Searching for new physics with nuclei

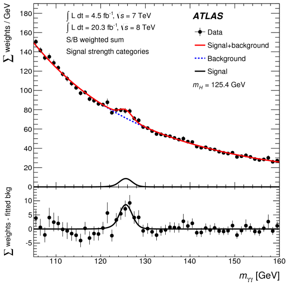
Emanuele Mereghetti

June 25th, 2018

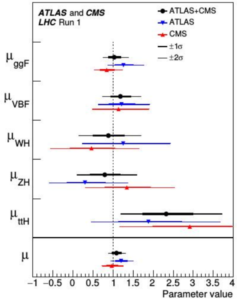
From nucleons to nuclei: enabling discovery for neutrinos, dark matter

Los Alamos
NATIONAL LABORATORY
EST. 1943

Introduction



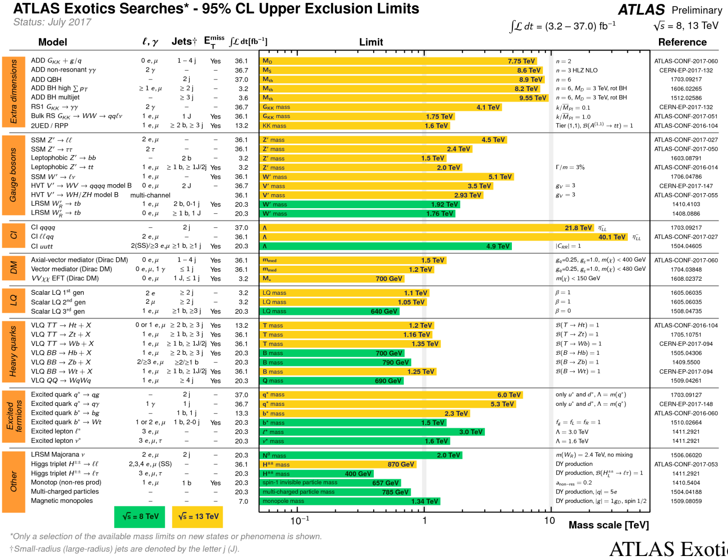
ATLAS collaboration, ‘14.



ATLAS & CMS, ‘16.

- the Standard Model works just fine
- last missing piece discovered @ LHC . . . and looks SM-like

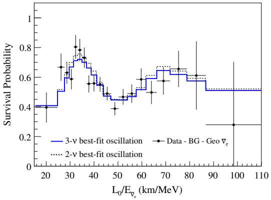
Introduction



ATLAS Exotics summary plots

- a lot of work, no evidence for new particles

Introduction



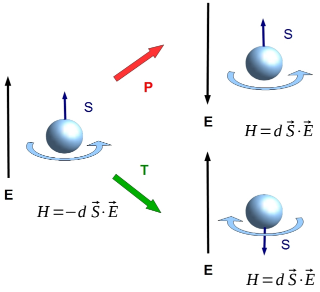
- neutrino masses

- baryogenesis

- Dark matter

nuclei extremely sensitive probes
competitive & complementary to LHC

CP violation



current bound on d_n
$|d_n| < 3.0 \cdot 10^{-13}\, e$ fm
J. M. Pendlebury *et al.*, '15

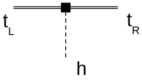
SM
$d_n \sim 10^{-19}\, e$ fm
M. Pospelov and A. Ritz, '05

1. permanent Electric Dipole Moments

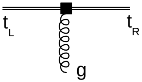
- signal of T and P violation (CP)
- insensitive to CP violation in the SM

