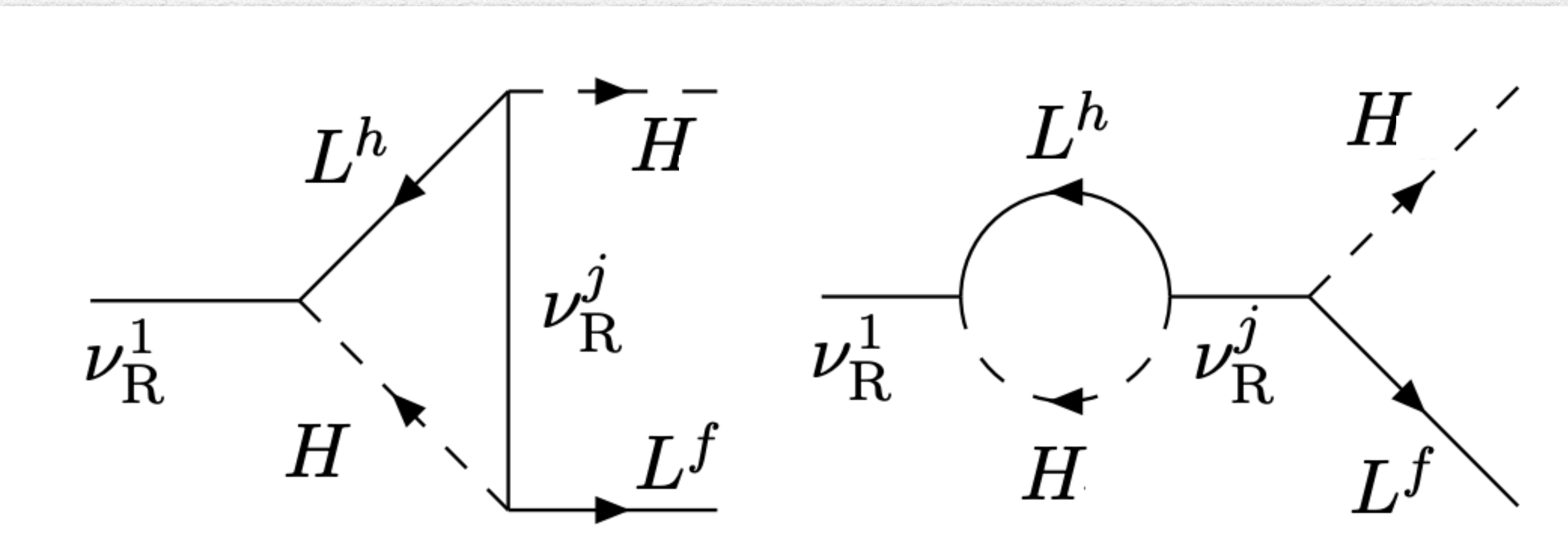


Minkowski; Gell-Mann, Ramond, Slansky; Mohapatra,Senjanovic; Schechter, Valle; Ma, Sarkar; Magg, Wetterich; Cheng, Li; Lazarides, Shafi; Foot,Lew, Joshi; Ma; Ma, Roy; Hambye,Lin,Notari,Papucci,Strumia; Bajc,nemevsek,Senjanovic;Dorsner,Filevi ez-Perez ++

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

Fukugida,Yanagida

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

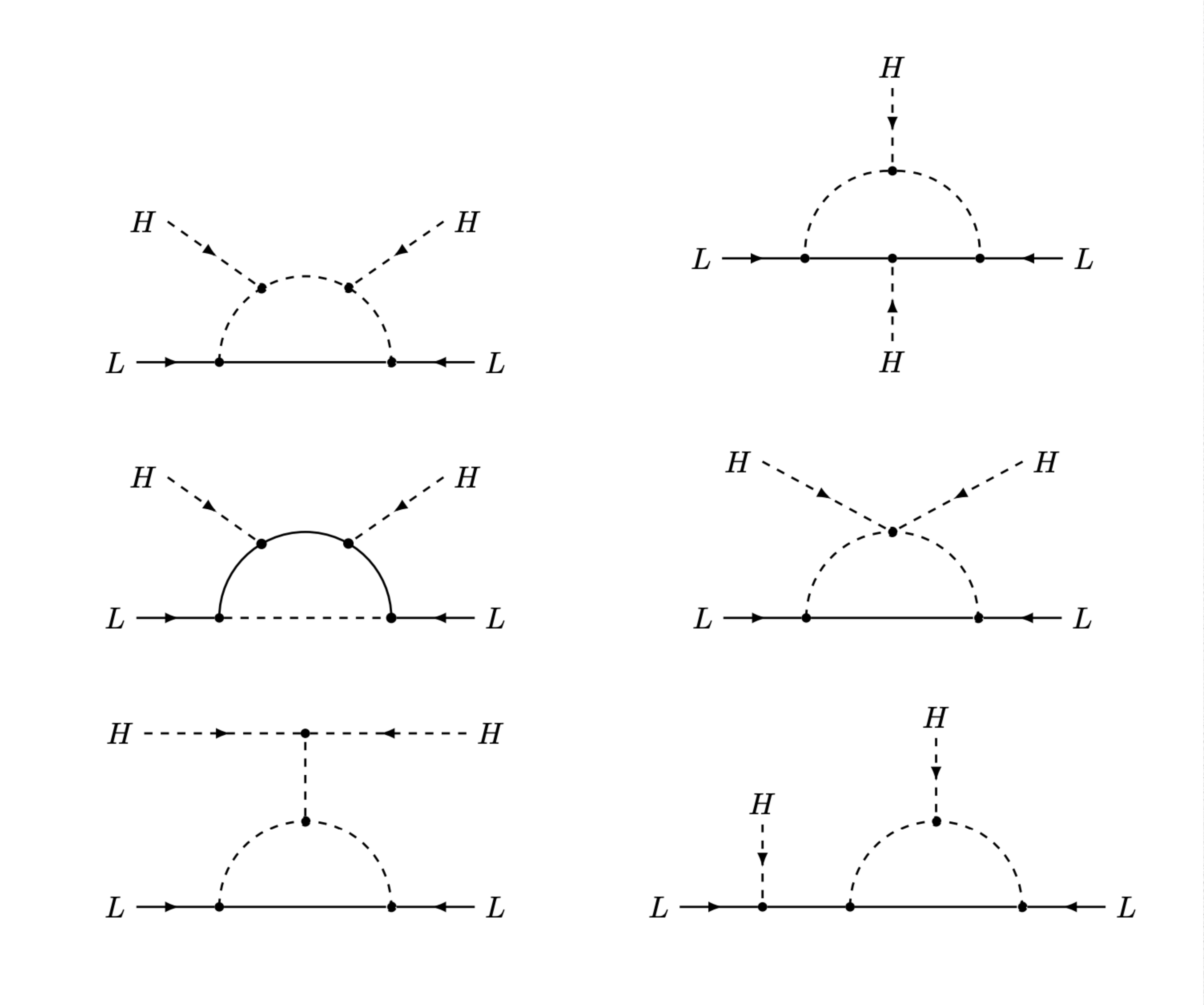


Bonus: gateway to explain baryon asymmetry of the Universe

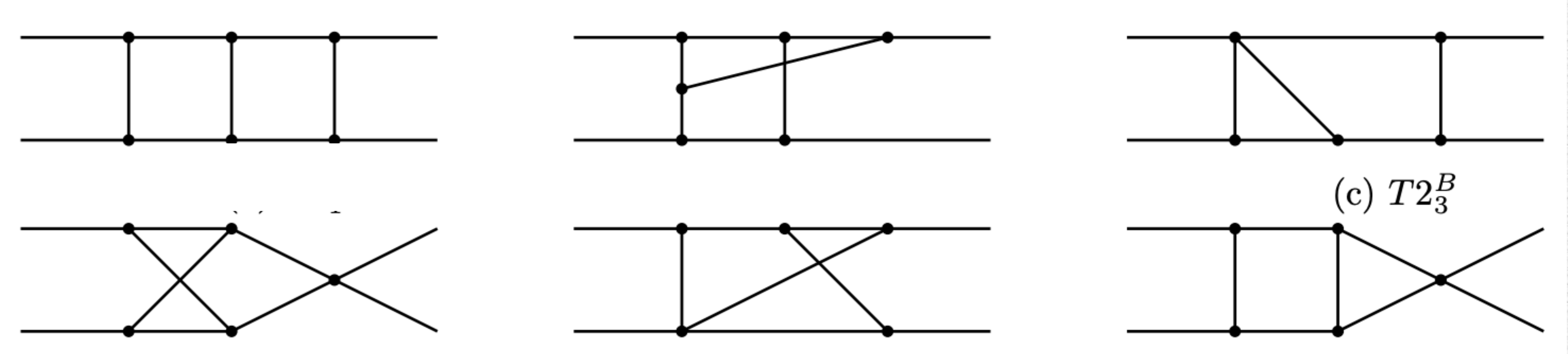
Shakarov's conditions => Leptogenesis

Neutrino mass models: “Baroque”

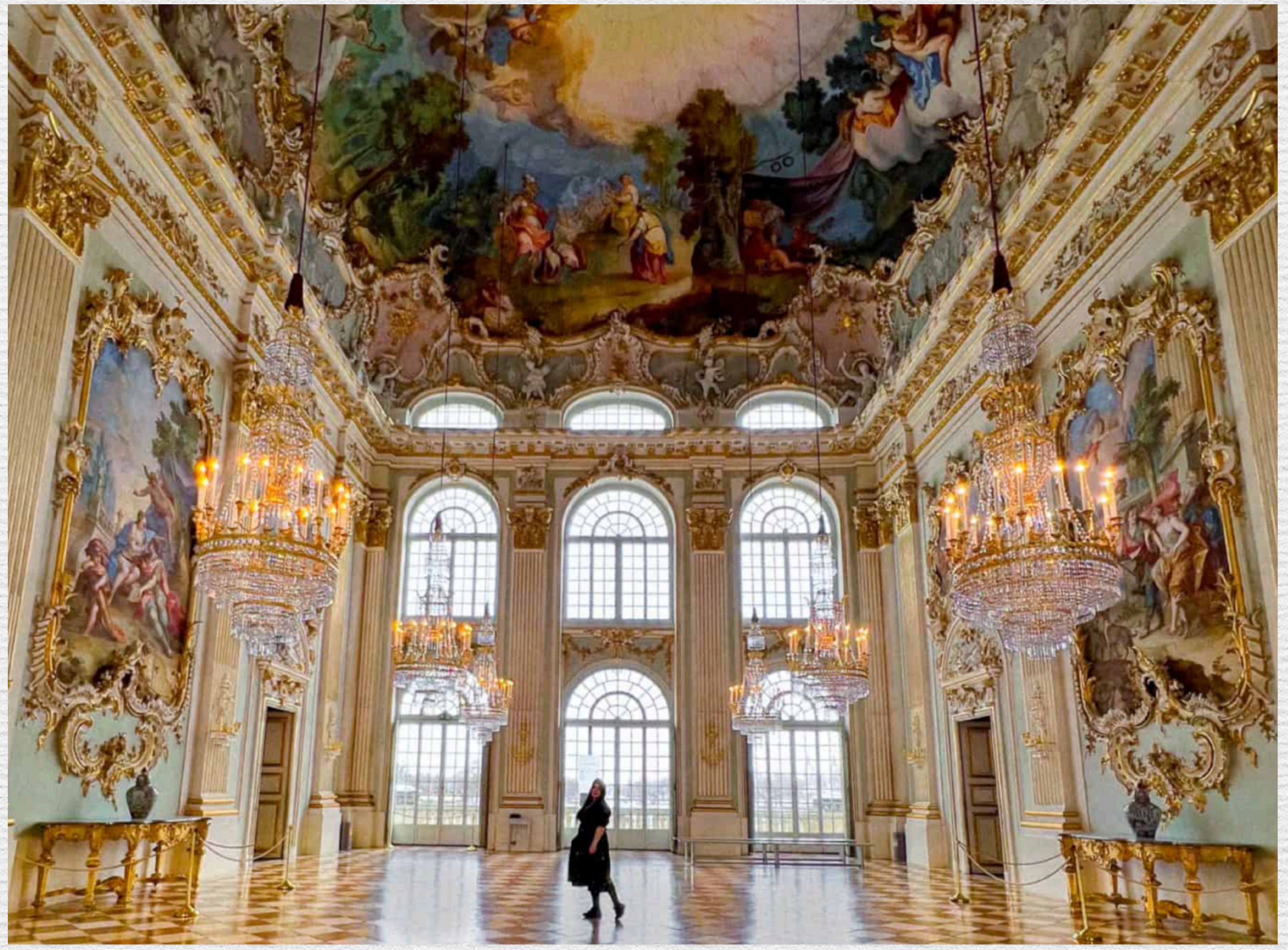
One-loop@ dimension-5:



Two-loop@ dimension-5:



Things only get more 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

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

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

Consider a nonrenormalisable operator (d >4) : $\mathcal{O}_5$ with d = 5

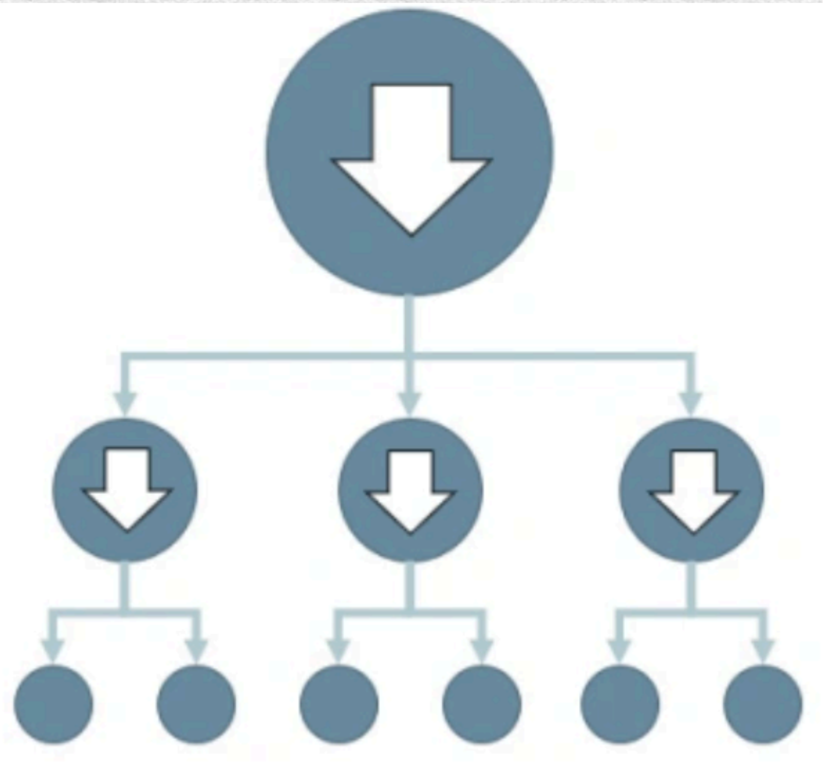
It will generate divergences at higher dimension. Example: a loop with two insertions of $\mathcal{O}_5$ will diverge as $\left(\frac{p^2}{\Lambda^2}\right)$=> requiring a counter-term with d=6.

