Neutrinoless Double-Beta Decay in Effective Field Theory

Jordy de Vries

"$0\nu\beta\beta$ in chiral EFT: LNV at dimension 7", 1708.09390, JHEP
"A new leading contribution to $0\nu\beta\beta$", 1802.10097, PRL
"A $0\nu\beta\beta$ master formula from effective field theory" 1806.02780, JHEP
"A renormalized approach to $0\nu\beta\beta$", arXiv:1904.xxxxx

With: V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa

Neutrinoless double beta decay in EFT

- Part I: **What is neutrinoless double beta decay and why bother?**

- Part II: An effective field theory approach: SM-EFT + chiral EFT

    1. Light Majorana mass (the Weinberg operator)
    2. Non-perturbative renormalization
    3. Higher-dimensional lepton number violation

The puzzle of the neutrino mass

- The Standard Model does not allow for a neutrino mass
- But of course neutrino oscillations ….. $P_{i\to j} \sim \sin^2\left(\frac{\Delta m_{ij} L}{2E}\right)$
- Easiest solution: add the gauge singlet ν_R and use Higgs mechanism

$$L_\nu = -y_\nu \, \bar{L}\tilde{\varphi}\nu_R + h.c. \rightarrow -\frac{y_\nu \, v}{\sqrt{2}}\bar{\nu}_L \nu_R \qquad y_\nu \sim 10^{-12} \quad \rightarrow m_\nu \sim 0.1\, eV$$

- Nothing wrong with this!

The puzzle of the neutrino mass

- The Standard Model does not allow for a neutrino mass
- But of course neutrino oscillations …..

$$P_{i\to j} \sim \sin^2\left(\frac{\Delta m_{ij} L}{2E}\right)$$

- Easiest solution: add the gauge singlet ν_R and use Higgs mechanism

$$L_\nu = -y_\nu \bar{L}\tilde{\varphi}\nu_R + h.c. \to -\frac{y_\nu\, v}{\sqrt{2}}\bar{\nu}_L \nu_R \qquad y_\nu \sim 10^{-12} \quad \to m_\nu \sim 0.1\, eV$$

- Nothing wrong with this! **But nothing forbids a new mass term !**

$$L_\upsilon = -M_R \nu_R^T C \nu_R \qquad M_R$$

New mass scale not linked to EW scale

- Diagonalize the neutrino mass matrix. If $M_R >> y_\nu v$

$$M_{diag} \approx \begin{pmatrix} (y_\nu v)^2 / M_R & 0 \\ 0 & M_R \end{pmatrix}$$

$$\nu = \nu_L + \nu_L^c \qquad\qquad N = \nu_R + \nu_R^c$$

Double beta decay with and without ν's

- Normal double beta decay (2νββ) has been observed

$$\left(A,Z\right)\to\left(A,Z+2\right)+2\,e^{-}+2\,\bar{\nu}_e$$

$$T_{1/2}^{2\nu}\left({}^{76}Ge\to{}^{76}Se\right)=\left(1.84^{+0.14}_{-0.10}\right)\times10^{21}\ yr$$

Gerda collaboration '15

- **Neutrinoless double beta decay (0νββ) looks similar**

$$\left(A,Z\right)\to\left(A,Z+2\right)+2\,e^{-}$$

Furry '39 $\Delta L=2$

- Violates Lepton Number by two units and **never been observed (yet) …**

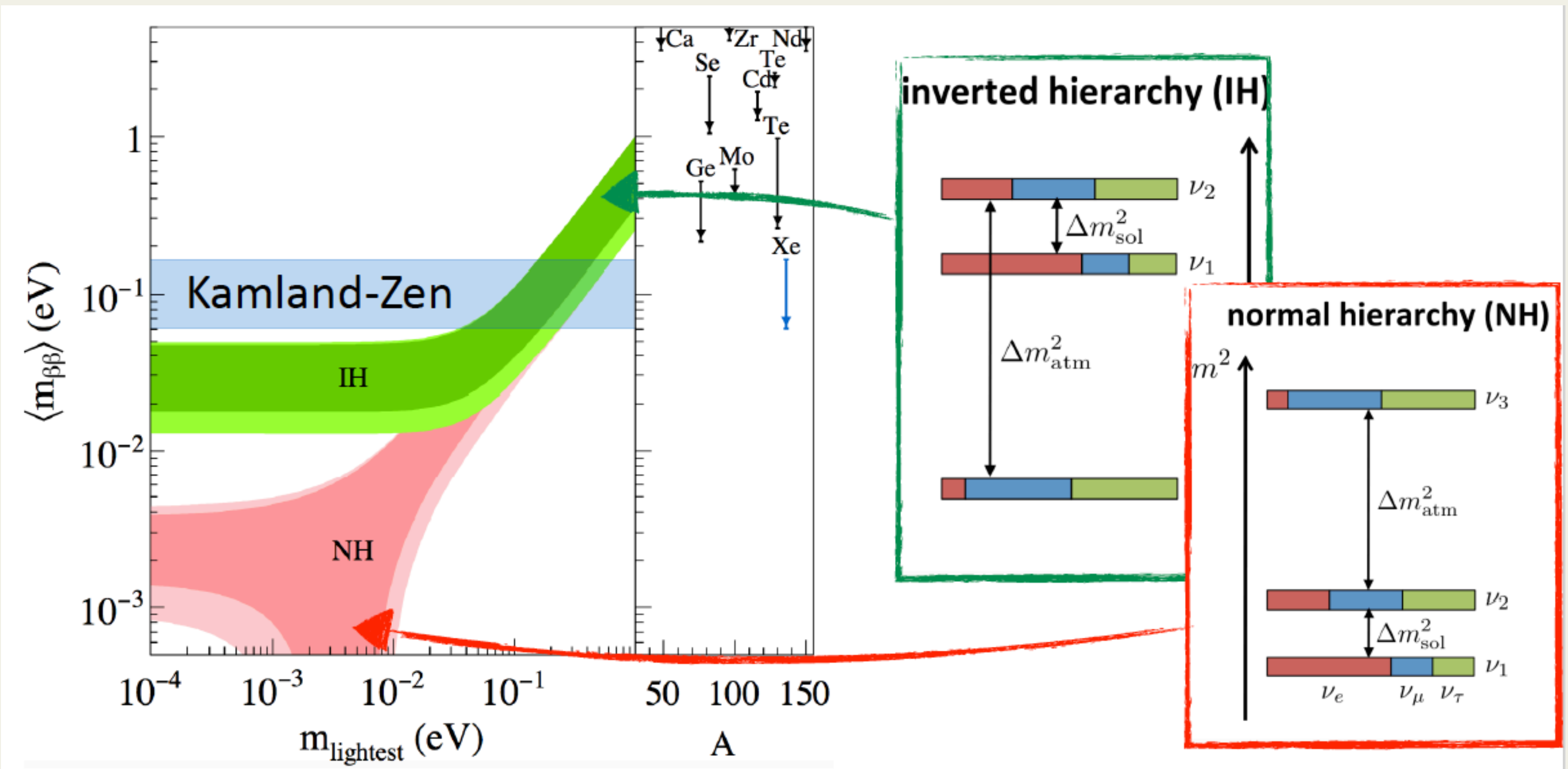
	Life time	Collaboration	year
^{76}Ge	8.0×10^{25} yr	GERDA	2018
^{130}Te	1.3×10^{25} yr	CUORE	2017
^{136}Xe	**1.1×10^{26} yr**	**KamLAND-Zen**	**2016**

Improvements upcoming

Standard interpretation

- **0νββ** induced by a light-neutrino exchange $m_{\beta\beta} = \sum U_{ei}^2 m_i$
- Function of neutrino masses + mixing angles + Majorana phases

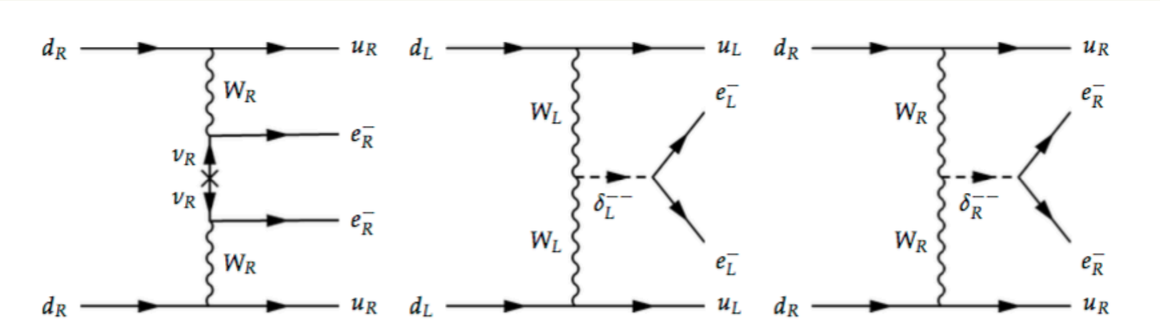
$$m_{\beta\beta} = m_{\nu 1} c_{12}^2 c_{13}^2 + m_{\nu 2} s_{12}^2 c_{13}^2 e^{2i\lambda_1} + m_{\nu 3} s_{13}^2 e^{2i(\lambda_2 - \delta_{13})}$$



- Interpretation of experimental results requires theory

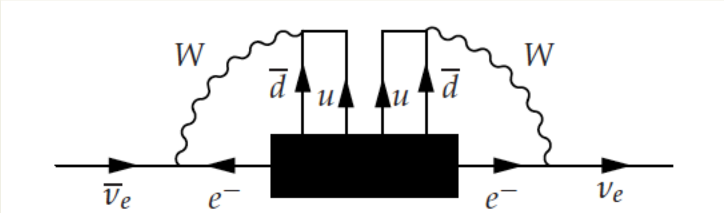
Non-Standard interpretation

- **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. Note **Schechter-Valle** theorem '82



The anatomy of the decay

- Decay can be roughly factorized into $$\frac{1}{T_{1/2}^{0\upsilon}} \sim m_{\beta\beta}^2 \cdot g_A^4 \cdot |M|^2 \cdot G$$

Energy

$> TeV$ $m_{\beta\beta}^2$ Lepton-number-violating (LNV) source
(not necessarily neutrino mass)

$\sim GeV$ g_A^4 Hadronic ME: quarks → hadrons (domain of ChPT and lattice-QCD)

$\sim 100 MeV$ $|M|^2 = \left|\left\langle 0^+ \middle| V_\upsilon \middle| 0^+ \right\rangle\right|^2$ Depends on 'neutrino-potential' (ChEFT) and many-body calculations

$\sim 10 MeV$ G Phase space factor, depends on Q value $\sim Q^5$
(of order 2-5 MeV for experimental targets)

This talk: neutrinoless double beta decay

- Part I: What is neutrinoless double beta decay and why bother?

- **Part II: An effective field theory approach: SM-EFT + chiral EFT**

  1. Light Majorana mass (the Weinberg operator)
  2. Non-perturbative renormalization
  3. Higher-dimensional lepton number violation

  -

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
- Consider the SM as an EFT $$L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$
- Contain SM fields only and obey SM gauge and Lorentz symmetry
- At energy E, operators of dimension (4+n) contribute as $\left(E/\Lambda\right)^n$
- **Gauge symmetry is restrictive: only 1 dim-5 operator** Weinberg '79

$$L_5 = \frac{c_5}{\Lambda}(L^T C\tilde{H})(\tilde{H}^T L) \qquad L^T = \left(\upsilon_L \; e_L\right) \qquad \Delta L = 2$$

- Majorana neutrino mass term after EWSB

$$m_\nu \sim eV \qquad \rightarrow \qquad \Lambda \sim c_5 \cdot 10^{14} GeV$$

Higher-order in the SM-EFT

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

Kobach '16

Dimension-five

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

- One operator
- Induces Majorana mass

Dimension-seven

Lehman '14

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

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

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

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

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

$6 : \psi^4 H + \text{h.c.}$	
$\mathcal{O}_{LLL\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L^i)(L^j C L^m) H^n$
$\mathcal{O}^{(1)}_{LLQ\bar{d}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L^i)(Q^j C L^m) H^n$
$\mathcal{O}^{(2)}_{LLQ\bar{d}H}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L^i)(Q^j C L^m) H^n$
$\mathcal{O}_{LL\bar{Q}uH}$	$\epsilon_{ij}(\bar{Q}_m u)(L^m C L^i) H^j$
$\mathcal{O}_{\bar{L}QQdH}$	$\epsilon_{ij}(\bar{L}_m d)(Q^m C Q^i)\tilde{H}^j$
$\mathcal{O}_{\bar{L}dddH}$	$(dCd)(\bar{L}d)H$
$\mathcal{O}_{\bar{L}uddH}$	$(\bar{L}d)(uCd)\tilde{H}$
$\mathcal{O}_{Leu\bar{d}H}$	$\epsilon_{ij}(L^i C\gamma_\mu e)(\bar{d}\gamma^\mu u) H^j$
$\mathcal{O}_{\bar{e}QddH}$	$\epsilon_{ij}(\bar{e}Q^i)(dCd)\tilde{H}^j$

- 12 ΔL=2 operators

Dimension-nine

Graesser '16
JdV et al '18

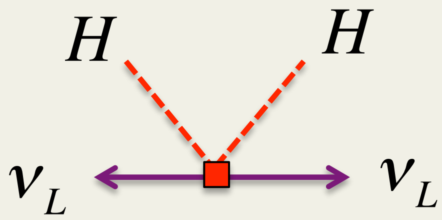
Full basis not known

19 4-quark 2-lepton operators after EWSB

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

- Various models (left-right symmetry, RPV SUSY) $c_5 << 1$ Prezeau et al '03
- 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

Crossing the electroweak scale



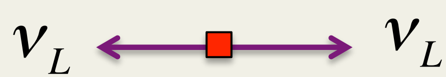
$$\frac{c_5}{\Lambda}(L^T C\tilde{H})(\tilde{H}^T L)$$

