Effective theory approach to double beta decay

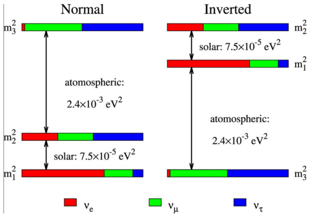
Emanuele Mereghetti

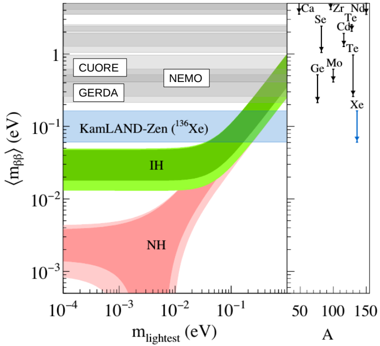
Neutrinoless double-beta decay
INT, June 27th, 2017

with V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, S. Pastore, A. Walker-Loud.

Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline





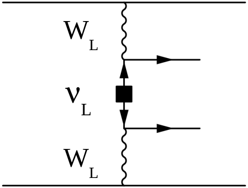
KamLAND-Zen coll., '16

physics beyond the SM!

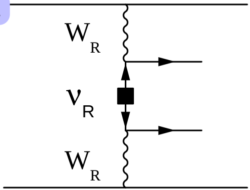
- neutrino have masses
- $0\nu\beta\beta$ experiments will determine the nature of m_ν

Introduction

1.



2.



1. $0\nu\beta\beta$ is directly connected to neutrino oscillation

Standard mechanism
light neutrino exchange

2. the connection is more indirect

   $0\nu\beta\beta$ is mediated by other LNV
   which give some/small neutrino mass

heavy particles,
new symmetries, . . .

Introduction

- a non-zero signal in next generation of experiments

lepton number violation!
neutrino are Majorana!

…however …
to discriminate between new physics scenarios

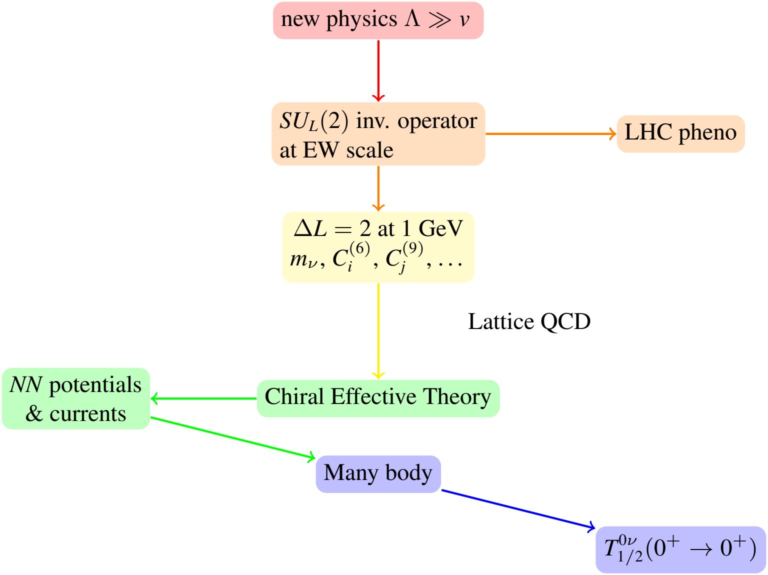
1. several different orthogonal systems/observables

   several isotopes, electron spectrum, …

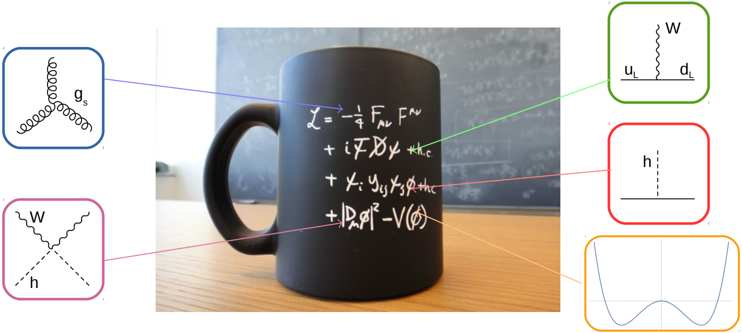
2. systematic connection to flavor and collider physics
3. precise theoretical predictions at high and low energy

one scale at a time:
Effective Field Theories

Strategy


new physics $\Lambda \gg v$
$SU_L(2)$ inv. operator at EW scale
LHC pheno
$\Delta L = 2$ at 1 GeV
$m_\nu, C_i^{(6)}, C_j^{(9)}, \ldots$
Lattice QCD
Chiral Effective Theory
NN potentials & currents
Many body
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)$

The Standard Model as an Effective Field Theory



Write down all possible operators with

- SM fields
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- dimension ≤ 4

$m_\nu = 0$
no ΔL interactions

assume no light sterile ν

The Standard Model as an EFT

- why stop at dim=4?

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_{i,5}}{\Lambda}\mathcal{O}_{5\,i} + \sum \frac{c_{i,6}}{\Lambda^2}\mathcal{O}_{6\,i} + \sum \frac{c_{i,7}}{\Lambda^3}\mathcal{O}_{7\,i} + \dots$$

- Λ is the scale of new physics $\qquad \Lambda \gg v = 246$ GeV
- $\mathcal{O}$s are expressed in terms of SM fields
- have the same symmetries as the SM

gauge symmetry!

but not accidental symmetries as L

The Standard Model as an EFT

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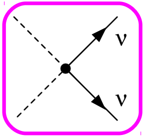
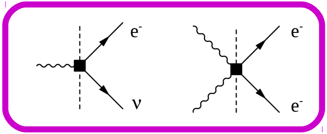
- **one** dimension 5 operator S. Weinberg, '79



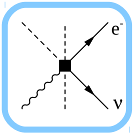
neutrino masses and mixings

$\Lambda \sim 10^{15}$ GeV

Dimension 7 operators



$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C (D_\mu L)_j\, H_m (D^\mu H)_n$$



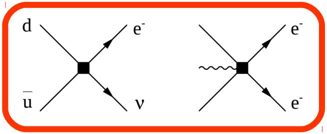
$$\varepsilon_{ij}\varepsilon_{mn}\, L_i^T C \gamma_\mu e\, H_j H_m (D^\mu H)_n$$

- 12 dim. 7 $\Delta L = 2$ operators L. Lehman '14

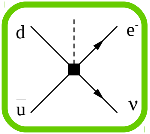
$$\mathcal{C}_i = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$$

- W couplings & semileptonic 4-fermion with the 'wrong' neutrino
- WWe^-e^- couplings