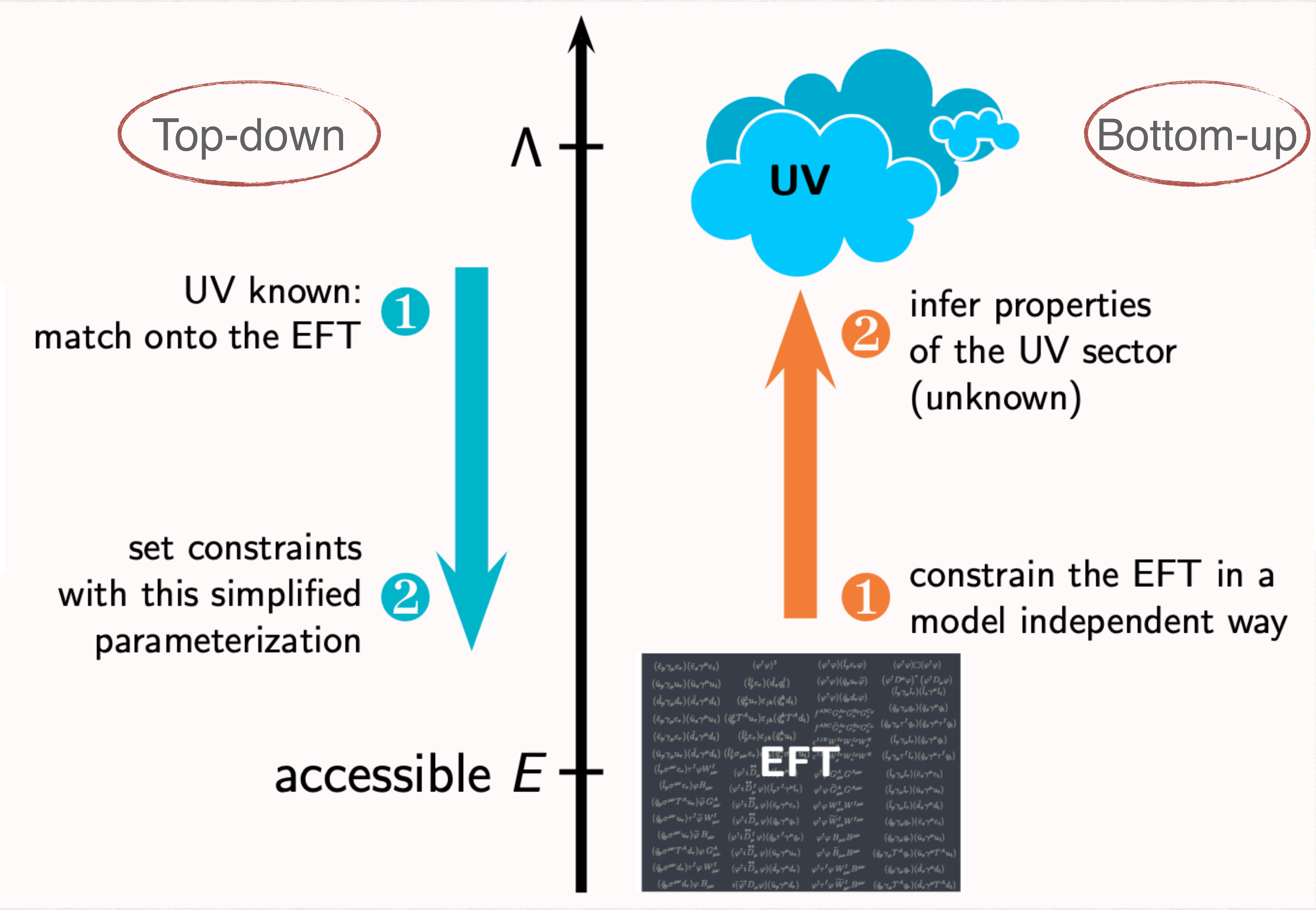
=> we need an infinite # of operators to absorb all the divergences

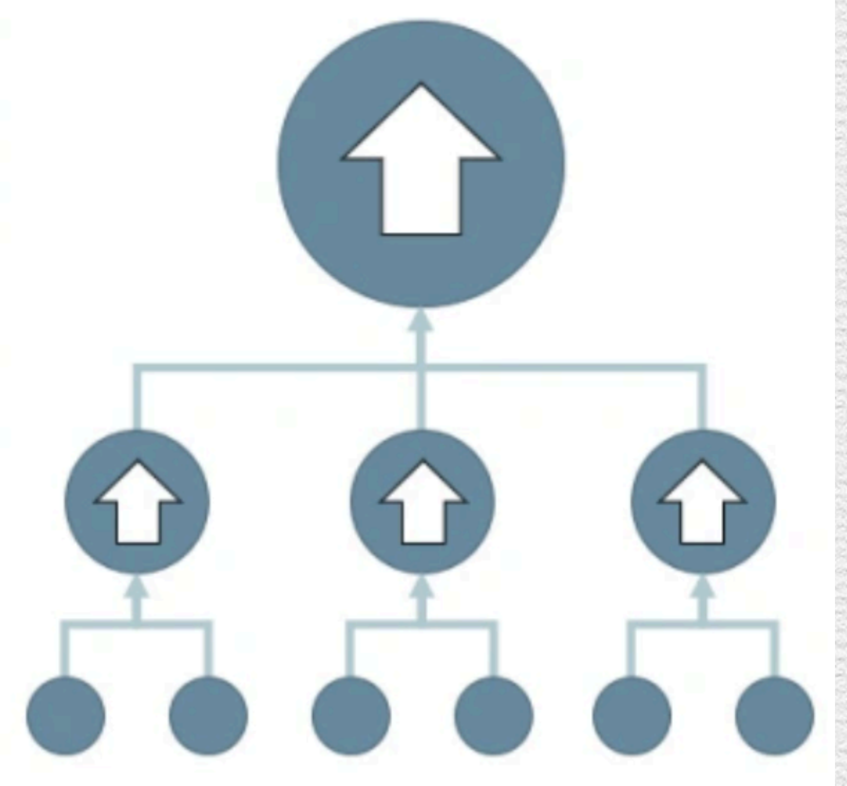
Appelquist,Carrazzone ++

Fortunately nature decouples: (i) there are no “+ve" powers of heavy scale (M), except in $\log$’s
(ii) $\log M$ can be absorbed into c_i’s

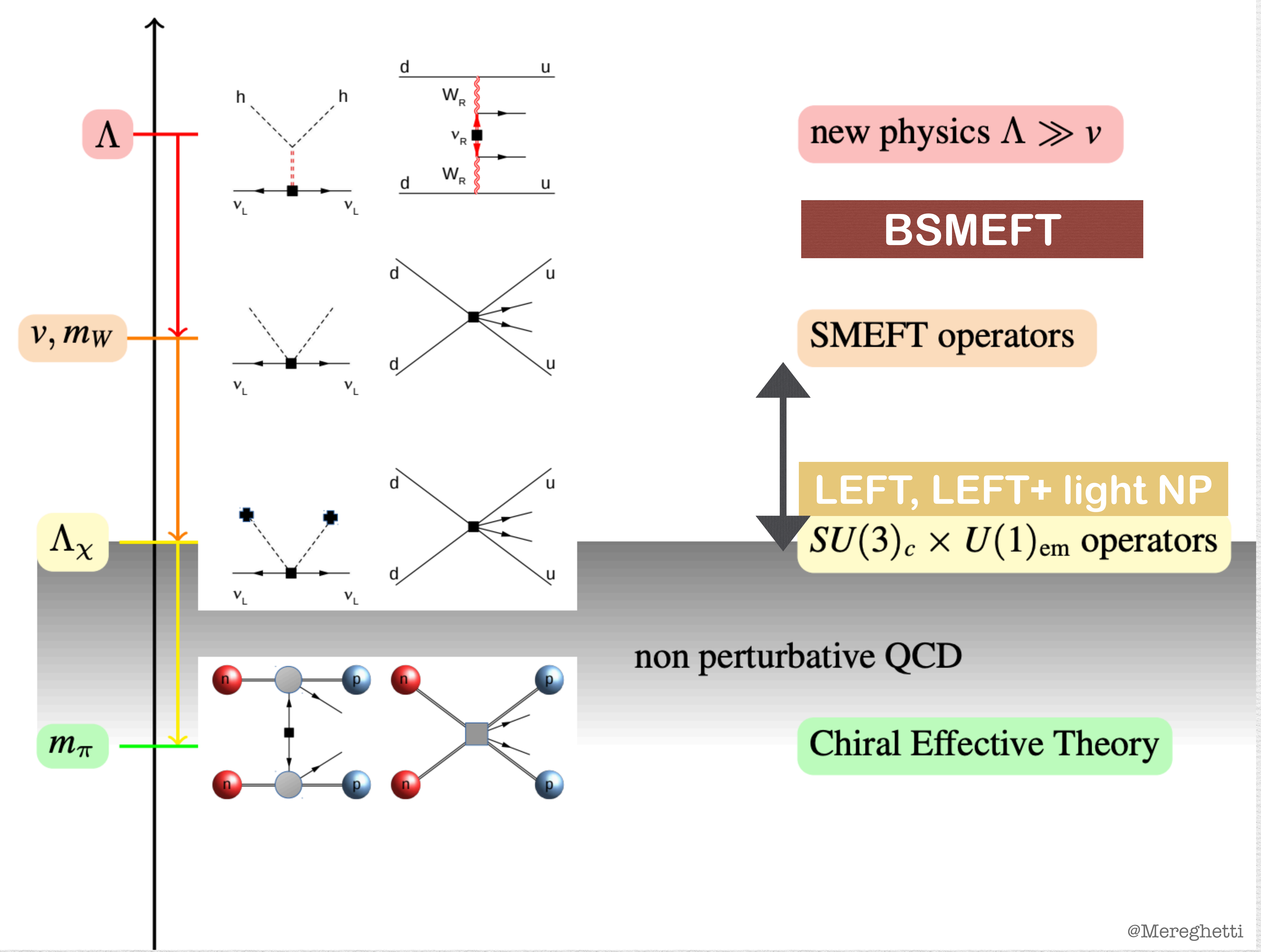
Connecting EFTs to Experiments







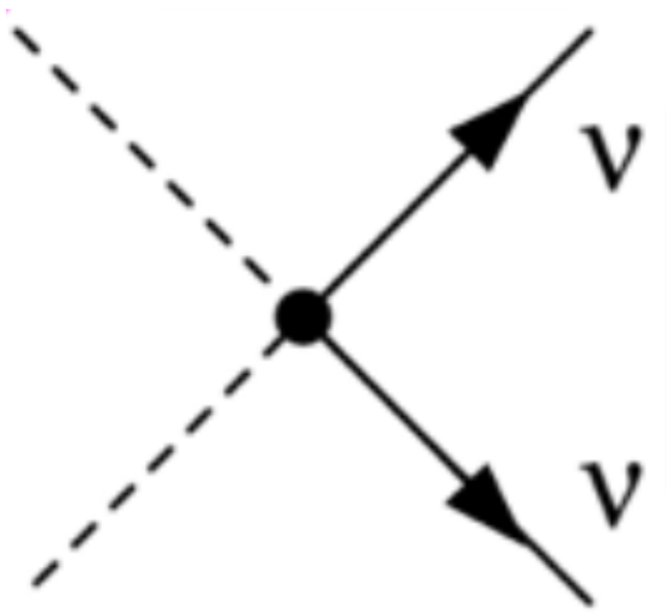
Some popular EFTs for BSM Phenomenology



Lepton Number Violation and SMEFT

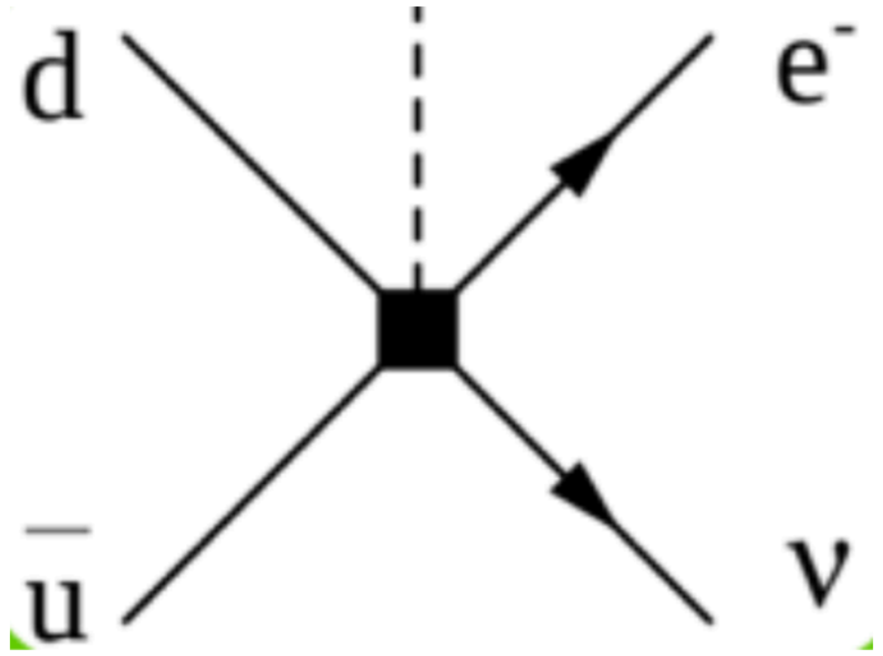
LNV SMEFT:

d=5



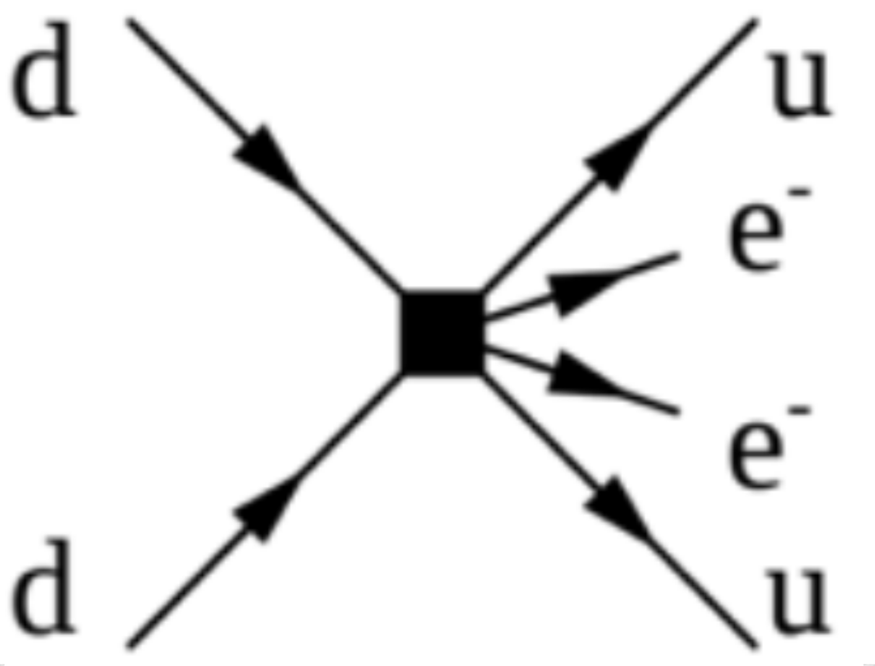
Weinberg '79

d=7



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

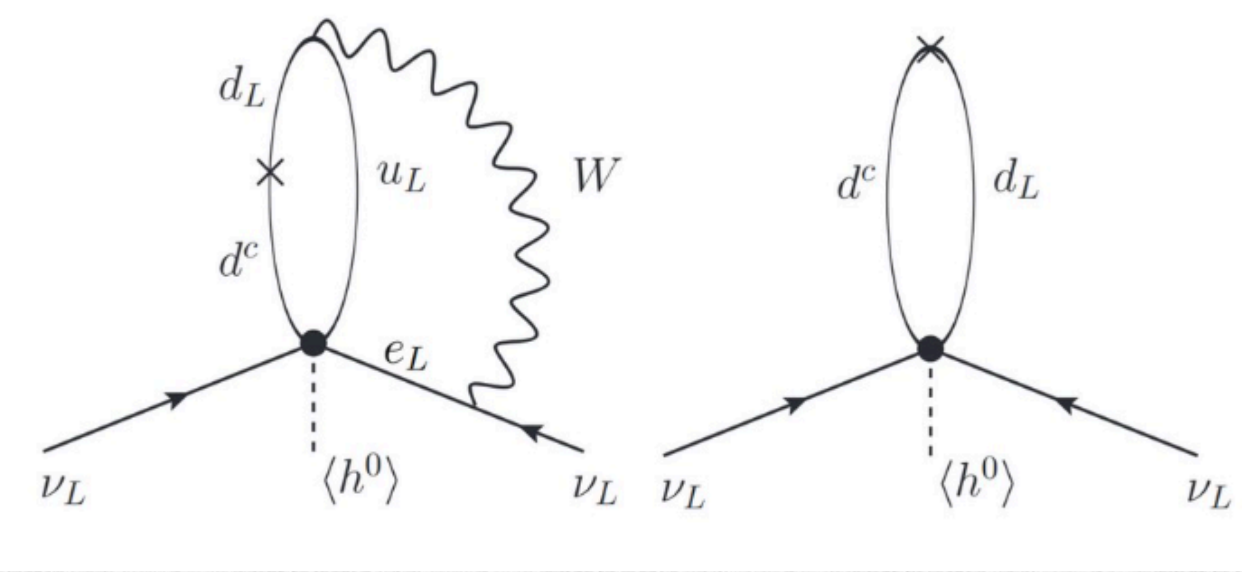
d=9

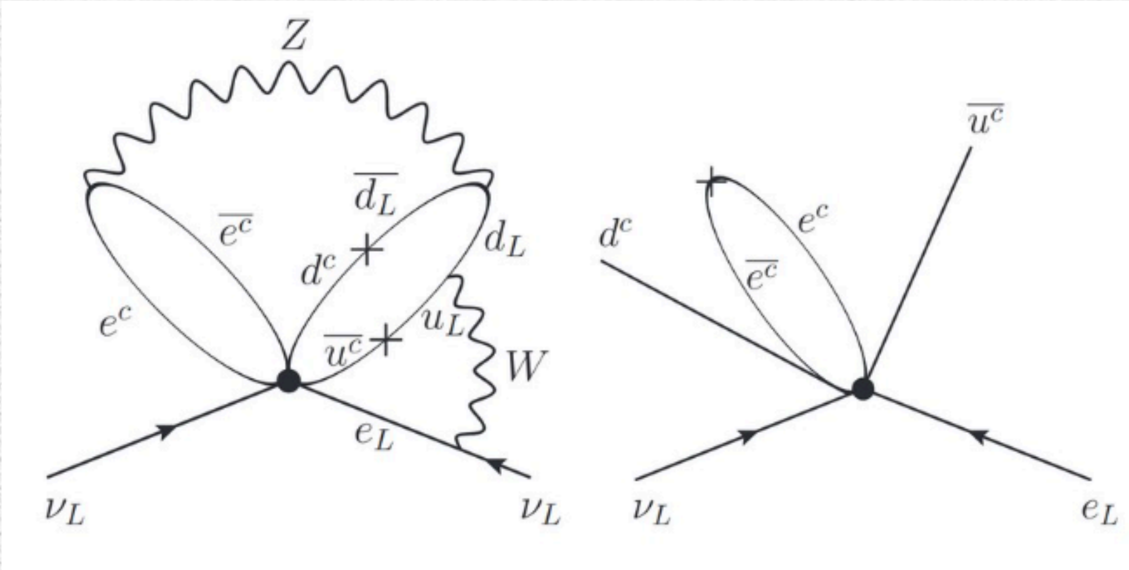


M. Graesser '16
Y. Liao and X. D. Ma '20

Neutrino mass:

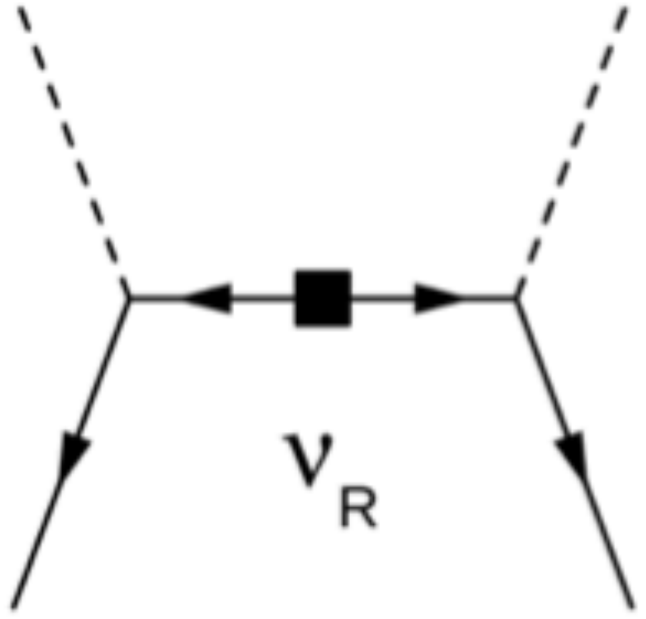
$$\frac{1}{\Lambda}\varepsilon_{ij}\varepsilon_{mn}L_i^T C L_m H_j H_n \rightarrow \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

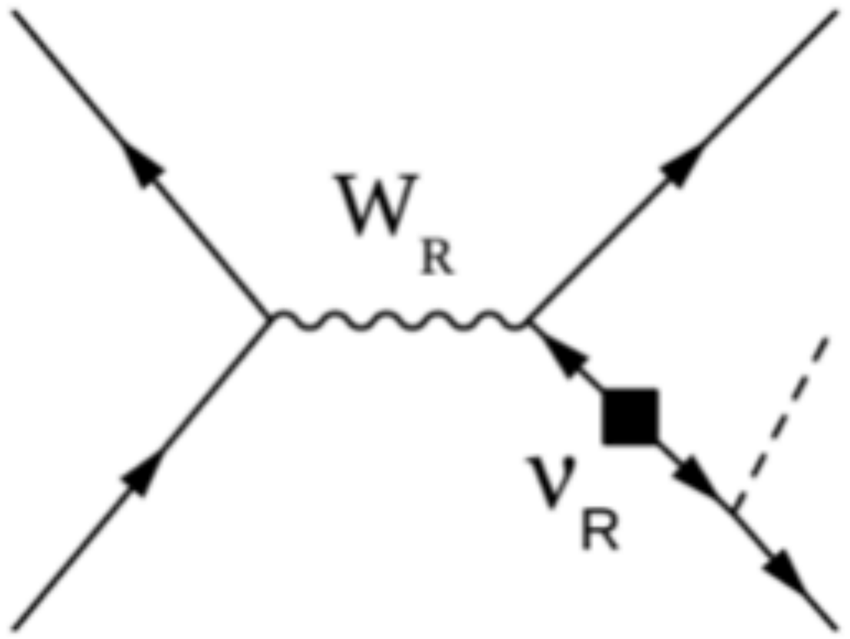


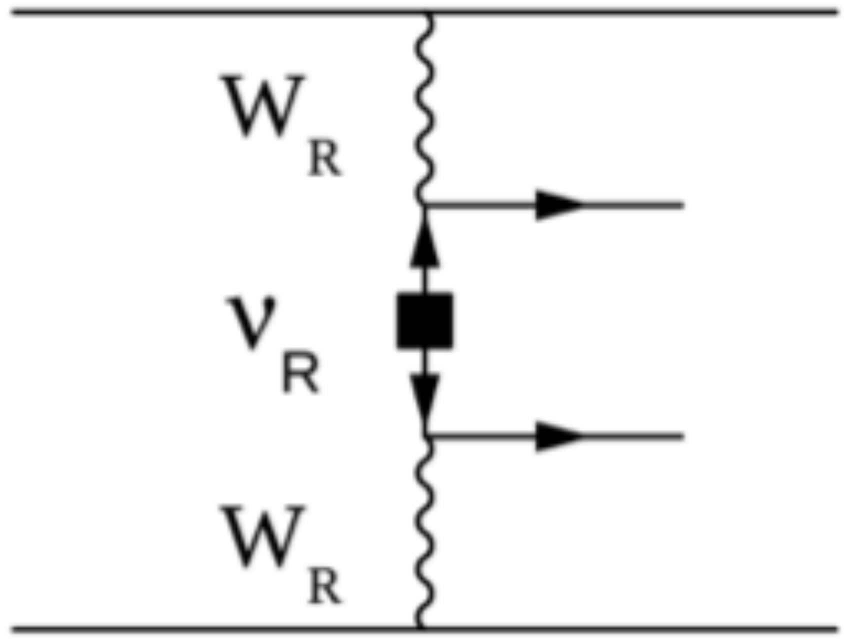


UV example:

LRSM: (L<->R) at high scale
Mohapatra and Pati '75
Senjanovic and Mohapatra '75







Lepton Number Violating 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

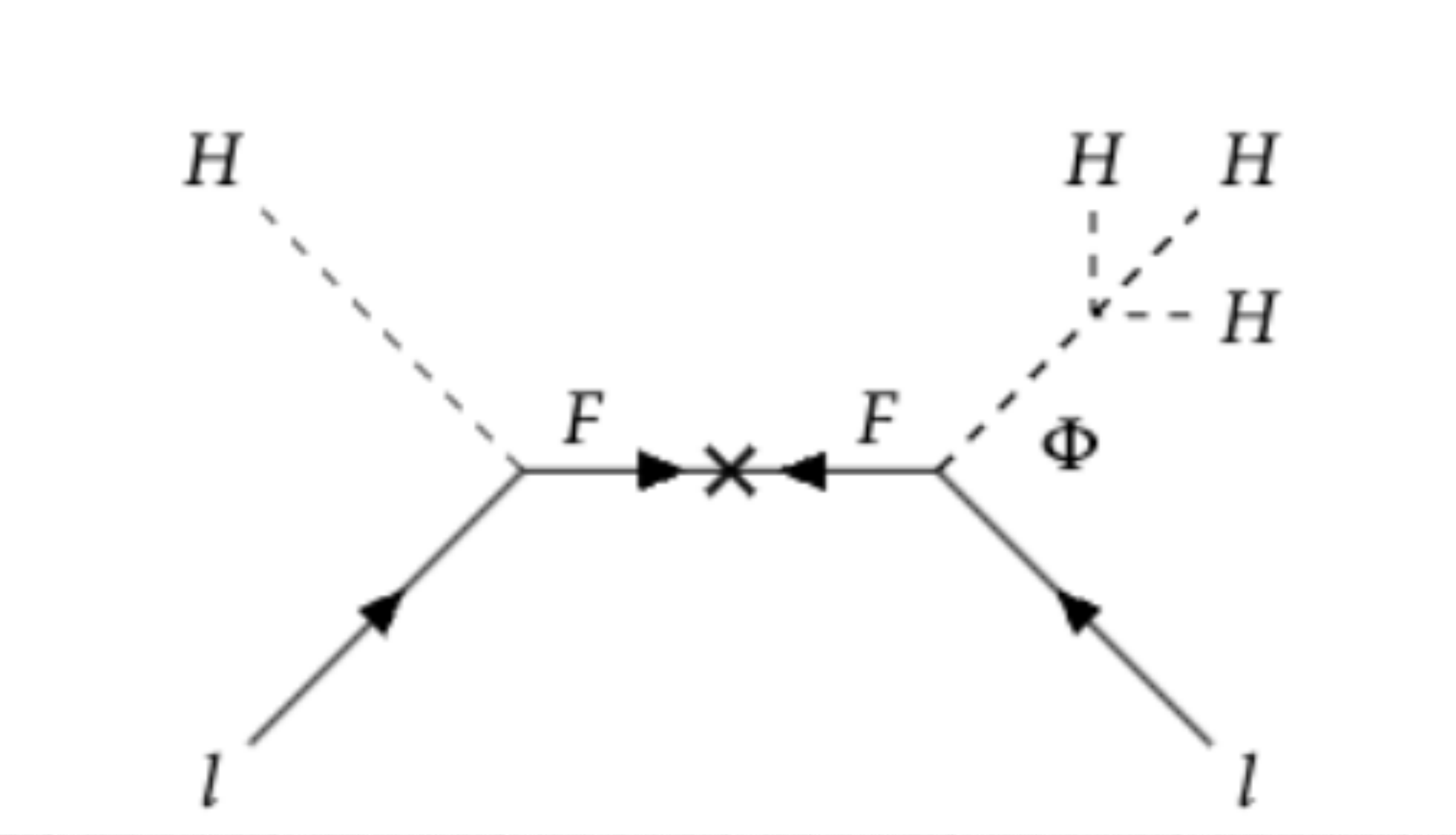
Further reduced in

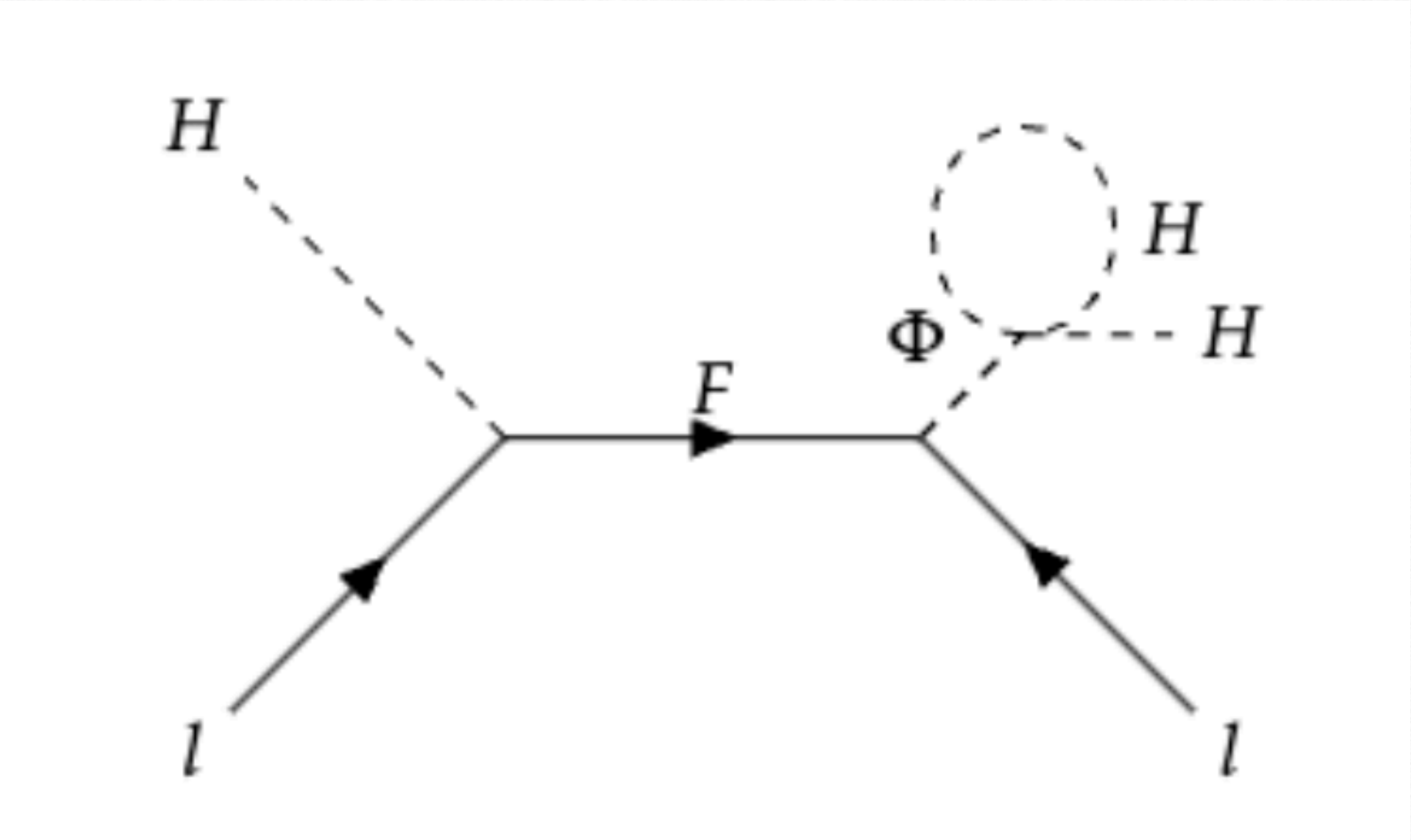
Liao, Ma '17

18 = 12+6 (indept. structures)

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

Why dimension-7 SMEFT operators?





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

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
$O^{S,prst}_{e\nu;LL}$	$(\overline{e_{Rp}}e_{Lr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{e\nu;LL} = -\frac{\sqrt{2}v}{8}(2C^{prst}_{\bar{e}LLLH} + C^{psrt}_{\bar{e}LLLH} + s \leftrightarrow t)$
$O^{S,prst}_{e\nu;RL}$	$(\overline{e_{Lp}}e_{Rr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{e\nu;RL} = -\frac{\sqrt{2}v}{2}(C^{sr}_{LeHD}\delta^{tp} + C^{tr}_{LeHD}\delta^{sp})$
$O^{T,prst}_{e\nu;LL}$	$(\overline{e_{Rp}}\sigma_{\mu\nu}e_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{e\nu;LL} = +\frac{\sqrt{2}v}{32}(C^{psrt}_{\bar{e}LLLH} - C^{ptrs}_{\bar{e}LLLH})$
$O^{S,prst}_{d\nu;LL}$	$(\overline{d_{Rp}}d_{Lr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{8}V_{xr}(C^{ptxs}_{\bar{d}LQLH1} + C^{psxt}_{\bar{d}LQLH1})$
$O^{T,prst}_{d\nu;LL}$	$(\overline{d_{Rp}}\sigma_{\mu\nu}d_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{32}V_{xr}(C^{ptxs}_{\bar{d}LQLH1} - C^{psxt}_{\bar{d}LQLH1})$
$O^{S,prst}_{u\nu;RL}$	$(\overline{u_{Lp}}u_{Rr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{u\nu;RL} = +\frac{\sqrt{2}v}{4}(C^{prst}_{\bar{Q}uLLH} + C^{prts}_{\bar{Q}uLLH})$
$O^{S,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}}u_{Lr})(\overline{\nu^c_s}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{du\nu e;LL} =$ $+\frac{\sqrt{2}v}{8}(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} - C^{psrt}_{\bar{d}LQLH2})$
$O^{S,prst}_{du\nu e;RL}$	$(\overline{d_{Lp}}u_{Rr})(\overline{\nu^c_s}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{du\nu e;RL} = +\frac{\sqrt{2}v}{2}V^*_{xp}C^{xrts}_{\bar{Q}uLLH}$
$O^{T,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{du\nu e;LL} =$ $+\frac{\sqrt{2}v}{32}(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} + C^{psrt}_{\bar{d}LQLH2})$
$O^{V,prst}_{du\nu e;LR}$	$(\overline{d_{Lp}}\gamma_\mu u_{Lr})(\overline{\nu^c_s}\gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}}c^{V,prst}_{du\nu e;LR} = +\frac{\sqrt{2}v}{2}V^*_{rp}C^{st}_{LeHD}$
$O^{V,prst}_{du\nu e;RR}$	$(\overline{d_{Rp}}\gamma_\mu u_{Rr})(\overline{\nu^c_s}\gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}}c^{V,prst}_{du\nu e;RR} = +\frac{\sqrt{2}v}{4}C^{psrt}_{\bar{d}LueH}$
$O^{S,prst}_{d\nu;RL}$	$(\overline{d_{Lp}}d_{Rr})(\overline{\nu^c_s}\nu_t)$	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

SMEFT & $0\nu\beta\beta$

Neutrinoless double beta decay

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

Half life

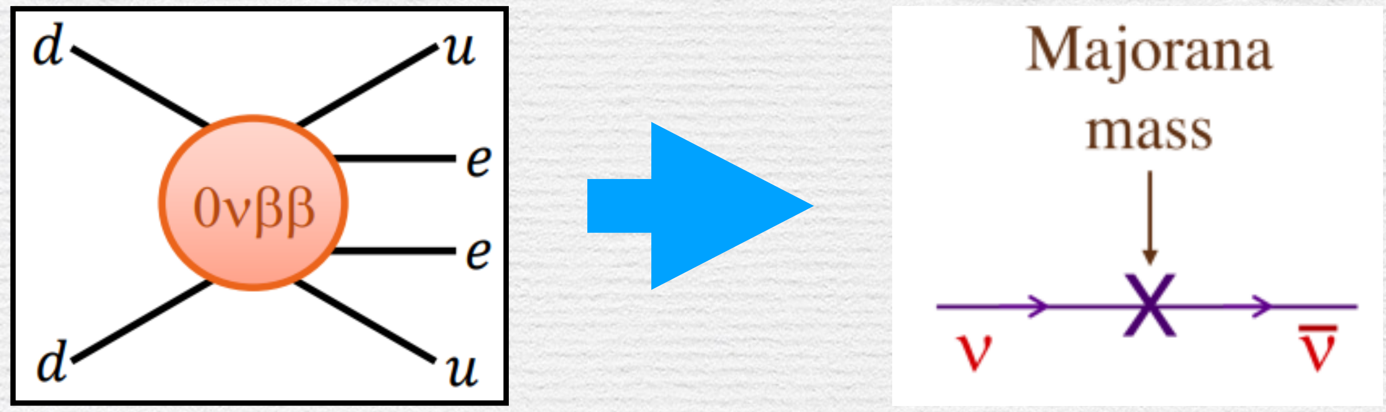
$$T^{0\nu}_{1/2} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\text{eV}}{\langle m_{\beta\beta}\rangle}\right)^2\,\text{y}$$

