Neutrinoless Double-Beta Decay in the Standard Model Effective Field Theory

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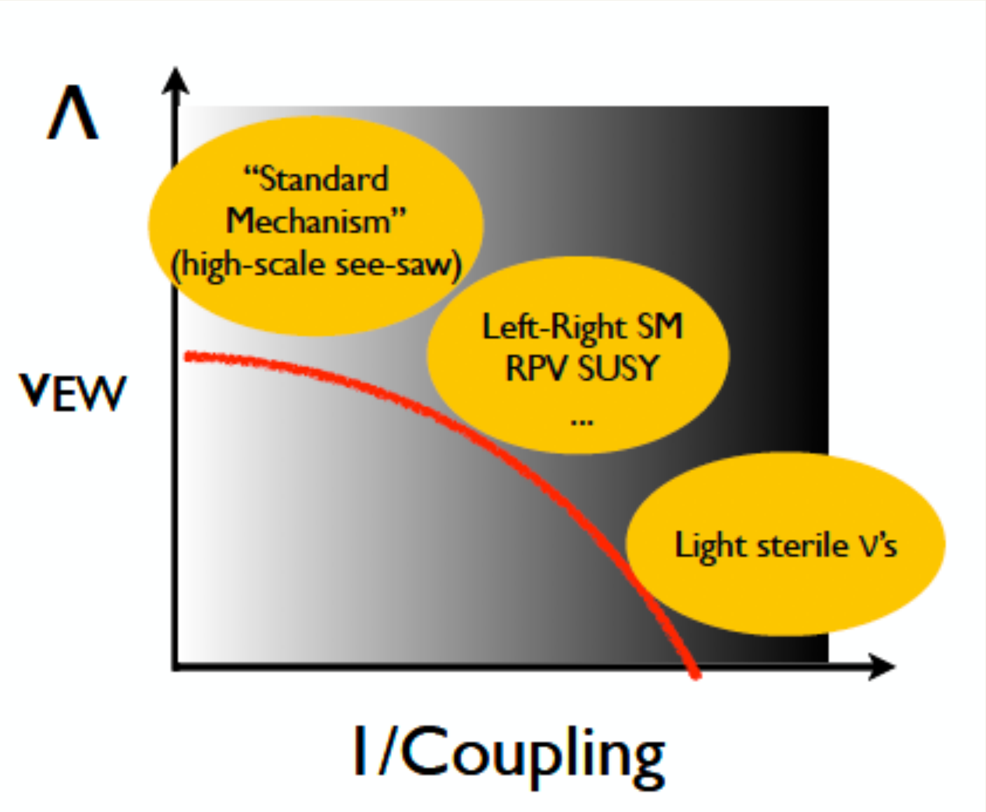
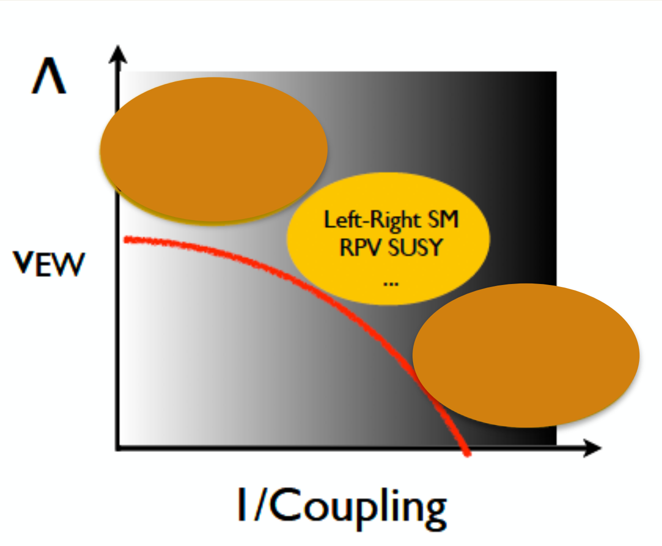
Non-standard mechanisms for 0vbb

- Vincenzo: ‘standard’ mechanism: exchange of light Majorana neutrinos.
- Appropriate for e.g. high-scale see-saw mechanism
- This talk focuses on LNV at lower scales

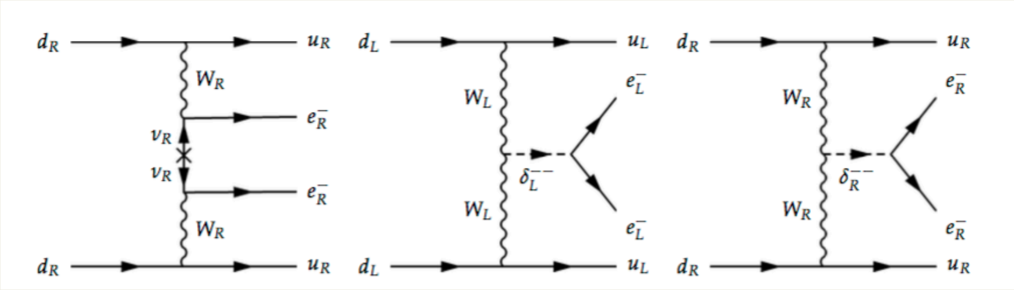


Picture from V. Cirigliano

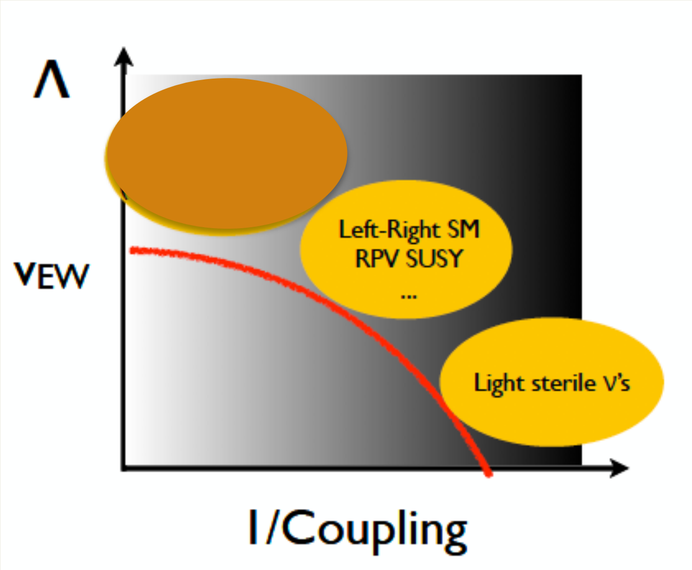
- **Part I: Non-standard mechanisms for 0vbb and the SM-EFT**

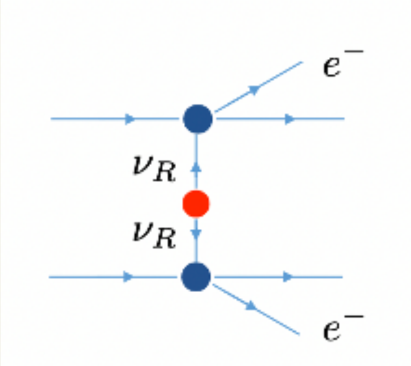


Thesis Duerr '10



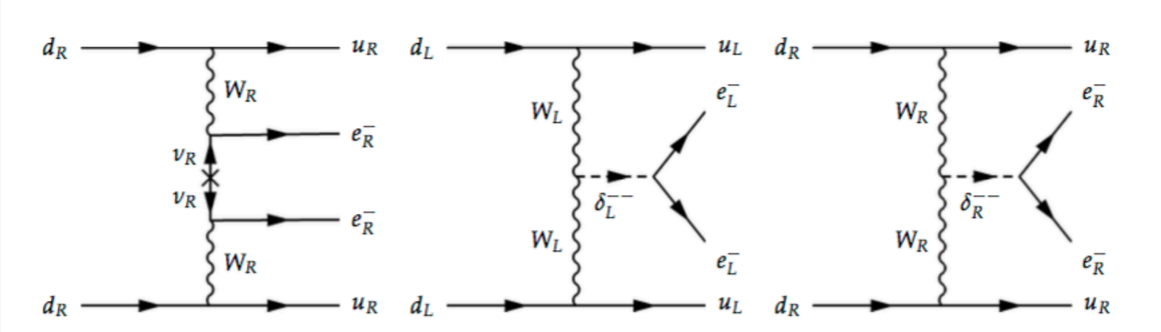
- Part II: Low-scale seesaw and 0vbb





Non-Standard interpretation

- **0νββ** does not have to be induced by light-neutrino exchange
- Many models induce lepton-number violation in different ways
- Example: in LR symmetric models (but also RPV SUSY, LQs, …)



Thesis Duerr '10

- No direct link to neutrino mass apart that nothing forbids Majorana masses

Applications of effective field theory

- **0νββ** is a low-energy nuclear process. Scale ~ m_π
- It cannot resolve UV `details'
- Suggest an **EFT** description of LNV.

See e.g.: Pas et al `99 `01, de Gouvea-Jenkins '07, Deppisch et al `12, de Gouvea-Vogel '13

- **At what scale do we start the EFT description ?**
- Could start around 1 GeV: build Lagrangian of ΔL=2 operators
- Symmetries: Lorentz, $U_{em}(1)$ x $SU_c(3)$, d.o.f light quarks, leptons, gluons

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \{ \epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu$$
$$+ \epsilon_6 J^\mu J^\nu j_{\mu\nu} + \epsilon_7 J J^{\mu\nu} j_{\mu\nu} + \epsilon_8 J_{\mu\alpha} J^{\nu\alpha} j^\mu_\nu \},$$

Pas et al `01

- Dimension-9 operators from products of hadronic currents, e.g.

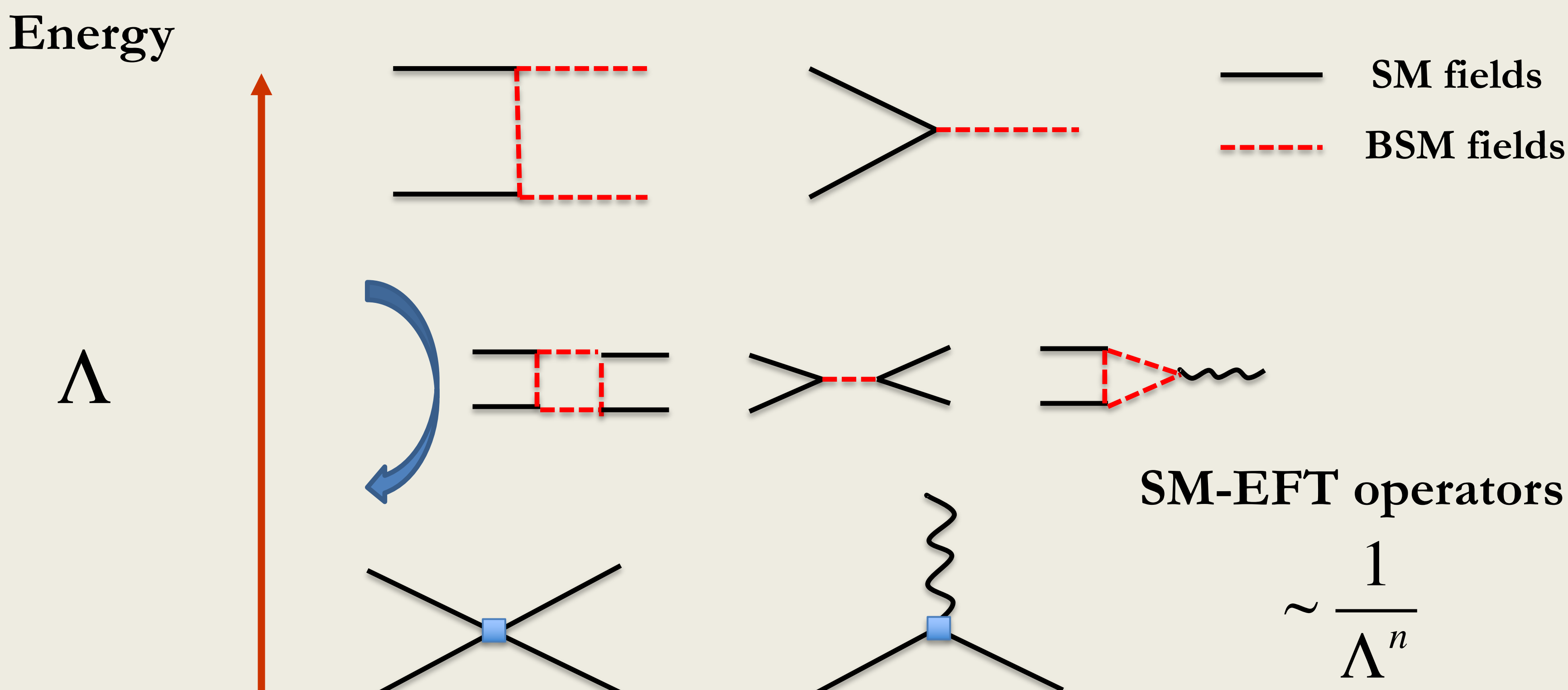
  $J^\mu = \bar{u}\gamma^\mu d$ and ΔL=2 currents, e.g. $j^\mu = \bar{e}\gamma^\mu e^c$