Dimension 7 operators



$$\varepsilon_{ij}\,\bar{d}\gamma_\mu u\, L_i^T C (D^\mu L)_j$$



$$\varepsilon_{ij}\varepsilon_{mn}\bar{d}L_i\, Q_j^T C L_m\, H_n$$

- 12 dim. 7 $\Delta L = 2$ operators

L. Lehman '14

$$\mathcal{C}_i = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$$

- W couplings & semileptonic 4-fermion with the 'wrong' neutrino
- WWe^-e^- couplings

Dimension 9 operators

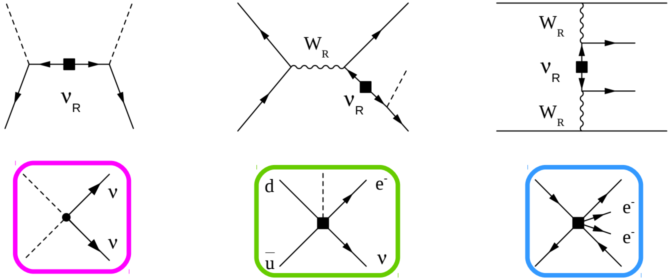
operator	content	hadron collider signatures			Low Energy	χPT ($\pi\pi$)
		same-sign dilepton	e+MET	dijet+ MET		
dimension 9						
LM1	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_b\ell^C_c)$	√	√	√	$\mathcal{O}_{1LR}\otimes(LL)$	LO
LM2	$i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu\lambda^A Q_c)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\overline{\ell}_b\ell^C_c)$	√	√	√	$\mathcal{O}^\lambda_{1LR}\otimes(LL)$	LO
LM3	$(\overline{u}_R Q_a)(\overline{u}_R Q_b)(\overline{\ell}_a\ell^C_b)$	√	√	√	$\mathcal{O}_{2RL}\otimes(LL)$	LO
LM4	$(\overline{u}_R\lambda^A Q_a)(\overline{u}_R\lambda^A Q_b)(\overline{\ell}_a\ell^C_b)$	√	√	√	$\mathcal{O}^\lambda_{2RL}\otimes(LL)$	LO
LM5	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a d_R)(\overline{Q}_c d_R)(\overline{\ell}_b\ell^C_d)$	√	√	√	$\mathcal{O}_{2LR}\otimes(LL)$	LO
LM6	$i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a\lambda^A d_R)(\overline{Q}_c\lambda^A d_R)(\overline{\ell}_b\ell^C_d)$	√	√	√	$\mathcal{O}^\lambda_{2LR}\otimes(LL)$	LO
LM7	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\overline{e}_R e^C_R)$	√	$\ddot{\frown}$	$\ddot{\frown}$	$\mathcal{O}_{3R}\otimes(RR)$	NNLO
LM8	$(\overline{u}_R\gamma^\mu d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	√	√	$\ddot{\frown}$	$\mathcal{O}^\mu_{RRLR}\otimes(LR)$	-
LM9	$(\overline{u}_R\gamma^\mu\lambda^A d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a\lambda^A d_R)(\overline{\ell}_b\gamma_\mu e^C_R)$	√	√	$\ddot{\frown}$	$\mathcal{O}^{\lambda\mu}_{RRLR}\otimes(LR)$	-
LM10	$(\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	√	√	$\ddot{\frown}$	$\mathcal{O}^\mu_{RRRL}\otimes(LR)$	-
LM11	$(\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_a)(\overline{\ell}_a\gamma_\mu e^C_R)$	√	√	$\ddot{\frown}$	$\mathcal{O}^{\lambda\mu}_{RRRL}\otimes(LR)$	-

$$\mathcal{C} = \left(\frac{v^5}{\Lambda^5}\right)$$

from M. Graesser, '16

- many dim. 9 operators
- most interesting: 4 quarks & 2 electron

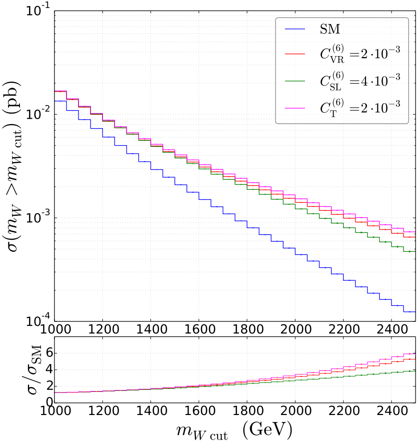
Connection to models



- specific models will match onto one or several operators
- e.g. LR symmetric model
  dim. 5, 7 & 9 (with different Yukawas)

can match any model to EFT

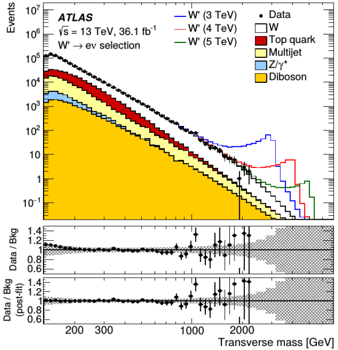
Dimension 7 at LHC



- affect $pp \to e\nu$: new V, A, S and T interactions

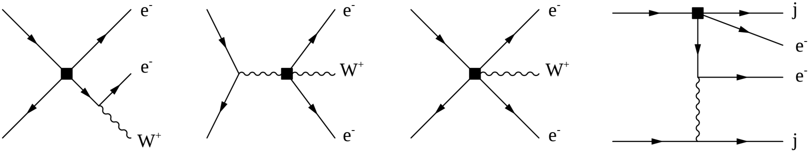
$$\mathcal{L} = -\frac{2G_F}{\sqrt{2}}\left\{ C_{\rm VR}^{(6)}\bar{d}_R\gamma^\mu u_R\,\nu_L^T C\gamma_\mu e_R + C_{\rm SL}^{(6)}\bar{d}_R u_L\,\nu_L^T C e_L + C_{\rm T}^{(6)}\bar{d}_R\sigma^{\mu\nu}u_L\,\nu_L^T C\sigma_{\mu\nu}e_L + \dots \right\}$$

Dimension 7 at LHC



- LHC can put some limits $\Lambda \lesssim 2.5$ TeV
- no way to disentangle from $\Delta L = 0$ non-standard couplings
- no way to tell Dirac from Majorana