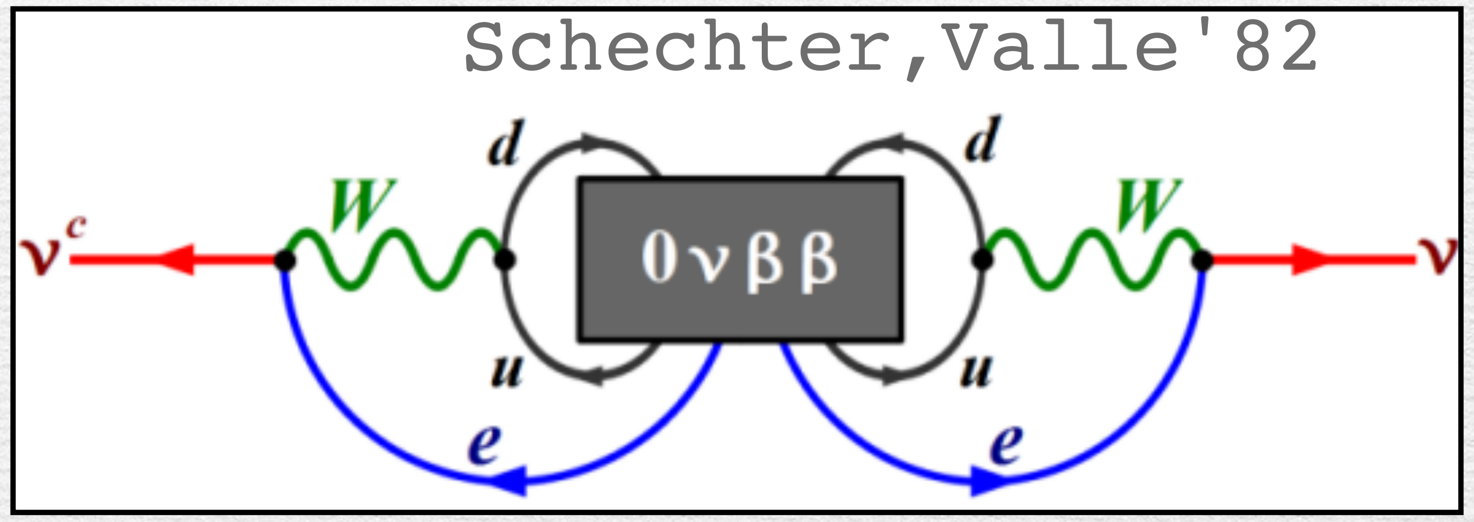
Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)

Graf, Deppisch, Iachello, Kotila (2018)++

Effective mass

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

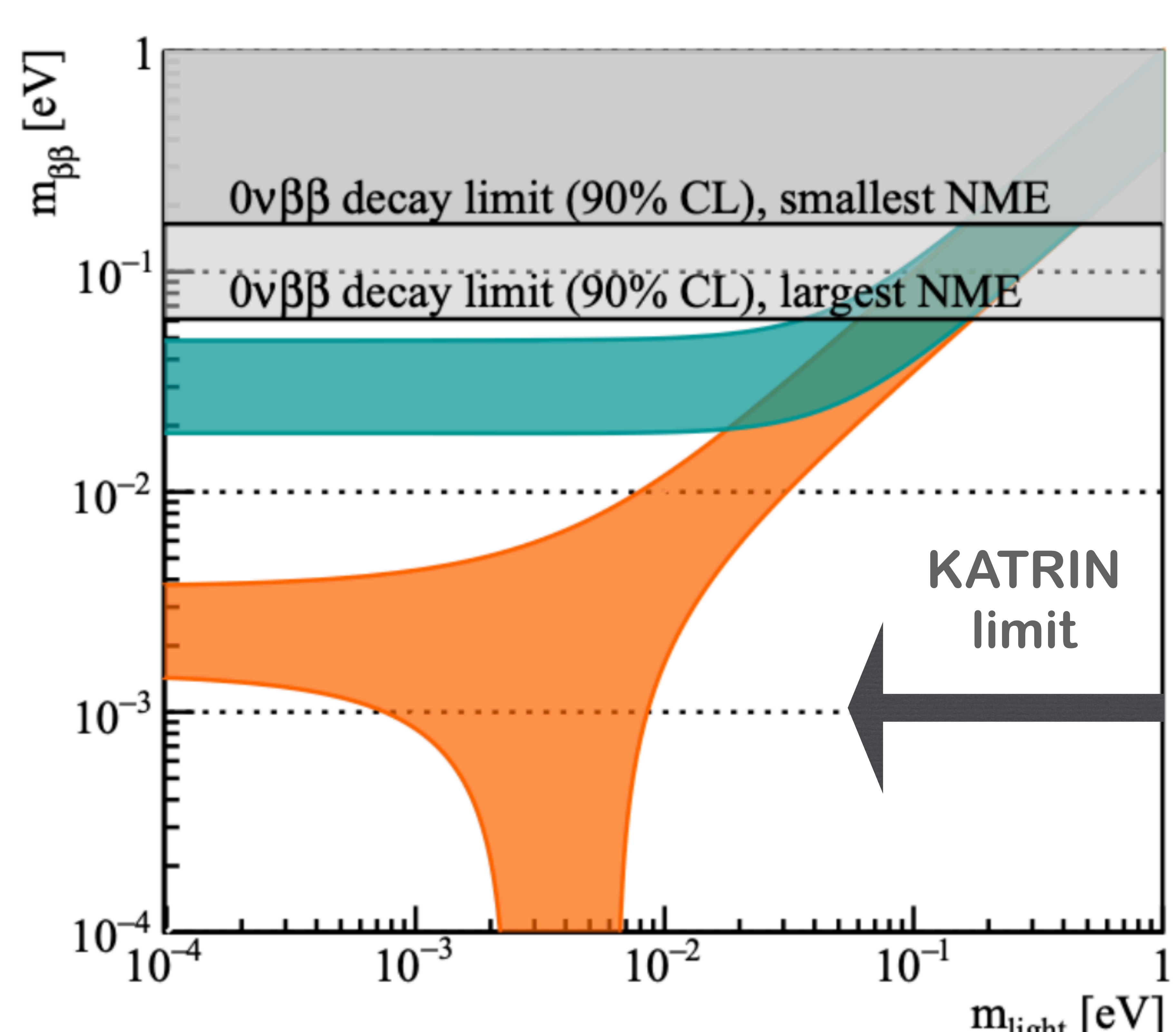




Many experiments: KamLAND-Zen, LEGEND, CUORE, NEMO-3, ...

Main source of uncertainty: Nuclear Matrix elements!

- **Non-relativistic expansion or χ-EFT**
- **Many body problem: isotope and operator dependent**
- **Different nuclear models**

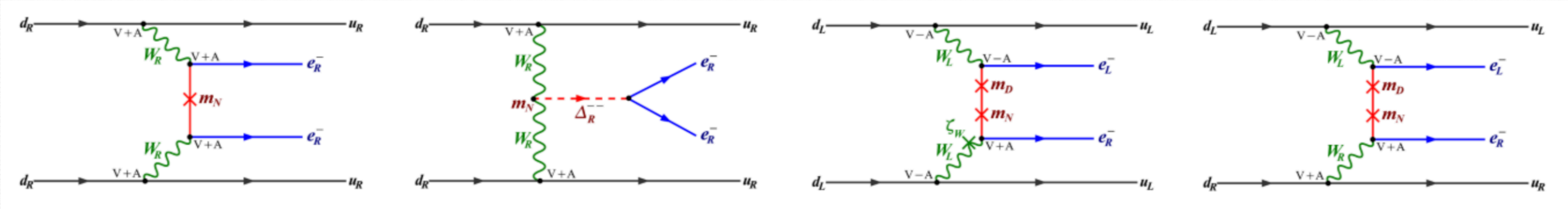


Rev. Mod. Phys. 95, 025002 (2023)

Neutrinoless double beta decay

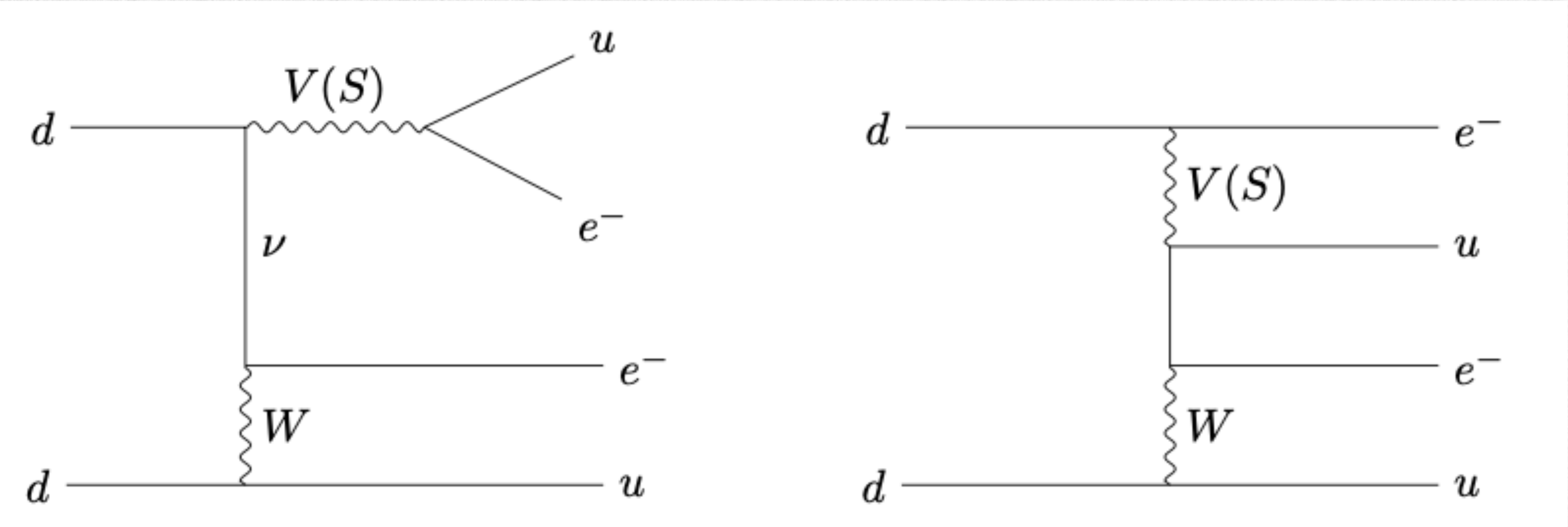
Many new physics scenarios can be responsible:

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:



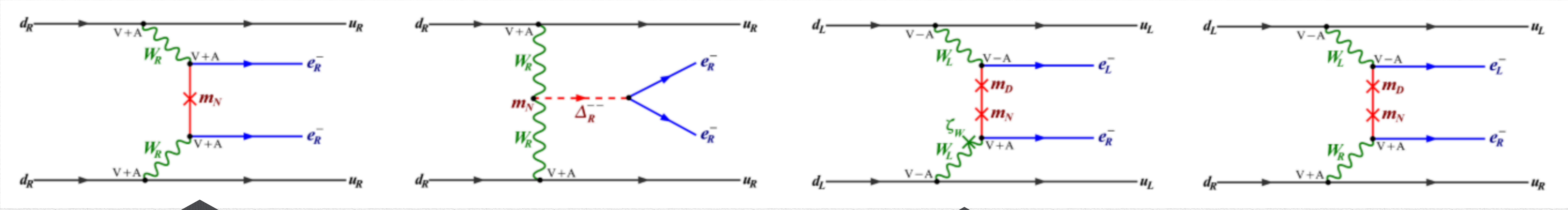
EFT approach helps!

RPV SUSY, Extra Dimensions, ++

Neutrinoless double beta decay

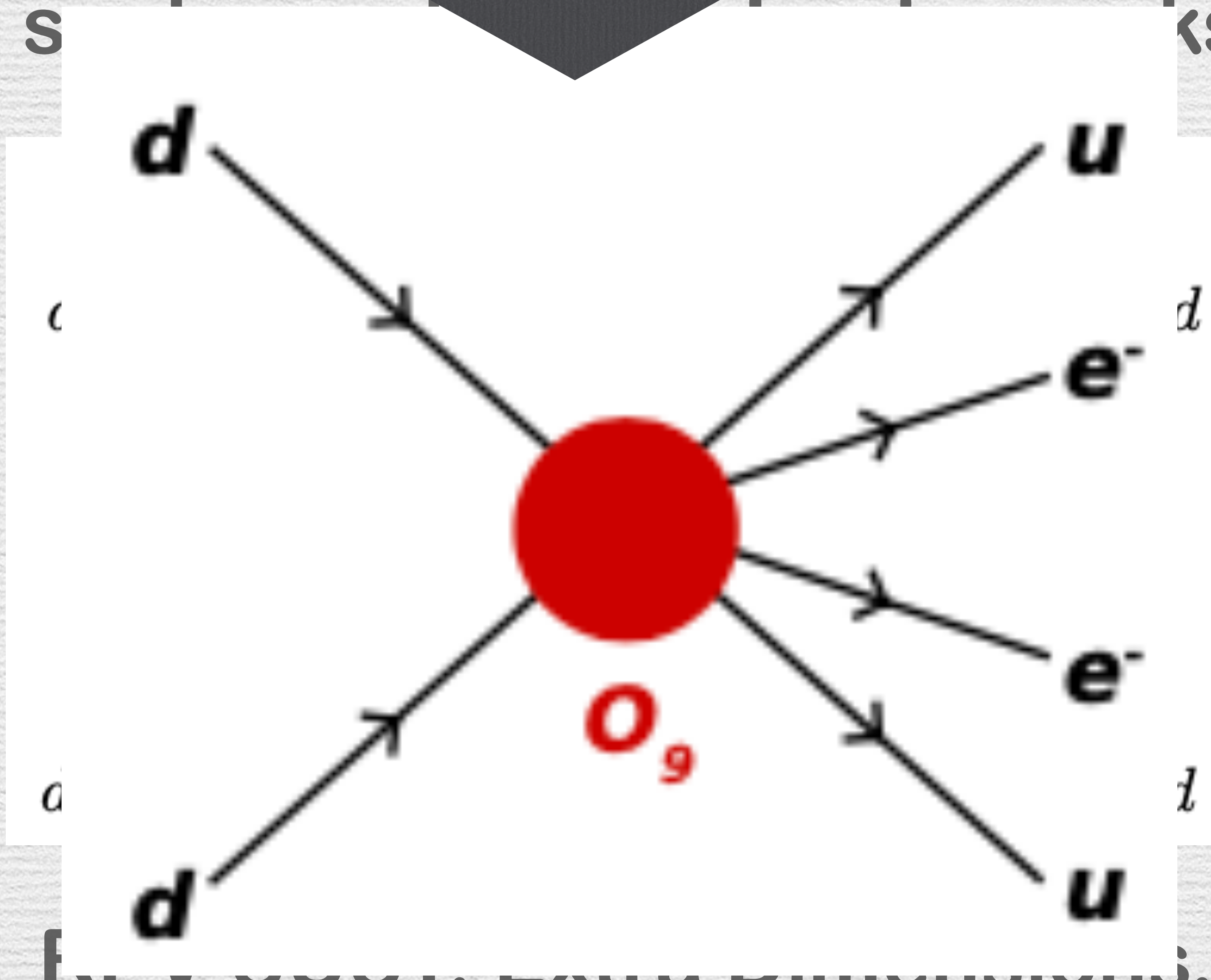
Many new physics scenarios can be responsible:

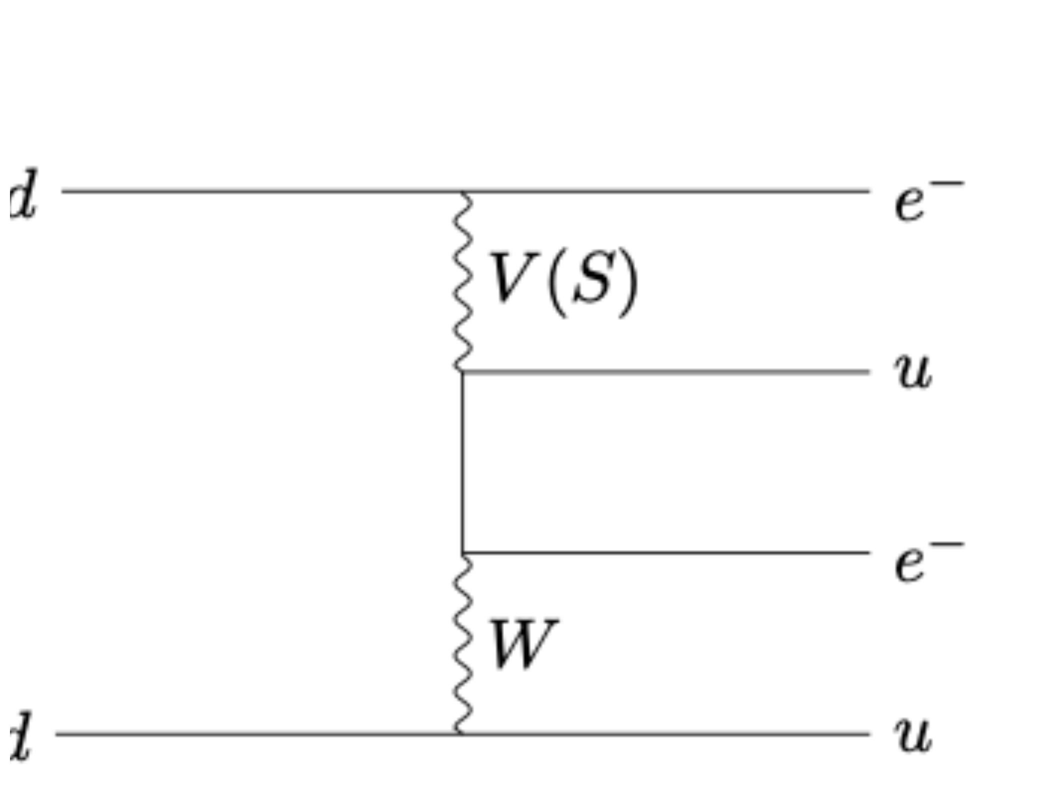
Left-Right Symmetric Model : $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