Standard Model EFT

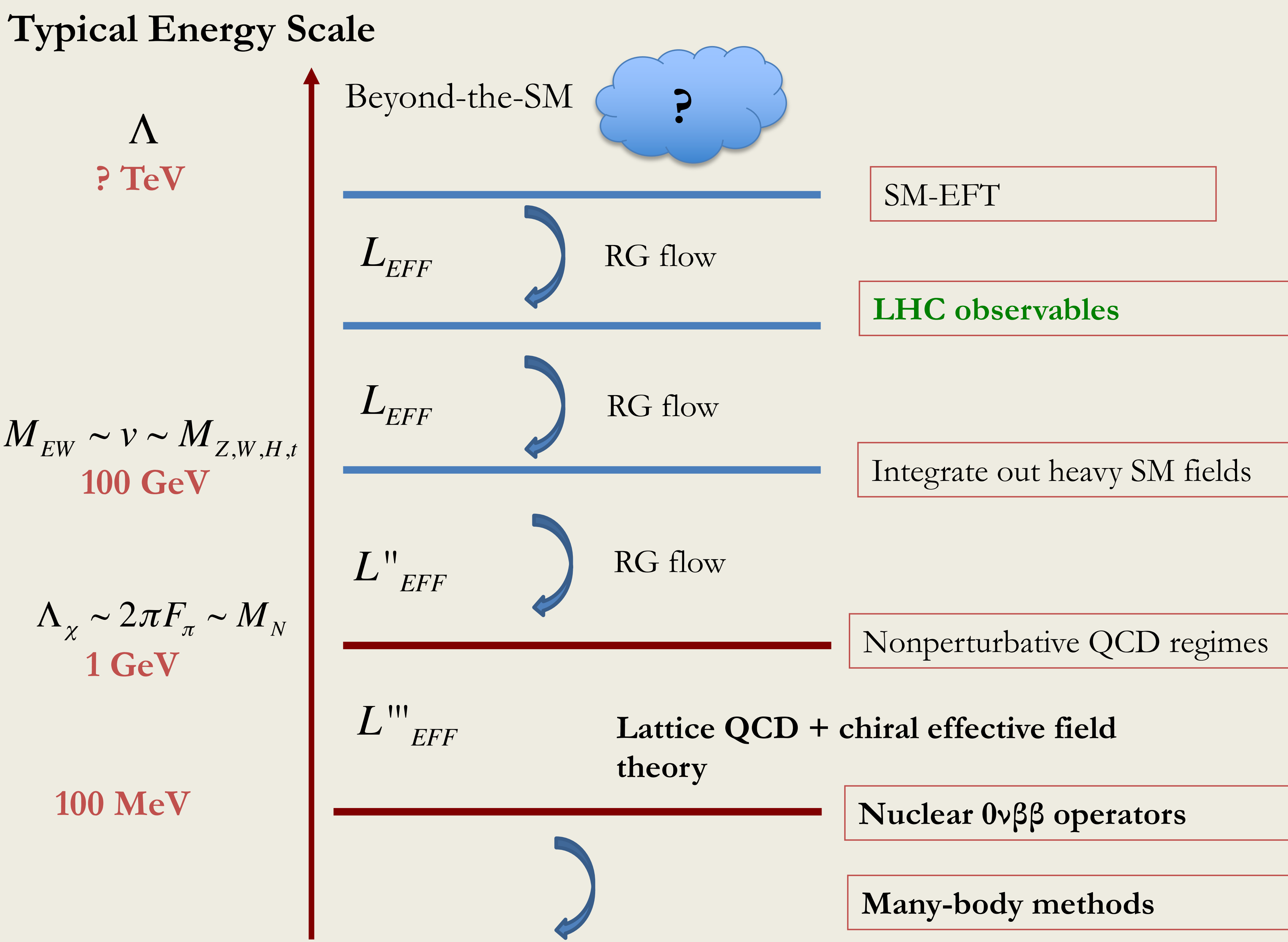
Buchmuller & Wyler '86
Gradzkowski et al '10

- **It might be advantageous to start above the electroweak scale**
  1. Matching to explicit UV-complete model is done at the scale where heavy particles are integrated out.
  2. Incorporate constraints from $SU_L(2)$ gauge symmetry
  3. Operators involve heavy SM fields (W,Z,h,t). 0vbb can be directly connected to other probes (LHC, flavor, etc)

See talk by. R. Ruiz



$$\sim \frac{1}{\Lambda^n}$$


Typical Energy Scale
Λ
? TeV
$M_{EW} \sim v \sim M_{Z,W,H,t}$
100 GeV
$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$
1 GeV
100 MeV
Beyond-the-SM
?
SM-EFT
L_{EFF}
RG flow
LHC observables
L_{EFF}
RG flow
Integrate out heavy SM fields
L''_{EFF}
RG flow
Nonperturbative QCD regimes
L'''_{EFF}
Lattice QCD + chiral effective field theory
Nuclear 0νββ operators
Many-body methods

Effective lepton number violation

- Lepton number = **accidental** symmetry in Standard Model (at zero T)
- But no longer once we allow for operators of dim>4
- SM as an EFT $$L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$
- Contain SM fields and obey SM gauge and Lorentz symmetry
- At energy E, operators of dim (4+n) $\sim (E/\Lambda)^n$

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- **Gauge symmetry is restrictive: only 1 dim-5 operator**

$$L_5 = \frac{c_5}{\Lambda}(L^T C \tilde{H})(\tilde{H}^T L) \qquad L^T = \left(\upsilon_L \; e_L\right)$$

Weinberg '79

- Contains **two** lepton fields and **no** anti-lepton fields →

$$L_5 \to c_5 \frac{v^2}{\Lambda} \nu_L^T C \nu_L$$ → **Majorana neutrino mass term**

$$m_\nu \sim 0.1\, eV \qquad \Lambda \sim c_5 \cdot 10^{15}\, GeV$$

Higher-order in the SM-EFT

- $\Delta L = 2$ operators only appear at odd dimensions 5, 7, ….. Kobach '16

Dimension-five

Weinberg '79

$$\mathcal{L}_5 = \frac{c_5}{\Lambda}(L^T C \tilde{H})(\tilde{H}^T L)$$

- One operator
- Induces Majorana mass

Dimension-seven

Lehman '14

$1 : \psi^2 H^4 + \text{h.c.}$	
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^i C L^m)H^j H^n (H^\dagger H)$

$2 : \psi^2 H^2 D^2 + \text{h.c.}$	
$\mathcal{O}^{(1)}_{LHD}$	$\epsilon_{ij}\epsilon_{mn} L^i C (D^\mu L^j) H^m (D_\mu H^n)$
$\mathcal{O}^{(2)}_{LHD}$	$\epsilon_{im}\epsilon_{jn} L^i C (D^\mu L^j) H^m (D_\mu H^n)$

$3 : \psi^2 H^3 D + \text{h.c.}$	
$\mathcal{O}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn}\left(L^i C \gamma_\mu e\right) H^j H^m D^\mu H^n$

$4 : \psi^2 H^2 X + \text{h.c.}$	
$\mathcal{O}_{LHB}$	$\epsilon_{ij}\epsilon_{mn}\left(L^i C \sigma_{\mu\nu} L^m\right) H^j H^n B^{\mu\nu}$
$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\tau^I \epsilon)_{mn}\left(L^i C \sigma_{\mu\nu} L^m\right) H^j H^n W^{I\mu\nu}$

$5 : \psi^4 D + \text{h.c.}$	
$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C D^\mu L^j)$
$\mathcal{O}^{(2)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C \sigma^{\mu\nu} D_\nu L^j)$
$\mathcal{O}^{(1)}_{\bar{L}QddD}$	$(Q C \gamma_\mu d)(\bar{L} D^\mu d)$
$\mathcal{O}^{(2)}_{\bar{L}QddD}$	$(\bar{L}\gamma_\mu Q)(d C D^\mu d)$
$\mathcal{O}_{ddd\bar{e}D}$	$(\bar{e}\gamma_\mu d)(d C D^\mu d)$

$6 : \psi^4 H + \text{h.c.}$	
$\mathcal{O}_{LLL\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L^i)(L^j C L^m)H^n$
$\mathcal{O}^{(1)}_{LLQ\bar{d}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L^i)(Q^j C L^m)H^n$
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$\mathcal{O}_{\bar{L}QQdH}$	$\epsilon_{ij}(\bar{L}_m d)(Q^m C Q^i)\tilde{H}^j$
$\mathcal{O}_{\bar{L}dddH}$	$(dCd)(\bar{L}d)H$
$\mathcal{O}_{\bar{L}uddH}$	$(\bar{L}d)(uCd)\tilde{H}$
$\mathcal{O}_{Leu\bar{d}H}$	$\epsilon_{ij}(L^i C \gamma_\mu e)(\bar{d}\gamma^\mu u)H^j$
$\mathcal{O}_{\bar{e}QddH}$	$\epsilon_{ij}(\bar{e}Q^i)(dCd)\tilde{H}^j$

- 12 ΔL=2 operators

Dimension-nine

Graesser '16 '18

Full basis not known

4-quark 2-lepton operators + 2 quark/2 lepton + Higgs currents

$\tilde{\varphi}^\dagger D_\mu \varphi$

- Seems crazy to go to dim-7 if expansion parameter is $\left(\frac{v}{\Lambda}\right)^2 \sim 10^{-24}$

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Graesser '16 '18

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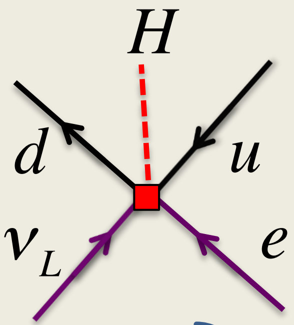
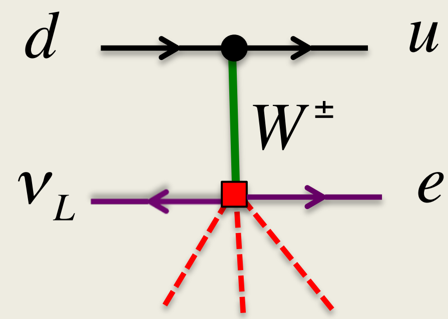
- Seems crazy to go to dim-7 if expansion parameter is $\left(\frac{v}{\Lambda}\right)^2 \sim 10^{-24}$
- Unless $c_5 << 1$ for whatever reason….
- Small Yukawa couplings, symmetries, radiative mass models, …..
- Example: in LR symmetry $c_5 \sim y_e^2 \sim 10^{-10}$ $c_7 \sim y_e \sim 10^{-5}$ $c_9 \sim y_e^0 \sim 1$
- Then if scale is low ~ $\Lambda \sim (10-100)\,TeV$ dim5 ~ dim7~ dim 9

Lowering the energy scale

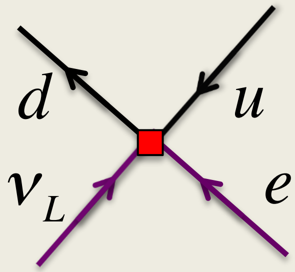




M_{EW}

100 GeV

** Higgs takes vev + integrate out W bosons



$$\sim c_7 \frac{v}{\Lambda^3}$$

- Beta-decay a la Fermi ~ dim-6
- But 'wrong' neutrino
- Hard to probe in single beta decay
- Scalar, Vector, Tensor $C_6^{S,V,T}$

$\Lambda_\chi \sim 2\pi F_\pi$

1 GeV

Hadronization

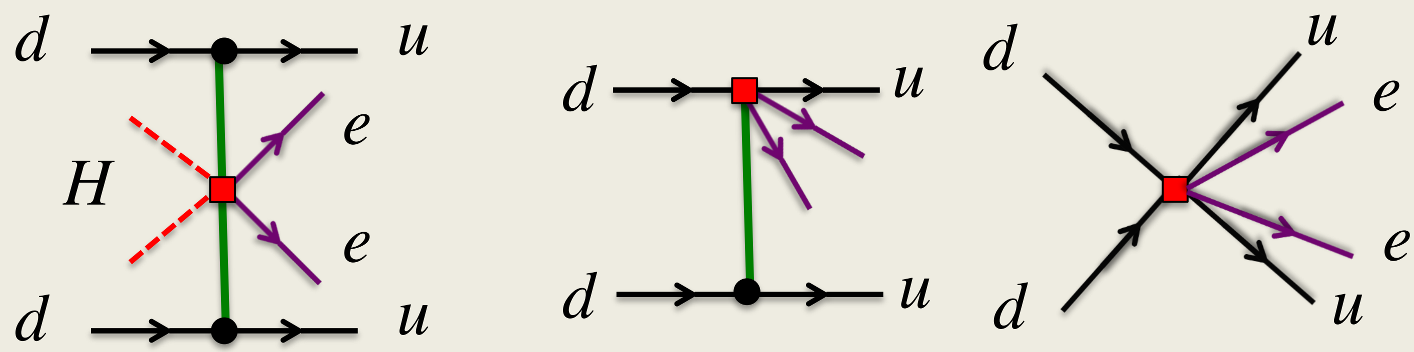
- Neutron and pion 'beta' decay operators + ….