Dimension 7 at LHC



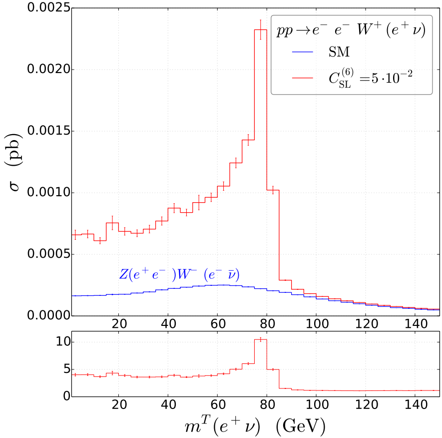
- to be sure is $\Delta L = 2$:
  analyze the neutrino with another weak interaction

$$pp \to e^- e^- W^+ (e^+ \nu)$$

$$pp \to e^- e^- W^+ (jj)$$

$$pp \to e^- e^- 2j$$

Dimension 7 at LHC



- to be sure is $\Delta L = 2$:
  analyze the neutrino with another weak interaction
  $pp \to e^- e^- W^+(e^+\nu)$

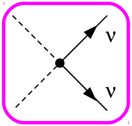
Low-energy Effective Lagrangian for $\Delta L = 2$

$\Delta L = 2$ Lagrangian at 1 GeV

Integrate out W & Higgs

$$\mathcal{L}_{\Delta L=2} = \mathcal{L}^{\Delta e=0}_{\Delta L=2} + \mathcal{L}^{\Delta e=1}_{\Delta L=2} + \mathcal{L}^{\Delta e=2}_{\Delta L=2}$$

- $\mathcal{L}^{\Delta e=0}_{\Delta L=2}$ includes ν masses and magnetic moments

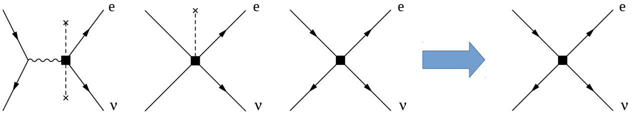


$$\mathcal{L}_{\Delta L=2} \quad = \quad -\frac{1}{2}(m_\nu)_{ij}\,\nu^{T\,j}\,C\nu^i + \mu_{ij}\,\nu^{T\,j}\,C\sigma^{\mu\nu}\nu^i\,eF_{\mu\nu} + \ldots$$

- $SU_L(2)$ invariance forces the couplings to scale Λ^{-1}

$$m_\nu \quad \sim \quad \mathcal{O}\left(\frac{v^2}{\Lambda}\right), \qquad \mu_{ij} \sim \mathcal{O}\left(\frac{1}{\Lambda}, \frac{v^2}{\Lambda^3}\right)$$

$\Delta L = 2$ Lagrangian at 1 GeV



- $\mathcal{L}_{\Delta L=2}^{\Delta e=1}$ starts at dim. 6
  β decay with the "wrong" neutrino, & all possible Lorentz structures

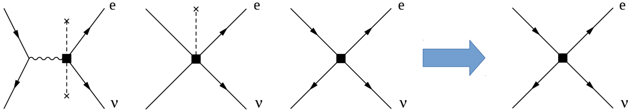
$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}} \Big\{ C^{(6)}_{\rm VL}\, \bar{d}_L \gamma^\mu u_L\, \nu_L^T\, C \gamma_\mu e_R + C^{(6)}_{\rm VR}\, \bar{d}_R \gamma^\mu u_R\, \nu_L^T\, C \gamma_\mu e_R$$

$$+ C^{(6)}_{\rm SL}\, \bar{d}_R u_L\, \nu_L^T\, C e_L + C^{(6)}_{\rm SR}\, \bar{d}_L u_R\, \nu_L^T\, C e_L + C^{(6)}_{\rm T}\, \bar{d}_R \sigma^{\mu\nu} u_L\, \nu_L^T\, C \sigma_{\mu\nu} e_L \Big\}$$

- two dim. 7 operators

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v} \Big\{ C^{(7)}_{\rm VL}\, \bar{d}_L \gamma^\mu u_L\, \nu_L^T\, C\, i \overleftrightarrow{\partial}_\mu e_L + C^{(7)}_{\rm VR}\, \bar{d}_R \gamma^\mu u_R\, \nu_L^T\, C i \overleftrightarrow{\partial}_\mu e_L \Big\}$$

$\Delta L = 2$ Lagrangian at 1 GeV



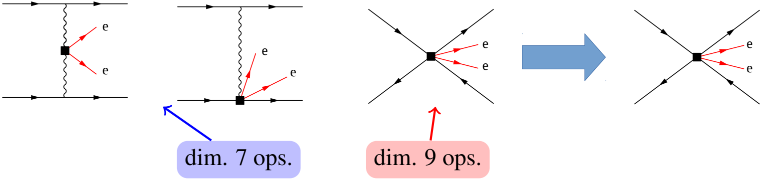
- $SU_L(2)$ invariance !

$$C_i^{(6)}, C_i^{(7)} = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$$

- effects of $C^{(7)}$ at low-energy suppressed by m_π/v
- **but** $C^{(6)}$, $C^{(7)}$ prop. to different high-energy operators

cannot neglect them

$\Delta L = 2$ Lagrangian at 1 GeV



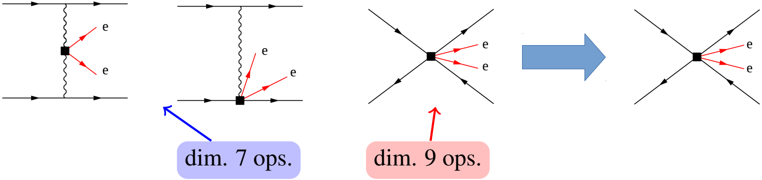
- $\mathcal{L}_{\Delta L=2}^{\Delta e=2}$ starts at dim. 9

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{2G_F^2}{v}\left[\sum_{i=\text{scalar}} \left(C_i^{(9)}\, \bar{e}_L C\, \bar{e}_L^T + C_i^{(9)\prime}\, \bar{e}_R C\, \bar{e}_R^T\right) O_i \;+\; \bar{e}_R \gamma_\mu C\, \bar{e}_L^T \sum_{i=\text{vector}} C_{iV}^{(9)}\, O_i^\mu\right]$$

Scalar operators

1. 1 LL LL four-quark: $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L\, \bar{u}_L\, \gamma_\mu d_L$
2. 2 LR LR four-quark: $\mathcal{O}_2 = \bar{u}_L d_R\, \bar{u}_L\, d_R$, $\quad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta\, \bar{u}_L^\beta\, d_R^\alpha$
3. 2 LL RR four-quark: $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L\, \bar{u}_R\, \gamma_\mu d_R$, $\quad \mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta\, \bar{u}_R^\beta\, \gamma_\mu d_R^\alpha$

$\Delta L = 2$ Lagrangian at 1 GeV



- $\mathcal{O}_1$ and $\mathcal{O}_{4,5}$ receive contributions from dim. 7 operators

$$C_1^{(9)}, C_{4,5}^{(9)} \sim \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$$