M_{EW}

100 GeV

Higgs takes vev

$$c_5\frac{v^2}{\Lambda}\nu_L^T C\nu_L$$



Neutrino Majorana Mass ~ dim-3

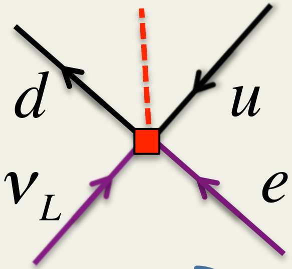
$\Lambda_\chi \sim 2\pi F_\pi$

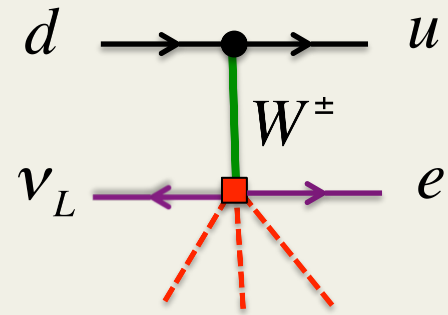
1 GeV

Integrate out 'hard' neutrinos and gluons/quarks

Match to effective hadronic operators

Dimension-7 operators

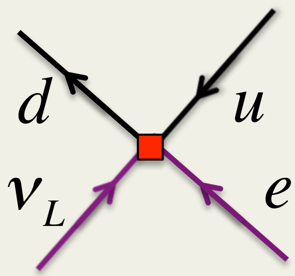




M_{EW}

100 GeV

Higgs takes vev + integrate out W bosons



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

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

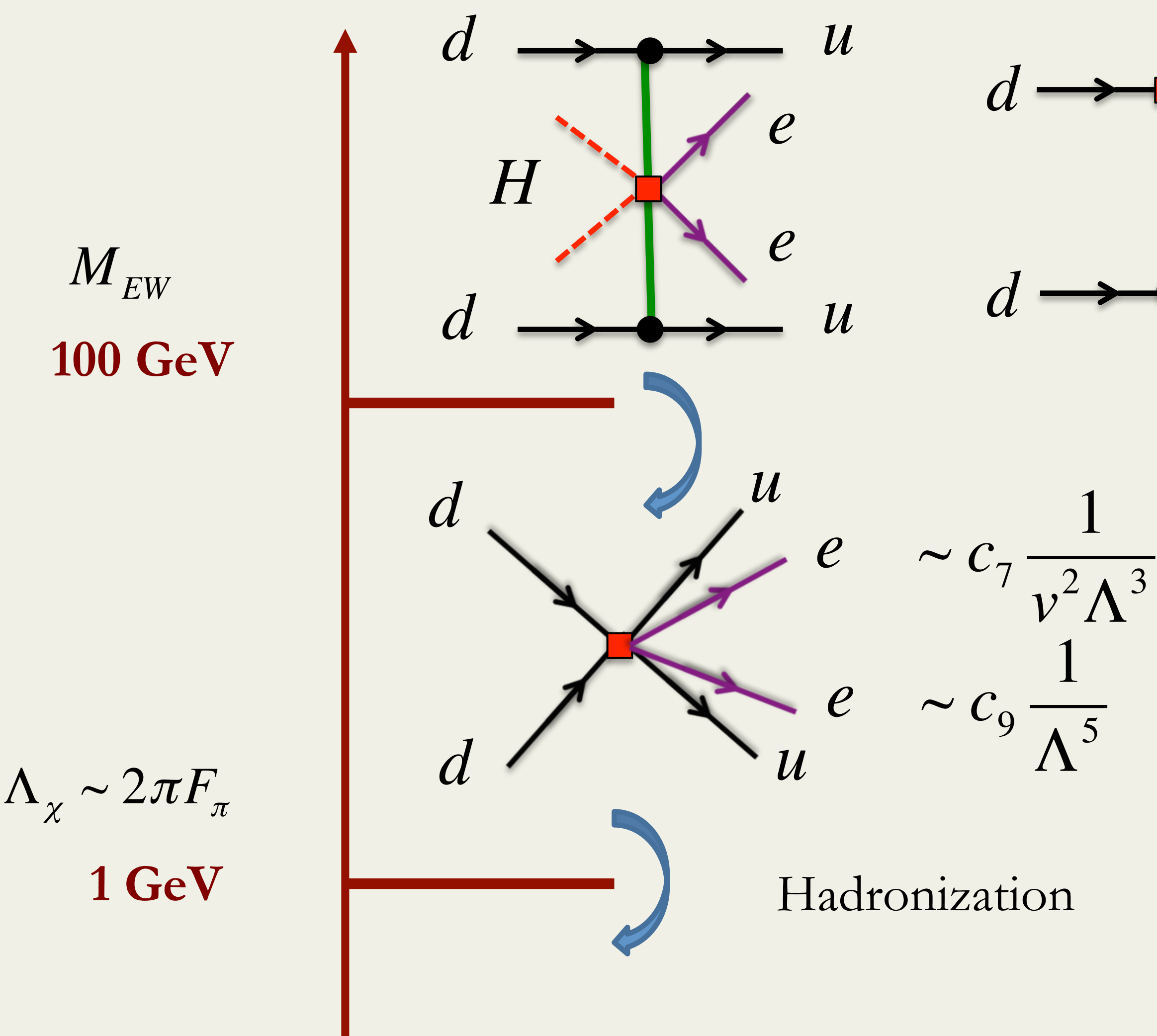
$\Lambda_\chi \sim 2\pi F_\pi$

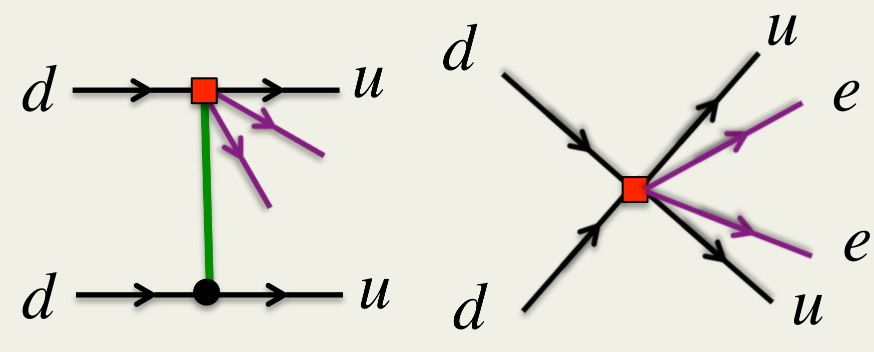
1 GeV

Hadronization

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

Dimension-9 operators





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

- Hadron-electron-electron couplings

Neutrinoless double beta decay in EFT

- Part I: What is neutrinoless double beta decay and why bother?

- Part II: An effective field theory approach: SM-EFT + chiral EFT

  1. **Light Majorana mass (the Weinberg operator)**

  2. Non-perturbative renormalization

  3. Higher-dimensional lepton number violation

Chiral effective field theory

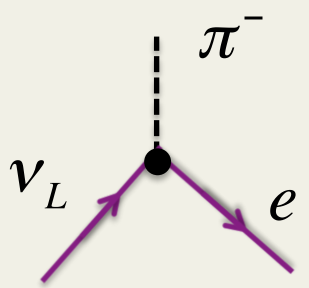
~ GeV $$L = L_{QCD} + L_{Fermi}$$

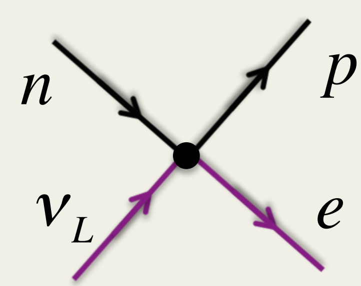
~100 MeV **LO strong:** $$L_\chi = L_{kin} - m_N \bar{N}N - \frac{1}{2} m_\pi^2 \pi^2 + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N$$

Weak interactions

Fermi **(F)** Gamow-Teller **(GT)**

$$L_{\chi,Fermi} = G_F f_\pi \left(\partial_\mu \pi^- \, \bar{e}_L \gamma^\mu \nu_L \right) + G_F \, \bar{p} \left(\gamma^\mu - g_A \gamma^\mu \gamma^5 \right) n \, \bar{e}_L \gamma^\mu \nu_L + \cdots$$





Chiral effective field theory

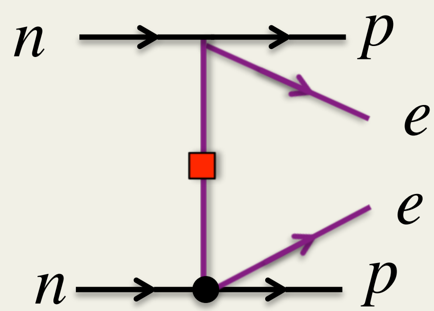
~ GeV $$L = L_{QCD} + L_{Fermi} - m_{\beta\beta}\nu_L^T C \nu_L$$

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

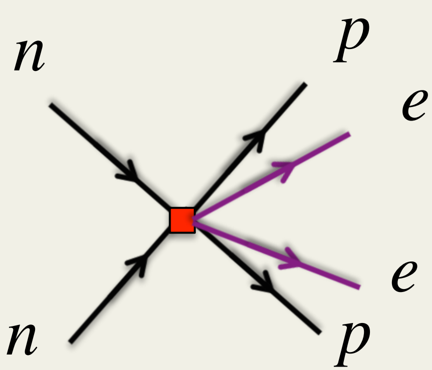
LO interaction : $\nu_L \longleftrightarrow \nu_L \quad \sim m_{\beta\beta}$

Leads to long-range nn→ pp + ee $\sim \dfrac{m_{\beta\beta}}{q^2}$

$$q \sim k_F \sim m_\pi$$



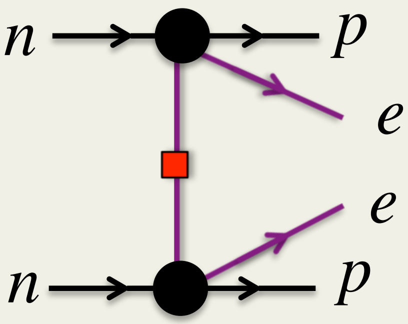
\`Hard' neutrino exchange $(E, |\vec{p}| > \Lambda_\chi)$ → short-range operators

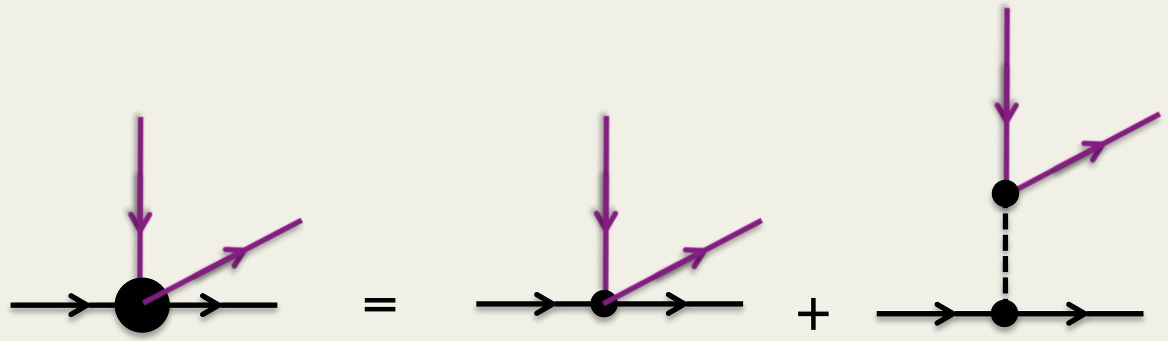


Expected at N²LO
(Weinberg counting or naïve dimensional analys) $\sim \dfrac{m_{\beta\beta}}{\Lambda_\chi^2}$

Majorana mass contribution

- Apply chiral EFT to construct a 'neutrino potential'
- **Standard mechanism: leading order**





$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\vec{q}^2}\left[1 - g_A^2\left(\vec{\sigma}_1\cdot\vec{\sigma}_2 - \vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}\,\frac{2m_\pi^2+\vec{q}^2}{(m_\pi^2+\vec{q}^2)^2}\right)\right] \otimes \bar{e}_L e_L^c$$

- LO long-range Coulomb-like potential $\sim 1/q^2$
- Close to 'standard' approach but no **Form Factors** or **Closure terms**
- All other contributions are higher order → **pretty simple at LO**

Quick look at higher orders

Cirigliano et al '17

- The EFT approach allows for systematic corrections

    1. Factorizable 'one-body' corrections (form factors)

$$g_A \longrightarrow g_A(q^2)$$

Quick look at higher orders

Cirigliano et al '17

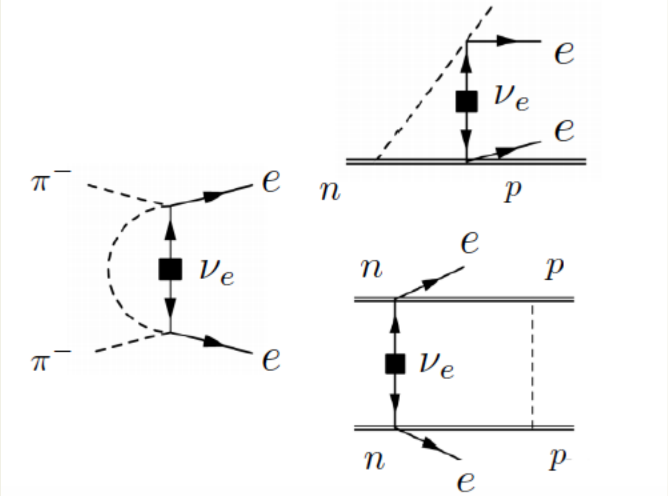
- The EFT approach allows for systematic corrections

1. Factorizable 'one-body' corrections

$$g_A \longrightarrow g_A(q^2)$$

2. New non-factorizable pieces

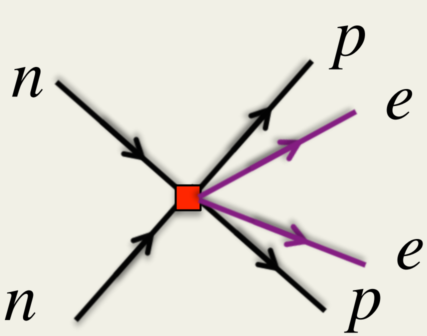
+ associated **counter terms**



Some diagrams are UV divergent…..

$$V_\nu^{N2LO} = \tau_1^+ \tau_2^+ \left(V_{loops,finite} + V_{UV} \log \frac{m_\pi^2}{\mu_{UV}^2} + V_{CT} \right) \quad \otimes \bar{e}_L e_L^c$$

- Counter terms appear at N²LO $\quad L_{CT} = C_\nu \left(\bar{p}n\right)\left(\bar{p}n\right) \quad \otimes \bar{e}_L e_L^c$
- Right size to absorb UV divergencies since loops bring factor $\quad \sim \dfrac{g_A^2 m_\pi^2}{(4\pi f_\pi^2)} \sim \dfrac{m_\pi^2}{\Lambda_\chi^2}$
- As expected: short-range at N²LO



Quick look at higher orders

Cirigliano et al '17

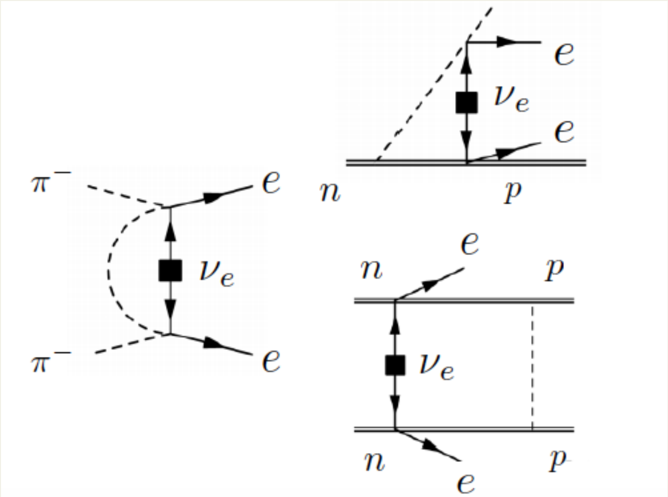
- The EFT approach allows for systematic corrections