large window for new physics!
exciting experimental program to close it

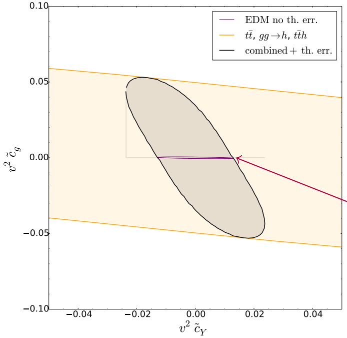
The reach of EDM experiments

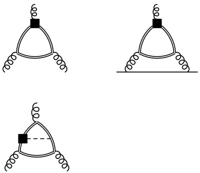


$$\frac{m_t\, v^2}{\Lambda^2}\,\bar{t}_L t_R h$$



$$\frac{m_t}{\Lambda^2}\,\bar{t}_L \sigma^{\mu\nu} t_R G_{\mu\nu}$$





one/two-loop running to gCEDM, qCEDM

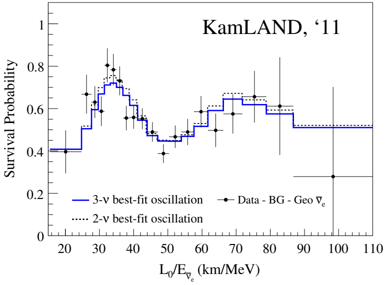
top CP-odd Yukawa and chromo-EDM

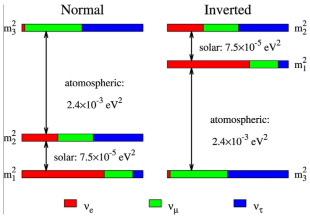
- important if baryogenesis comes from top sector
- EDM bounds much stronger than collider

$\Lambda \sim$ 1-4 TeV

- . . . but hadronic uncertainties weaken bounds

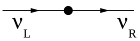
Lepton number violation



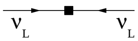


- neutrino have masses
- and know a great deal from oscillation
- what's the origin of neutrino masses?
  Dirac or Majorana?

BSM physics!

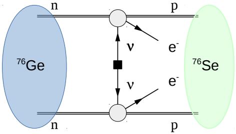


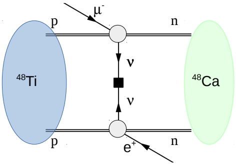
$m_i \bar{\nu}_R^i \nu_L^i$

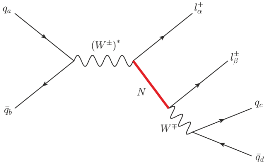


$m_i {\nu^T}_L^i C \nu_L^i$

Lepton number violation





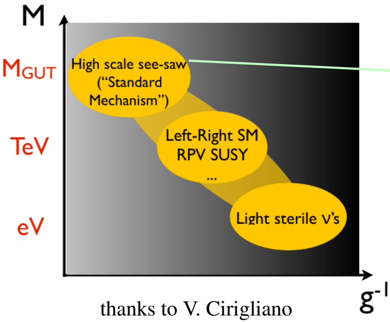


2. searches for $\Delta L = 2$ signal probe ν Majorana nature

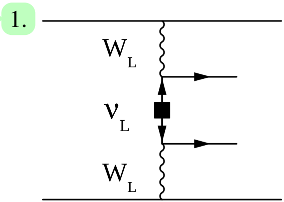
possible iff νs have a Majorana mass

- neutrinoless double beta decay ($0\nu\beta\beta$)
- (μ^-, e^+) conversion
- $K^+ \to \pi^- e^+ e^+,\ \pi^- e^+ \mu^+,\ \pi^- \mu^+ \mu^+$
- $pp \to jje^- e^-$

Lepton number violation



thanks to V. Cirigliano



Next generation of experiments sensitive to a variety of LNV scenarios

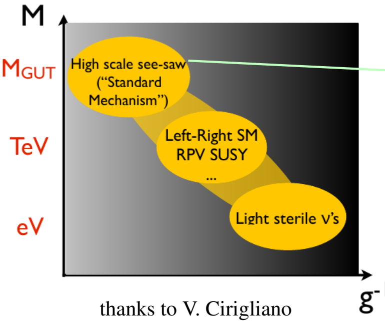
1. LNV originates at very high scales

- $0\nu\beta\beta$ only relevant experiment

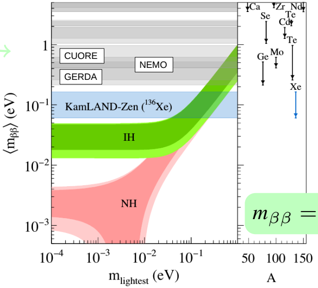
$$K^+ \to \pi^- l^+ l^+, (\mu^-, e^+) \text{ need to improve by 10-20 orders} \ldots$$