- $C_1^{(9)\prime}, C_i^{(9)}$ receive contributions from dim. 9 operators   see M. Graesser's talk

$$C_1^{(9)\prime}, C_i^{(9)} \sim \mathcal{O}\left(\frac{v^5}{\Lambda^5}\right)$$

Chiral EFT

$$\mathcal{L}_{\Delta L=2}(\nu, e, u, d) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj}C\nu^i + C_\Gamma\, \nu^T C\, \Gamma e\, \mathcal{O}_\Gamma + C_{\Gamma'} e^T C\, \Gamma' e\, \mathcal{Q}_{\Gamma'}$$

quark bilinear

four-quark

match onto theory of nucleons and pions

$$\mathcal{L}_{\Delta L=2}(\nu, e, \pi, N) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj}C\nu^i + C_\Gamma^\chi\, \nu^T C\, \Gamma e\, \mathcal{O}_\Gamma^\chi + C_{\Gamma'}^\chi e^T C\, \Gamma' e\, \mathcal{Q}_{\Gamma'}^\chi$$

Chiral EFT

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- $\mathcal{O}_\Gamma^\chi$ and $\mathcal{Q}_\Gamma^\chi$ contain N and π fields

$$\mathcal{O}^\chi : \partial_\mu \pi^+,\ \bar{N}\tau^- \boldsymbol{\sigma} N, \ldots, \qquad \mathcal{Q}^\chi : \pi^+\pi^+,\ \bar{N}\tau^- \boldsymbol{\sigma}\cdot\nabla\pi^+ N$$

Chiral EFT

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match onto theory of nucleons and pions

quark bilinear

four-quark

$$\mathcal{L}_{\Delta L=2}(\nu, e, \pi, N) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj} C \nu^i + C^\chi_\Gamma\, \nu^T C\, \Gamma e\, \mathcal{O}^\chi_\Gamma + C^\chi_{\Gamma'} e^T C\, \Gamma' e\, \mathcal{Q}^\chi_{\Gamma'}$$

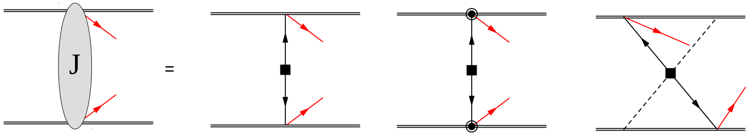
- $\mathcal{O}^\chi_\Gamma$ and $\mathcal{Q}^\chi_\Gamma$ contain N and π fields

$$\mathcal{O}^\chi : \partial_\mu \pi^+,\ \bar{N}\tau^- \boldsymbol{\sigma} N, \dots, \qquad \mathcal{Q}^\chi : \pi^+\pi^+,\ \bar{N}\tau^- \boldsymbol{\sigma}\cdot\nabla\pi^+ N$$

- C^χ_Γ, $C^\chi_{\Gamma'}$ are non ptb. functions of the quark-level couplings

$$C^\chi_\Gamma \stackrel{?}{=} C^\chi_\Gamma(m_\nu, C_\Gamma, C'_\Gamma), \qquad C^\chi_{\Gamma'} \stackrel{?}{=} C^\chi_{\Gamma'}(m_\nu, C_\Gamma, C'_\Gamma)$$

Chiral EFT



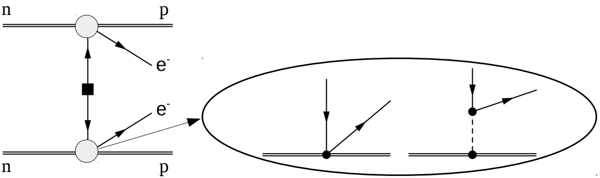
$\mathcal{O}(1)$ $\mathcal{O}\left(\frac{Q^2}{\Lambda_\chi^2}\right)$

- current and potentials: perturbative expansion in Q/Λ_χ
- iterate potentials to find bound states (non perturbative)

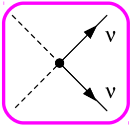
Goals

1. write down $\mathcal{O}_\Gamma^\chi$, $\mathcal{Q}_{\Gamma'}^\chi$
2. estimate the couplings
3. write down $0\nu\beta\beta$ currents

Hadronic matrix elements for $\Delta L = 2$



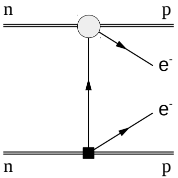
1. standard mechanism



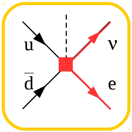
- leading effects are long distance
- at LO: nucleon axial and vector form factors
- at N^{2}LO: two-body currents, short-range effects, rel. corrections …

well determined hadronic input

Hadronic matrix elements for $\Delta L = 2$



2. $\mathcal{L}^{(6,7)}_{\Delta L=2}$

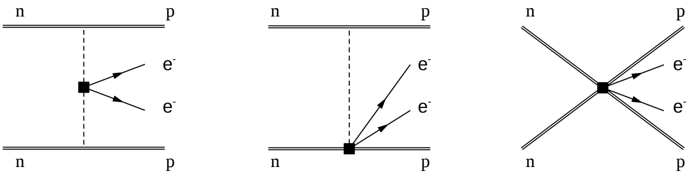


- still long distance
- at LO: nucleon axial, vector, scalar, pseudoscalar and tensor form factors

M. Doi, T. Kotani, E. Takasugi, '85,
H. Pas, M. Hirsch, H. V. Klapdor-Kleingrothaus, S. G. Kovalenko, '99.

well determined hadronic input

Hadronic matrix elements for $\Delta L = 2$



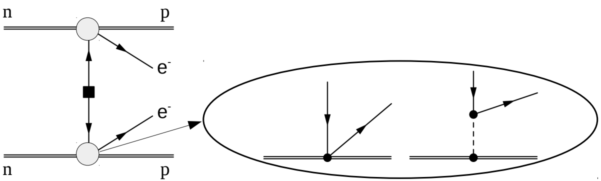
- $\mathcal{L}^{(9)}_{\Delta L=2}$: new short distance effects

- $\pi\pi e^c e$ operators
- $NN\pi e^c e$ operators
- $NN\,NNe^c e$ operators

G Prezeau, M. Ramsey-Musolf, P. Vogel, '03

need to fix LECs!