  1. Factorizable 'one-body' corrections

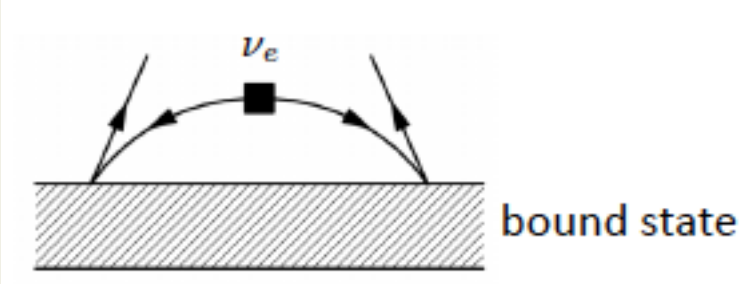
     $$g_A \longrightarrow g_A(q^2)$$

  2. New non-factorizable pieces

     + associated **counter terms**



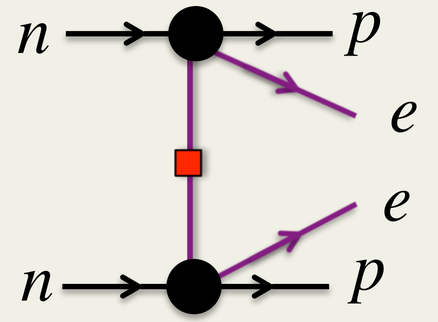
- Closure corrections from ultrasoft neutrino exchange
- Depends on **nuclear excited states**
- Appear at N^{2}LO ~ $\dfrac{(E_n - E_0)}{(4\pi k_F)} \sim \dfrac{q^2}{\Lambda_\chi^2}$



- Correspond to so-called 'closure corrections'

Review by Doi et al '83

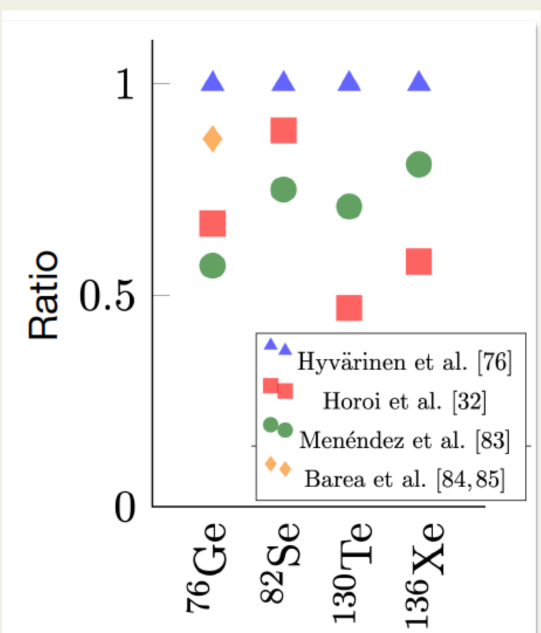
The neutrino amplitude



- At LO the 'standard' mechanism is long-range

$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\vec{q}^2}\left[1 - g_A^2\left(\vec{\sigma}_1\cdot\vec{\sigma}_2 - \vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}\,\frac{2m_\pi^2+\vec{q}^2}{(m_\pi^2+\vec{q}^2)^2}\right)\right]\otimes \bar{e}_L e_L^c$$

- All other corrections at least N^{2}LO ! Confirmed by many-body calculations
- **Different methods have roughly a factor 2 to 3 `many-body spread'**



Nuclear structure problem ?

QPRA (Hyvarinen/Suhonen '15)

Shell model (Horoi/Neacsu '17 & Menendez '18)

IBM (Barea et al '15 '18)

Or could there be other problem?

Back to the basics

- Size of short-range piece was estimated by perturbation theory (NDA)
- Let's test this by studying the most simple process: nn → pp +ee

"A new leading contribution to 0νββ", 1802.10097, PRL 120

Back to the basics

- Size of short-range piece was estimated by perturbation theory (NDA)
- Let's test this by studying the most simple process: nn → pp +ee

"A new leading contribution to 0νββ", 1802.10097, PRL 120

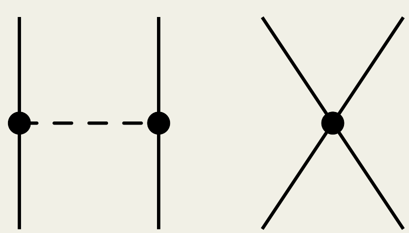
- First describe NN scattering by solving LS equation

$$T = V + VG_0T$$

- The potential calculated in **perturbation theory from chiral Lagrangian**
- Leading-order potential is simple (corrections discussed later)

$$L_\chi = L_{kin} - m_N \bar{N}N + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N + C_0 \, \bar{N}N\bar{N}N$$

LO



$$V^{^1S_0}_{strong}(LO) = C_0 - \frac{g_A^2}{4 f_\pi^2} \frac{m_\pi^2}{\vec{q}^{\,2} + m_\pi^2} + \cdots$$

Nucleon-nucleon scattering

- Need to ‘regulate’ the potential (physics should be regulator independent!)

$$V_{strong}^{{}^1S_0} = C_0 - \frac{g_A^2}{4 f_\pi^2} \frac{m_\pi^2}{\vec{q}^2 + m_\pi^2} \qquad V \to e^{-\frac{p^6}{\Lambda^6}} V \, e^{-\frac{p'^6}{\Lambda^6}} \qquad C_0(\Lambda)$$

$$T(p',p,E) = V(p',p) + \int dl \, V(p',l) \frac{l^2}{E - l^2/m_N + i\varepsilon} T(l,p)$$

- The counter term is fitted to low-energy data (**scattering lengths**)
- Predictions are made for nucleon-nucleon **phases shifts** (all energies)

Nucleon-nucleon scattering

- Need to 'regulate' the potential (physics should be regulator independent!)

$$V_{strong}^{{}^1S_0} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\vec{q}^{\,2}+m_\pi^2} \qquad V \to e^{-\frac{p^6}{\Lambda^6}}\, V\, e^{-\frac{p'^6}{\Lambda^6}} \qquad C_0(\Lambda)$$

$$T(p',p,E) = V(p',p) + \int dl\, V(p',l)\frac{l^2}{E - l^2/m_N + i\varepsilon}T(l,p)$$

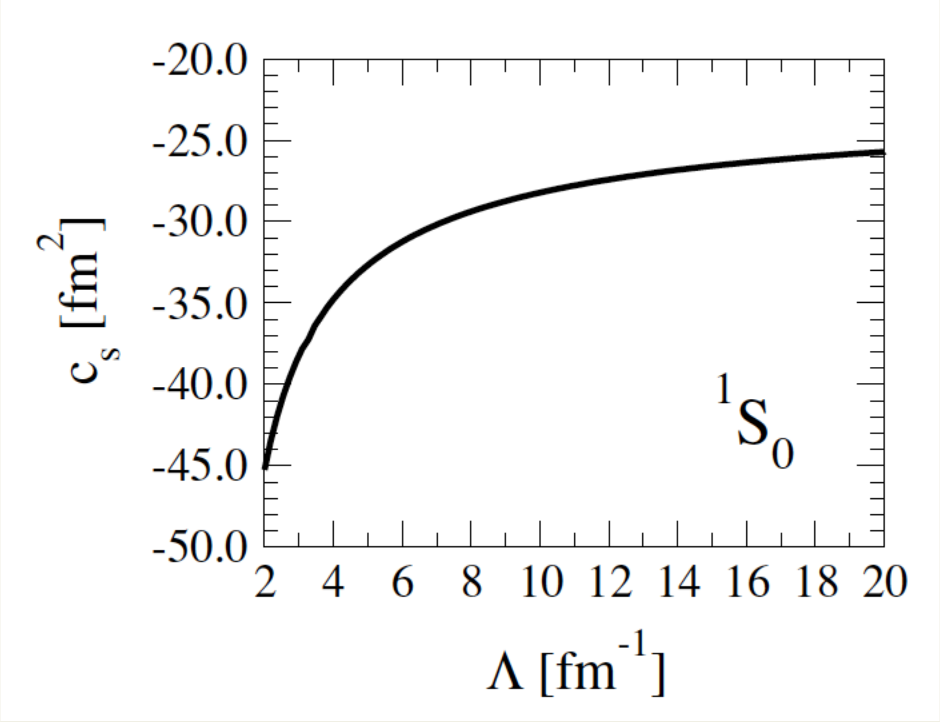
- The counter term is fitted to low-energy data (**scattering lengths**)
- Predictions are made for nucleon-nucleon **phases shifts** (all energies)

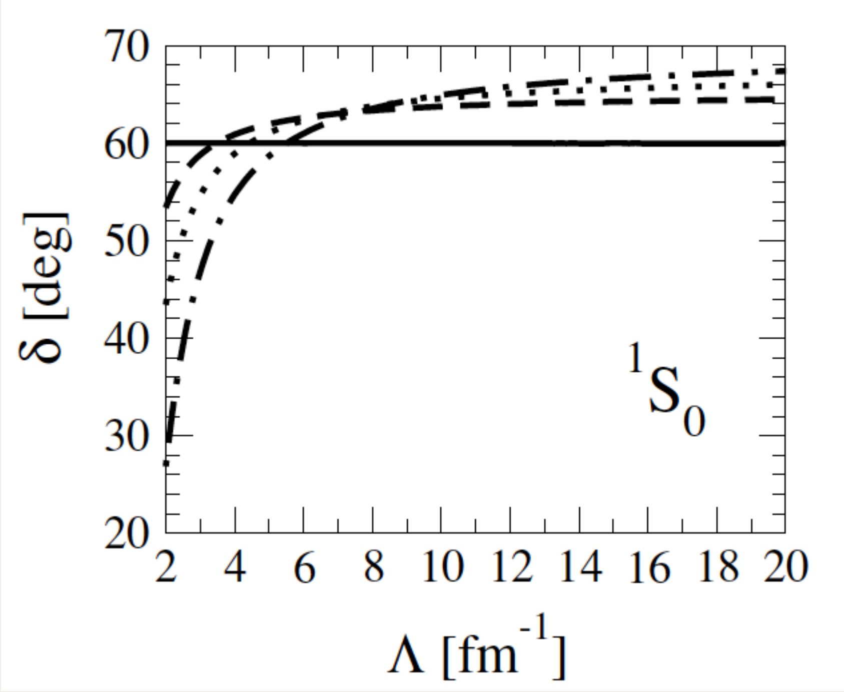
- Λ is a momentum cut-off. It should be $\Lambda \geq M_{high}$ so that we do not miss soft physics. **In practice** $\Lambda \cong M_{high}$ **is often useful.**
- **But one should check first that** $\Lambda >> M_{high}$ **can be taken in principle !!**

- Note: 3 different regulators used in actual calculations (dim-reg, coordinate space cut-off, momentum space cut-off)

Nucleon-nucleon scattering

- Counter term shows a logarithmic dependence on cut-off
- **But phase shifts are cut-off independent (for Lambda > 600 MeV)**