- direct connection between ν oscillations and $0\nu\beta\beta$

Lepton number violation



thanks to V. Cirigliano



$m_{\beta\beta} = U_{ei}^2 m_i$

Next generation of experiments sensitive to a variety of LNV scenarios

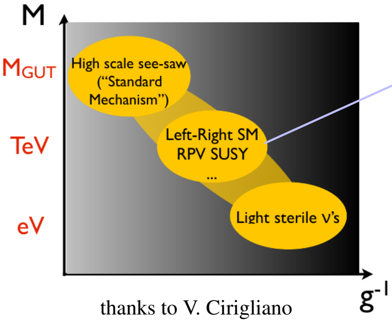
1. LNV originates at very high scales

- $0\nu\beta\beta$ only relevant experiment

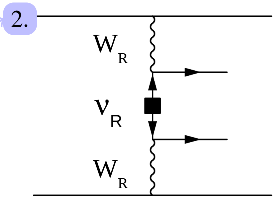
$$K^+ \to \pi^- l^+ l^+, (\mu^-, e^+) \text{ need to improve by 10-20 orders} \ldots$$

- direct connection between ν oscillations and $0\nu\beta\beta$
- clear goals: rule out inverted hierarchy

Lepton number violation



thanks to V. Cirigliano

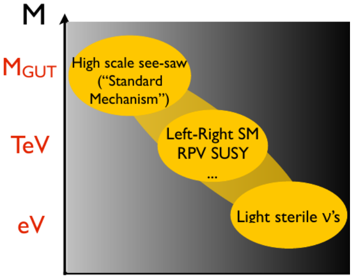


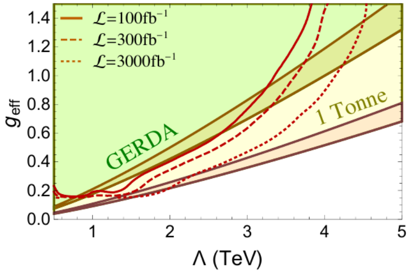
Next generation of experiments sensitive to a variety of LNV scenarios

2. LNV at intermediate scales

- $0\nu\beta\beta$ is mediated by new particles
- could be accessible at colliders

Lepton number violation





T. Peng, M. Ramsey-Musolf, P. Winslow, '15

Next generation of experiments sensitive to a variety of LNV scenarios

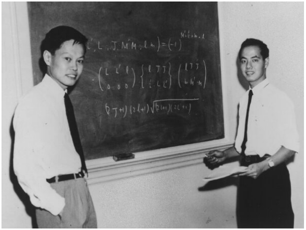
2. LNV at intermediate scales

   $0\nu\beta\beta$ is mediated by new particles

   could be accessible at colliders

general framework to interpret $0\nu\beta\beta$ exp?

Non-standard charged current interactions

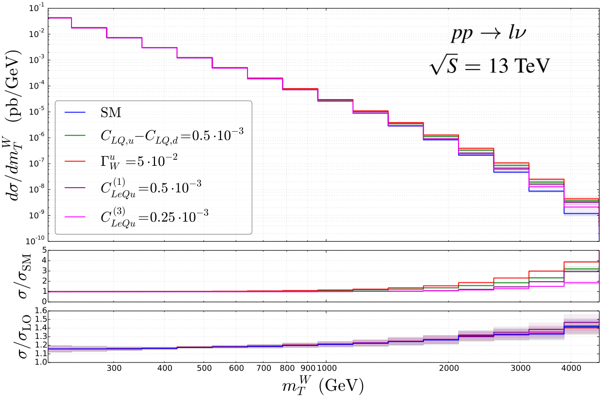


- are there non-standard vector, axial, scalar, or tensor currents?

W_R bosons, heavy Higgses, ...

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{4G_F}{\sqrt{2}}\Big\{\bar{\nu}_L\gamma^\mu e_L \bar{d}_L\gamma_\mu\left(C_{LQ,D}V^\dagger_{CKM} - V^\dagger_{CKM}C_{LQ,U}\right)u_L \\
& +\bar{\nu}_L e_R\,\left(\bar{d}_R C_{LedQ}V^\dagger_{CKM}u_L + \bar{d}_L V^\dagger_{CKM}C^{(1)}_{LeQu}u_R\right) + \bar{\nu}_L\sigma^{\mu\nu}e_R\,\bar{d}_L V^\dagger_{CKM}C^{(3)}_{LeQu}\sigma_{\mu\nu}u_R\Big\}
\end{aligned}
$$