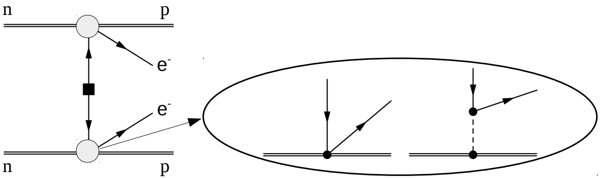
Standard mechanism



At LO

$$J_V^\mu = (g_V, \mathbf{0}) \qquad g_V = 1$$

$$J_A^\mu = -g_A\left(0, \boldsymbol{\sigma} - \frac{\mathbf{q}}{\mathbf{q}^2 + m_\pi^2}\,\boldsymbol{\sigma}\cdot\mathbf{q}\right) \qquad g_A = 1.27$$



At LO

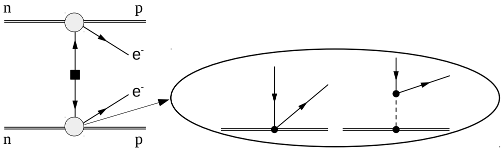
$$J_V^\mu = (g_V, \mathbf{0}) \qquad g_V = 1$$

$$J_A^\mu = -g_A \left(0, \boldsymbol{\sigma} - \frac{\mathbf{q}}{\mathbf{q}^2 + m_\pi^2}\boldsymbol{\sigma}\cdot\mathbf{q}\right) \qquad g_A = 1.27$$

The neutrino potential

$$V_{SM} = \mathcal{A}\frac{m_{\beta\beta}}{\mathbf{q}^2}\left\{\mathbf{1}\times\mathbf{1} - g_A^2\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)}\left(1 - \frac{2}{3}\frac{\mathbf{q}^2}{\mathbf{q}^2+m_\pi^2} + \frac{1}{3}\frac{(\mathbf{q}^2)^2}{(\mathbf{q}^2+m_\pi^2)^2}\right)\right.$$
$$\left. - \frac{g_A^2}{3}S^{12}\left(-\frac{2\mathbf{q}^2}{\mathbf{q}^2+m_\pi^2} + \frac{(\mathbf{q}^2)^2}{(\mathbf{q}^2+m_\pi^2)^2}\right)\right\}.$$

Standard mechanism. Higher orders



At N^2LO $\quad \mathcal{O}(\mathbf{q}^2/\Lambda_\chi^2)$

$$J_V^\mu = \left(g_V(\mathbf{q}^2), \frac{\mathbf{P}}{2m_N} - \frac{i(1+\kappa_1)}{2m_N}\boldsymbol{\sigma}\times\mathbf{q}\right) \qquad \kappa_1 = 3.7$$

$$J_A^\mu = -g_A(\mathbf{q}^2)\left(\frac{\boldsymbol{\sigma}\cdot\mathbf{P}}{2m_N}, \boldsymbol{\sigma} - \frac{\mathbf{q}}{\mathbf{q}^2+m_\pi^2}\boldsymbol{\sigma}\cdot\mathbf{q}\right)$$

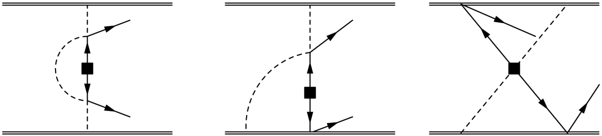
1. correction to the one-body currents (magnetic moment, radii, …)

$$g_A(\mathbf{q}^2) = g_A\left(1 - r_A^2\frac{\mathbf{q}^2}{6} + \dots\right) \qquad r_A = 0.47(7)\text{fm}$$

R. Gupta, *et al* ‘17

2. two-body corrections to V and A currents

Loop corrections to the standard mechanism



3. short range effects
   e.g. from the VV component of current

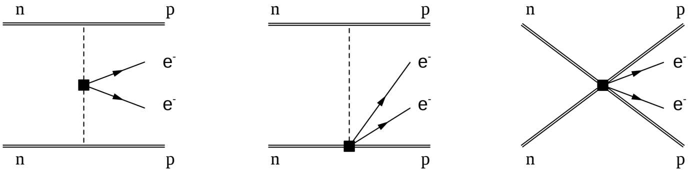
$$V_{\mathrm{N^2LO}} = \mathcal{A}\, m_{\beta\beta} \frac{g_A^2}{3} (\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{12}) \frac{1}{(4\pi F_\pi)^2} \left\{ L_\pi \left(\frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} - 3 \frac{(\mathbf{q}^2)^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right) + f\left(\frac{\mathbf{q}^2}{m_\pi^2} \right) \right\}$$

V. Cirigliano, W. Dekens, EM, S. Pastore, A. Walker-Loud, preliminary

- UV divergence $L_\pi = \log \frac{\mu^2}{m_\pi^2} + c_i$,
  need local counterterms, encode physics at ~ 1 GeV

see potentials in S. Pastore's talk

Loop corrections to the standard mechanism



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$$V_{\mathrm{N^2LO}} = \mathcal{A}\, m_{\beta\beta} \frac{g_A^2}{3} (\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{12}) \frac{1}{(4\pi F_\pi)^2}$$
$$\left\{ L_\pi \left(\frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} - 3 \frac{(\mathbf{q}^2)^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right) + f\left(\frac{\mathbf{q}^2}{m_\pi^2} \right) \right\}$$

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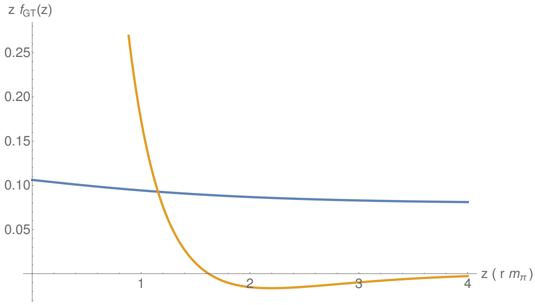
Loop corrections to the standard mechanism

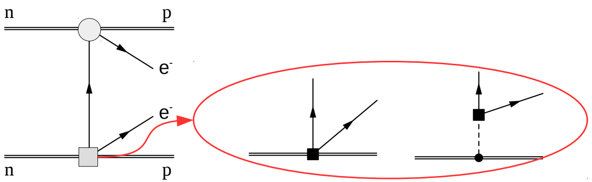


- $f(\mathbf{q}^2/m_\pi^2)$: non-analytic dependence of the loops

$$f(x) = \frac{2(1-x^2)}{x(1+x)} \log(1+x) - 2 + \frac{7x}{1+x^2}$$

- probe much shorter ranges
- is it important? . . . in progress

Non-standard long-range contributions



- need axial, vector, pseudoscalar (P) and tensor (T) currents
- P dominated by pion pole, prop. to the quark condensate

$$J_P = g_A B \frac{1}{\mathbf{q}^2 + m_\pi^2} \boldsymbol{\sigma} \cdot \mathbf{q} \qquad B(2\text{GeV}) = 2.4(2)\text{GeV}$$