Fit to 10 MeV data

50 MeV

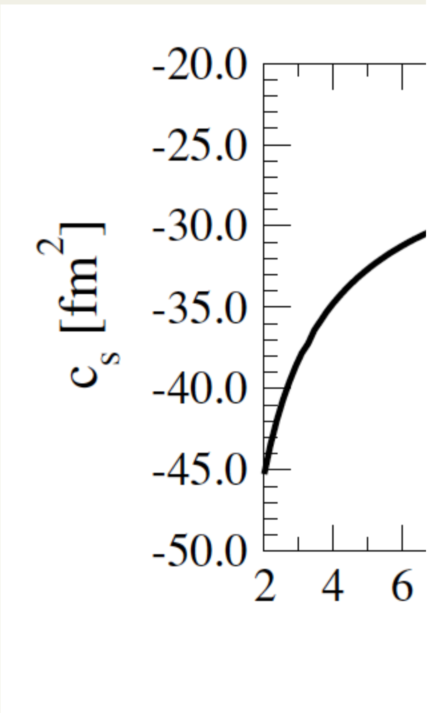
100 MeV

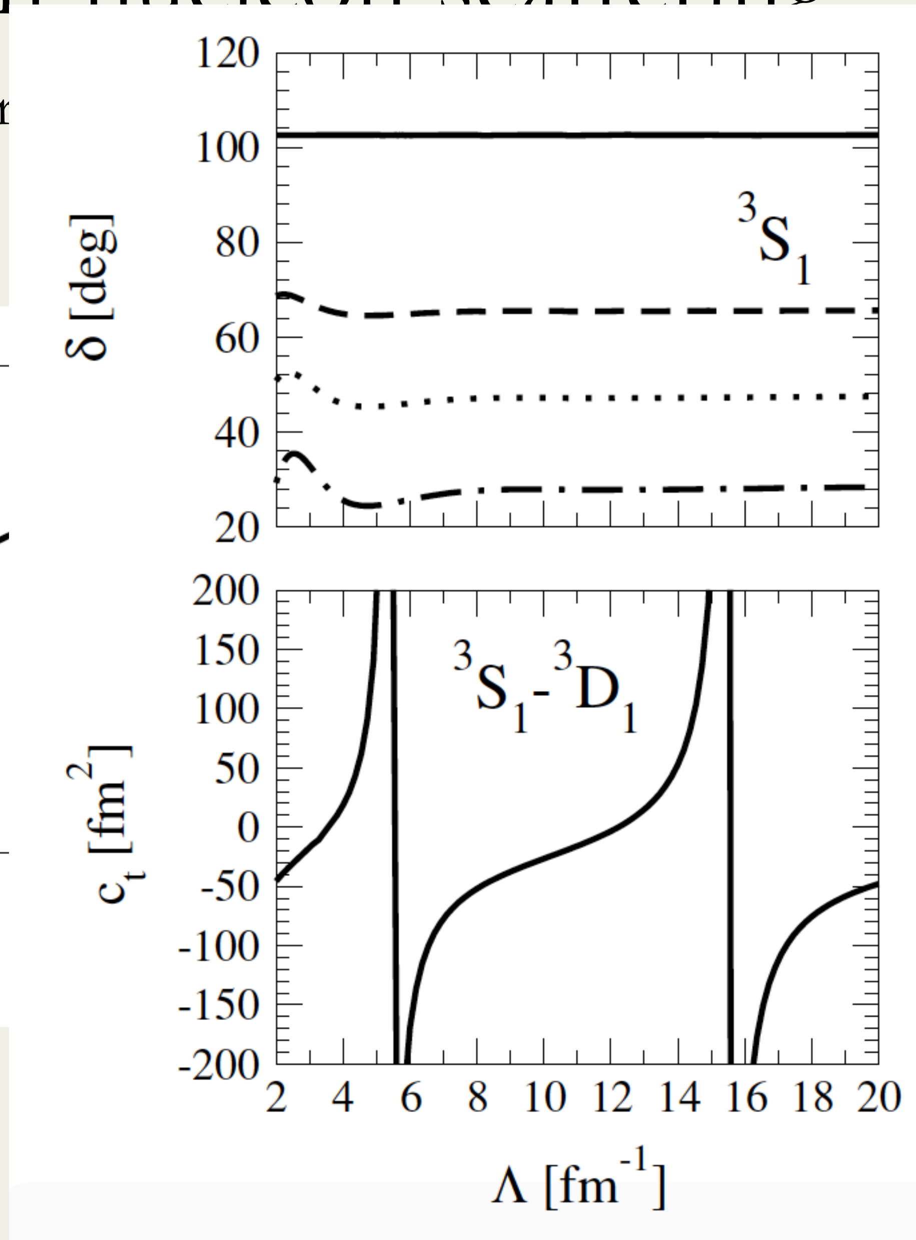
190 MeV

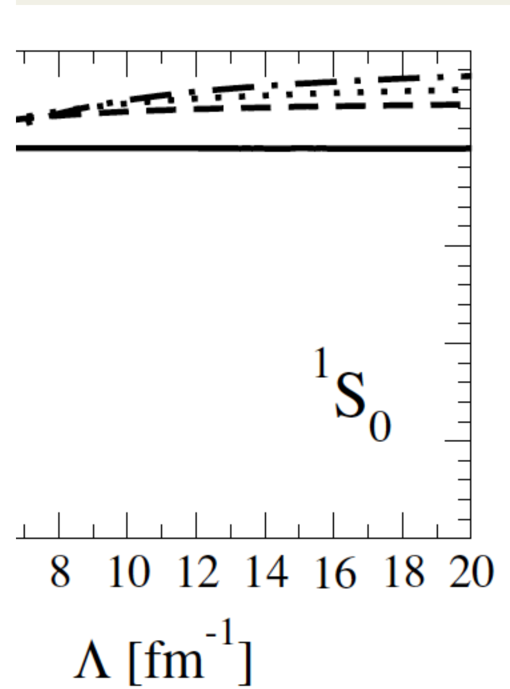
Nogga et al '05

Nucleon-nucleon scattering

- Counter ter… ut-off
- **But phase … ambda > 600 MeV)**



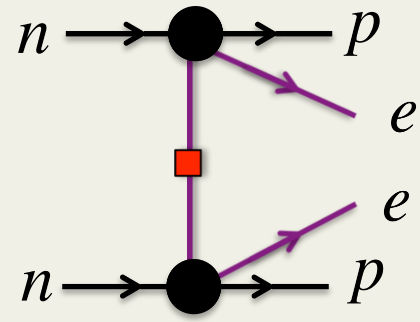




50 MeV
100 MeV
190 MeV

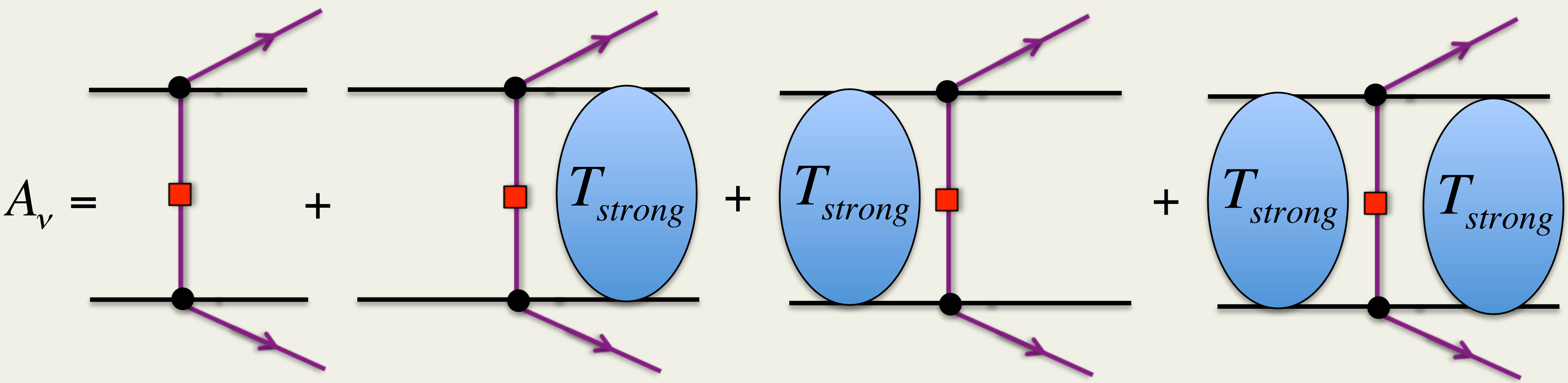
Nogga et al ‘05

The neutrino amplitude



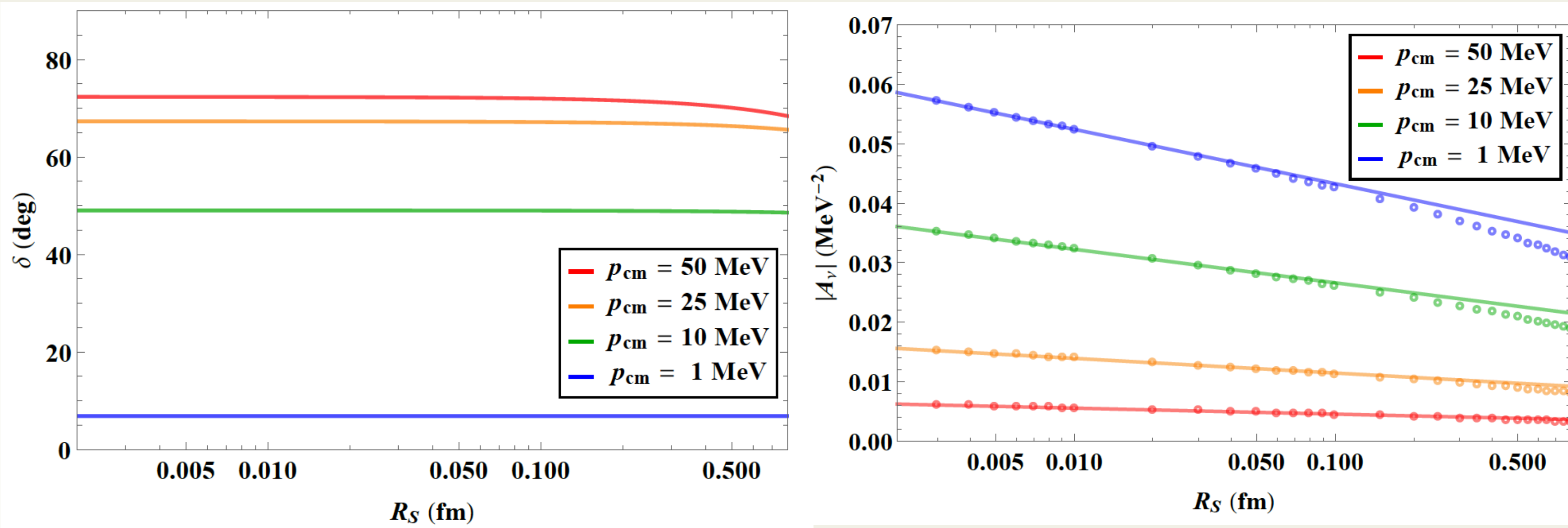
- Now insert the neutrino potential

$$A_\nu = V_\nu + V_\nu G_0 T_{LO} + T_{LO} G_0 V_\nu + T_{LO} G_0 V_\nu G_0 T_{LO}$$

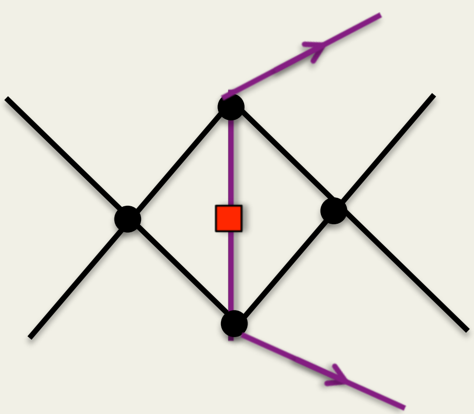


- **Can be measured in principle → should be independent of regulator !!**

The neutrino amplitude



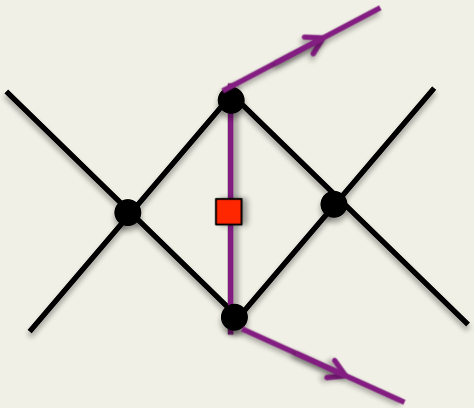
- But it is not... The amplitude depends logarithmically on the regulator.

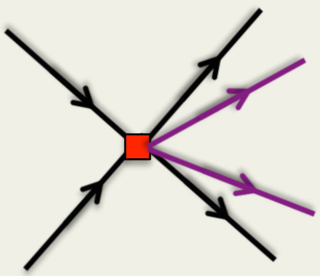


$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\varepsilon}+\log\frac{\mu^2}{p^2}\right)$$

Non-perturbative renormalization

- Now a divergence is nothing scary in an EFT calculation
- It just signals dependence on hard scales → need a counter term
- The surprising thing perhaps is that it violates NDA (but happens in other cases too)





$\sim g_\nu^{NN}$

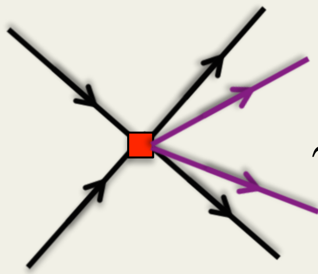
- Contact term comes with new LEC ~ QCD dynamics at $< \left(\Lambda_\chi\right)^{-1}$
- **Neutrino mass $m_{\beta\beta}$ not directly connected to decay rate**
- This is not expected to be a small correction ! **It is leading order !**

- **A counter term gets the job done though !**

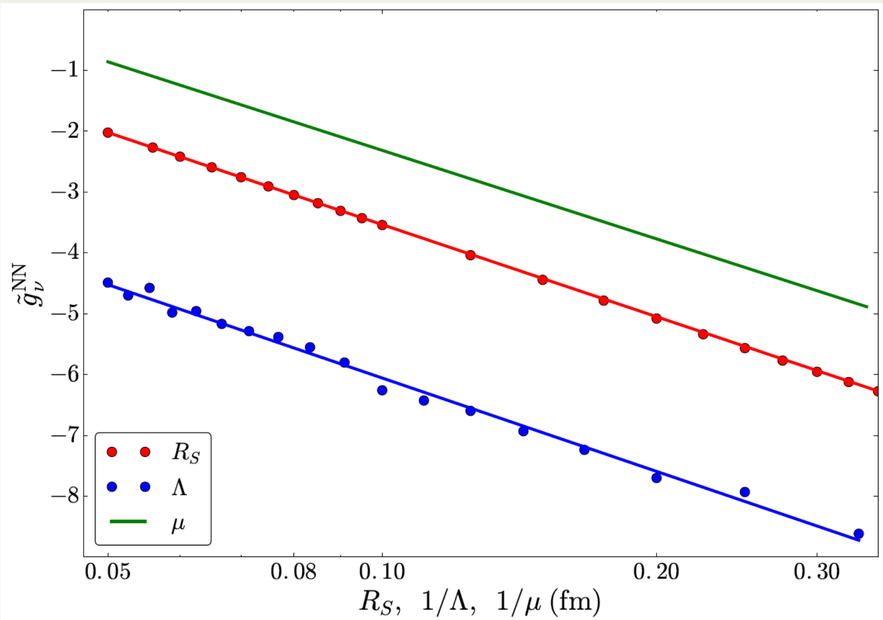
Non-perturbative renormalization

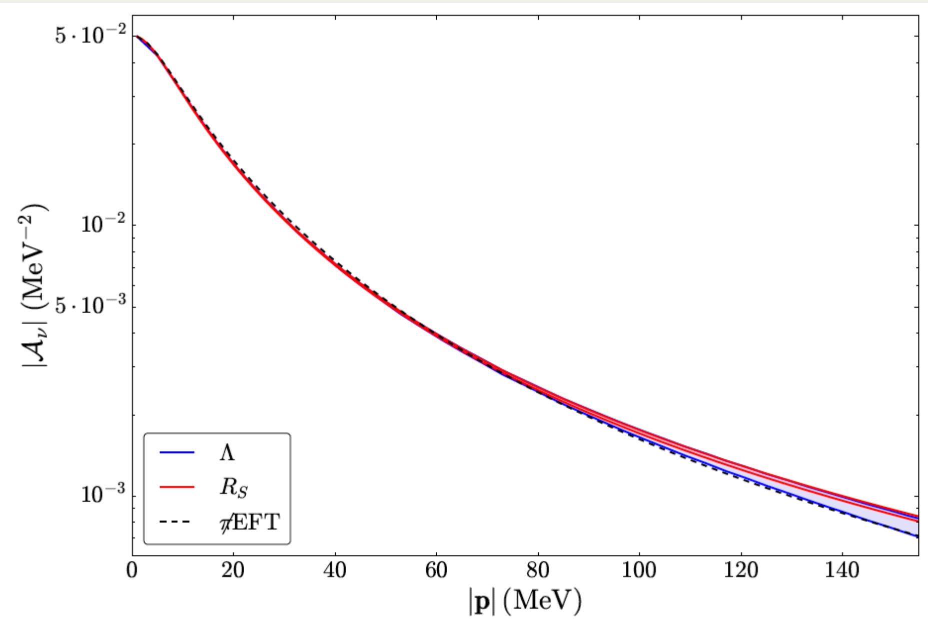
Fit the counter term to a 'measurement' at some kinematic point

$$\frac{1}{G_F^2 m_{\beta\beta}} A_\nu(p = 1\ MeV) = 0.05\ MeV^{-2}$$



$\sim g_\nu^{NN}$





Determining the counter term

- Can we determine the LEC of the counter term in absence of data ?