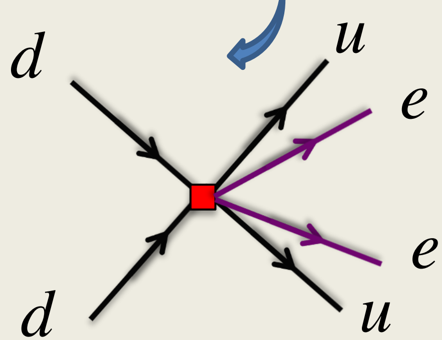
**** One-loop QCD RGE included for all operators**

Lowering the energy scale

M_{EW}

100 GeV





$\sim c_7 \dfrac{1}{v^2\Lambda^3}$

$\sim c_9 \dfrac{1}{\Lambda^5}$

- 0νββ operators ~ 'dim 9'
- Scalar and Vector operators

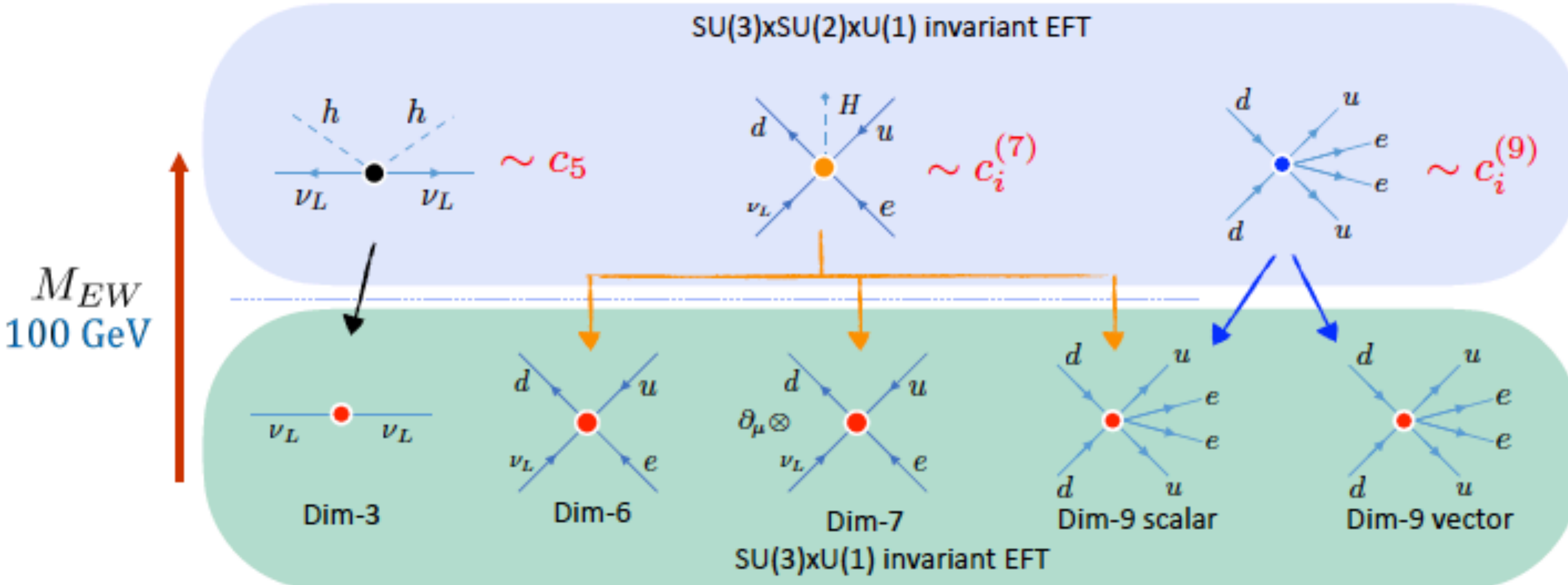
$\Lambda_\chi \sim 2\pi F_\pi$

1 GeV

Hadronization

- Hadrons-electron-electron couplings

Summary of the perturbative part



Hadronization

Now it gets more problematic….

Chiral effective field theory

- Make use of the great progress in ab initio nuclear calculations

  See e.g. single-beta decay spectra Gysberg et al, Nature '19

- Use chiral EFT to match quark-gluon operators to hadronic operators
- Incorporates **symmetries** of QCD (**Lorentz/chiral/isospin/gauge**)
- **Systematic power counting** in

$$Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi \qquad \Lambda_\chi \cong 1\,GeV$$

- Close and fruitful connection to **lattice QCD**
- Systematic inclusion of **ultrasoft, potential, hard** virtual neutrinos
- Treat **NN forces and 0vbb currents** on the same footing

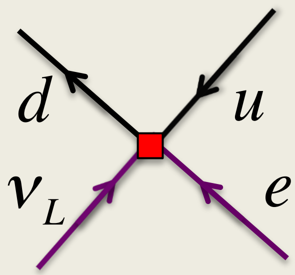
Prezeau et al' 03, Cirigliano, JdV et al '17 '18 '19

Recent 0vbb EFT without chiral EFT: Graf et al '18 Horoi/Neacsu '17

The 'dim 6' pieces

$\Lambda_\chi \sim 2\pi F_\pi$

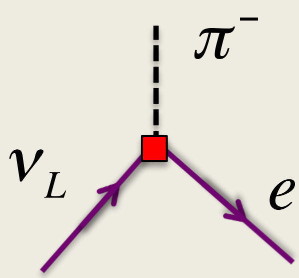
> 1 GeV

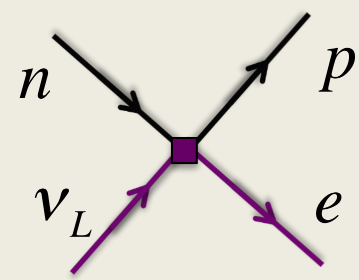


- LNV operators handled same way
- Scalar, Vector, Tensor
- Change the 'standard' chiral sources (l, r, s, p, t) accordingly

$$l_\mu = c_7^l \frac{v}{\Lambda^3} \bar{e}_R \gamma^\mu \nu_L^c \, \tau^+ \qquad r_\mu = c_7^r \frac{v}{\Lambda^3} \bar{e}_R \gamma^\mu \nu_L^c \, \tau^+$$

$$s + ip = c_7^s \frac{v}{\Lambda^3} \bar{e}_L \nu_L^c \, \tau^+ \qquad t_{\mu\nu} = c_7^t \frac{v}{\Lambda^3} \bar{e}_L \sigma^{\mu\nu} \nu_L^c \, \tau^+$$





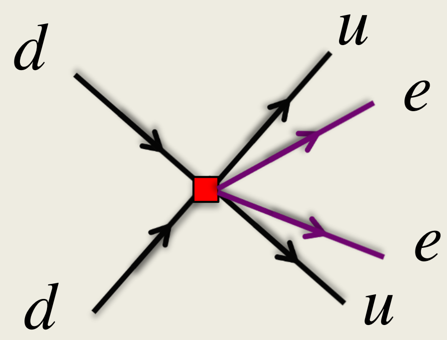
Cirigliano et al '17

- Need nucleon charges: g_A, g_S, g_T, g_M (known pretty well)
- One unknown low-energy constant (LEC) at NLO

The 'dim 9' pieces

$\Lambda_\chi \sim 2\pi F_\pi$

> 1 GeV

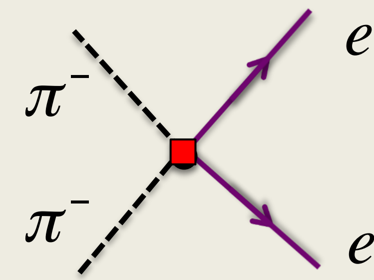


- No standard sources for these terms
- In LR models e.g:

$$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \; \bar{e}_L C \bar{e}_L^T$$
$$O_5 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha \; \bar{e}_L C \bar{e}_L^T$$

Prezeau et al '03

- 2 LECs $g_{4,5}$ … In principle unknown
- But related by SU(3) to $K \to \pi\pi$
- Lattice for Kaon processes (FLAG '16)



Cirigliano et al '16 '17

$$g_4 = -(2.5 \pm 1.2) GeV^2 \qquad g_5 = -(11 \pm 4) GeV^2$$

- Agrees with direct lattice QCD computation

Nicholson et al '18

$$g_4 = -(1.9 \pm 0.2) GeV^2 \qquad g_5 = -(8 \pm 0.6) GeV^2$$

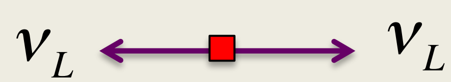
- **Color octet operators large.**

The chiral Lagrangian

~ GeV $$L = L_{QCD} + L_{Fermi} - m_{\beta\beta} \nu_L^T C \nu_L \; + C_\Gamma \, \bar{e} \Gamma \bar{\nu}^T \; O_{2q}^{\Gamma} + C_{\Gamma'} \, \bar{e} \Gamma' e^c \; O_{4q}^{\Gamma'}$$

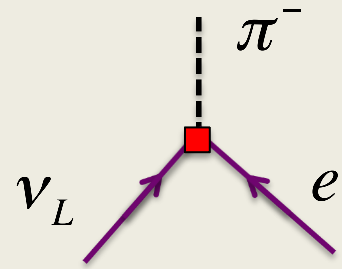
~100 MeV **Neutrinos are still degrees of freedom in the low-energy EFT**

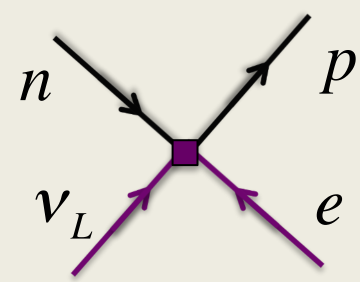
ΔL=2 Majorana mass



$\sim m_{\beta\beta}$

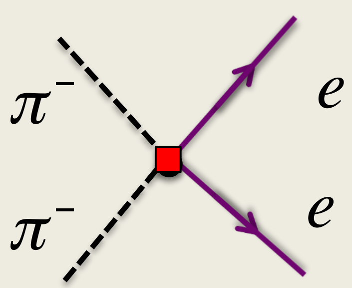
ΔL=2 beta decay

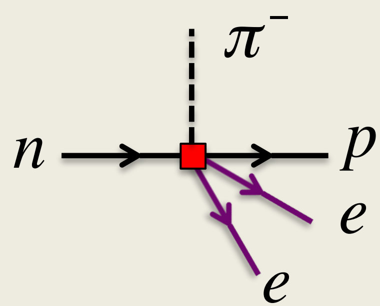


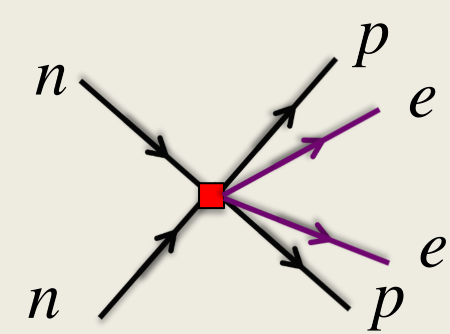


ΔL=2

'neutrinoless'

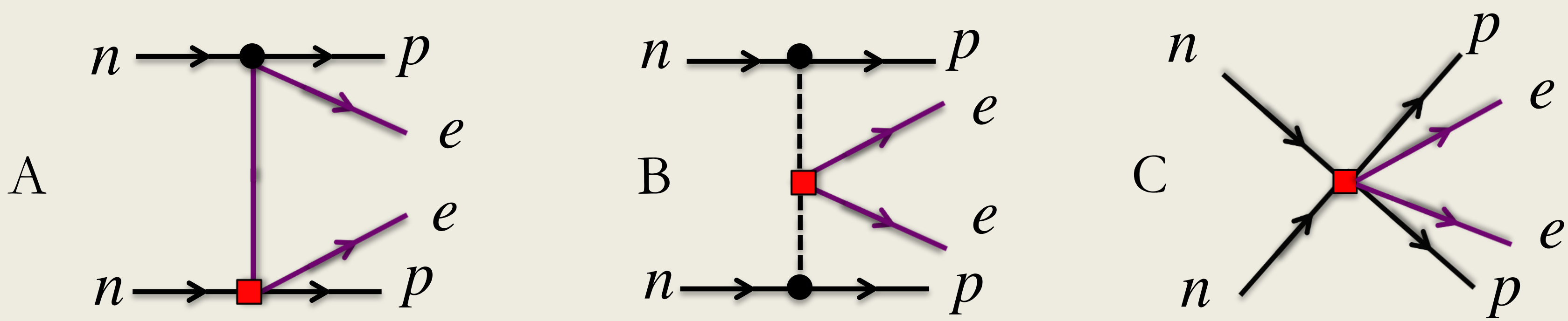






The 'neutrino potential'

- Derive the nn → pp + ee transition operator order-by-order (LO shown)



- Long-range LECs are known well. Short-distance not at all. **LO problem!**

$n \to pe\nu,\ \pi \to e\nu$		$\pi\pi \to ee$	
g_A	1.271 ± 0.002 [58]	$g_1^{\pi\pi}$	0.36 ± 0.02 [44]
g_S	0.97 ± 0.13 [59]	$g_2^{\pi\pi}$	2.0 ± 0.2 GeV^2 [44]
g_M	4.7 [58]	$g_3^{\pi\pi}$	$-(0.62 \pm 0.06)$ GeV^2 [44]
g_T	0.99 ± 0.06 [59]	$g_4^{\pi\pi}$	$-(1.9 \pm 0.2)$ GeV^2 [44]
$\lvert g'_T \rvert$	$\mathcal{O}(1)$	$g_5^{\pi\pi}$	$-(8.0 \pm 0.6)$ GeV^2 [44]
B	$2.7\,\mathrm{GeV}$	$\lvert g_{\mathrm{T}}^{\pi\pi} \rvert$	$\mathcal{O}(1)$
$n \to p\pi ee$		$nn \to pp\,ee$	
$\lvert g_1^{\pi N} \rvert$	$\mathcal{O}(1)$	$\lvert g_1^{NN} \rvert$	$\mathcal{O}(1)$
$\lvert g_{6,7,8,9}^{\pi N} \rvert$	$\mathcal{O}(1)$	$\lvert g_{6,7}^{NN} \rvert$	$\mathcal{O}(1)$
$\lvert g_{\mathrm{VL}}^{\pi N} \rvert$	$\mathcal{O}(1)$	$\lvert g_{\mathrm{VL}}^{NN} \rvert$	$\mathcal{O}(1)$
$\lvert g_{\mathrm{T}}^{\pi N} \rvert$	$\mathcal{O}(1)$	$\lvert g_{\mathrm{T}}^{NN} \rvert$	$\mathcal{O}(1)$
		$\lvert g_\nu^{NN} \rvert$	$\mathcal{O}(1/F_\pi^2)$
		$\lvert g_{VL,VR}^{E,m_e} \rvert$	$\mathcal{O}(1)$
		$\lvert g_{2,3,4,5}^{NN} \rvert$	$\mathcal{O}((4\pi)^2)$