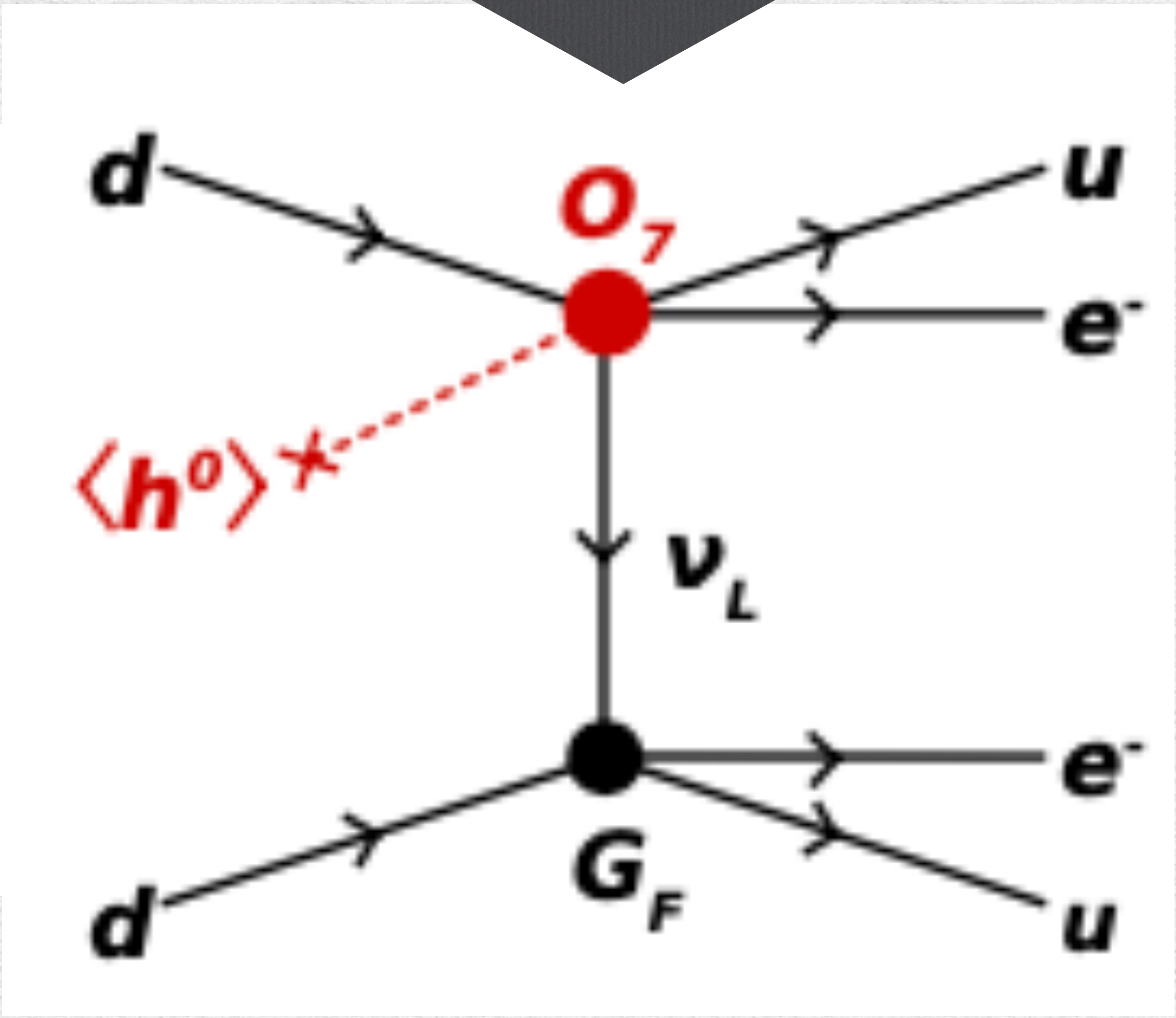


Deppisch, Hirsch, Päs ‘12

s ... ks:







... , ++

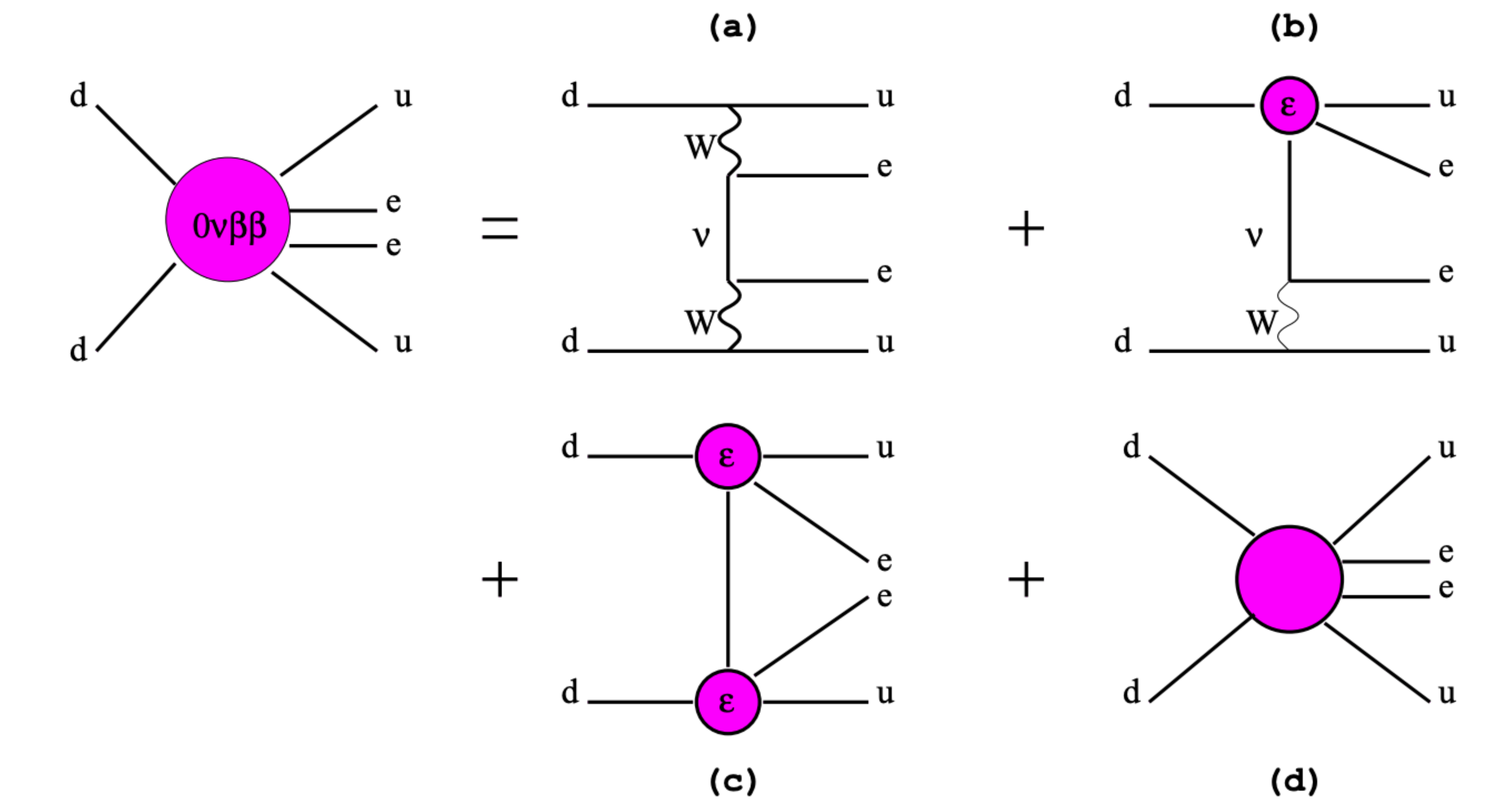
Neutrinoless double beta decay: EFT approach

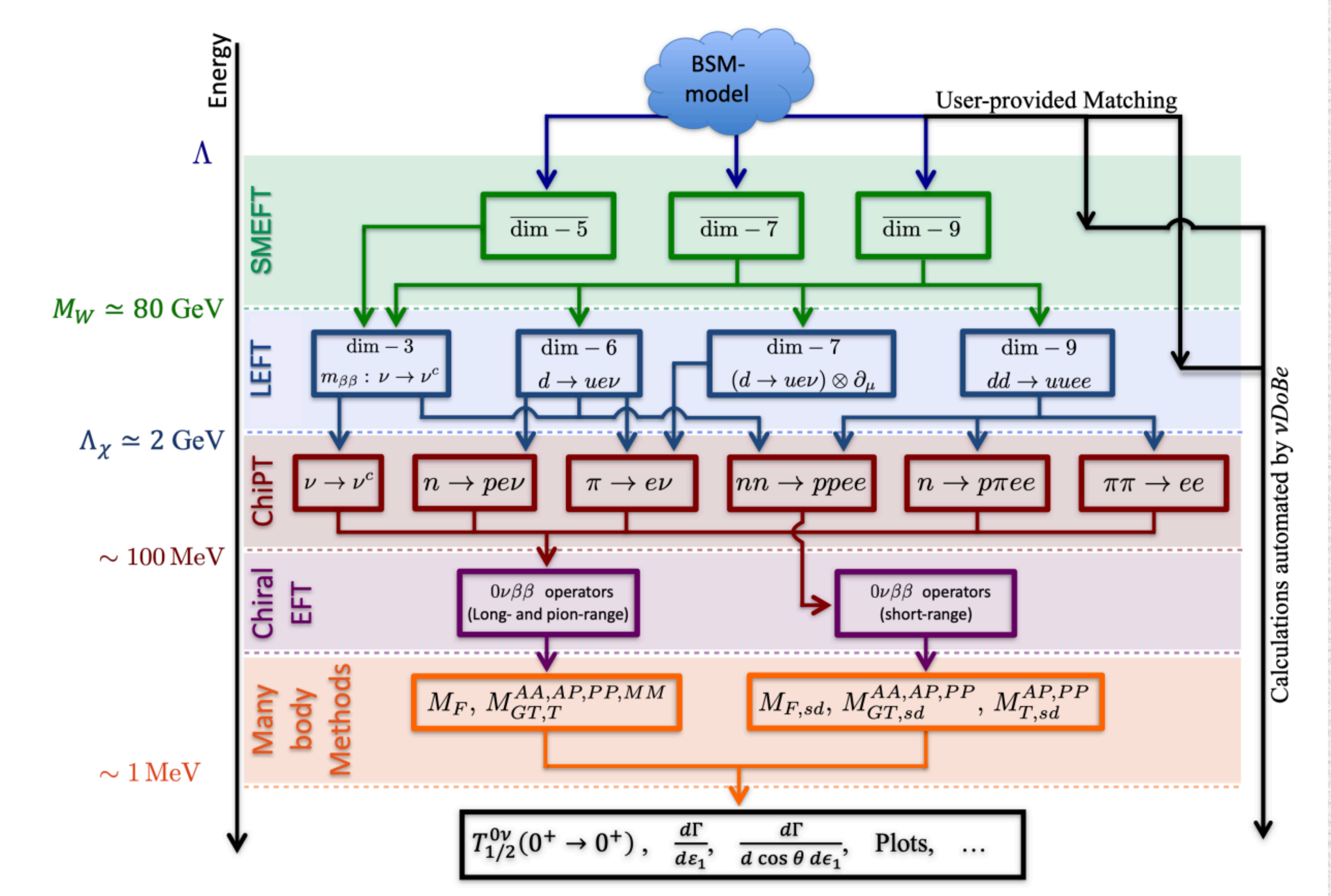
Start from SMEFT and match to LEFT:

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

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

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





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

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

LEFT Wilson Coefficient	Value	SMEFT Wilson Coefficient	Value [TeV^{-3}]	Λ_{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

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

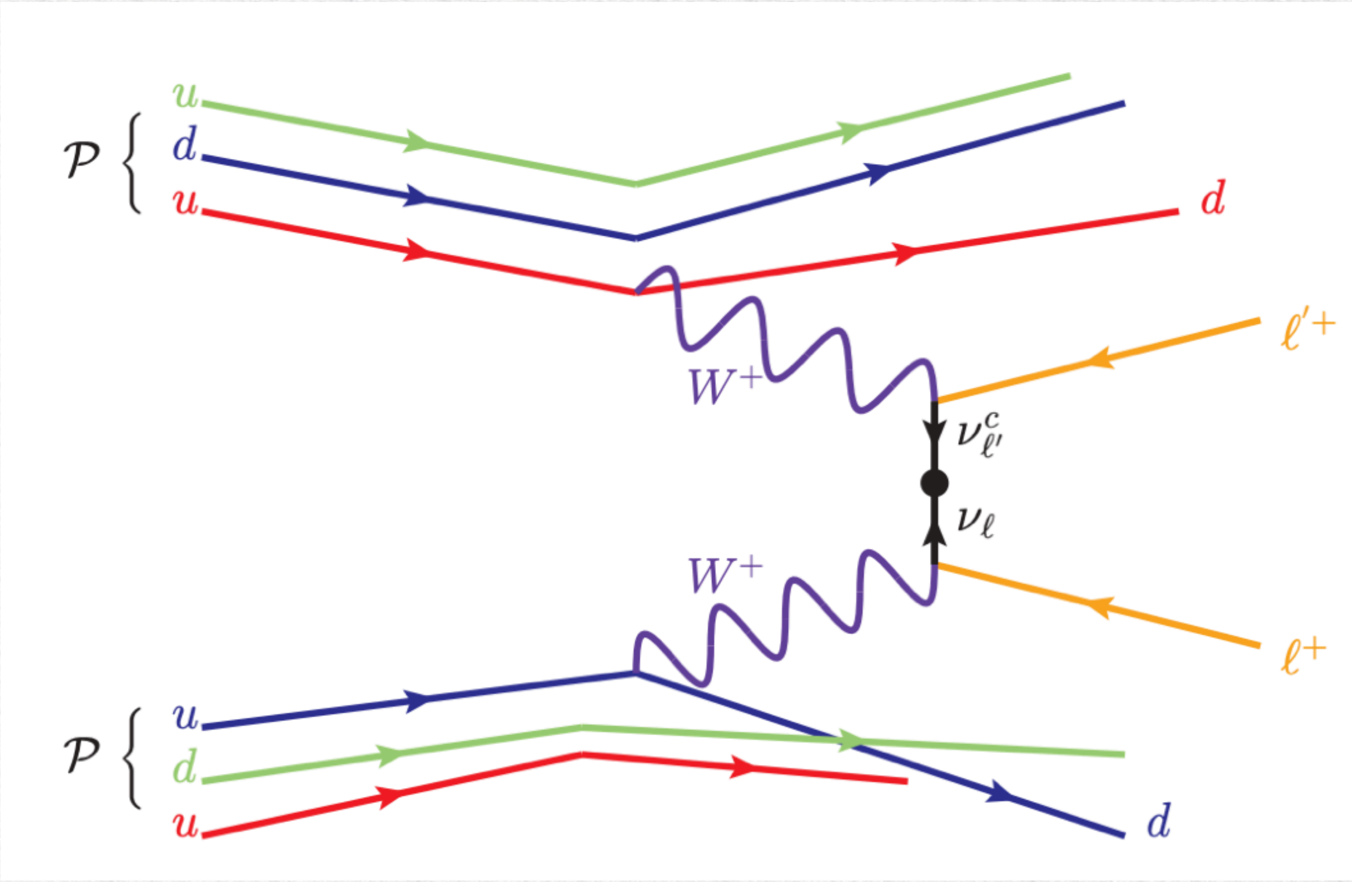
Assumption:

single LEFT operator dominance*

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

SMEFT &
LNV Direct Collider Searches

LNV SMEFT at Colliders



Dim-5: Weinberg operator

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

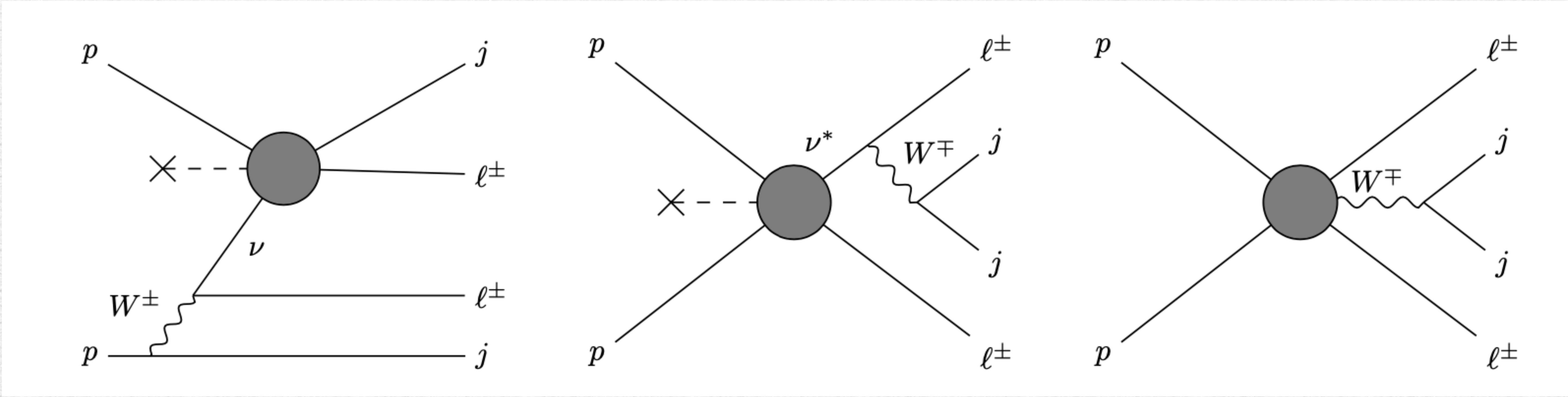
100TeV FCC : $\Lambda \lesssim 48$ TeV

Fuks, Neundorf, Peters, Ruiz, Saimpert '21

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

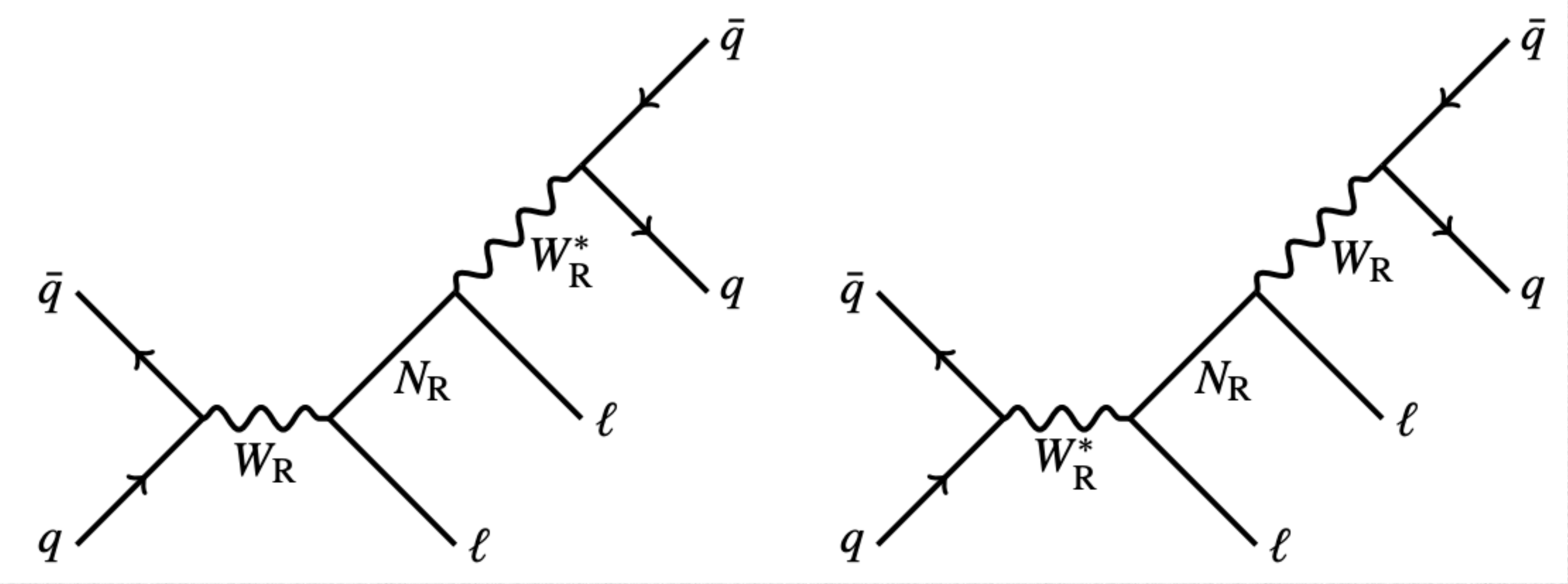
our main mode of interest:

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



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

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

Major Caveats:

(i) validity of EFT (ii) resonant production

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

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

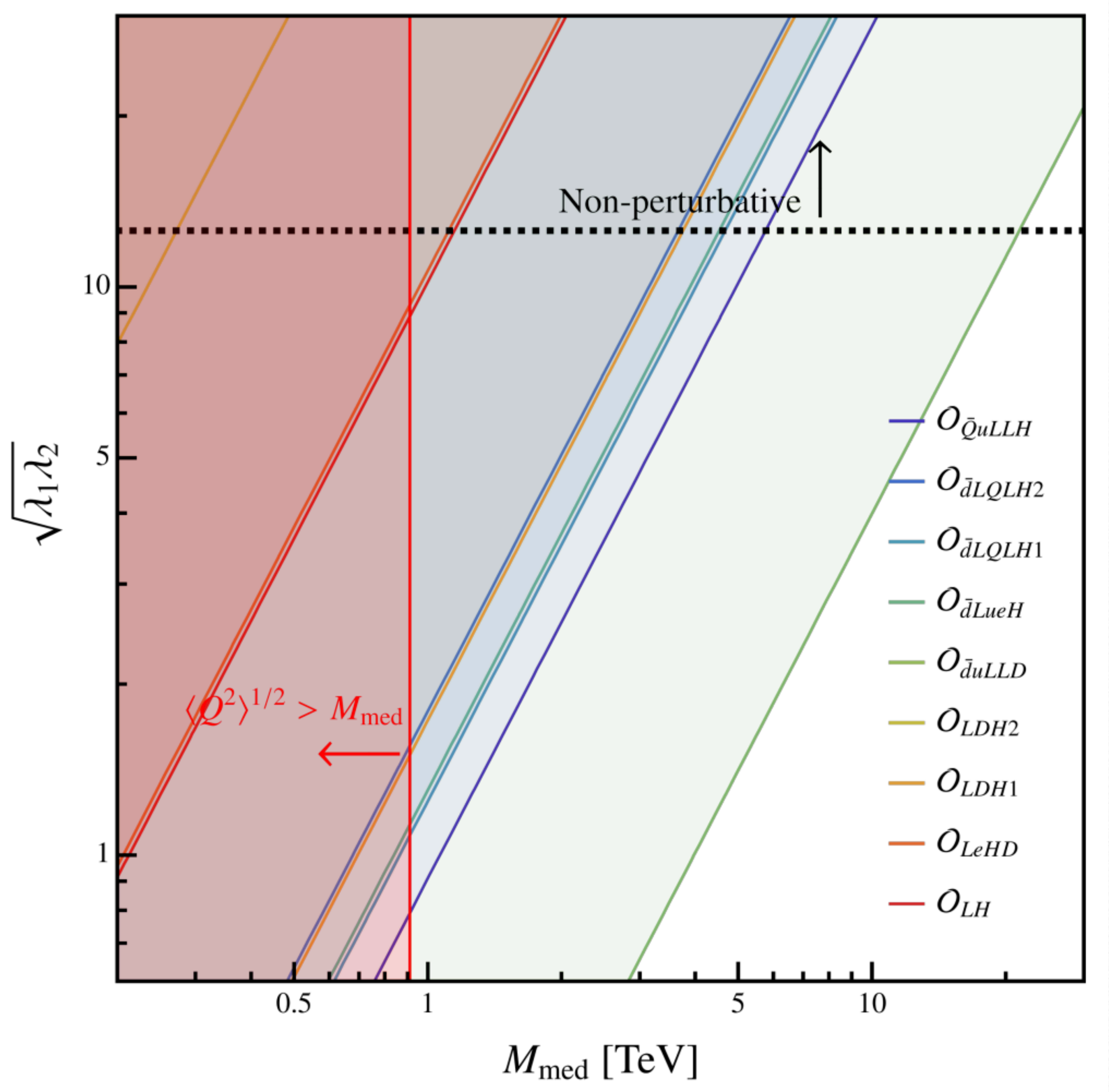
Avg. momentum exchange:

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

$Q_0 \rightarrow$ Min final state invariant mass : 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 $M_{\rm med} > Q_{\rm tr}$



Validity of the EFT approach for Direct LNV Collider searches

Resonant production is not captured by the EFT approach

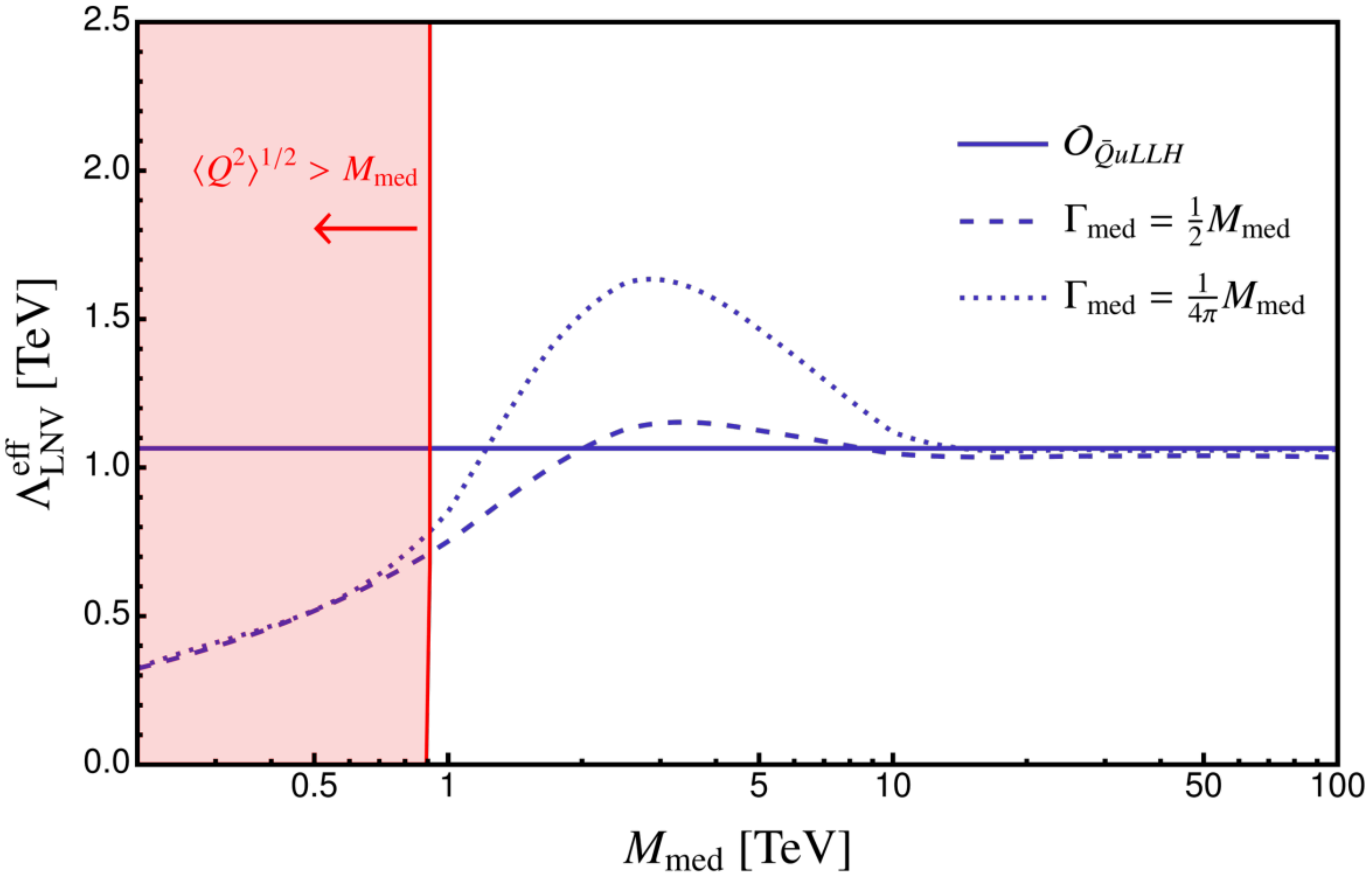
$$\mathcal{L} \supset \lambda_1 \bar{d}_L u_R \chi^* + \lambda_2 \bar{e}_L^c \nu_L \chi + \text{h.c.}$$

$$\frac{\lambda_1 \lambda_2}{M_{\text{med}}^2} = \frac{v}{(\Lambda_{\text{LNV}}^{\text{eff}})^3}$$

For small mediator widths:

EFT approach underestimates the limits

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



Many Other probes!

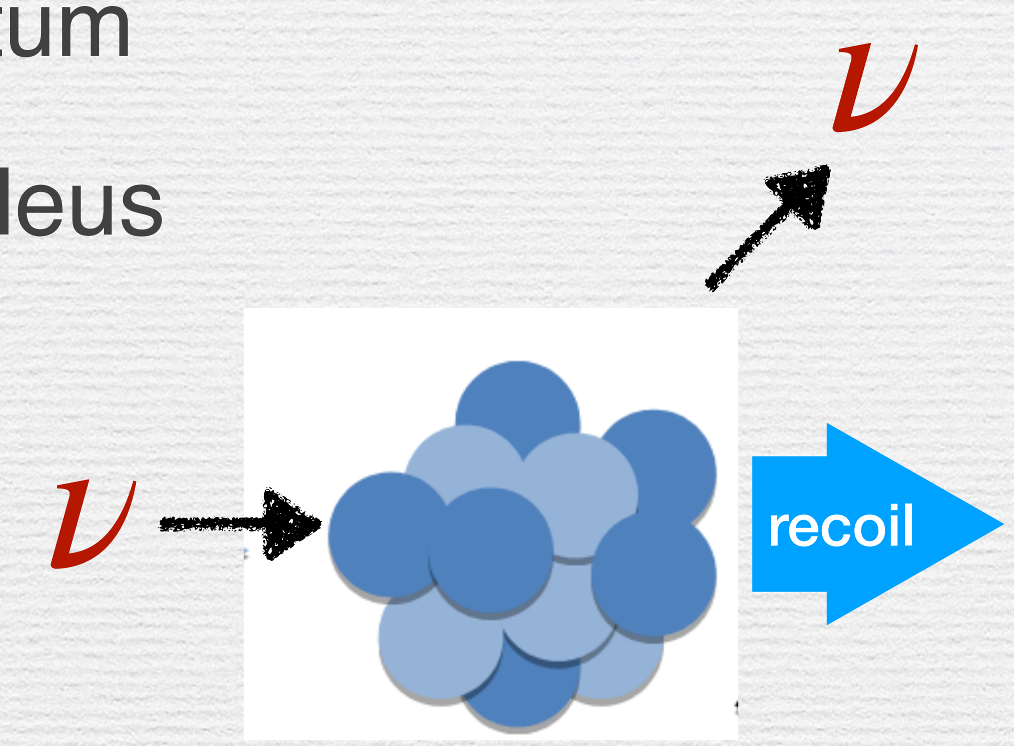
Neutral Current LNV@ low energy

CEνNS experiments

First observation: Akimov et al. Science‘17

Neutrino scatters with low-momentum transfer elastically from entire nucleus

$$E_\nu \lesssim \frac{hc}{R_N} \sim \mathcal{O}(10\ \text{MeV})$$



The nuclear recoil energy: $E_r^{\text{max}} = \frac{2E_\nu^2}{M_A} \sim \mathcal{O}(\text{KeV})$

SM allowed but hard to observe due to tiny recoil energy!

GNI:

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

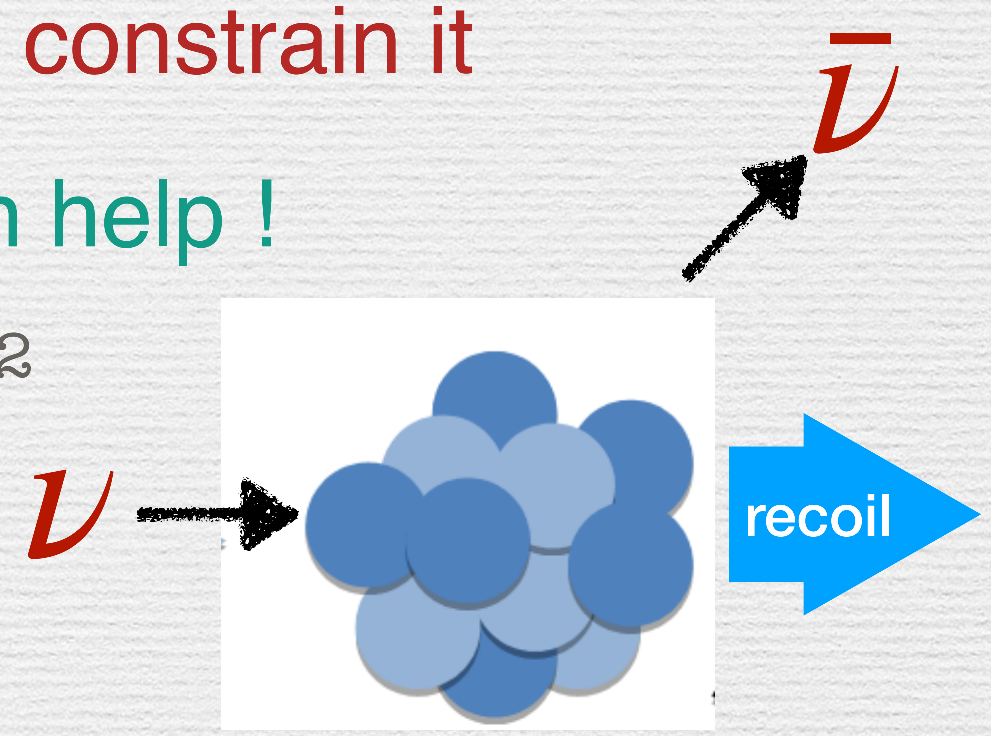
LNV

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

Can’t directly discover LNV but can constrain it

Distributions with γ in final state can help !