We have identified **two potential strategies to get** g_ν^{NN}

1. Lattice QCD calculations of nn → pp + ee (obvious but hard).
   Interesting progress on ππ→ ee

Nicholson et al '18, Feng et al '18

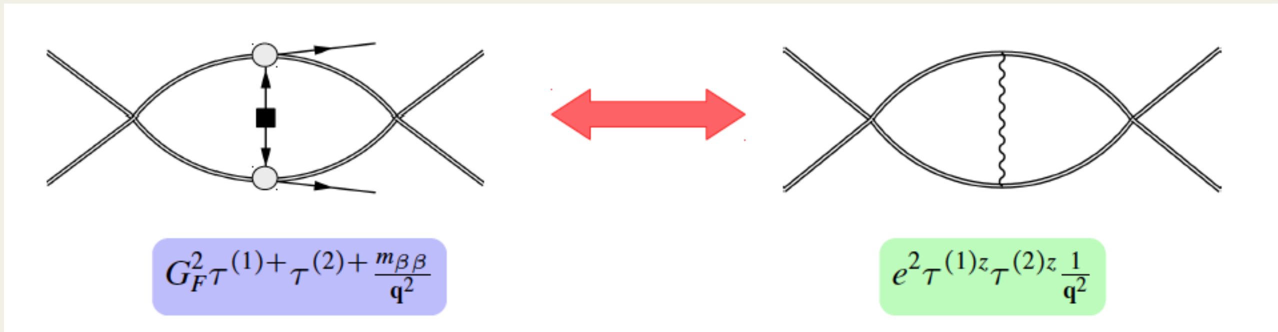
CAN THIS BE DONE ??

2. Chiral symmetry to connect to measured isospin-violating processes

- **Convincingly (IMO) demonstrates need for LO counterterm**
- **So far cannot give the full determination of** g_ν^{NN}

Using chiral symmetry

- The shape of the neutrino potential is very similar to photon exchange



- LO scattering of nn, pp, and np is the same
- EM and isospin-breaking changes the picture
- Dominant contributions from photon exchange + pion-mass splitting

$$V_{\mathrm{CIB}}^{^1S_0} = \frac{e^2}{4}\left(\tau_3^{(1)}\tau_3^{(2)} - \frac{1}{3}\boldsymbol{\tau}^{(1)}\cdot\boldsymbol{\tau}^{(2)}\right)\frac{1}{\mathbf{q}^2}\left\{1 + \frac{g_A^2}{F_\pi^2}\frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{e^2}\left(\frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2}\right)^2\right\}.$$

- **In Weinberg counting short-range operators at N²LO**

Waltz, Epelbaum, Meißner '01

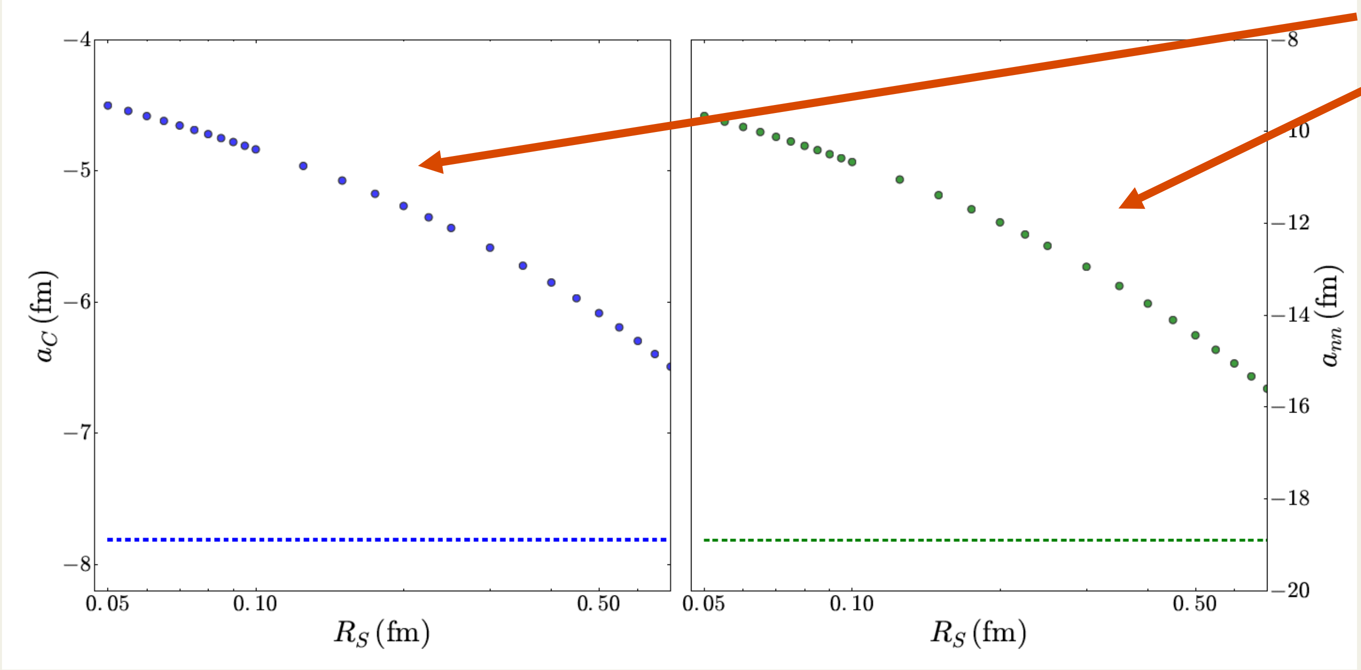
Charge-independence breaking

- So the idea is: we calculate the scattering lengths

$$a_{nn} \qquad a_{np} \qquad a_{pp}$$

- Weinberg counting: once LO strong counter term is fitted to a_{np} then $\mathbf{a_{nn}}$ **and $\mathbf{a_{pp}}$ are predicted. They should be cut-off independent**

Log dependence !!!



Charge-independence breaking

- So the idea is: we calculate the scattering lengths

$$a_{nn} \qquad a_{np} \qquad a_{pp}$$

- Weinberg counting: once LO strong counter term is fitted to a_{np} then **a_{nn} and a_{pp} are predicted. They should be cut-off independent**

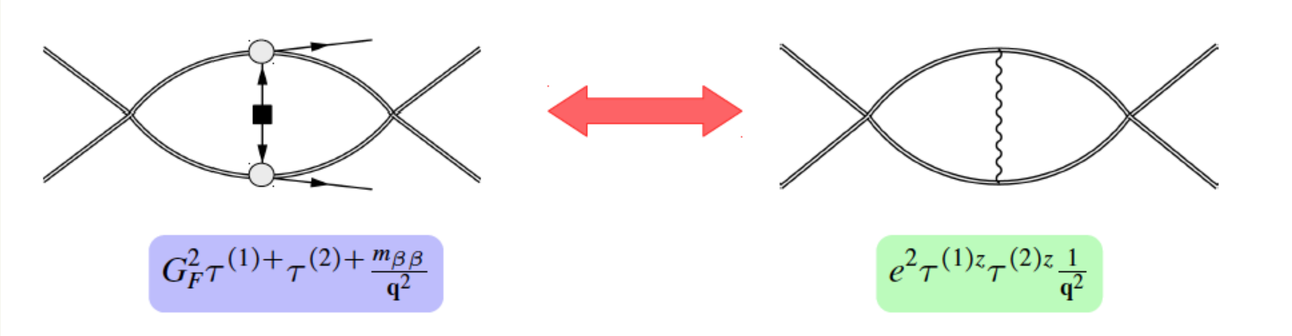
- We need to add a short-range CIB operator to describe data
- In fact: **high-quality potentials** include that term (also chiral ones)

$$C_{CIB} \sim fm^2 \sim O\left(\frac{1}{f_\pi^2}\right) >> O\left(\frac{1}{\Lambda_\chi^2}\right)$$

- Weinberg counting failure confirmed by data
- **Conclusion: Coulomb-like potentials in $^1S_0$-waves need counter terms**

A bit deeper

- The connection can be deepened



- Construct contact operators from EM I=2 operators

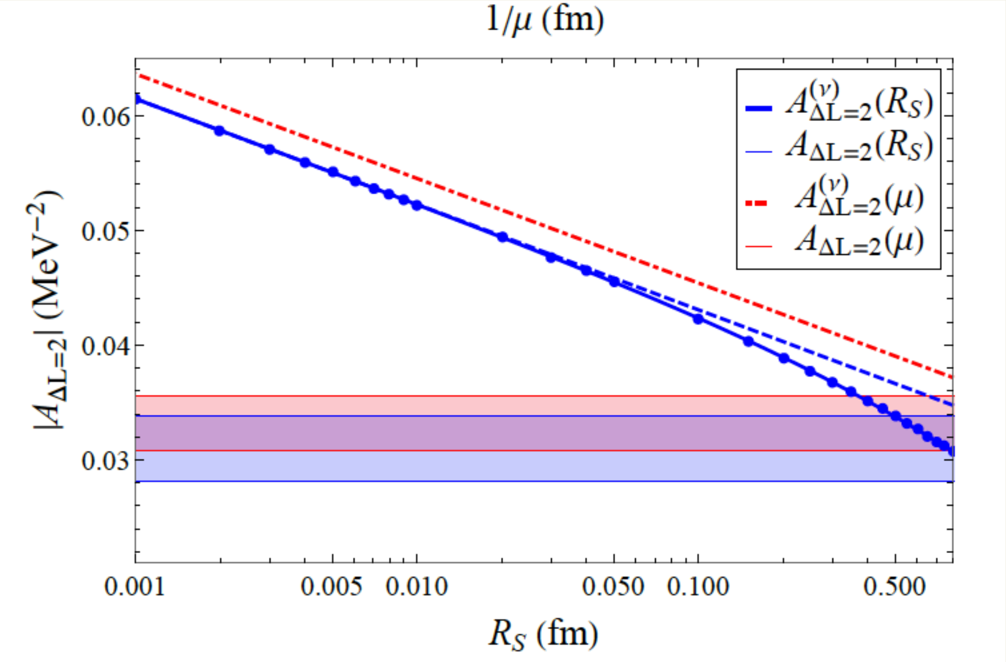
$$C_1\left(\bar{N}Q_L N\,\bar{N}Q_L N - \frac{Tr[Q_L^2]}{6}\bar{N}\vec{\tau}N\cdot\bar{N}\vec{\tau}N + L \leftrightarrow R\right) \qquad Q_{L,R} = u^\dagger Q_{L,R} u$$

$$C_2\left(\bar{N}Q_L N\,\bar{N}Q_R N - \frac{Tr[Q_L Q_R]}{6}\bar{N}\vec{\tau}N\cdot\bar{N}\vec{\tau}N + L \leftrightarrow R\right)$$

- **Fit to the CIB data gives us $C_1 + C_2$ for each value of regulator**
- for neutrinoless double beta we need $g_\nu^{NN} = C_2$
- For now we assume $C_1=C_2$ but this gives an **undetermined error**

Partial success

- Recalculate amplitude with modified neutrino potential including CT



Cirigliano et al, PRL '18

- Total amplitude is regulator independent: **data-driven !**
- For regulators R_S ~ (0.3-0.8) fm (Lambda ~ 0.4 – 1 GeV) about 20-30% corrections (**but based on $C_1=C_2$!!**)

- The effect is amplified in $\Delta I=2$ transitions

Ab initio calculations of light nuclei

- We study neutrinoless double beta decay in light nuclei Pastore et al, PRC '17

$$^{6}He \to {}^{6}Be + e + e \qquad {}^{12}Be \to {}^{12}C + e + e$$

- Wave functions from QMC calculations with chiral potential Piarulli et al, PRC '14
- The CIB counter term extracted from potential → $g_\nu^{NN} = C_{CIB}$
- **Study impact of short-range versus long-range neutrino potential**

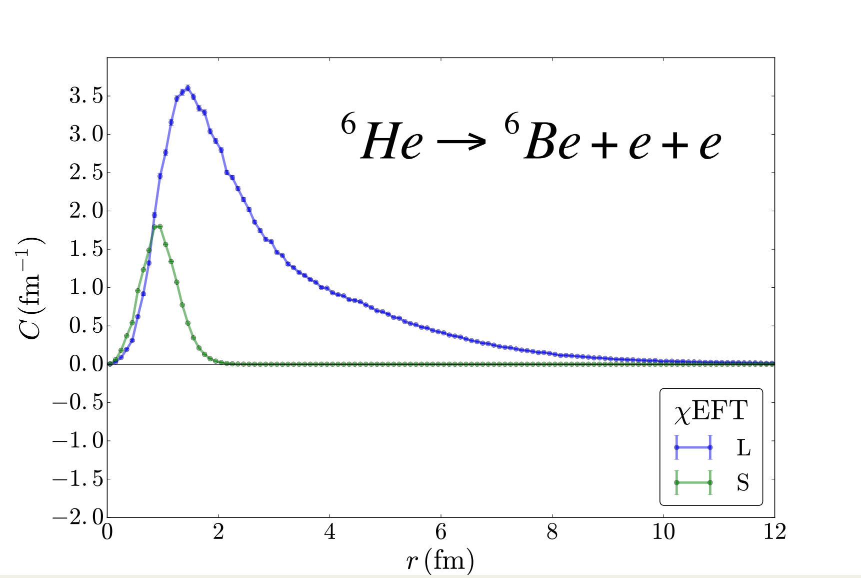
Dimensionless NME	Long range	Short range
$^{6}He \to {}^{6}Be + e + e$	7.8	1.2
$^{12}Be \to {}^{12}C + e + e$	0.7	0.55

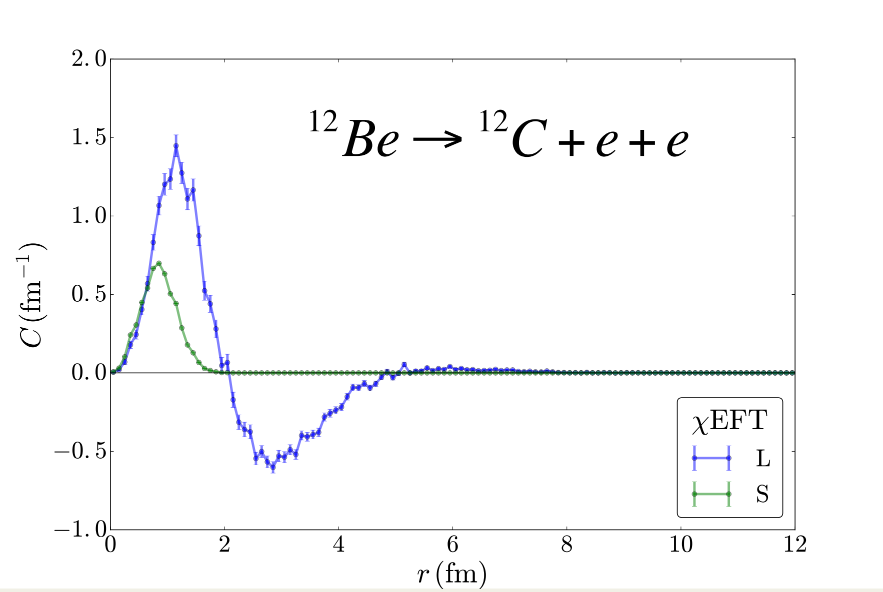
- **Confirms that new CT is bigger than N^2LO**
- In both cases significant but relatively much bigger for ^{12}Be
- We checked that other corrections are really N^2LO (few percent level)

Ab initio calculations of light nuclei

$$A_\nu = \int dr\, C(r) \qquad C(r) = C_{Long}(r) + C_{Short}(r)$$

Cirigliano et al, in prep





- ΔI=2 transitions: orthogonal initial and final-state wave functions
- Feature of all isotopes of experimetnal interest
- Node causes cancellation in the long-range matrix elements
- **All together: Strong evidence for significance of** g_ν^{NN}

Neutrinoless double beta decay in EFT

- Part I: What is neutrinoless double beta decay and why bother?