Active lattice QCD efforts to determine LECs

Nicholson et al '18
Tuo et al '19
Detmold, Murphy '20

The neutrinoless decay rate

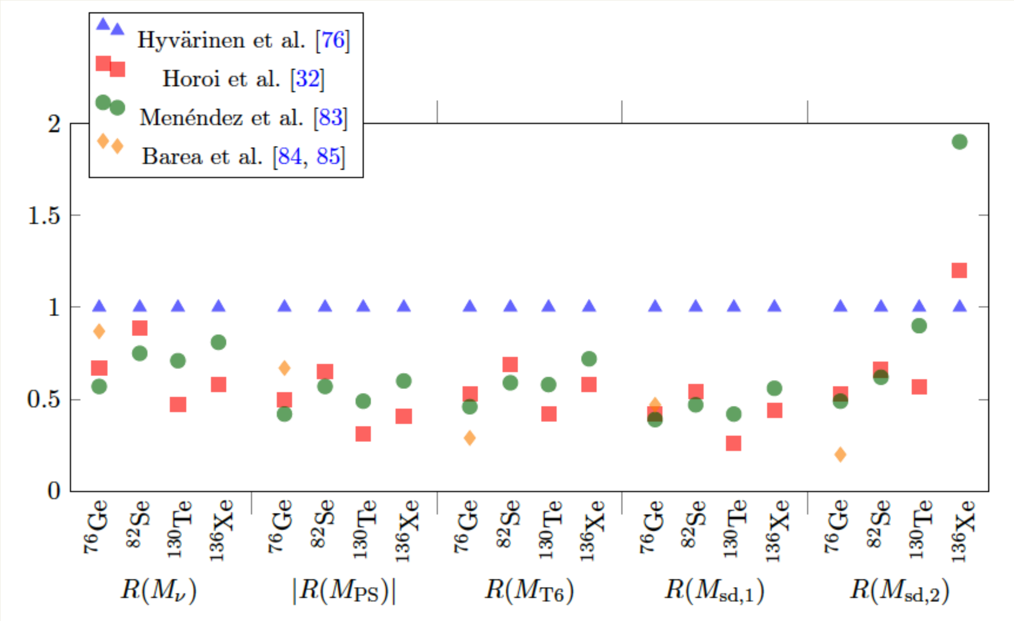
Decay rate $$\Gamma \sim \int d^3k_1 d^3k_2 \,|A|^2 F(Z,E_1) F(Z,E_2) \delta(E_1 + E_2 + E_f - M_i)$$

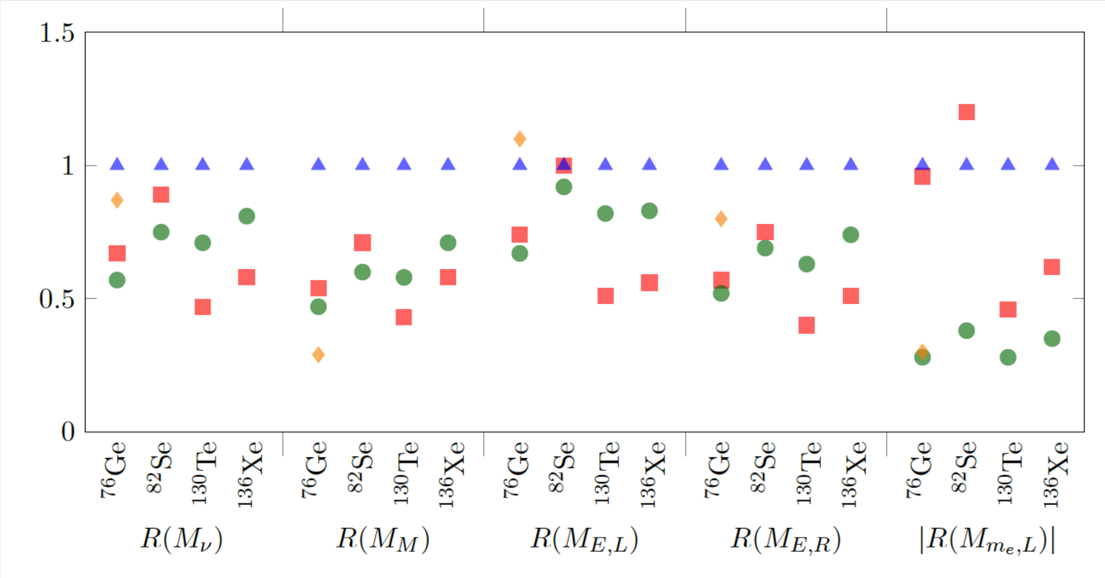
- **Amplitude** $A = \sum_i \langle 0^+ | V_\nu^i | 0^+ \rangle \otimes \bar{e}(k_1)\ \Gamma^i e^c(k_2)$
- Electron phase space integrals are known — Kotila/Iachello `12, Stefanik et al `14
- **Nuclear Mattix Elements (NMEs)** $M_i = \langle 0^+ | V_\nu^i | 0^+ \rangle$

- **All NMEs for non-standard LNV contained in 'standard' mechanism**
- Can use existing calculations: **QPRA** (Hyvarinen/Suhonen '15)
  Shell model (Horoi/Neacsu '17 & Menendez '17)
  IBM (Barea et al '15)
- Going towards first-principle ChEFT calculations — Yao et al, PRL '20

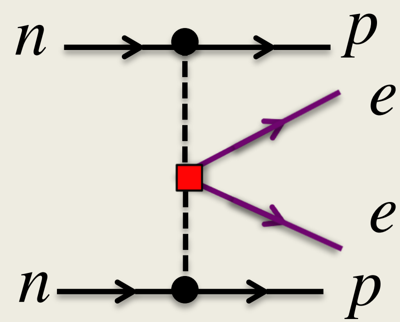
Many-body uncertainties for SM-EFT

- Leading-order requires 9 combinations of NMEs
- Uncertainties similar to standard scenario
- Short-distance matrix elements more 'spread' in the applied method





Chiral symmetry matters



- Chiral properties important to include ! Example:

$$L = \left[C_2\, \overline{u_L} d_R \overline{u_L} d_R + C_3\, \overline{u_L}^{\alpha} d_R{}^{\beta} \overline{u_L}^{\alpha} d_R{}^{\beta}\right]$$

- Large contributions from pi-pi effects

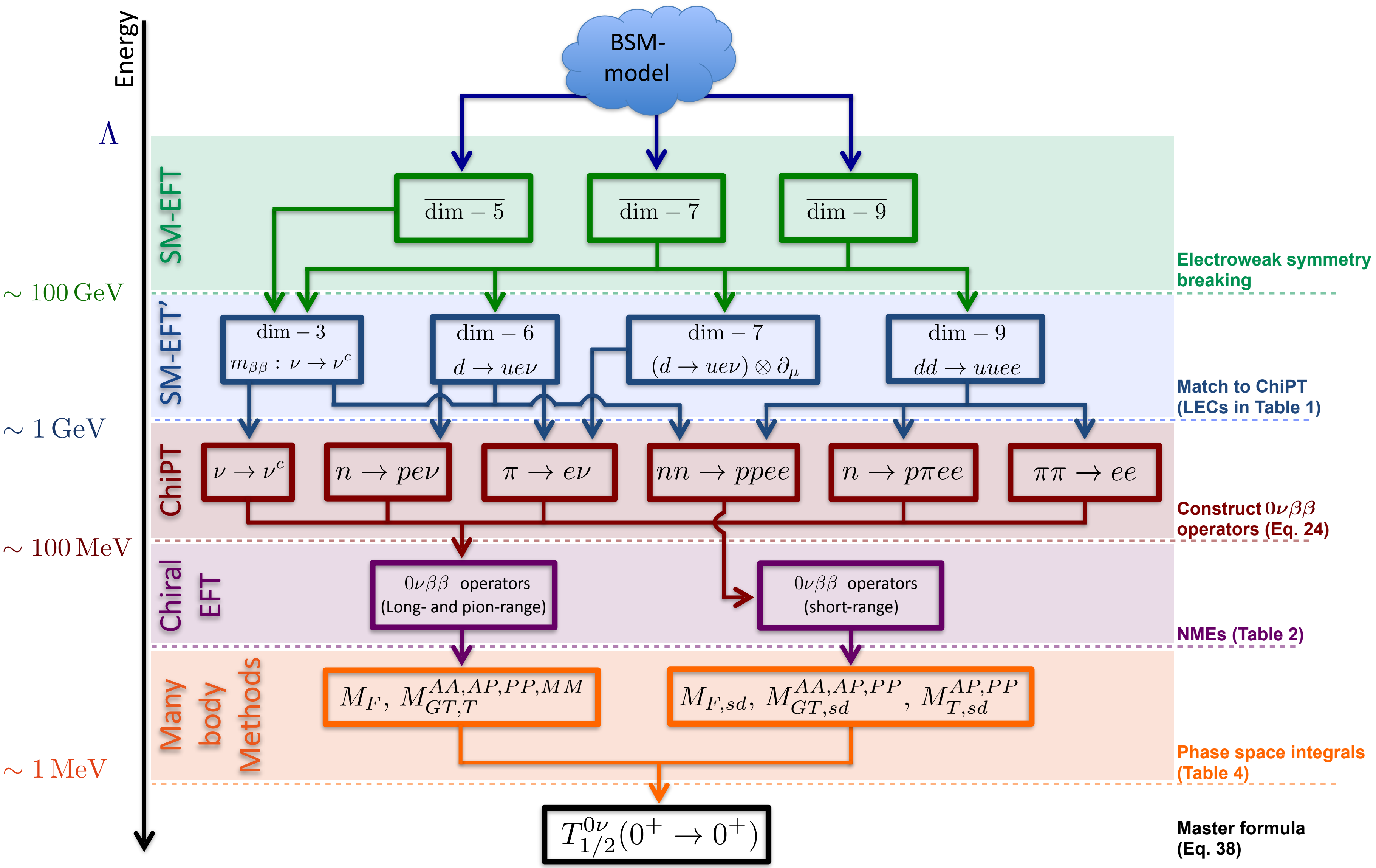
$$M = \frac{-1}{2m_N^2}\left(C_2 g_2^{\pi\pi} + C_3 g_3^{\pi\pi}\right)\left(\frac{1}{2} M_{GT,sd}^{AP} + M_{GT,sd}^{PP}\right) \cong 0.3\ C_2 - 0.1\ C_3$$

- Non-chiral approach based on factorization

$$\langle pp|L|nn\rangle = C_2 \langle p|\overline{u_L} d_R|n\rangle\langle p|\overline{u_L} d_R|n\rangle = \frac{g_s^2}{4}\bar{p}n\bar{p}n$$

- Insert short-distance NME $M_{fac} = \frac{-g_S^2}{2g_A^2}\frac{m_\pi^2}{m_N^2} C_2\, M_{F,sd} \cong 10^{-3}\ C_2$
- Misses contributions by factor 100 and ignores the color octet operators

‘The neutrinoless double-beta metro map’

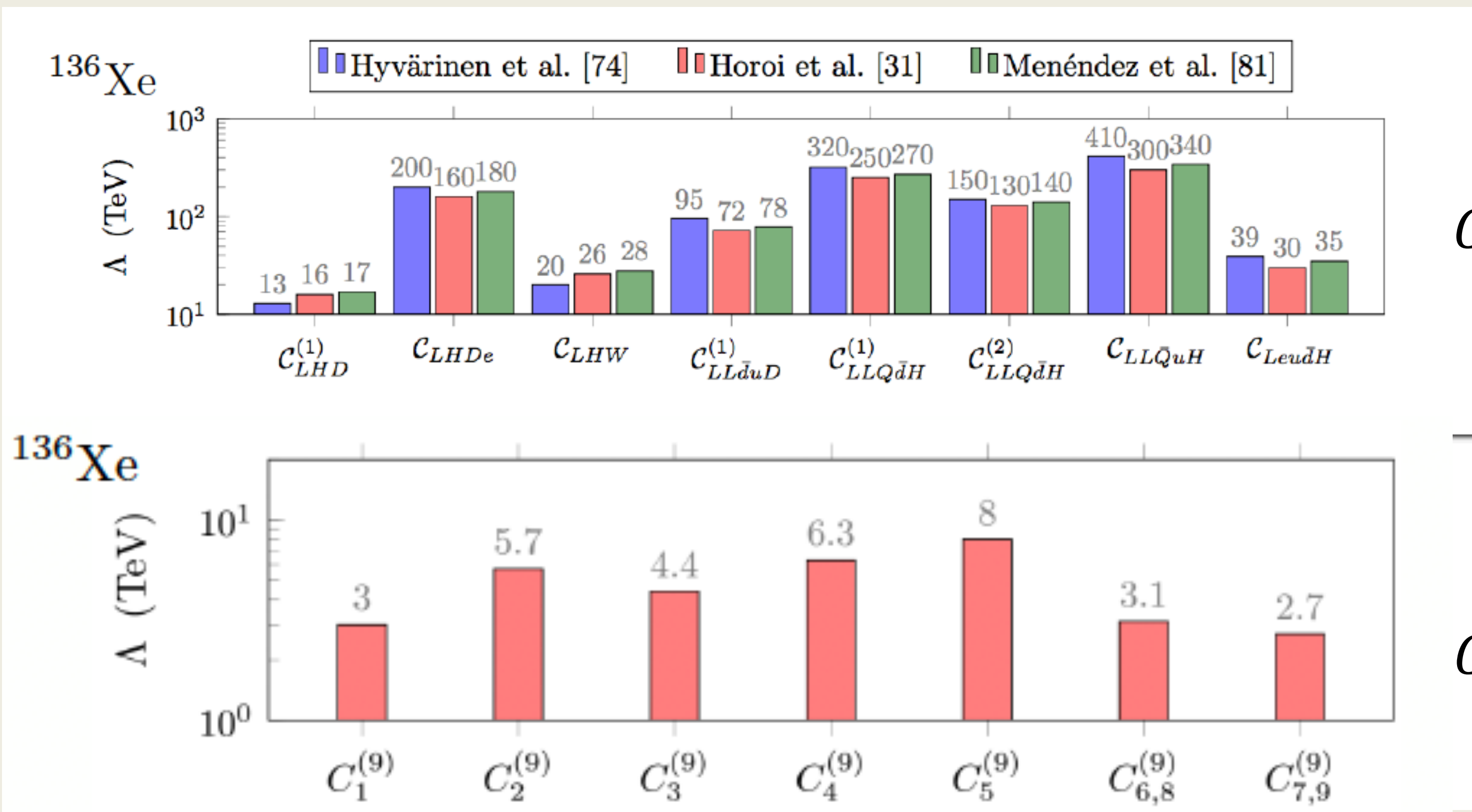


Mathematica notebook walks through steps automatically

Limits on LNV sources

- KAMLAND limit $T_{1/2}^{0\nu}\left({}^{136}Xe \rightarrow {}^{136}Ba\right) > 1.07\times 10^{26}\ yr$