FLAG '16

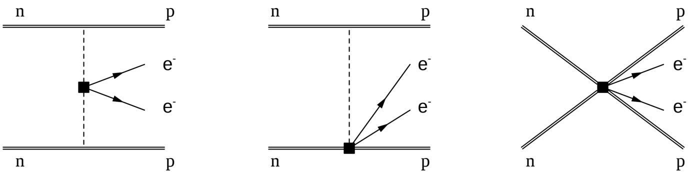
- neutrino potential

$$V_P(\mathbf{q}^2) = \qquad B\left(C_{\rm SL}^{(6)} - C_{\rm SR}^{(6)}\right) \frac{1}{\mathbf{q}^2} \left(\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{12}\right) \left\{ -\frac{1}{3} \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} + \frac{1}{3} \frac{(\mathbf{q}^2)^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right\}$$

- similar story for T, A, V

more details in M. Horoi's talk,

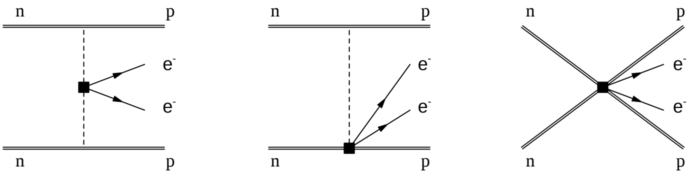
Short-distance contributions



Construct the representations of

1. LL LL four-quark: $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \, \gamma_\mu d_L$
2. LR LR four-quark: $\mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R$, $\quad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha$
3. LL RR four-quark: $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \, \gamma_\mu d_R$, $\quad \mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta \, \bar{u}_R^\beta \, \gamma_\mu d_R^\alpha$

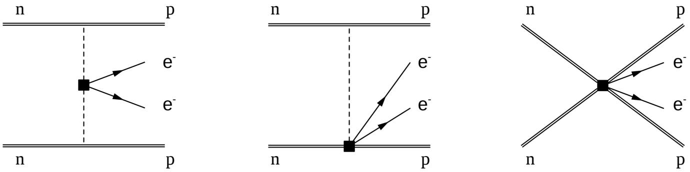
Short-distance contributions



Only few couplings are important (at LO)

$$\mathcal{L} = \frac{2G_F^2}{\sqrt{2}v}\left\{\frac{1}{2}C_{\pi\pi}F_\pi^2\pi^-\pi^- + \frac{1}{2}C_{\pi\pi}^{(1)}F_\pi^2\partial_\mu\pi^-\partial^\mu\pi^- + \sqrt{2}g_A F_\pi C_{\pi N}\,\bar{p}S\cdot(\partial\pi^-)n + C_{NN}\bar{p}n\,\bar{p}n\right\}\bar{e}C\,\bar{e}^T,$$

relative importance depends on $\mathcal{O}'s$ chiral properties!



case 1 can construct a non-derivative pionic operator at LO
$\mathcal{O}_{2,3}$ & $\mathcal{O}_{4,5}$

$$C_{\pi\pi} = C^{(9)}_{2,3,4,5} \times \mathcal{O}(\Lambda_\chi^2), \qquad C^{(1)}_{\pi\pi}, C_{\pi N}, C_{NN} = C^{(9)}_{2,3,4,5} \times \mathcal{O}\,(1)$$

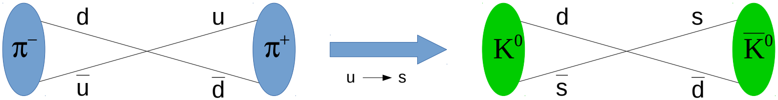
$\pi\pi$ exchange dominates

case 2 no non-derivative pionic operator at LO, $\mathcal{O}_1$

$$C^{(1)}_{\pi\pi}, C_{\pi N}, C_{NN} = C^{(9)}_{1} \times \mathcal{O}\,(1)$$

LECs for $\pi\pi$, π & contact of the same size

$\pi\pi$ matrix elements

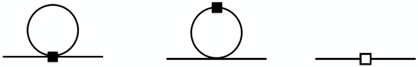


- chiral symmetry relates $\pi^- \to \pi^+$ to $K_0 \to \bar{K}_0$ M. Savage '99

1. LL LL $\mathcal{O}_1 = \bar{u}_L\gamma^\mu d_L\, \bar{u}_L\, \gamma_\mu d_L$ $(\mathbf{27_L}, \mathbf{1_R})$ $\frac{5}{3} g_{27\times 1} F_0^4 L_{\mu 12} L^\mu_{12}$
2. LR LR $\mathcal{O}_{2,3} = \bar{u}_L d_R\, \bar{u}_L\, d_R$ $(\bar{\mathbf{6}}_\mathbf{L}, \mathbf{6_R})$ $g_{6\times\bar{6}} \frac{F_0^4}{4} \mathrm{Tr}(t^a U\, t^b U)$
3. LL RR $\mathcal{O}_{4,5} = \bar{u}_L\gamma^\mu d_L\, \bar{u}_R\, \gamma_\mu d_R$ $(\mathbf{8_L}, \mathbf{8_R})$ $g_{8\times 8} \frac{F_0^4}{4} \mathrm{Tr}(t^a U\, t^b U^\dagger)$

$$U = \exp\left(\frac{\sqrt{2} i \pi}{F_0}\right), L_\mu = i U^\dagger \partial_\mu U.$$

$\pi\pi$ matrix elements. Loop corrections



- at tree level

$$\mathcal{M}^{\pi\pi}_{6\times\bar{6}} \equiv \langle\pi^+|O^{1+i2,1+i2}_{6\times\bar{6}}|\pi^-\rangle \quad = \quad \langle\bar{K}^0|O^{6-i7,6-i7}_{6\times\bar{6}}|K^0\rangle \equiv \mathcal{M}^{K\bar{K}}_{6\times\bar{6}}$$
$$\mathcal{M}^{\pi\pi}_{8\times 8} \equiv \langle\pi^+|O^{1+i2,1+i2}_{8\times 8}|\pi^-\rangle \quad = \quad \langle\bar{K}^0|O^{6-i7,6-i7}_{8\times 8}|K^0\rangle \equiv \mathcal{M}^{K\bar{K}}_{8\times 8}\ .$$