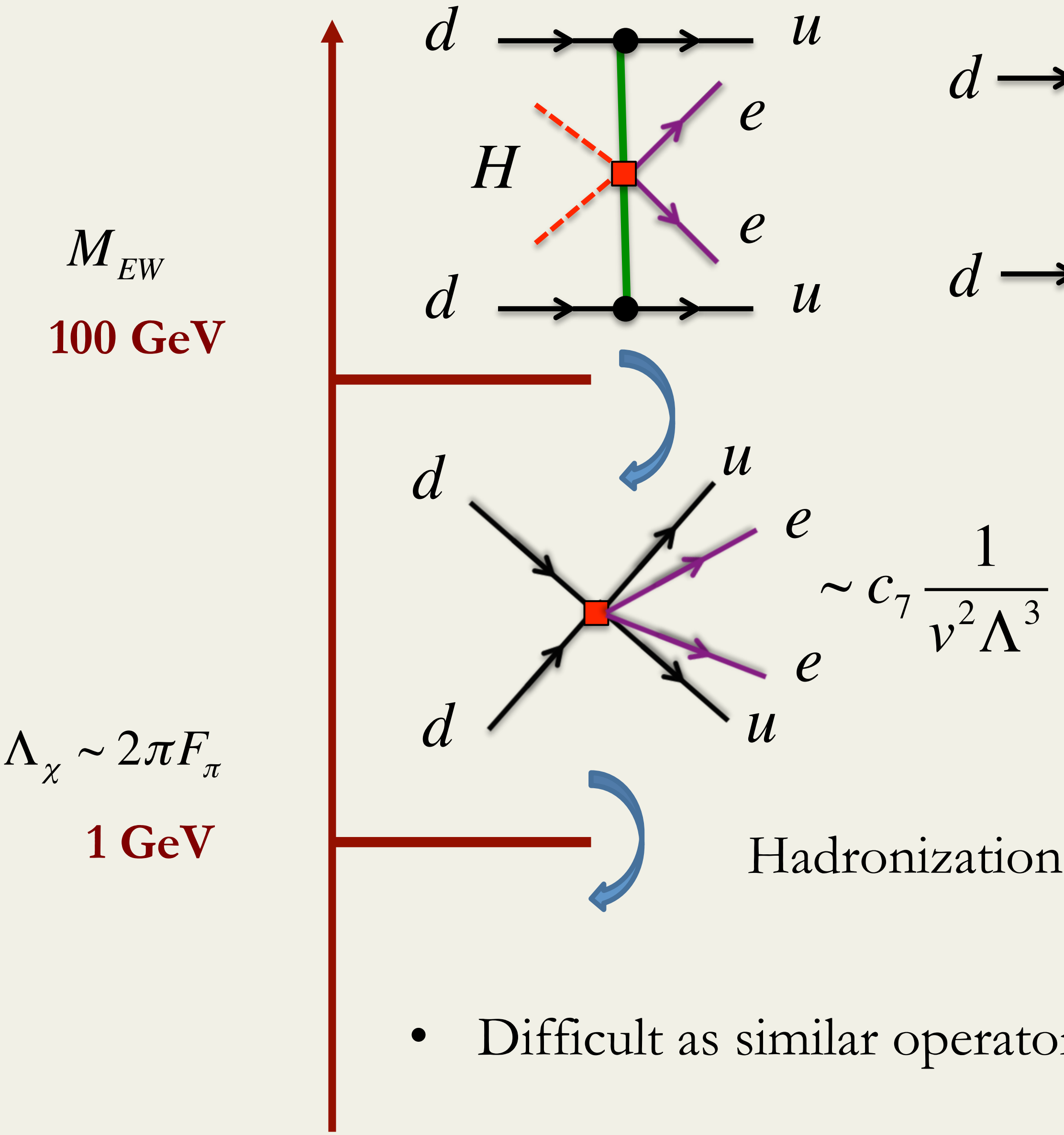
- Part II: An effective field theory approach: SM-EFT + chiral EFT

  1. Light Majorana mass (the Weinberg operator)

  2. Non-perturbative renormalization

  3. **Higher-dimensional lepton number violation**

Crossing the electroweak scale



- $0\nu\beta\beta$ operators ~ 'dim 9'
- Several operators with left- and/or right-handed quarks

- Difficult as similar operators not in 'standard' beta decay

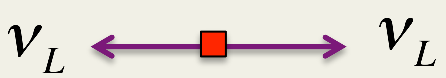
Chiral effective field theory

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

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

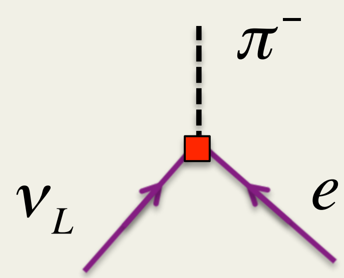
Prezeau et al '03
JdV et al '17 '18

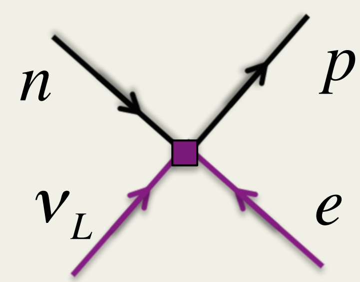
ΔL=2 Majorana mass



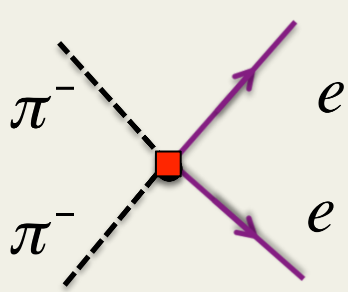
$\sim m_{\beta\beta}$

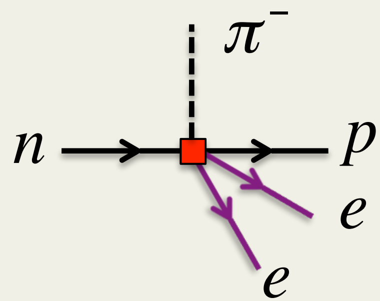
ΔL=2 beta decay

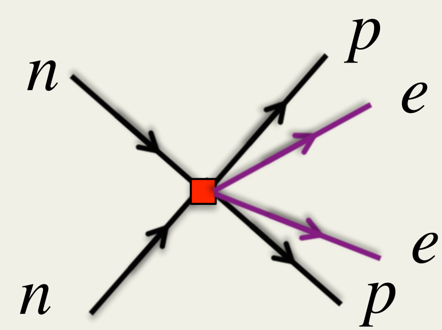




ΔL=2
'neutrinoless'

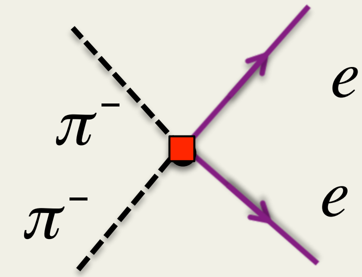






Higher-dimensional LNV sources

- Certain dim-7 and dim-9 LNV operators lead to
- Quite some nice lattice progress Nicholson et al '18

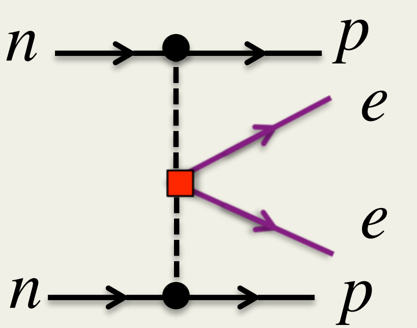


$\sim g_{1,2}$

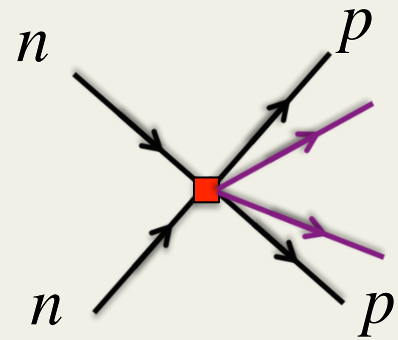
$$L^{(9)}_{\Delta L=2} = \left\{C_1^{(9)} \bar{u}_L \gamma^\mu d_L \ \bar{u}_L \gamma^\mu d_L + C_4^{(9)} \bar{u}_L \gamma^\mu d_L \ \bar{u}_R \gamma^\mu d_R \right\} \frac{\bar{e}_L e_L^c}{v^5}$$

$$g_1 = -(1.9 \pm 0.2)\, GeV^2 \qquad g_2 = -(8 \pm 0.6)\, GeV^2$$

- In Weinberg Counting the LO neutrino potential becomes



$$\sim \frac{1}{q^2 + m_\pi^2}$$



- Same UV behaviour as light-neutrino exchange → Need a LO counter term
- But in many cases the LECs were poorly known anyway ....

Higher-dimensional LNV sources

- Ce… $\sim g_{1,2}$
- Qu…

$L^{(9)}_{\Delta L}$ …

- In …

n …

n- …

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

- Sar… …nter term
- But in many cases the LECs were poorly known anyway ....

Many-body uncertainties for SM-EFT

- At LO we require 9 combinations of NMEs (much less then normally calculated)
- All required NMEs can be lifted from existing literature

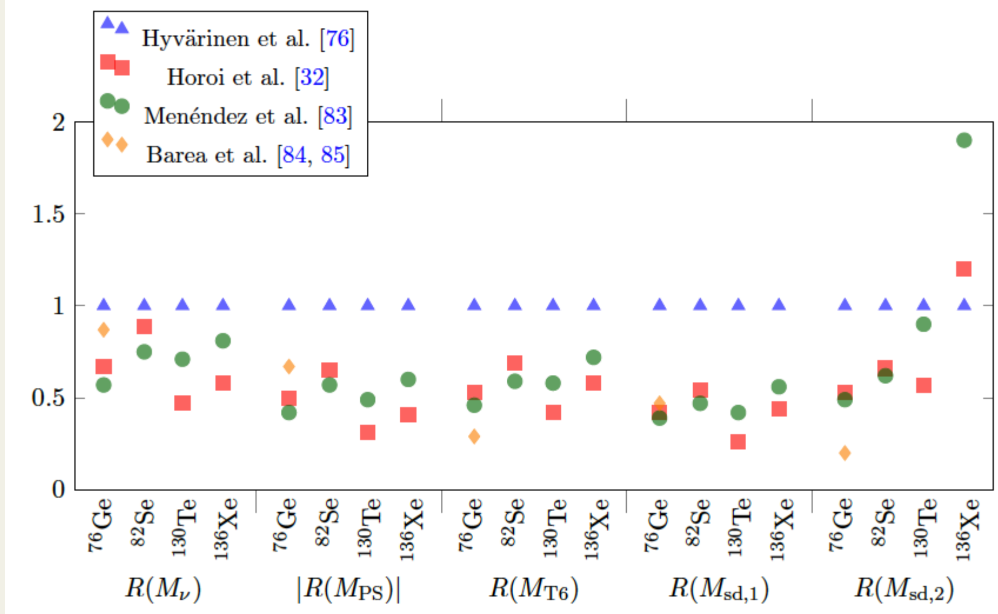
- **Uncertainties similar to standard scenario**

- Use chiral symmetry arguments for consistency checks

NMEs	^{76}Ge			
	[74]	[31]	[81]	[82, 83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_{T}^{AA}	–	–	–	
M_{T}^{AP}	-0.35	0.01	-0.01	
M_{T}^{PP}	0.10	0.00	0.00	
M_{T}^{MM}	-0.04	0.00	0.00	

Hyvarinen/Suhonen ’15
Menendez et al ’17 ‘18
Barea et al ‘15 ’18
Horoi/Neacsu ‘17

NMEs	^{76}Ge			
$M_{F,\,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,\,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,\,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,\,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,\,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,\,sd}^{PP}$	0.32	0.00	0.02	0.38



Redundancies

- The dozens of NMEs calculated only differ by **partial** N2LO corrections
- Many are redundant at LO !