- Dim-7 operators $C_7 \sim (v/\Lambda)^3$ are probed at 10-100 TeV
- Dim-9 operators $C_9 \sim (v/\Lambda)^5$ are probed at few TeV
- Difference between operators due to chiral/phase space suppression factors

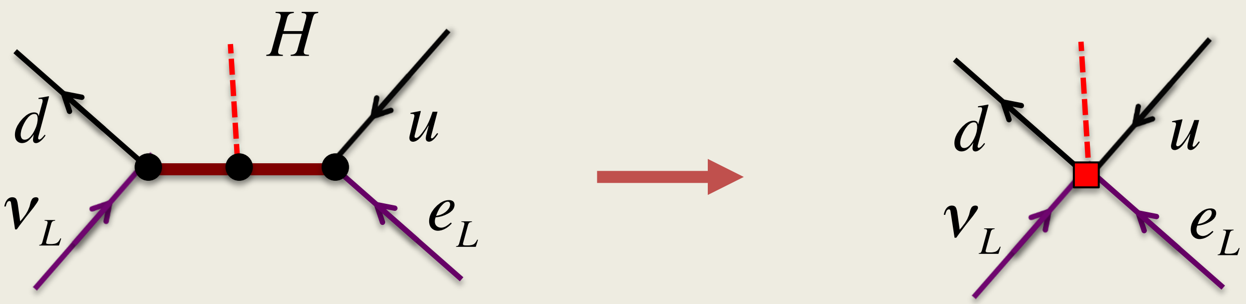


$C_7 \sim (v/\Lambda)^3$

$C_9 \sim (v/\Lambda)^5$

Phenomenology

- Particular dimension-7 operator (e.g. appearing in eptoquark models)

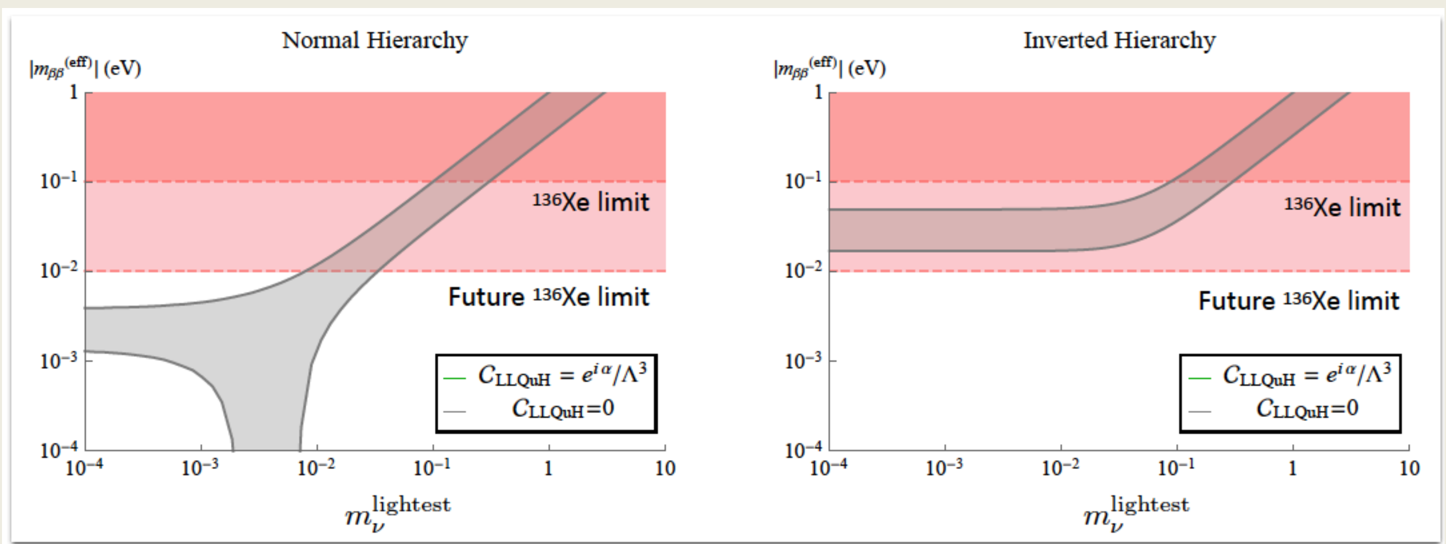


$C_7 \sim (v/\Lambda)^3$

$\Lambda > 400\ TeV$

$\Lambda_{LHC} > 5\ TeV$

- Operator has **same 'leptonic'** structure as standard mechanism
- Interference with Majorana mass: **interpretation needs care**



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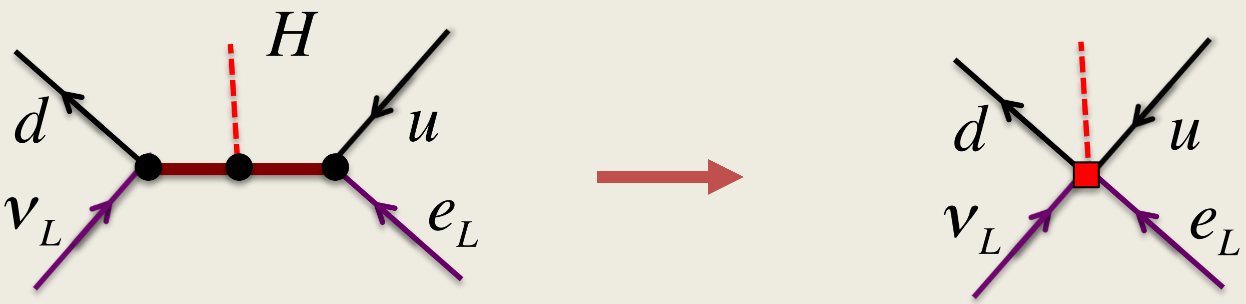

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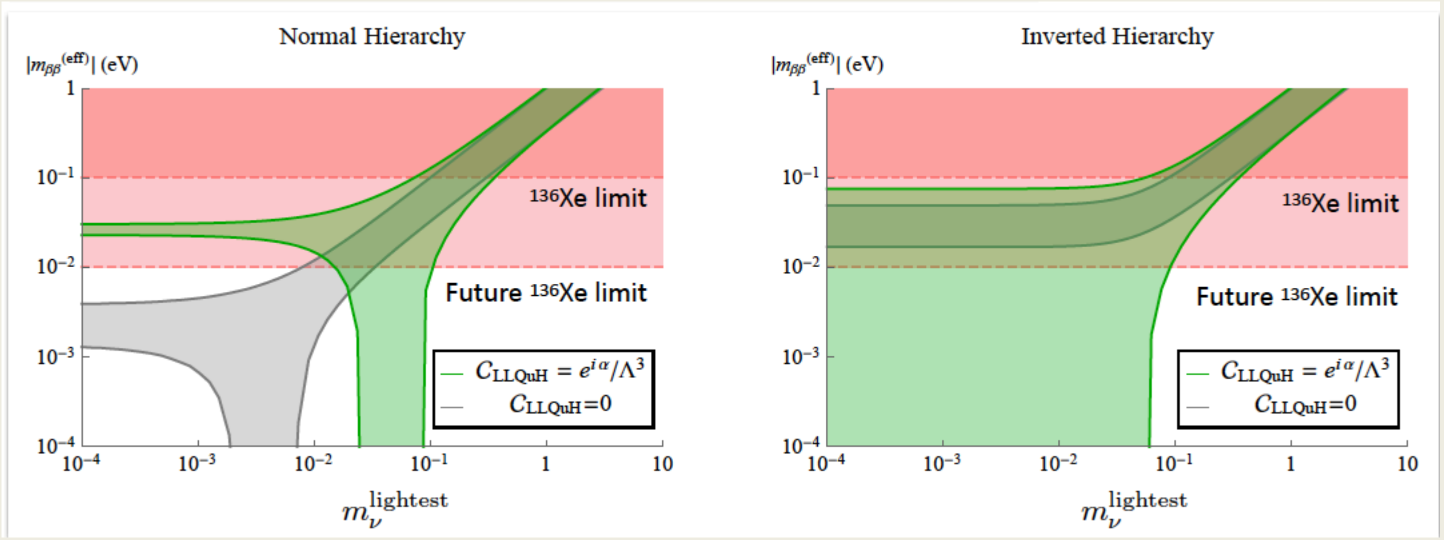
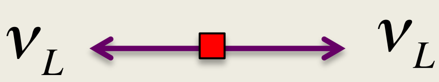


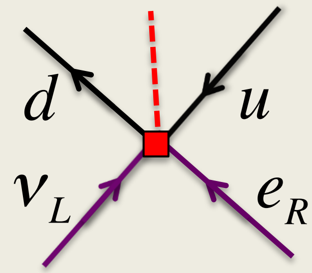
- **Signal in next-generation does not mean inverse hierarchy per se**

Disentangling LNV sources

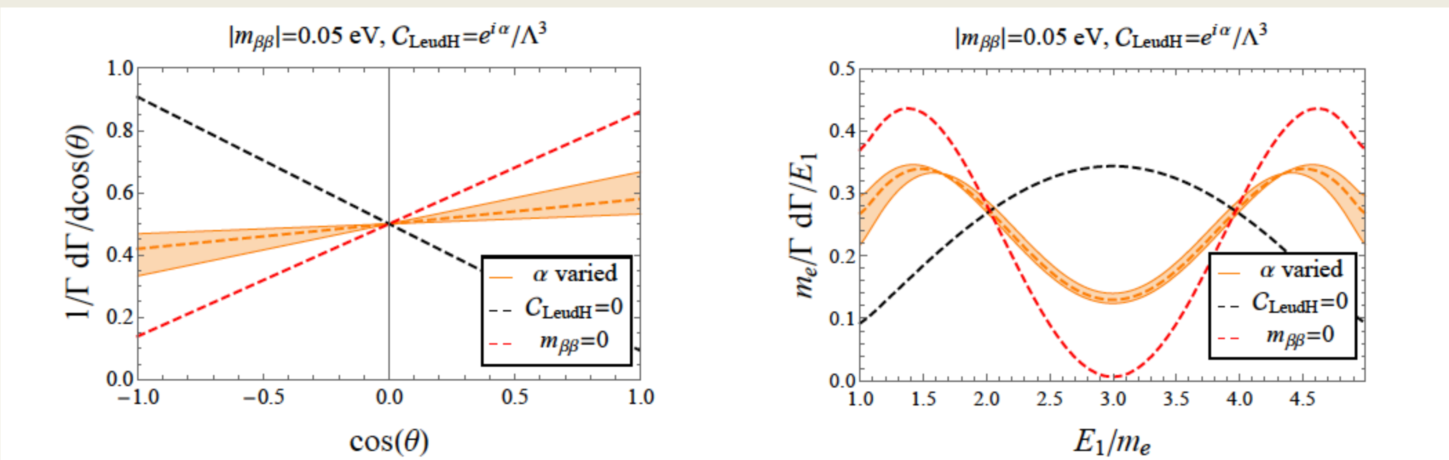
- A single measurement can be from any LNV operator
- Isotope ratios not too discriminating (NME uncertainties)
- Instead: **angular & energy** distributions of the outgoing electrons
- This might be science fiction for now