Bolton, Deppisch, Fridell, Harz, **CH**, Kulkarni ‘22



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

Changed Current LNV NSI @ LBL Oscillation experiments

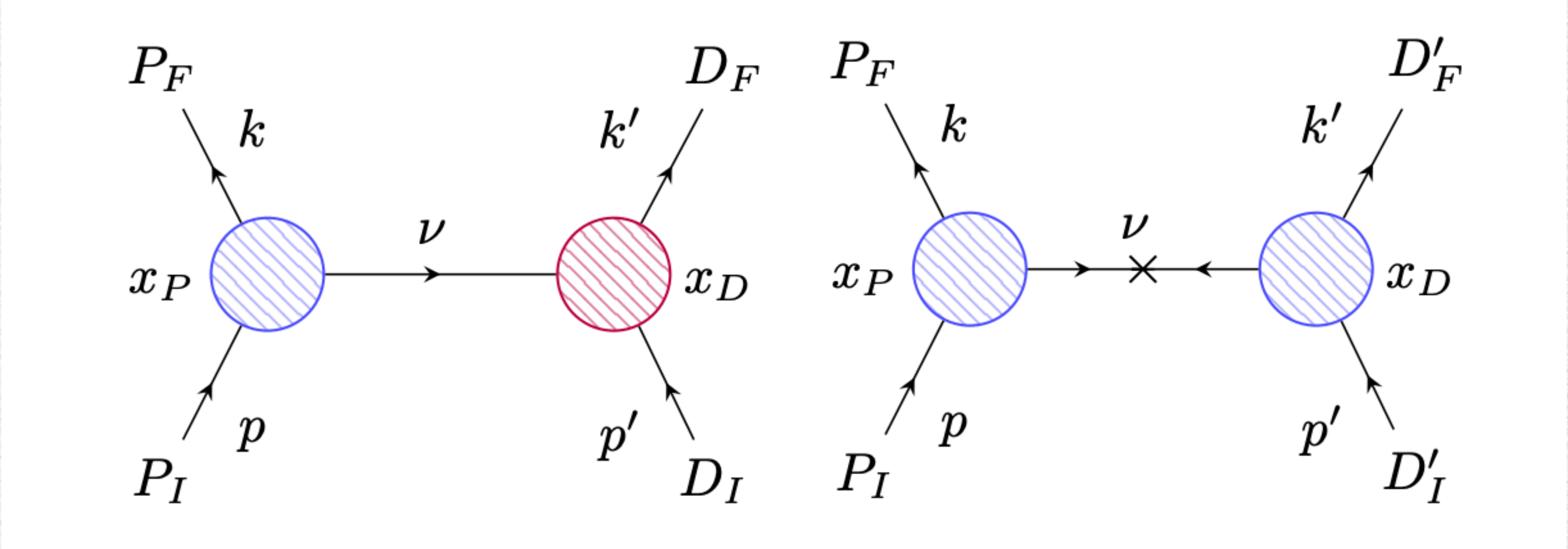
Bolton, Deppisch'19

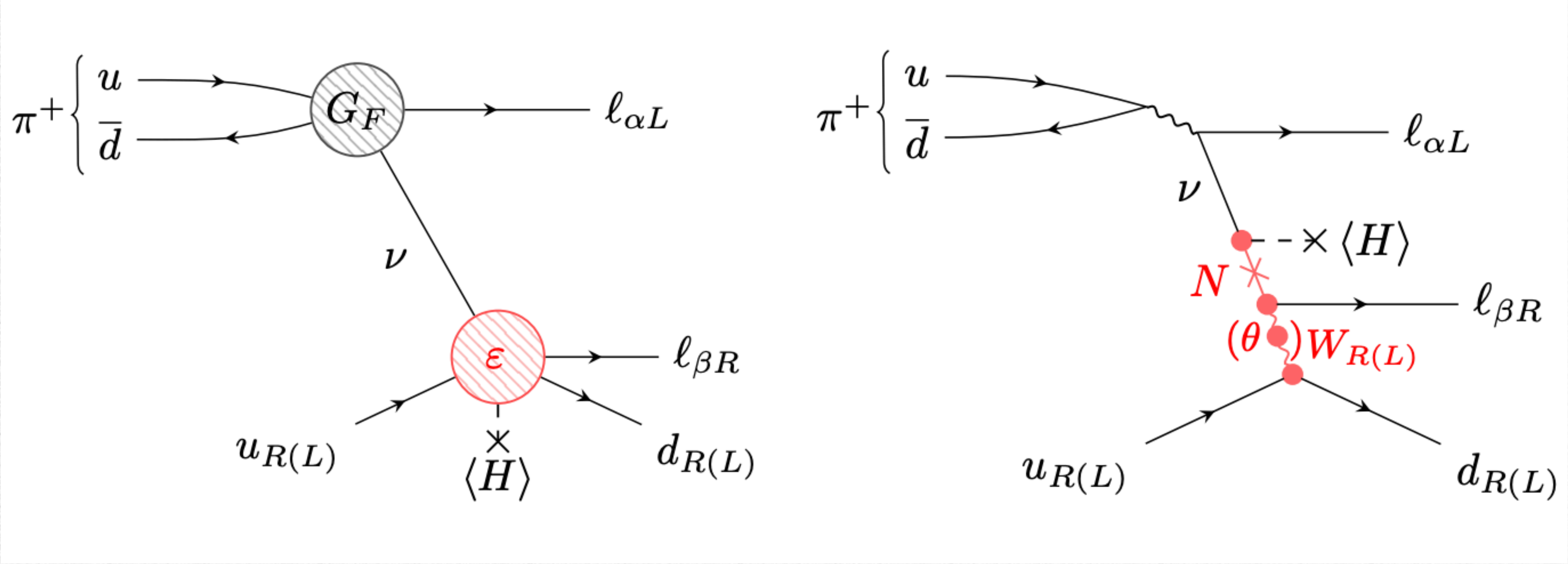
Production charge blind

Detection sensitive to outgoing lepton charge

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

$$S_{\mu\mu} \approx \frac{\int dE_{\mathbf{q}} \sum_{\rho,\sigma} \frac{d\Gamma_{\nu_\mu}}{dE_{\mathbf{q}}} \cdot P^{(\rho,\sigma)}_{\nu_\mu \to \bar\nu_\mu} \cdot \sigma_{\bar\nu_\mu}}{\int dE_{\mathbf{q}} \sum_{\rho,\sigma} \frac{d\Gamma_{\nu_\mu}}{dE_{\mathbf{q}}} \cdot P^{(\rho,\sigma)}_{\nu_\mu \to \nu_\mu} \cdot \sigma_{\nu_\mu}}$$





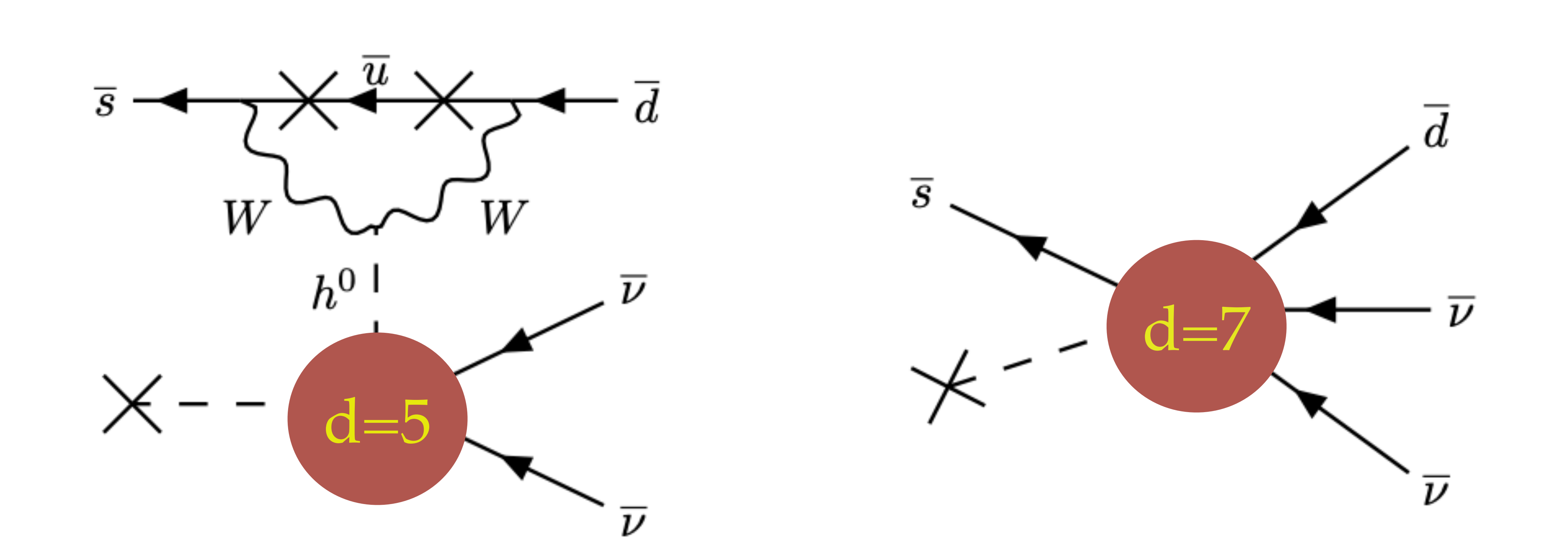
$$\mathcal{L}^{d=6}_{\mathrm{LEFT}} \supset \frac{4G_F}{\sqrt2}\left[c^{V,prst}_{du\nu e;LR}(\overline{d_{Lp}}\gamma_\mu u_{Lr})(\overline{\nu^c_s}\gamma^\mu e_{Rt}) + c^{V,prst}_{du\nu e;RR}(\overline{d_{Rp}}\gamma_\mu u_{Rr})(\overline{\nu^c_s}\gamma^\mu e_{Rt})\right]$$

$$\mathcal{L}^{d=6}_{\mathrm{LEFT}} = \frac{4G_F}{\sqrt2}\Big[c^{S,prst}_{du\nu e;LL}(\overline{d_{Rp}}u_{Lr})(\overline{\nu^c_s}e_{Lt}) + c^{S,prst}_{du\nu e;RL}(\overline{d_{Lp}}u_{Rr})(\overline{\nu^c_s}e_{Lt}) + c^{T,prst}_{du\nu e;LL}(\overline{d_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}e_{Lt})\Big] .$$

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

LNV dim-7 SMEFT @ Rare meson and τ decays

Weak constraints from $\tau^\pm \to \ell^\mp_\alpha P^\pm_i P^\pm_j$ $K^+ \to \pi^- \ell^+ \ell^+$



$$M \to M' \nu\nu$$

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

LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV^{-3}]	Λ_{NP} [TeV]	Observable
Current Bound				
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	1.3×10^{-6}	4.8×10^{-4}	12.8	$K_L \to \nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	2.5×10^{-7}	9.6×10^{-5}	21.8	$K^+ \to \pi^+ \nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	2.6×10^{-7}	9.9×10^{-5}	21.6	$K^0 \to \pi^0 \nu\nu$
Future Sensitivity				
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	8.4×10^{-8}	3.2×10^{-5}	31.5	$K^+ \to \pi^+ \nu\nu$
$c^{S,ds\gamma\gamma}_{d\nu;LL}$	1.4×10^{-7}	5.2×10^{-5}	26.8	$K^0 \to \pi^0 \nu\nu$

LEFT Wilson Coefficient	Value	$C_{\bar{d}LQLH1}$ [TeV^{-3}]	Λ_{NP} [TeV]	Observable
Current Bound				
$c^{S,sb\gamma\gamma}_{d\nu;LL}$	3.6×10^{-4}	0.14	1.9	$B \to K^{(*)} \nu\nu$
$c^{S,sb\gamma\delta}_{d\nu;LL}$	2.7×10^{-4}	0.21	1.7	$B \to K^{(*)} \nu\nu$
$c^{T,sb\gamma\delta}_{d\nu;LL}$	0.6×10^{-4}	0.18	1.75	$B \to K^* \nu\nu$
Future Sensitivity (50 ab^{-1})				
$c^{S,sb\gamma\gamma}_{d\nu;LL}$	0.6×10^{-4}	0.02	3.5	$B \to K \nu\nu$
$c^{S,sb\gamma\delta}_{d\nu;LL}$	0.6×10^{-4}	0.05	2.8	$B \to K \nu\nu$
$c^{T,sb\gamma\delta}_{d\nu;LL}$	0.3×10^{-4}	0.08	2.3	$B \to K^* \nu\nu$

Assumptions:
1. single LEFT operator dominance*
2. lepton flavour universality**

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:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\Big\{ c^{S,\mu ee\mu}_{e\nu;LL}\,(\overline{\mu_R} e_L)\,(\overline{\nu^c_e}\nu_\mu) + c^{S,e\mu e\mu}_{e\nu;LL}\,(\overline{e_R}\mu_L)\,(\overline{\nu^c_e}\nu_\mu) + c^{T,\mu ee\mu}_{e\nu;LL}\,(\overline{\mu_R}\sigma_{\mu\nu} e_L)\,(\overline{\nu^c_e}\sigma^{\mu\nu}\nu_\mu) + c^{T,e\mu e\mu}_{e\nu;LL}\,(\overline{e_R}\sigma_{\mu\nu}\mu_L)\,(\overline{\nu^c_e}\sigma^{\mu\nu}\nu_\mu)\Big\} + \text{h.c.}$$

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

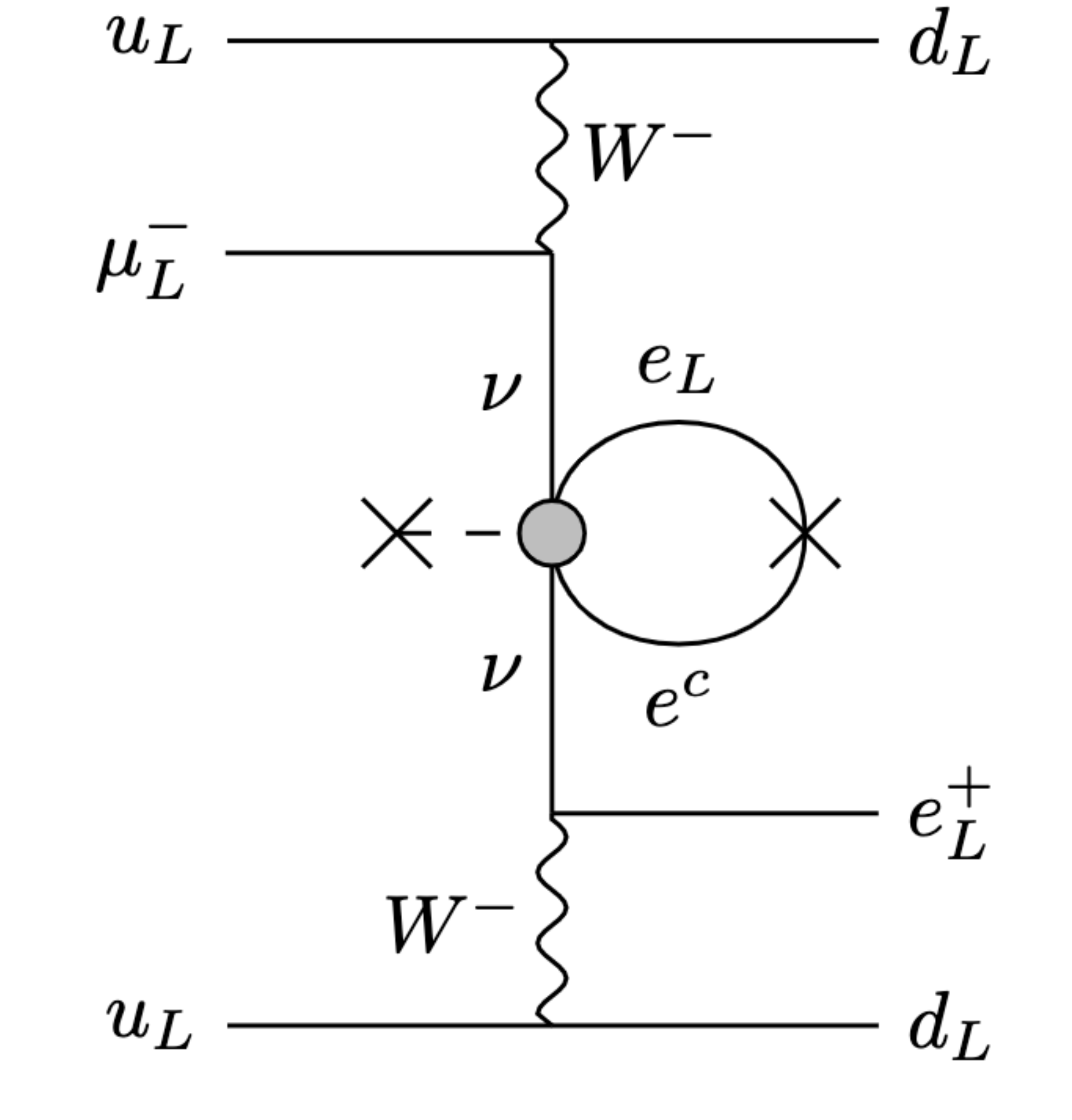
CC process $p\,\bar{\nu}_e \to e^+ n$ was used to identify $\bar{\nu}_e$ B. Armbruster et al PRL '03