- EFT predicts LO relations between NMEs

$$M^{PP}_{GT,sd} = -\frac{1}{2}M^{AP}_{GT,sd} - M^{PP}_{GT}\,, \qquad M^{PP}_{T,sd} = -\frac{1}{2}M^{AP}_{T,sd} - M^{PP}_{T}\,,$$

$$M^{AP}_{GT,sd} = -\frac{2}{3}M^{AA}_{GT,sd} - M^{AP}_{GT}\,, \qquad M^{MM}_{GT} = \frac{g_M^2 m_\pi^2}{6g_A^2 m_N^2}M^{AA}_{GT,sd}\,,$$

- **Hold up to 10% corrections for different many-body methods !**
- Used to find sign/factor 2 mistakes in literature

$$H_{GTN} = \frac{2R}{\pi m_e m_p}\int h_A^2(q^2) j_0(qr) q^2\, dq\,, \qquad (20d)$$

$$H_{GT'} = \frac{2R^2}{\pi m_p}\int \frac{q^2 h_A^2(q^2)}{q(q+\bar{E})} j_0(qr) q^2\, dq\,, \qquad (20e)$$

$$H_{GT''} = \frac{2R^3}{\pi m_p}\int \frac{q^2 h_A^2(q^2)}{q+\bar{E}} j_0(qr) q^2\, dq\,, \qquad (20f)$$

$$H_{GT\pi\nu} = \frac{2R}{\pi}\int \frac{h_{GT\pi\nu}^2(q^2)}{q(q+\bar{E})} j_0(qr) q^2\, dq\,, \qquad (20g)$$

$$H_{GT1\pi} = -\frac{2R}{\pi}\int h_A^2(q^2)\frac{q^2/m_\pi^4}{1+q^2/m_\pi^2} j_0(qr) q^2\, dq\,, \qquad (20h)$$

$$H_{GT2\pi} = -\frac{4R}{\pi}\int h_A^2(q^2)\frac{q^2/m_\pi^4}{(1+q^2/m_\pi^2)^2} j_0(qr) q^2\, dq\,, \qquad (20i)$$

$$H_F = \frac{2R}{\pi}\int \frac{h_V^2(q^2)}{q(q+\bar{E})} j_0(qr) q^2\, dq\,, \qquad (20j)$$

$$H_{F\omega} = \frac{2R}{\pi}\int \frac{h_V^2(q^2)}{(q+\bar{E})^2} j_0(qr) q^2\, dq\,, \qquad (2$$

$$H_{Fq} = \frac{2R}{\pi} r\int \frac{h_V^2(q^2)}{q+\bar{E}} j_1(qr) q^2\, dq\,, \qquad ($$

$$H_{FN} = \frac{2R}{\pi m_e m_p}\int h_V^2(q^2) j_0(qr) q^2\, dq\,, \qquad (2$$

$$H_{F'} = \frac{2R^2}{\pi m_p}\int \frac{q^2 h_V^2(q^2)}{q(q+\bar{E})} j_0(qr) q^2\, dq\,, \qquad (20n)$$

$$H_T = -\frac{2R}{\pi}\int \frac{h_T^2(q^2)}{q(q+\bar{E})} j_2(qr) q^2\, dq\,, \qquad (20o)$$

$$H_{Tq} = \frac{2R}{3\pi}\sqrt{\frac{2}{3}}\, r C^{(2)}(\hat{\mathbf{r}})\int \frac{h_A^2(q^2)}{q+\bar{E}} j_1(qr) q^2\, dq\,, \qquad (20p)$$

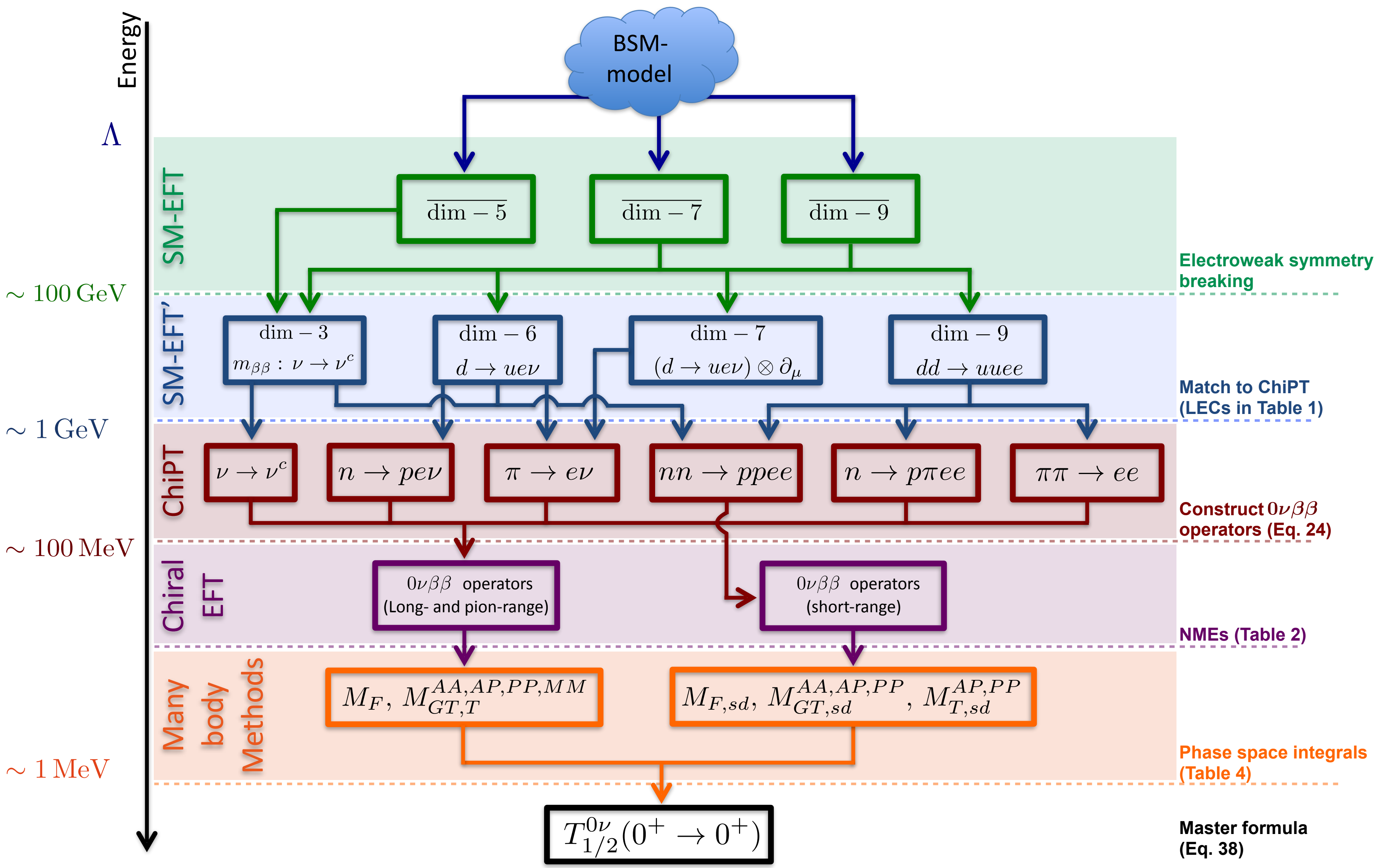
$$H_{T'} = -\frac{2R^2}{\pi m_p}\int \frac{q^2 h_A^2(q^2)}{q(q+\bar{E})} j_2(qr) q^2\, dq\,, \qquad (20q)$$

$$H_{T''} = -\frac{2R^3}{\pi m_p}\int \frac{q^2 h_A^2(q^2)}{q+\bar{E}} j_2(qr) q^2\, dq\,, \qquad (20r)$$

$$H_{T\pi\nu} = -\frac{2R}{\pi}\int \frac{h_{T\pi\nu}^2(q^2)}{q(q+\bar{E})} j_2(qr) q^2\, dq\,, \qquad (20s)$$

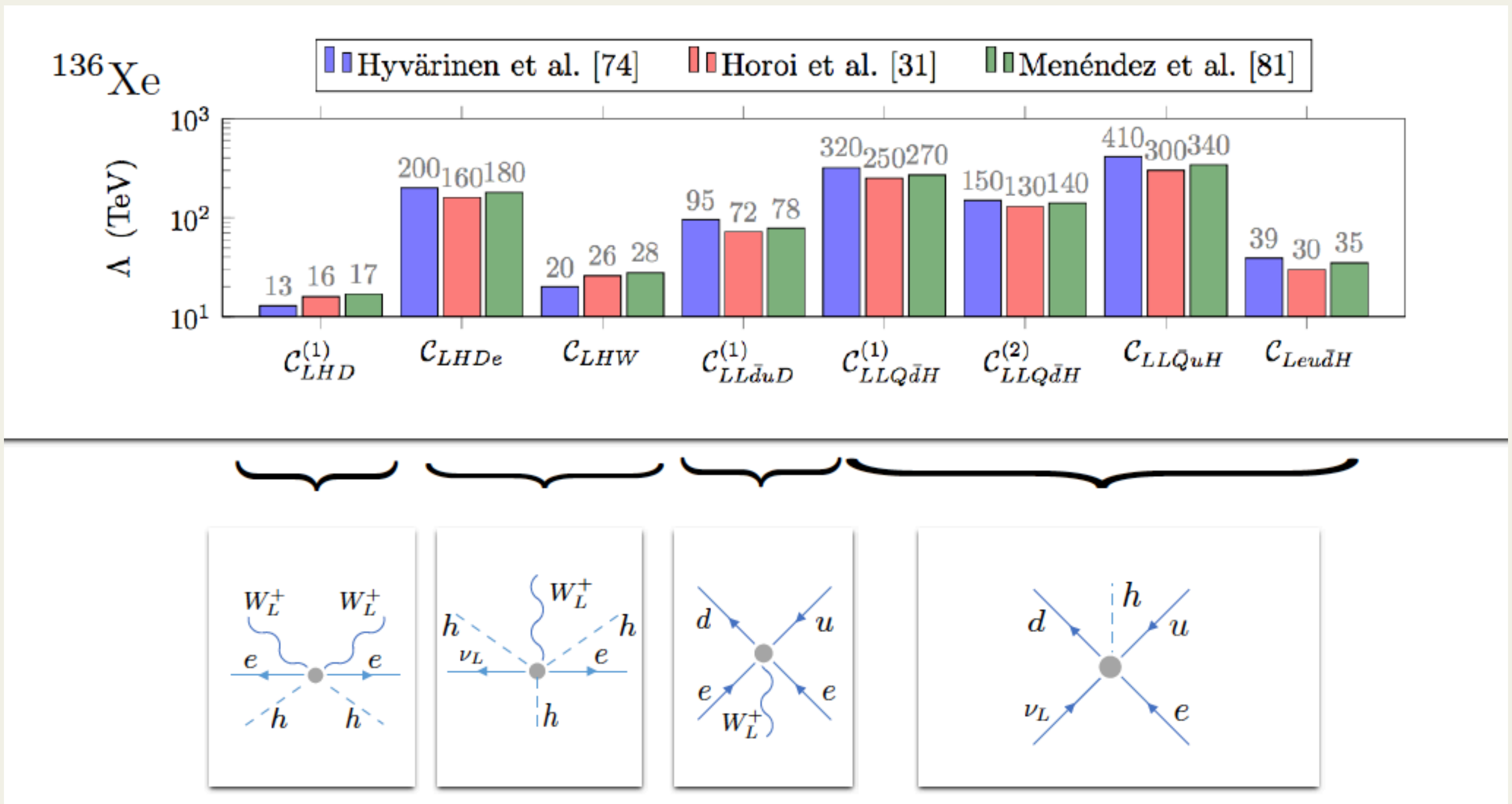
$$H_{T1\pi} = \frac{2R}{\pi}\int h_A^2(q^2)\frac{q^2/m_\pi^4}{1+q^2/m_\pi^2} j_2(qr) q^2\, dq\,, \qquad (20t)$$

‘The neutrinoless double-beta metro map’



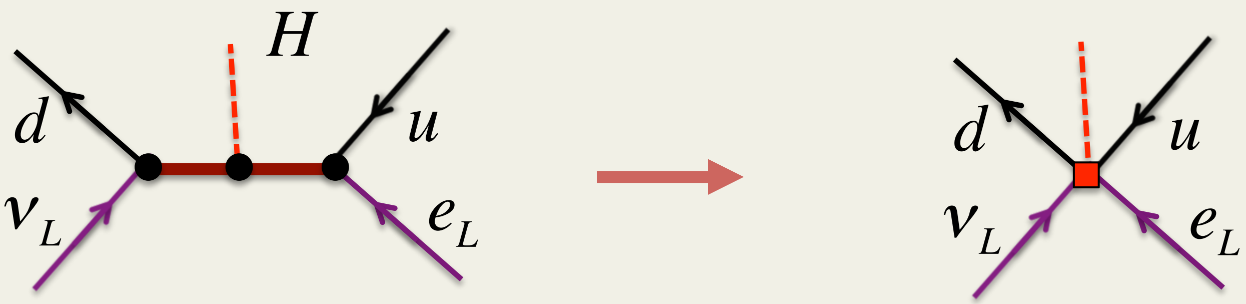
Limits on LNV sources

- We have now connected TeV LNV sources to low-energy data
- **KAMLAND experiment** $T^{0\nu}_{1/2}\left({}^{136}Xe \to {}^{136}Ba\right) > 1.07\times 10^{26}\ yr$
- Limit LNV sources: dim5 $m_{\beta\beta} < 0.084\ eV$
- And also dim7 (or dim9) : assume $C_i \sim (v/\Lambda)^3$