Fogli et al '09
Lisi et al '15
Cirigliano et al '17





$$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$$



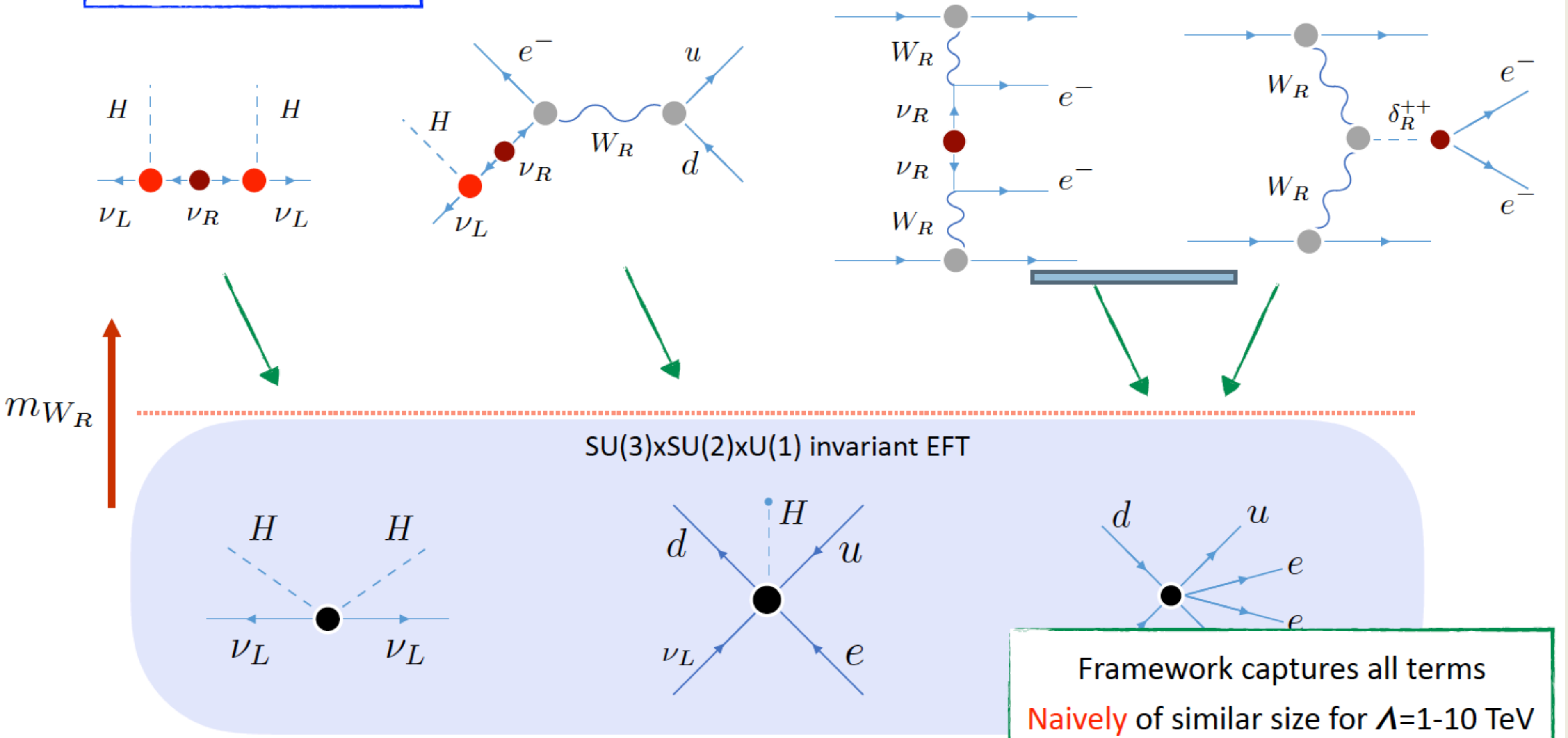
- Of course if scale is low, we can use other probes of LNV (e.g. LHC)

An example: LR model

Mohapatra, Pati, Salam, Senjanovic '75
Prezeau et al '03
Nemevsek et al '11
Cirigliano et al '18

- (red dot) $\sim y_e = m_e/v$
- (dark red dot) $\Delta L = 2$

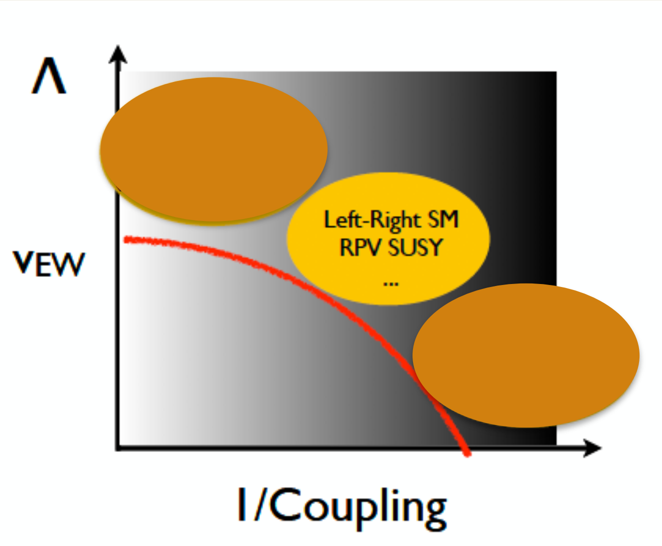
See Juan's talk next !



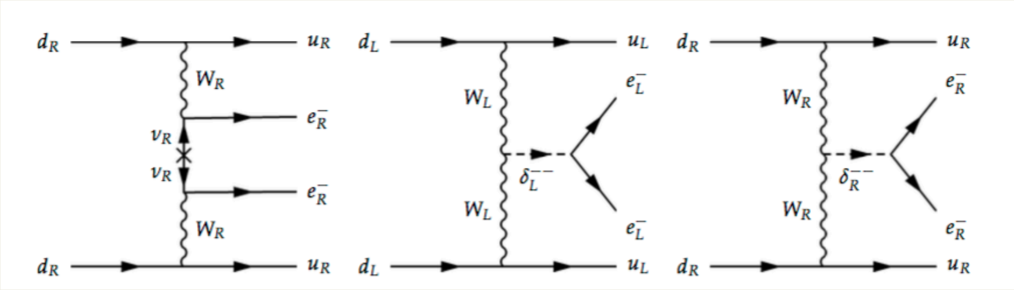
Framework captures all terms
Naively of similar size for Λ=1-10 TeV

dim-5 $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$ dim-7 $\sim y_e \left(\frac{v}{\Lambda}\right)^3$ Dim-9 $\sim \left(\frac{v}{\Lambda}\right)^5$

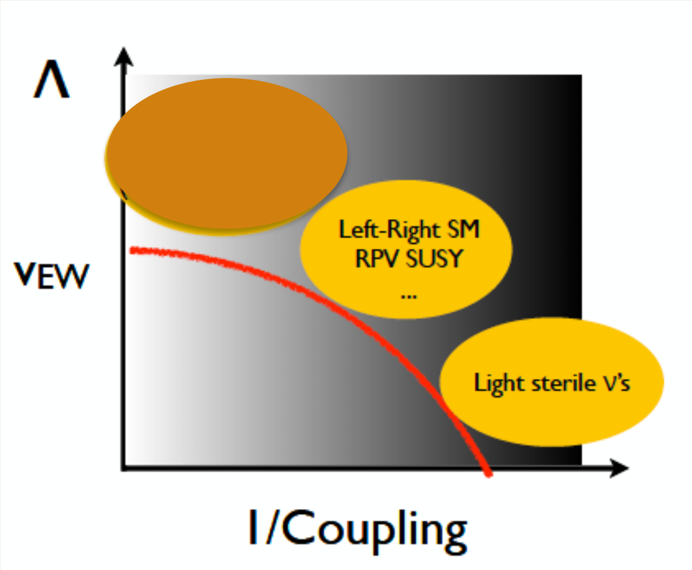
- Part I: Non-standard mechanisms for 0vbb and the SM-EFT

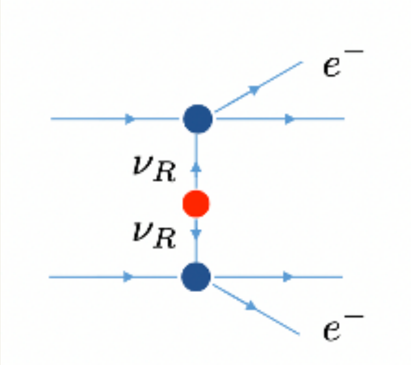


Thesis Duerr '10



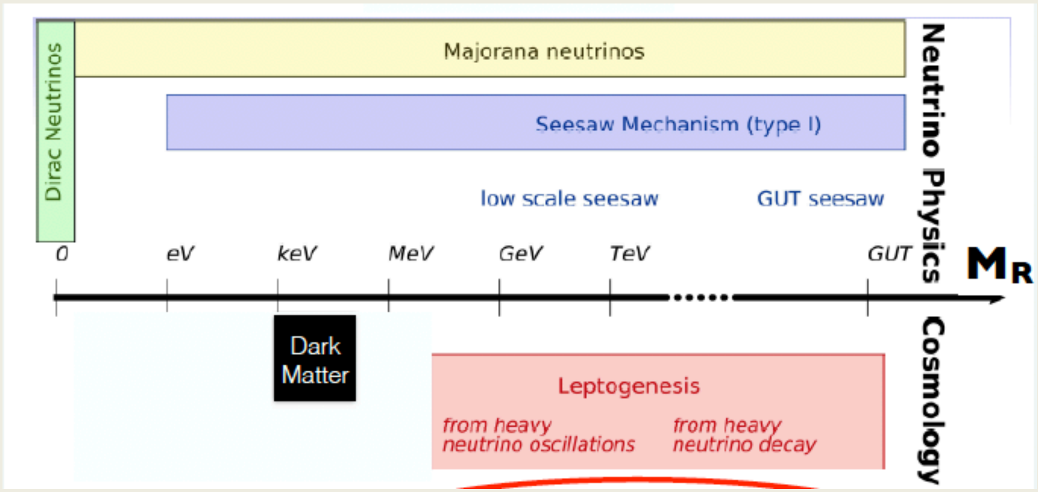
- **Part II: Low-scale seesaw and 0vbb**





The role of light (almost) sterile neutrinos

- If Yukawa couplings are small (and why not?) ν_R could appear at any scale



Akhmedov et al '98
Canetti et al '12
Drewes/Garbrecht '15

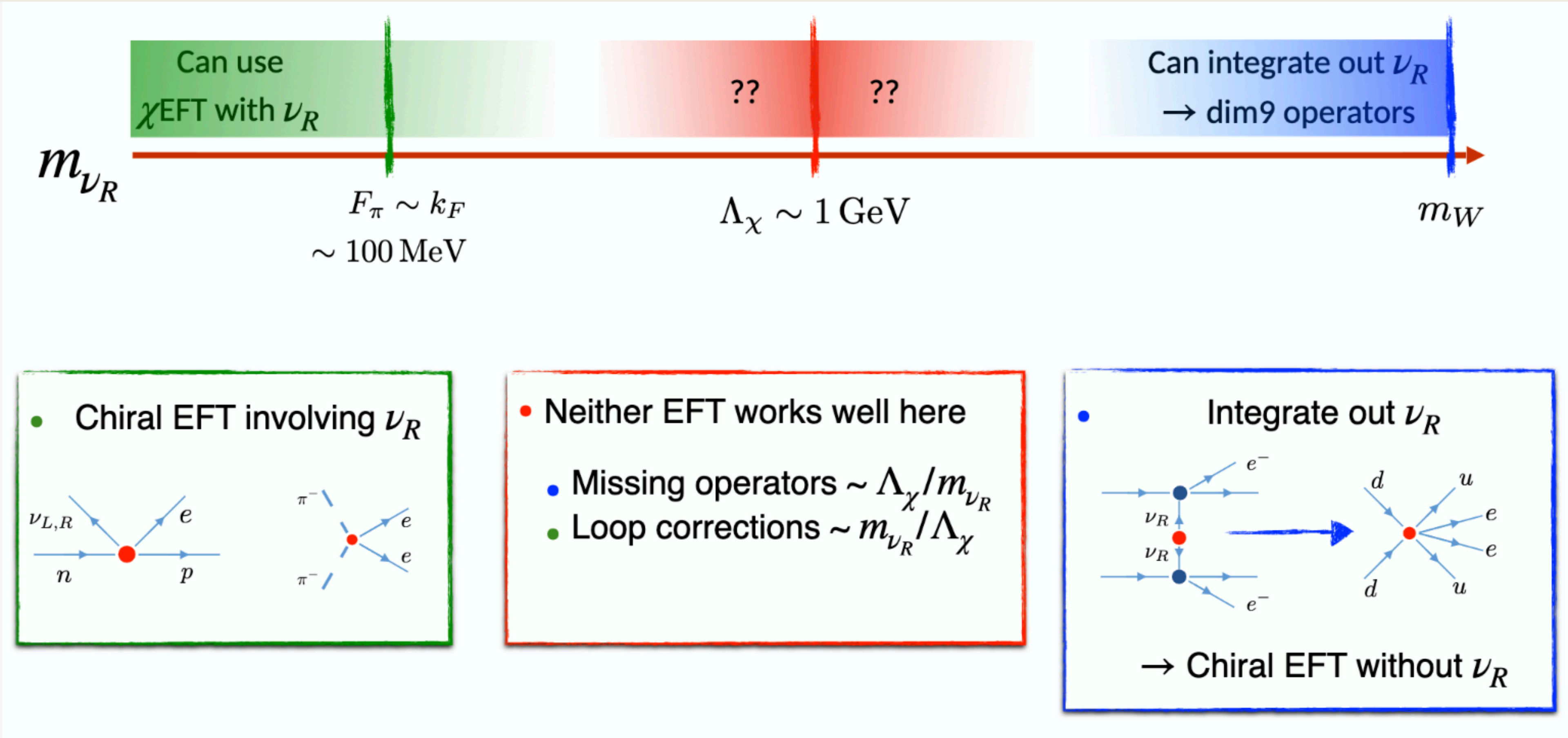
- Sterile neutrinos could interact with decoupled BSM sector (e.g. mLRSM)
- Can be described in the neutrino-extended SMEFT

$$L = L_{SMEFT} - \frac{1}{2}\nu_R^c M_R \nu_R - \bar{L} Y_D \nu_R \tilde{H} + L_{6,\nu R} + L_{7,\nu R}$$