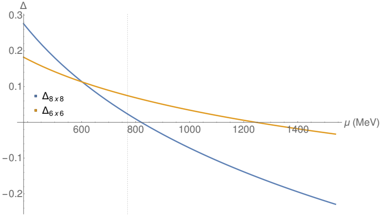
- different loop corrections for $\pi\pi$ and $K\bar{K}$

$$\mathcal{M}^{\pi\pi}_{8\times 8} \quad = \quad \mathcal{M}^{K\bar{K}}_{8\times 8} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{8\times 8}) \ = \ \mathcal{M}^{K\bar{K}}_{8\times 8} \times R_{8\times 8}$$
$$\mathcal{M}^{\pi\pi}_{6\times\bar{6}} \quad = \quad \mathcal{M}^{K\bar{K}}_{6\times\bar{6}} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{6\times\bar{6}}) \ = \ \mathcal{M}^{K\bar{K}}_{6\times\bar{6}} \times R_{6\times\bar{6}}\ ,$$

corrections to decay constants

everything else

$\pi\pi$ matrix elements. Loop corrections



$$\Delta_{8\times 8} = \frac{1}{(4\pi F_0)^2}\left[\frac{m_\pi^2}{4}(-4+5L_\pi) - m_K^2(-1+2L_K) + \frac{3}{4}m_\eta^2 L_\eta - a_{8\times 8}\left(m_K^2 - m_\pi^2\right)\right]$$

- $a_{8\times 8}, a_{6\times\bar{6}}$ unknown LECs

  can be extracted from $m_s, \bar{m}$ dependence of $\mathcal{M}^{K\bar{K}}$

- loop corrections are small

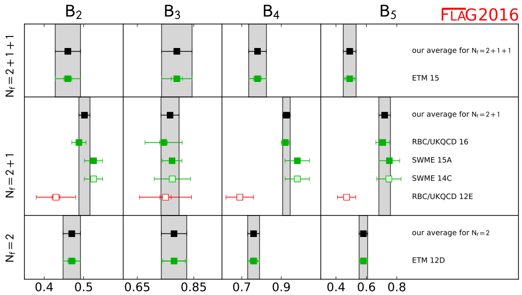
$$\Delta_{8\times 8} = 0.02 \pm 0.30, \qquad \Delta_{6\times 6} = 0.07 \pm 0.20$$

error from scale variation

- most of the correction from F_π/F_K

$$R_{8\times 8} = 0.72 \pm 0.21, \qquad R_{6\times\bar{6}} = 0.76 \pm 0.14$$

Extraction of the $\pi\pi$ ME



- using FLAG averages of $K_0 - \bar{K}_0$

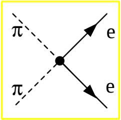
$$\langle\pi^+|\mathcal{O}_2|\pi^-\rangle = -(2.7 \pm 0.3 \pm 0.5) \times 10^{-2}\ \mathrm{GeV}^4$$
$$\langle\pi^+|\mathcal{O}_3|\pi^-\rangle = (0.9 \pm 0.1 \pm 0.2) \times 10^{-2}\ \mathrm{GeV}^4$$
$$\langle\pi^+|\mathcal{O}_4|\pi^-\rangle = -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \mathrm{GeV}^4$$
$$\langle\pi^+|\mathcal{O}_5|\pi^-\rangle = -(11 \pm 2 \pm 3) \times 10^{-2}\ \mathrm{GeV}^4$$

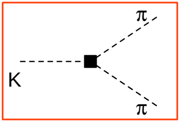
benchmark for direct LQCD calc.

A. Nicholson, '16 & talk here

LQCD error χPT error

$\pi\pi$ matrix element for LL LL operators





- chiral corrections to $\mathcal{M}^{K\bar{K}}$ are large
- better use $K \to \pi\pi$

Savage, '99

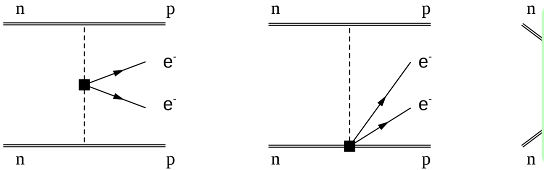
- using RBC & UKQCD '15 for $\langle \pi^+\pi^- | \mathcal{O}_{27} | K^+ \rangle$

$$\langle \pi^+ | \mathcal{O}_1 | \pi^- \rangle = (1.0 \pm 0.1 \pm 0.2) \times 10^{-4}\ \mathrm{GeV}^4$$

- quite small . . . follows chiral counting very well
- at the same order, need πNN and $NN\,NN$ operators

no info at the moment
hyperon decays?

Neutrino potentials from χEFT



$$g_{8\times 8} = -(1.7\,\mathrm{GeV})^2$$
$$g^{\mathrm{mix}}_{8\times 8} = -(3.6\,\mathrm{GeV})^2$$
$$g_{6\times \bar{6}} = -(1.8\,\mathrm{GeV})^2$$
$$g^{\mathrm{mix}}_{6\times \bar{6}} = +(1.0\,\mathrm{GeV})^2$$
$$g_{27\times 1} = +0.4$$

- $\pi\pi$ contribution

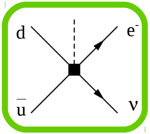
$$V^{\pi\pi}_{SD}(\mathbf{q}^2) = \mathcal{A}\,\frac{1}{v}\left\{C^{(9)}_4 g_{8\times 8} + C^{(9)}_5 g^{\mathrm{mix}}_{8\times 8} - C^{(9)}_2 g_{6\times\bar{6}} - C^{(9)}_3 g^{\mathrm{mix}}_{6\times\bar{6}} + \frac{5}{3} m_\pi^2 C^{(9)}_1 g_{27\times 1}\right\}$$
$$\frac{g_A^2}{6}\left(\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)} - S^{(12)}\right)\frac{\mathbf{q}^2}{(\mathbf{q}^2+m_\pi^2)^2}$$

- LEC are well determined
- πN and NN contributions

$$V_{SD}(\mathbf{q}^2) = \mathcal{A}\,\frac{C^{(9)}_1}{v}\left\{C_{\pi N,\,27}\frac{\mathbf{q}^2}{\mathbf{q}^2+m_\pi^2} + C_{NN,\,27}\right\},$$

- for $\mathcal{O}_1$ all three pieces important $\Longrightarrow$ check size of nuclear ME!