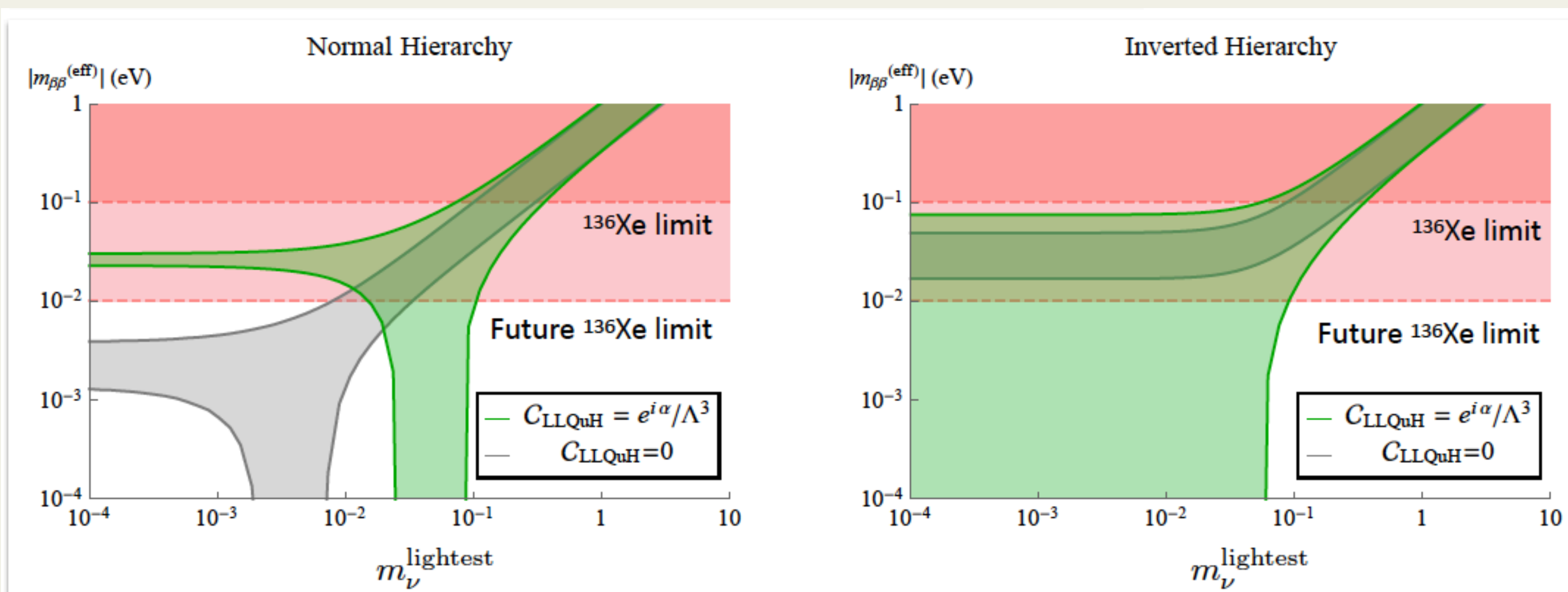
Phenomenology

- Particular dimension-7 operator e.g. appearing in LeptoQuark models



$$C_7 \sim (v / \Lambda)^3$$
$$\Lambda > 400\ TeV$$
$$\Lambda_{LHC} > 5\ TeV$$

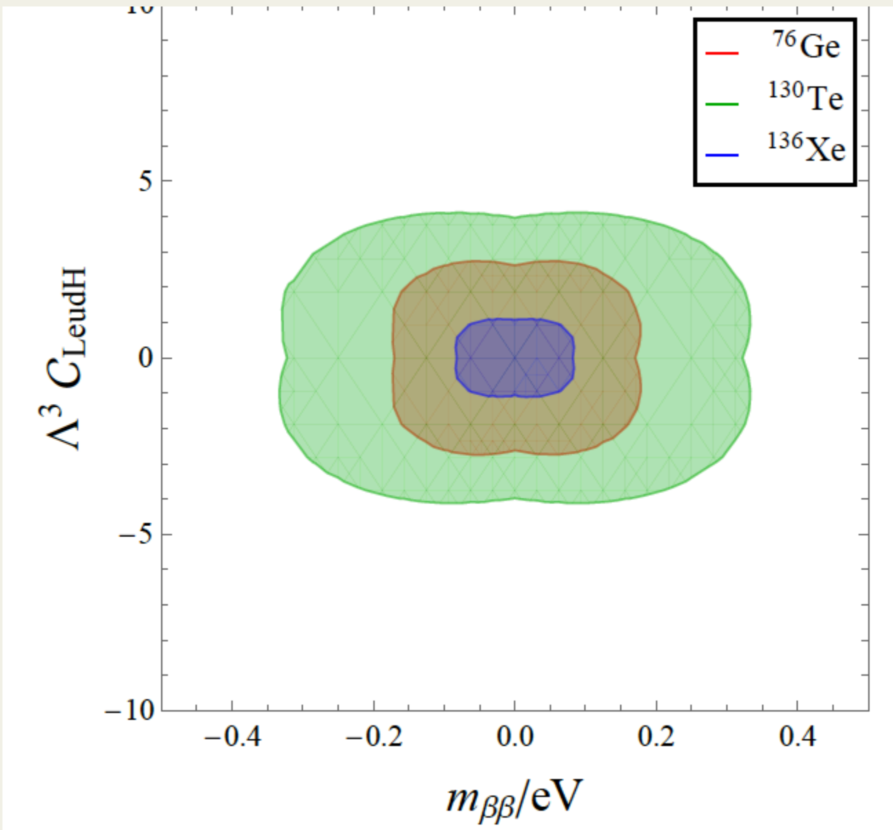
- Operator has **same 'leptonic'** structure as 'standard Majorana mechanism'
- Interference with Majorana mass: **interpretation needs care**



Disentangling LNV sources

- A single measurement can be from any LNV operator
- Need several measurements to unravel the source

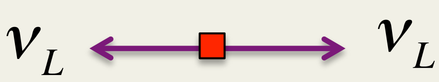
- However, total rates in different isotopes not very helpful….
- Similar Q values and all $0^+ \rightarrow 0^+$

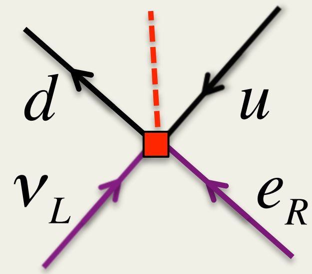


Disentangling LNV sources

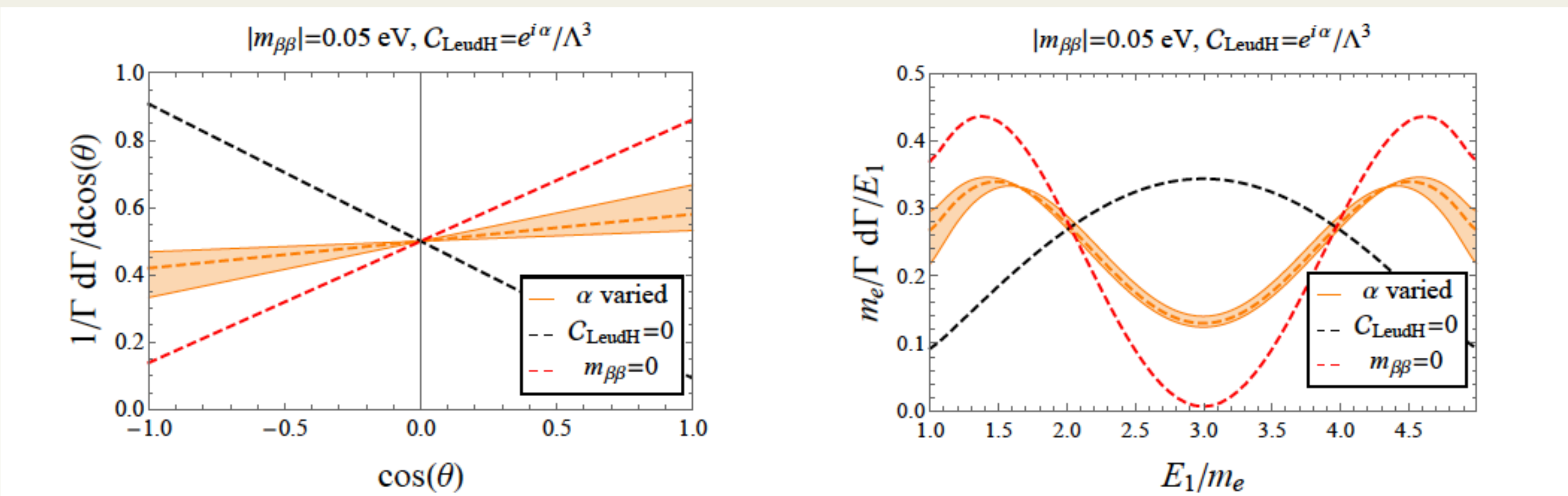
- A single measurement can be from any LNV operator
- Need several measurements to unravel the source

- Instead: **angular & energy** distributions of the outgoing electrons





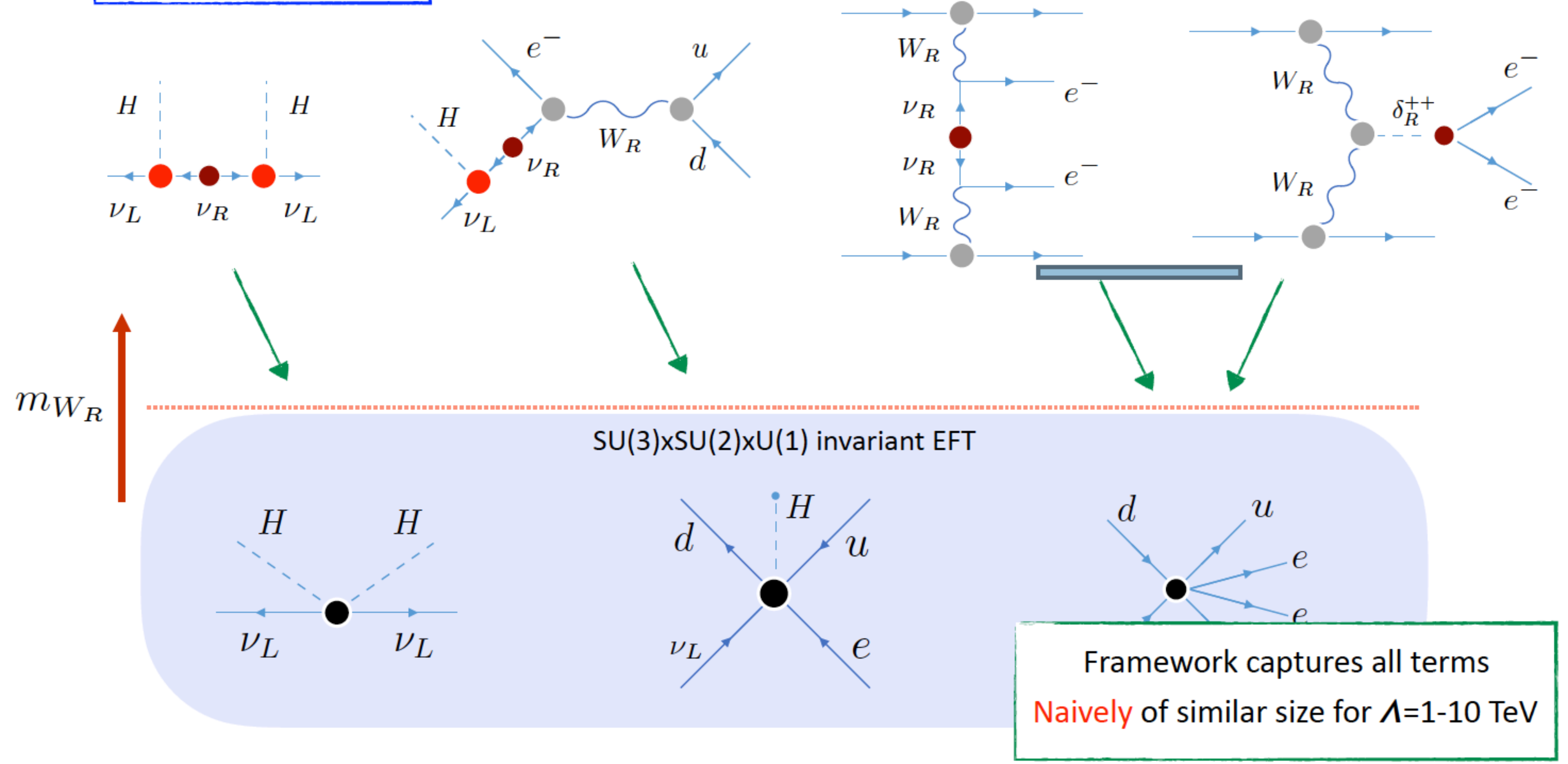
$$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$$



An example: LR model

$\sim y_e = m_e/v$

$\Delta L = 2$



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

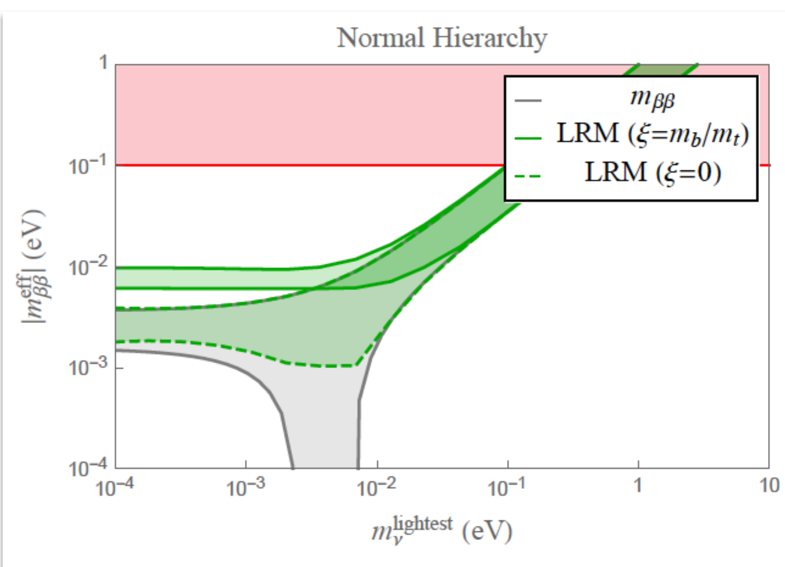
Matching to specific models

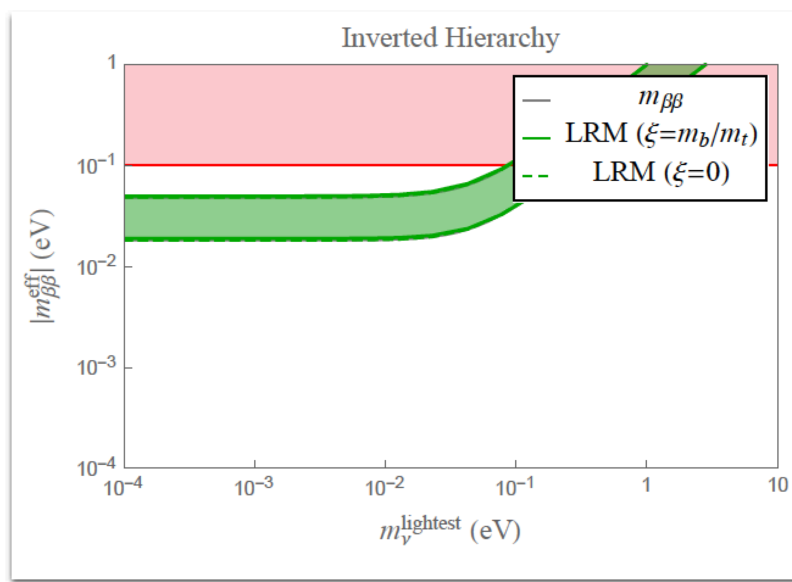
- In principle difficult phenomenology.
- **But just match to SM-EFT operators and then turn the crank**
- Obtain the neutrinoless double beta decay rate in an EFT expansion in:

$$T \sim \left(\frac{v}{\Lambda}\right)^{\alpha} \left(\frac{\Lambda_\chi}{v}\right)^{\beta} \left(\frac{m_\pi}{\Lambda_\chi}\right)^{\gamma}$$

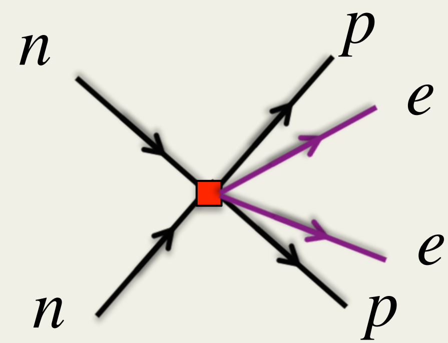
$$m_{W_R} = 4.5\,\mathrm{TeV}, \qquad m_{\nu_R} = 10\,\mathrm{TeV}, \qquad m_{\delta_R^{++}} = 4\,\mathrm{TeV}$$

- Assume right-handed neutrino mixing follows the PMNS matrix





Conclusion/Summary

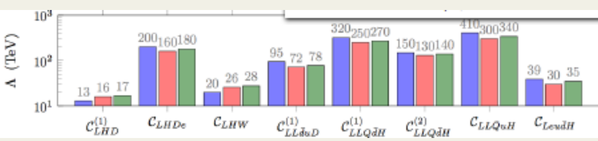


Neutrinoless Double Beta Decay

- ✓ 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
- **Main result: a LO contact nn→pp + ee operator must be added**



Phenomenology

- ✓ Current experiments set very strong limits (>500 TeV in some cases)
- ✓ Differential measurements can disentangle certain sources
- ✓ **Master formula to include all contributions up to dim-9**
- ✓ **Future: add light extra neutrino states + link to LHC + LG**