- Repeat all EFT steps but include sterile neutrinos explicitly
- Main complication: **neutrino mass dependence of matrix elements**

del Aguil et al '08, Aparici et al '09, Bhattacharya/Wudka '15, Liao/Ma '16 Cai et al '17, Chala et al '21

The tedious MeV-GeV regime

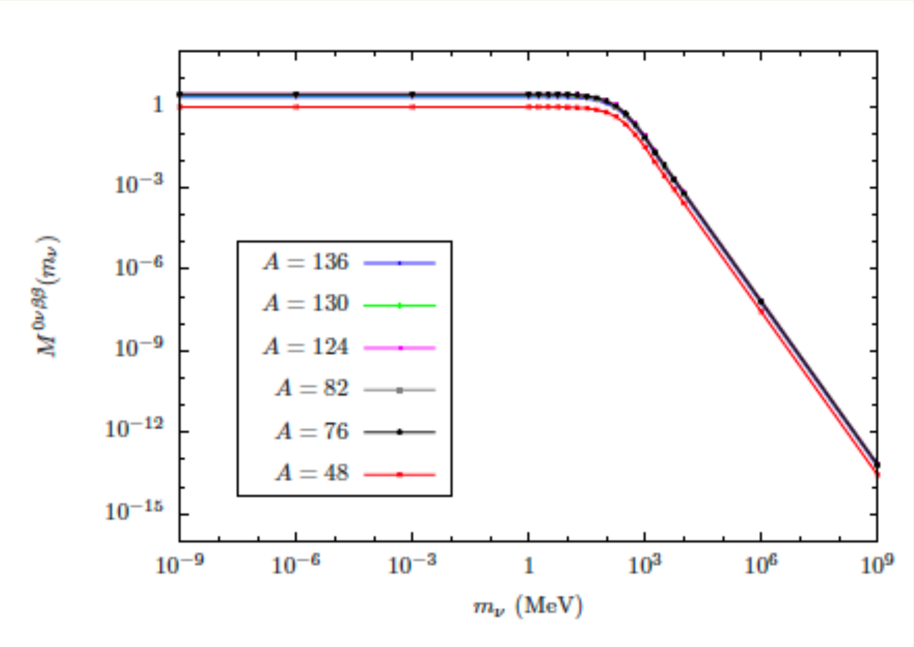


- In the small and large regimes, we have clear QCD guidance
- Interpolate middle region: non-trivial m_ν-dependence

Mass dependence of the NMEs

- The nuclear matrix elements seem to have a simple m_i dependence

$$h_K^{ab}(r, m_i) = \frac{2}{\pi} R_A \int_0^\infty d|\mathbf{q}| \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_i^2} h_K^{ab}(\mathbf{q}^2)\, j_\lambda(|\mathbf{q}|r)$$



Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez ’14

See also: Faessler et al ‘09 , Kovalenko et al ’09, Barea et al ‘15

Minimal-see-saw corrections

- Consider for simplicity a 3+1 model with sterile mass m_i
- Say m_i small compared to nuclear scale $k_F \sim p \sim 100$ MeV

Mitra et al '11

Blennow et al '14

$$\frac{1}{p^2 - m_i^2} = \frac{1}{p^2} + \frac{m_i^2}{p^4} + \mathcal{O}\left(\frac{m_i^4}{p^6}\right)$$

$$M^{0\nu\beta\beta}(m_i) = M^{0\nu\beta\beta}(0)\left[1 + \frac{m_i^2}{p^2} + \mathcal{O}\left(\frac{m_i^4}{p^4}\right)\right]$$

- Then in minimal see-saw the leading contributions vanish (unitarity)

$$\sum_{i=1}^{4} m_i U_{ei}^2 = 0\,,$$

Corrections scale as →

$$\sum_{i=1}^{4} U_{ei}^2 m_i^3 / k_F^2 \neq 0$$

e.g. Bolton et al '19

- Seem to scale as m_i^3 in small m_i regime (used in phenomenological studies)

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Mitra et al '11

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e.g. Bolton et al '19

- Seem to scale as m_i^3 in small m_i regime (used in phenomenological studies)
- **This might be too simple !** Careful when LO pieces vanish!
- EFT analysis shows contributions from ultrasoft neutrinos ($p_i \sim m_i \sim k_F^2/m_N$)

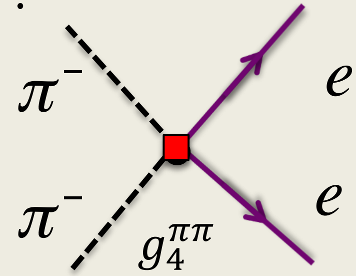
$$\sum_n \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \frac{1}{E_\nu} \left[\frac{\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle}{E_\nu + E_2 + E_n - E_i - i\varepsilon} + \frac{\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle}{E_\nu + E_1 + E_n - E_i - i\varepsilon}\right]$$

- **Work in progress**, but we find $m_i^2/(k_F)$ and $m_i \log(m_i^2)$ corrections
- **Enhanced sensitivity to O(KeV-MeV) neutrinos in minimal see-saw?**

Mass dependence of LECs

- Example mLRSM: mass eigenstates with LH + RH interactions
- If $m_i >> \text{GeV}$, integrate it out and obtain dim-9 operators. E.g. :

$$L = \frac{1}{m_i}\left[C_4\, \overline{u_L}\gamma^{\mu} d_L \overline{u_R}\gamma_{\mu}\, d_R\right]\bar{e}_L C \bar{e}_L^T$$



- Lead to the 'pionic' operator with known LEC: $g_4^{\pi\pi}$

- If $m_{\nu R}$ << MeV, then long-distance and 'hard' neutrino contributions
- 'Hard' neutrino exchange directly related to EM pion mass splitting

$$g_{\rm LR}^{\pi\pi}(m_i = 0) = \frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{2e^2} \simeq 0.8 F_\pi^2$$

- If we increase m_i the amplitudes must match

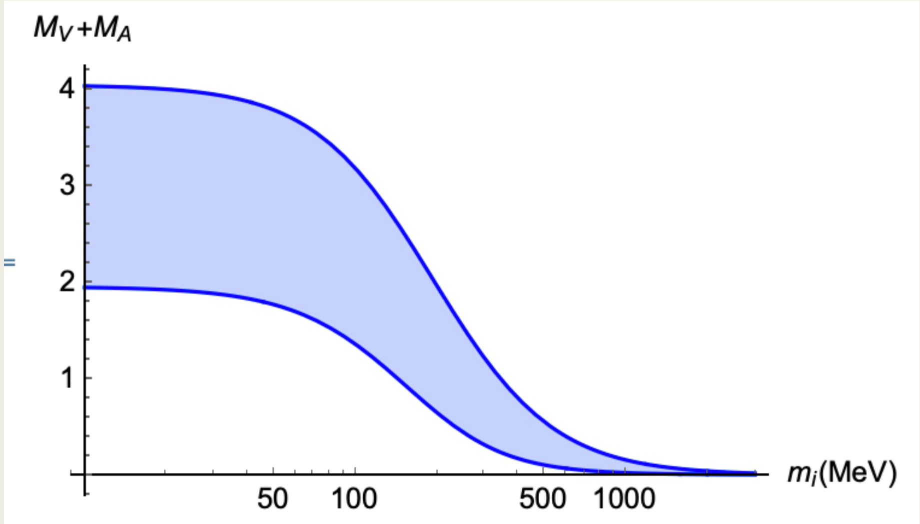
$$g_4^{\pi\pi} = -4 \frac{m_i^2 g_{\rm LR}^{\pi\pi}(m_i)}{F_\pi^2}\bigg|_{m_i \geq \Lambda_\chi}$$

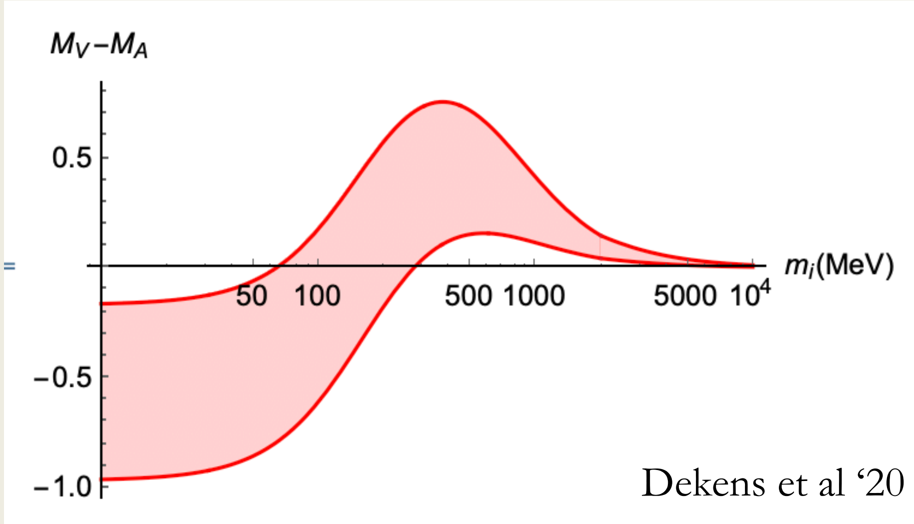
- **This requires a non-trivial mass dependence of LECs.**
- Dispersive (Knecht et al '98, Braaten et al '92) + matching to obtain the implicit m_i dependence of hadronic low-energy constants

Combine NMEs + LECs

Sterile neutrino interacts with mixing

Sterile neutrino interacts with mixing + right-handed BSM interactions





- Uncertainties from LECs and NMEs (similar sized)
- Non-trivial behaviour due to m_i dependence of QCD matrix elements
- `Standard mechanism' similar to previous interpolations Barea et al '15
- Non-standard mechanisms can show enhanced sensitivity to GeV neutrinos

Illustration of the framework

- Consider a simple toy-model 3+1 sterile (not realistic: 2 massless neutrinos)
- Too small 0vbb rates in minimal scenario
- Disclaimer: small neutrino regime $m_{\nu R}$<< MeV not too reliable perhaps