Bounds on new physics. Example 1



$$\left(\frac{v^3}{\Lambda^3}\right)\, \varepsilon_{ij}\, \bar{Q}_L^m u_R\, L^m C L^i\, H^j$$

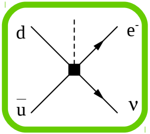
- matches onto $C_{\rm SR}^{(6)}$
- from $pp \to l\nu_l$, $\Lambda > 2.5$ TeV
- from $0\nu\beta\beta$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{01} g_A^4 \left| \frac{m_{\beta\beta}}{m_e} M_{SM} + \frac{B}{m_e} C_{\rm SR}^{(6)} \left(\frac{1}{2} M_{GT}^{AP} + M_{GT}^{PP} + \frac{1}{2} M_T^{AP} + M_T^{PP} \right) \right|^2$$

phase space
J. Kotila and F. Iachello, '12

matrix elements
J. Hyvarinen and J. Suhonen, '15

Bounds on new physics. Example 1



$$\left(\frac{v^3}{\Lambda^3}\right) \varepsilon_{ij}\, \bar{Q}_L^m u_R\, L^m C L^i\, H^j$$

- matches onto $C_{\rm SR}^{(6)}$
- from $pp \to l\nu_l$, $\Lambda > 2.5$ TeV
- from $0\nu\beta\beta$ e.g. ^{136}Xe

$$\left[T_{1/2}^{0\nu}\right]^{-1} = 14.6 \cdot 10^{-15} {\rm yr}^{-1} g_A^4 \left| 2.9 \frac{m_{\beta\beta}}{m_e} - 0.6 \cdot 10^3 \frac{\rm MeV}{m_e} C_{\rm SR}^{(6)} \right|^2$$

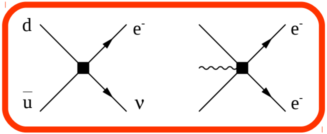
phase space
J. Kotila and F. Iachello, '12

matrix elements
J. Hyvarinen and J. Suhonen, '15

- $T_{1/2}^{0\nu} > 1.07 \cdot 10^{26}$ yr KamLAND-Zen, '16

$\Lambda > 325$ TeV

Bounds on new physics. Example 2



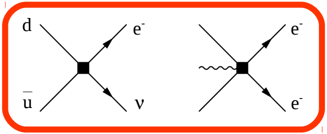
$$\left(\frac{v^3}{\Lambda^3}\right)\varepsilon_{ij}\,(\bar{d}\gamma_\mu u)(L^T C (D^\mu L)_j)$$

- matches onto $C^{(7)}_{\mathrm{VR}}$ & $C^{(9)}_4$ generate $C^{(9)}_5$ via running

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{01} g_A^4 \left| \frac{m_{\beta\beta}}{m_e} M_{SM} + \frac{m_\pi^2}{m_e v} C^{(7)}_{\mathrm{VL}} \left(\frac{1}{2} M^{AP}_{GT} + M^{PP}_{GT} + \frac{1}{2} M^{AP}_{T} + M^{PP}_{T}\right) + \frac{1}{v m_e}\left(C^{(9)}_4 g_{8\times 8} + C^{(9)}_5 g^{\mathrm{mix}}_{8\times 8}\right)\left(M^{sd}_{GT} + M^{sd}_{T}\right)\right|^2$$

- short range dominates $\quad g^{(\mathrm{mix})}_{8\times 8} \gg m_\pi^2$

Bounds on new physics. Example 2



$$\left(\frac{v^3}{\Lambda^3}\right) \varepsilon_{ij}\,(\bar{d}\gamma_\mu u)(L^T C (D^\mu L)_j)$$

- matches onto $C_{\mathrm{VR}}^{(7)}$ & $C_4^{(9)}$
  generate $C_5^{(9)}$ via running

$$\left[T_{1/2}^{0\nu}\right]^{-1} = 14.6 \cdot 10^{-15}\mathrm{yr}^{-1} g_A^4 \left|2.9\frac{m_{\beta\beta}}{m_e} - 10\frac{\mathrm{MeV}}{m_e}\left(2\cdot 10^{-3} C_{\mathrm{VL}}^{(7)} + 1.2\, C_4^{(9)} + 5.3\, C_5^{(9)}\right)\right|^2$$

phase space
J. Kotila and F. Iachello, '12

matrix elements
J. Hyvarinen and J. Suhonen, '15

- short range dominates $\quad g_{8\times 8}^{(\mathrm{mix})} \gg m_\pi^2$

$\Lambda > 110$ TeV

Conclusions

EFTs & $0\nu\beta\beta$ decay:

- model independent connection with collider observables
- model independent parameterization of low-energy $\Delta L = 2$ operators
- organize contributions to neutrino potentials

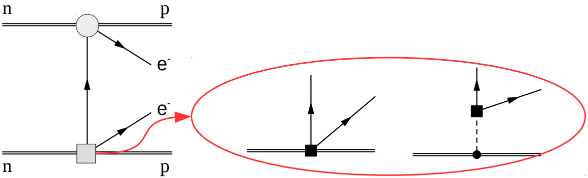
to be checked by realistic calculations!

- determine low-energy hadronic couplings for non-standard mechanisms

e.g. $\pi\pi$ couplings

$g_{8\times 8}$, $g_{6\times\bar{6}}$, $g_{27\times 1}$

Backup



- T dominated by nucleon interaction, prop. to the tensor charge

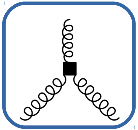
$$J_T^{\mu\nu} = -2g_T(\mathbf{q}^2)\varepsilon^{\mu\nu\alpha\beta}\left(v_\alpha + \frac{p_\alpha + p'_\alpha}{2m_N}\right)S_\beta - i\frac{g'_T(\mathbf{q}^2)}{2m_N}(v^\mu q^\nu - v^\nu q^\mu)$$
$$-\frac{g''_T(\mathbf{q}^2)}{m_N}\varepsilon^{\alpha\beta\mu\nu}q_\alpha S_\beta \ .$$

$g_T(0) = 1.020(76)$ PNDME collaboration

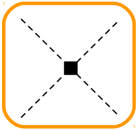
- neutrino potential

$$V(\mathbf{q}^2) = 2\tau^{(1)+}\tau^{(2)+}\, 2G_F^2\, m_N C_{\mathrm{T}}^{(6)}\, \frac{1}{\mathbf{q}^2}\, \bar{u}(k_1)\, P_R C\bar{u}^t(k_2) \left\{ g'_T(\mathbf{q}^2) g_V(\mathbf{q}^2)\frac{\mathbf{q}^2}{m_N^2} \right.$$
$$\left. +4\frac{g_A(\mathbf{q}^2)g''_T(\mathbf{q}^2) - g_T(\mathbf{q}^2)g_M(\mathbf{q}^2)}{g_M(\mathbf{q}^2)^2}\left(h_{GT}^{MM}(\mathbf{q}^2)\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)} + h_T^{MM}(\mathbf{q}^2)S^{(12)}\right)\right\} (1)$$

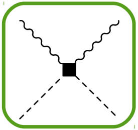
The Standard Model as an EFT



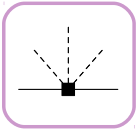
three/four bosons



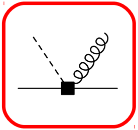
h self-coupling



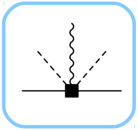
scalar-gauge



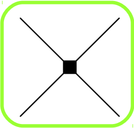
Yukawa



dipole



vector/axial currents



four-fermion

- **many** dimension 6 $\propto 1/\Lambda^2$ half of them CPV!

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .

- no $\Delta L = 2$ operators