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

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

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

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



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 Gouvêa et al ‘16

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

Small contributions for dim-7 SMEFT

Neutrino magnetic moment

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

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

Solar: Borexino

Reactor: GEMMA, TEXONO, CONUS

Accelerator: LSND, DUNE

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

$\Lambda > 10$ TeV

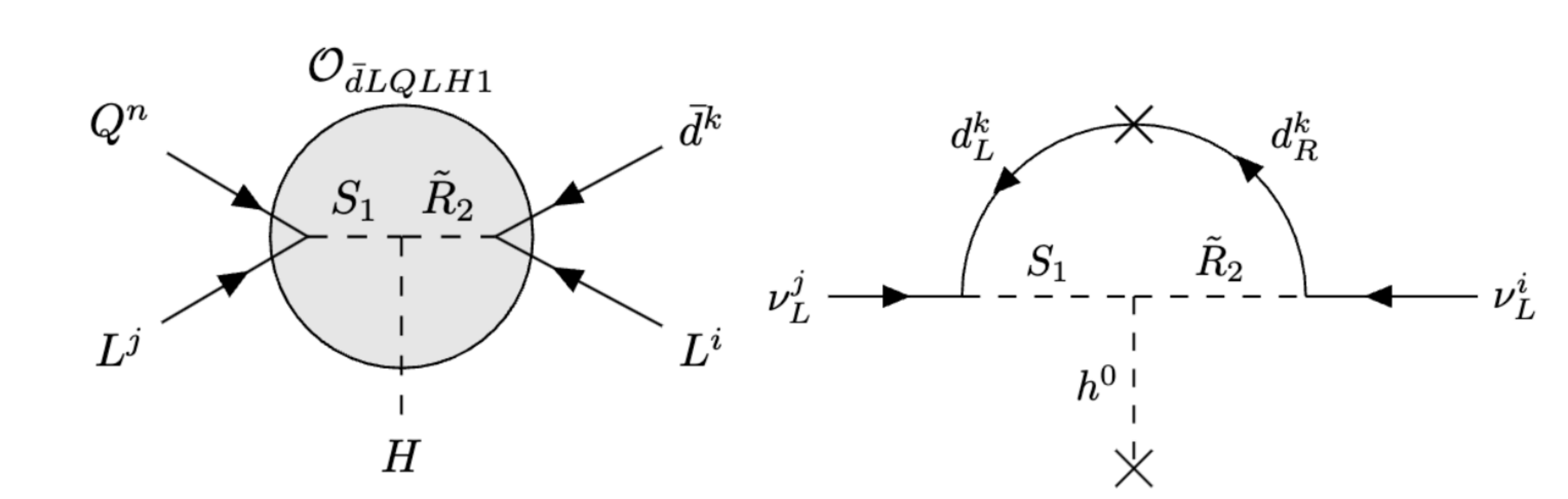
Competitive with $0\nu\beta\beta$

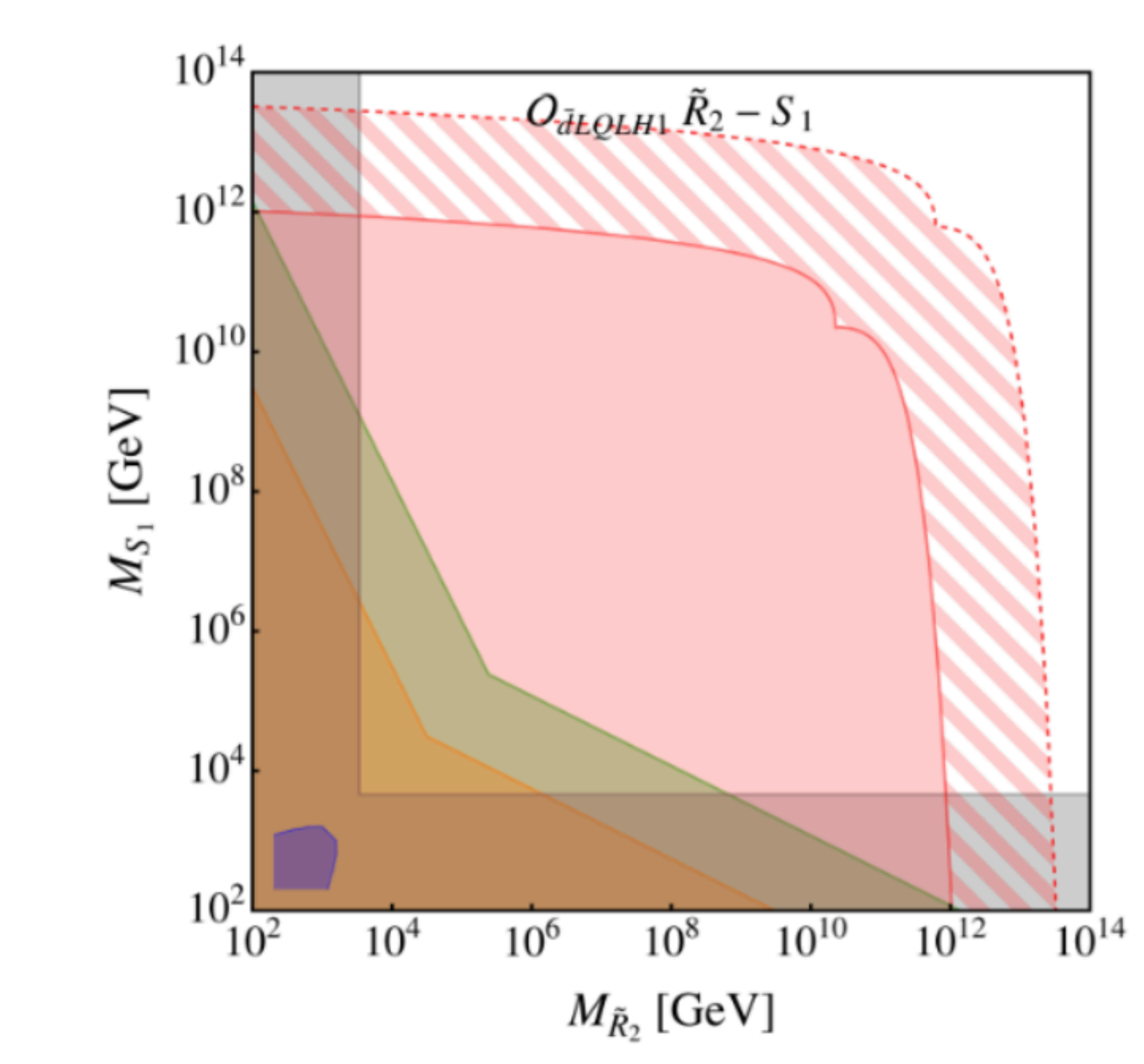
Constraints from Light Neutrino Masses

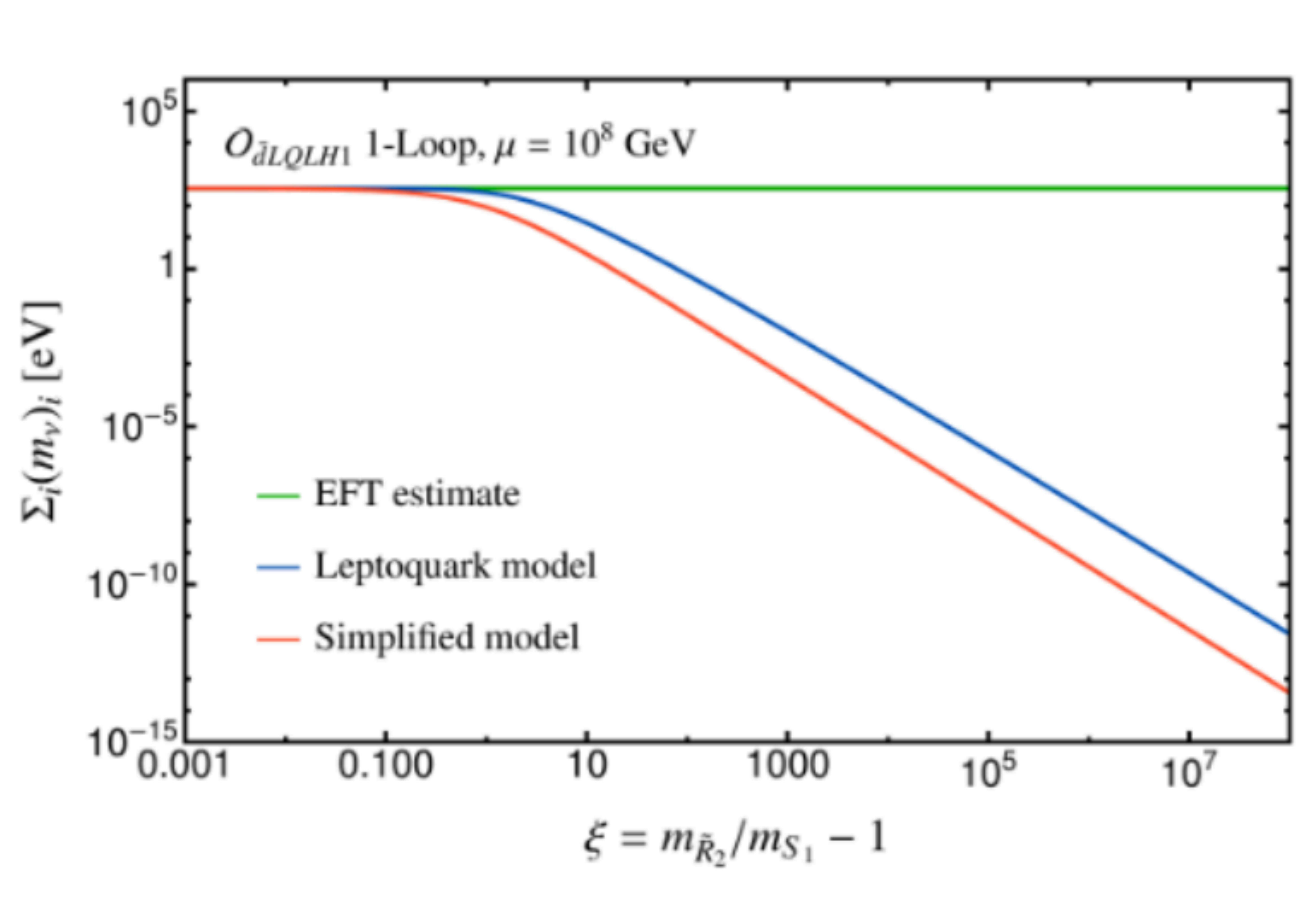
Light neutrino mass: UV example

Limitation of cut-off regularization:

hierarchy between NP scales







Light neutrino mass 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 $\Lambda \to M_W$

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

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

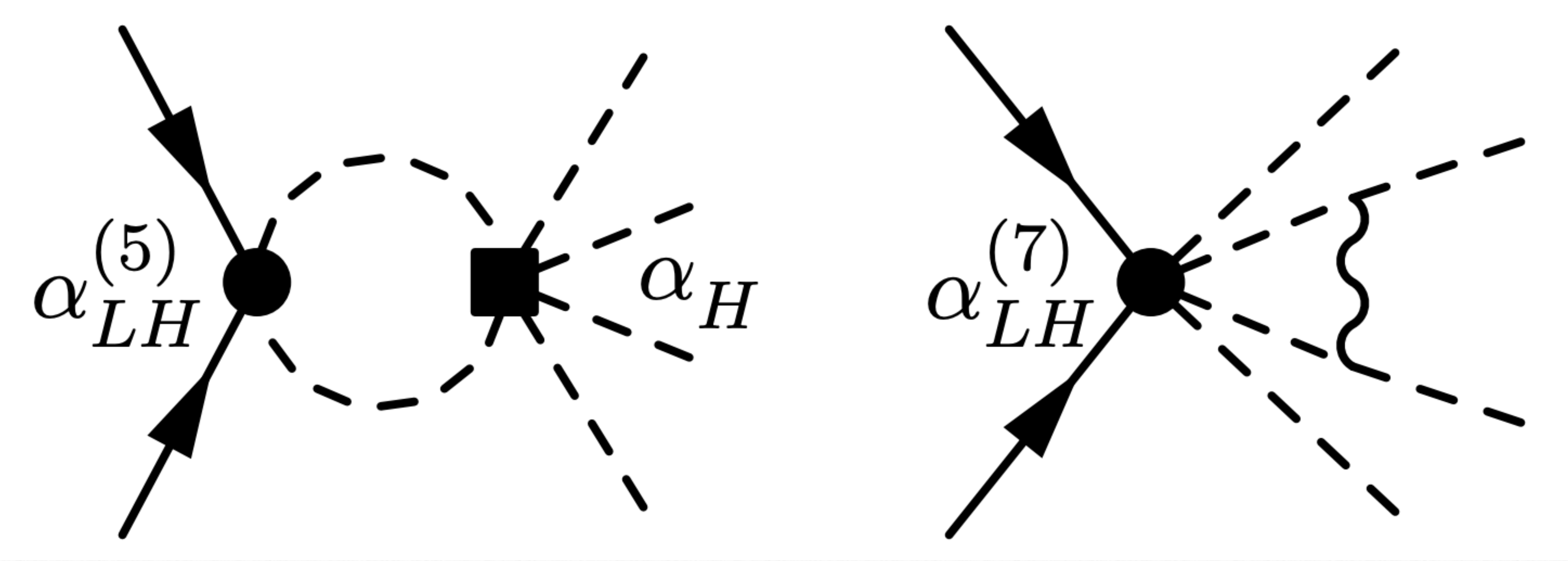
$C_{LeHD}:\ \Lambda > 6\,\mathrm{TeV}$ $\quad C_{LHW}:\ \Lambda > 460\,\mathrm{TeV}$

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

Dim reg provides a robust approach

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

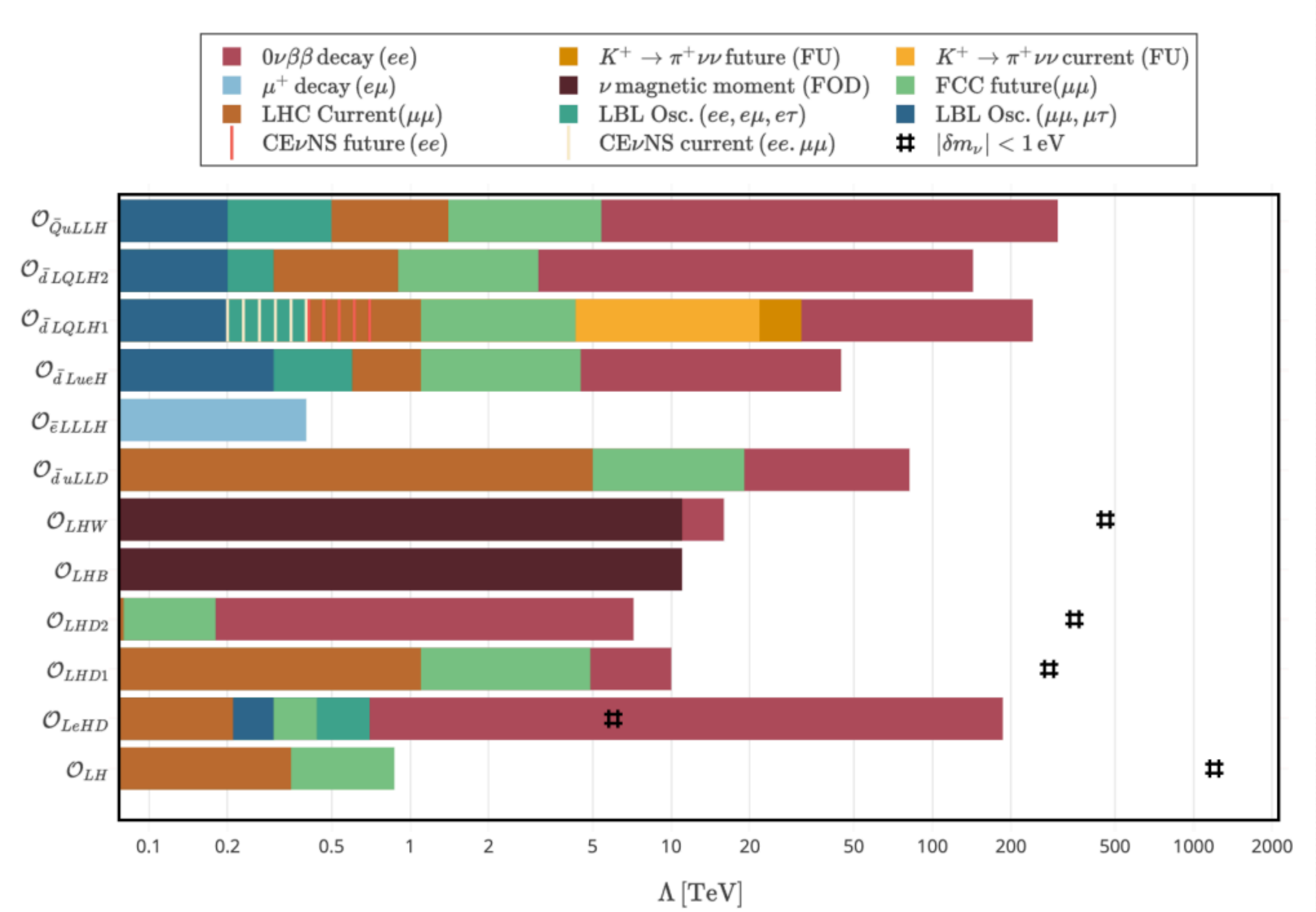
$$\mu\frac{\mathrm{d}C_7^i}{\mathrm{d}\mu} = \gamma_{ij}^{(7,7)}C_7^j + \gamma_i^{(7,5)}C_5C_5C_5 + \gamma_{ij}^{(7,6)}C_5C_6^j$$



Chala, Titov '21; Di Zhang '23,24 ++

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

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



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

Conclusions

Operator	Collider	$0\nu\beta\beta$	LBL Osc.	μ_ν	μ^+-decay	CEνNS	Meson decay
$\mathcal{O}_{LH}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LeHD}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{LHD1}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LHD2}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LHB}$	-	-	-	✓	-	✓	-
$\mathcal{O}_{LHW}$	-	✓	-	✓	-	✓	-
$\mathcal{O}_{\bar{d}uLLD}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{\bar{e}LLLH}$	-	-	-	-	✓	-	-
$\mathcal{O}_{\bar{d}LueH}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{d}LQLH1}$	✓	✓	✓	-	-	✓	✓
$\mathcal{O}_{\bar{d}LQLH2}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{Q}uLLH}$	✓	✓	✓	-	-	✓	-

EFTs provide robust frameworks to parametrize and constrain LNV BSM physics

The new physics scale hierarchy, EFT loop effects requires a more careful approach