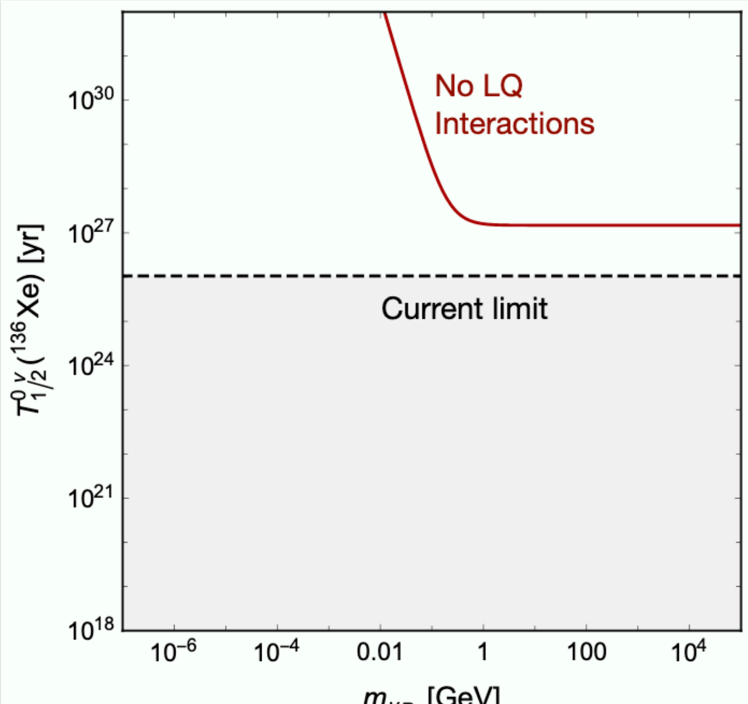


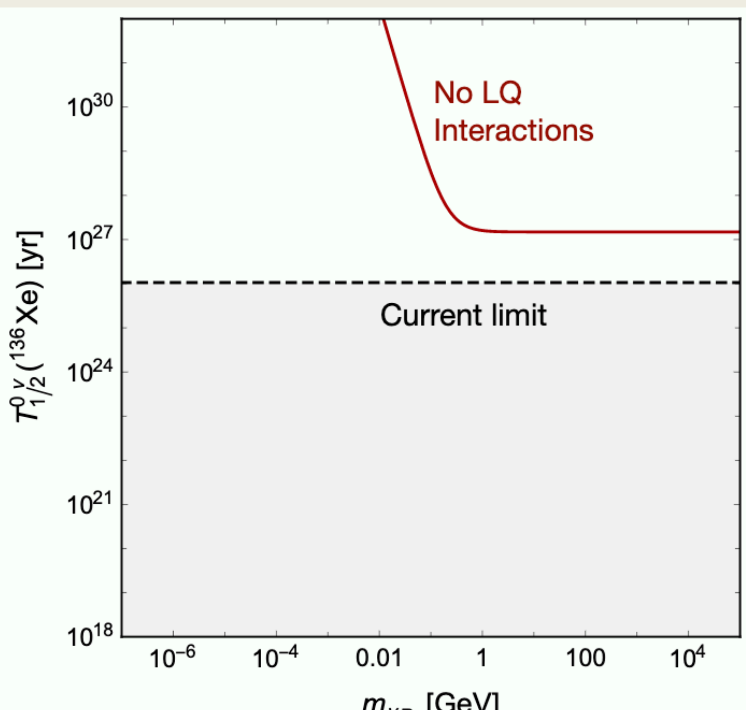
Illustration of the framework

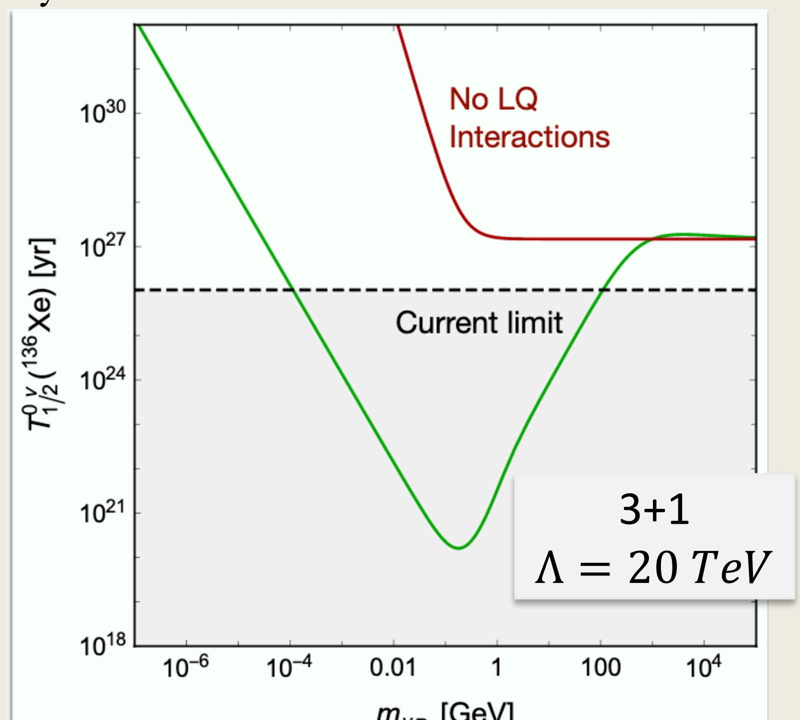
- Consider a simple toy-model 3+1 sterile (not realistic: 2 massless neutrinos)
- Too small 0vbb rates in minimal scenario
- Disclaimer: small neutrino regime $m_{\nu R}$<< MeV not too reliable perhaps
- Sensitivity to non-standard interactions ? Example: leptoquarks

$$\mathcal{L}^{(6)}_{\Delta L=0} = \frac{2G_F}{\sqrt{2}}\left[\bar{c}^{(6)}_{\substack{\mathrm{SR}\\ ea}}\, \bar{u}_L d_R \bar{e}_L \nu_{Ra} + \bar{c}^{(6)}_{\substack{\mathrm{T}\\ ea}}\, \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma^{\mu\nu} \nu_{Ra}\right]$$

$$\mathcal{L}_{\mathrm{LQ}} = -y^{\overline{RL}}_{ab}\, \bar{d}_{Ra} \tilde{R}^i \epsilon^{ij} L^j_{Lb} + y^{\overline{LR}}_{ab}\, \bar{Q}^i_{La} \tilde{R}^i \nu_{Rb}$$

- Just an illustration: can be matched to any non-standard interaction

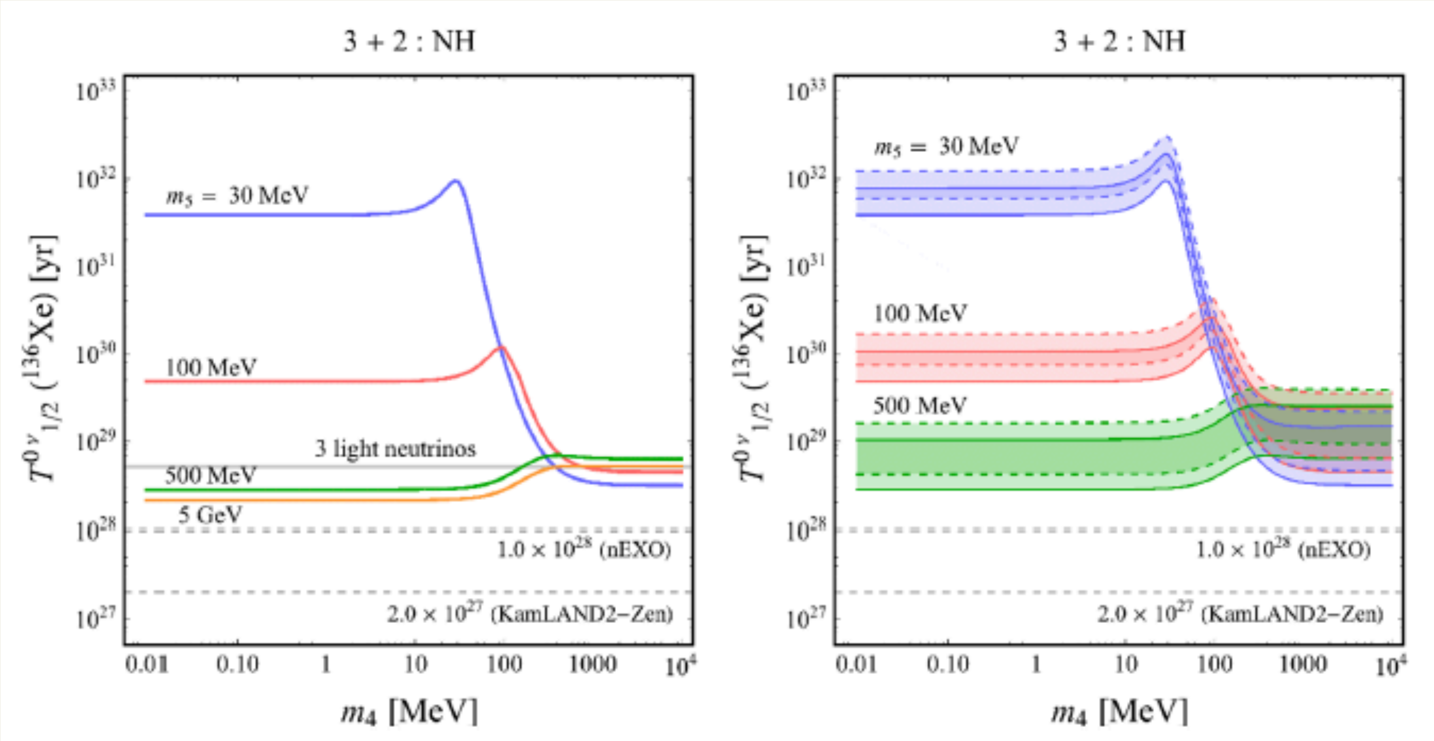




3+2 models

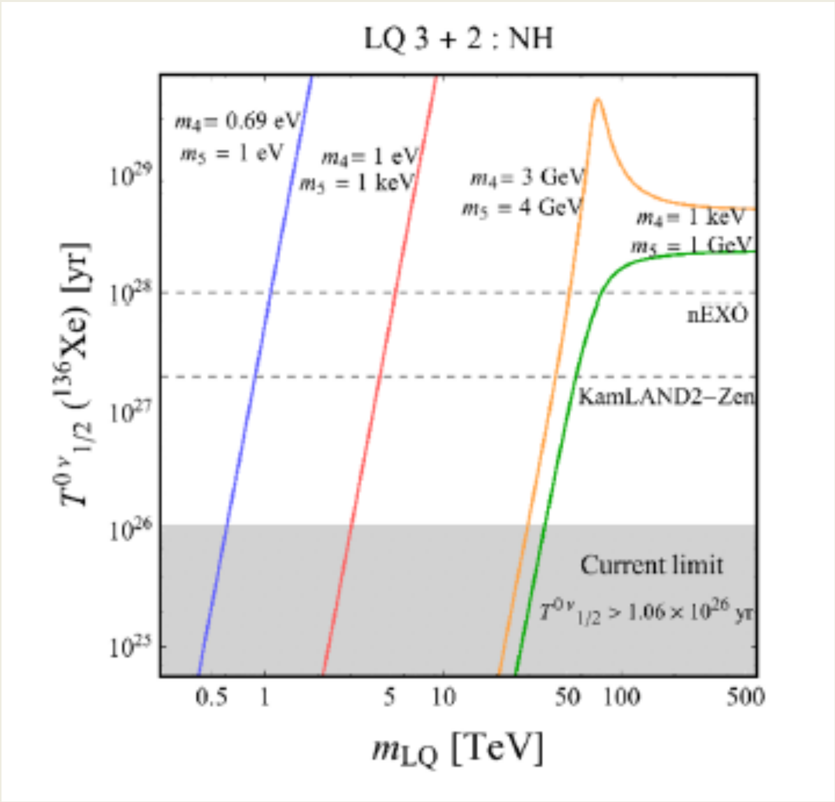
Donini et al '12
Dekens et al '20

- More realistic 3+2 model fitted to mass splitting and oscillation data
- Other angles/phases chosen as O(1) (no scan)



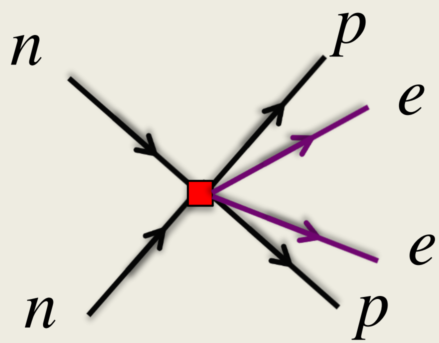
- In general, nEXO cannot probe minimal 3+2 models in NH

3+2 models + non-standard interaction



- Non-standard interactions at 10-100 TeV depending on sterile masses
- Framework is setup to study any model with light or heavy sterile neutrinos
- **Plan: make code public and provide ready-to-use tool**
- Useable in global analysis of νSMEFT with LHC/Cosmology/Flavor

Conclusion/Summary



Neutrinoless Double Beta Decay

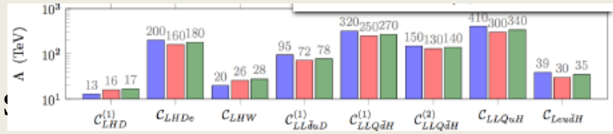
- ✓ Powerful search for BSM physics (probe high scales)
- ✓ Well motivated in order to probe nature of neutrino masses
- ✓ **However, complicated low-energy observable**

Standard Model EFT and chiral EFT frameworks

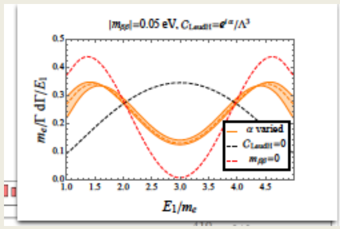
- ✓ Keep track of **symmetries** (gauge/lepton#/chiral) from Tev to nuclear scales
- ✓ Chiral EFT to organize neutrino potential in systematic fashion
- ✓ Light sterile neutrinos included but complicate matters!

Phenomenology

- ✓ Current experiments set very strong limits (>500 TeV in s

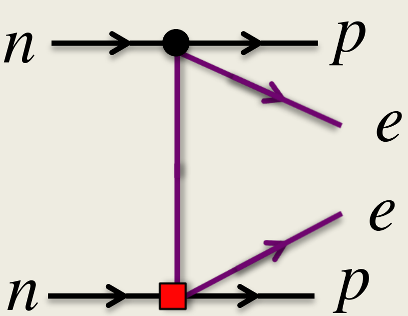


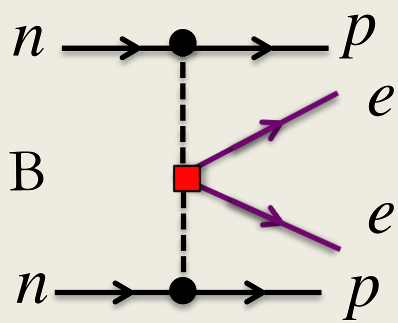
- ✓ Differential measurements can disentangle certain sources
- ✓ Sterile neutrinos at MeV-GeV scale lead to interesting pheno

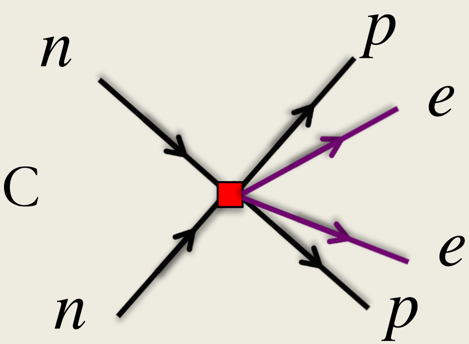


Derive the 'neutrino potential'

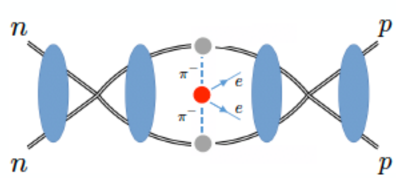
- Similar derivation for 'non-standard' LNV terms. More topologies:

A


B


C


- The long-range LECs are known pretty well. Short-distance not at all.
- Unfortunately, long-distance processes (A & B) are not physical by themselves



$$\sim m_N^2 \int d^3q\, d^3k \frac{1}{m_N E - \vec{q}^{\,2}} \frac{1}{(\vec{q}-\vec{k})^2} \frac{1}{m_N E' - \vec{k}^2}$$

- **Integrals are divergent and topology 'C' is always leading order !**
- See Vincenzo's slides from Monday for more details
- Higher-order corrections from: pion loops, N^2LO LECs, closure corrections