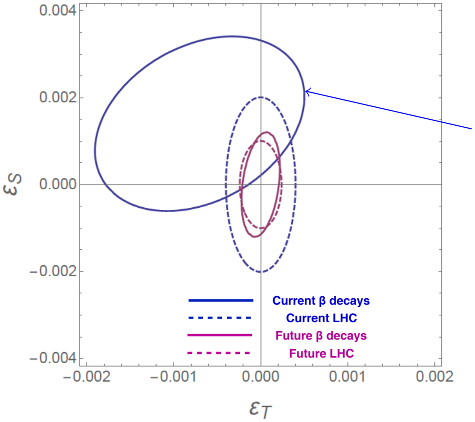
Non-standard charged current interactions at the LHC



S. Alioli, W. Dekens, M. Girard, EM, '18

- look at the m_T^W spectrum in $pp \to l\nu$ and $m_{l^+l^-}$ in $pp \to l^+l^-$

Non-standard charged current interactions



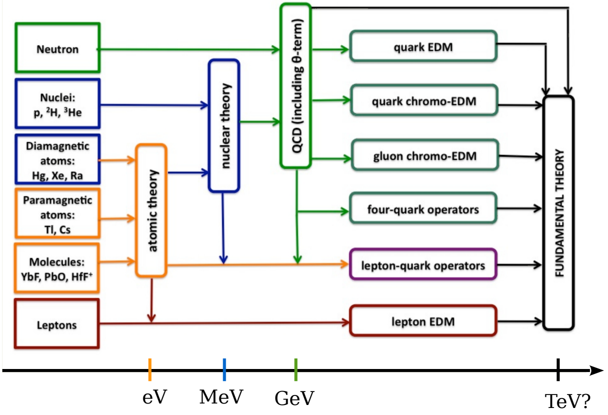
global fit to nuclear β decay
M. González-Alonso, *et al*, ‘18

R. Gupta *et al.*, ‘18

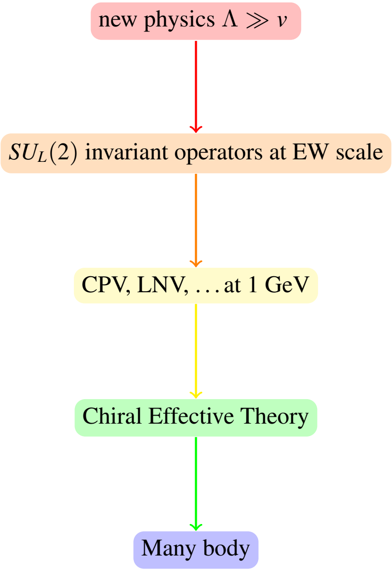
- ϵ_S and ϵ_T from pion and nuclear β decays

  $\pi \to e\nu\gamma$, β-ν correlation, Fierz interference term, …
- nice complementarity with LHC

The inverse problem



Effective Field Theories



- model independent link to collider phenomenology
- minimal set of low-energy CPV, LNV, ... operators
- connection with flavor/low energy probes
- from quarks to hadrons non-perturbative matching (LQCD)
- EDMs of nucleons & light nuclei
- $0\nu\beta\beta$ transition potential

- half-life anatomy

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G_{01}\, g_A^4\, |M^{0\nu}|^2 + \dots \qquad M^{0\nu} = \langle 0^+ | V_\nu | 0^+ \rangle$$

What EFTs can do:

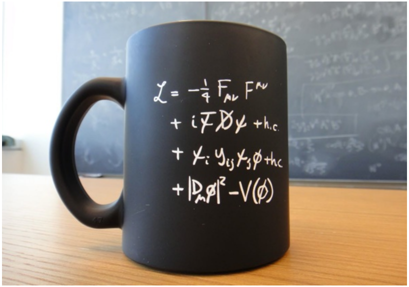
parametrize $0\nu\beta\beta$ w. few coefficients
that can be matched to models

identify QCD input & its uncertainty

systematically derive the ν potentials
check NME in simpler systems

Outline

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_R

The Standard Model as an EFT

- why stop at dim=4?

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

$$\Lambda \gg v = 246\,\mathrm{GeV}$$

- $\mathcal{O}$ have the same symmetries as the SM

  gauge symmetry!

  but not accidental symmetries as L

The Standard Model as an EFT

- why stop at dim=4?

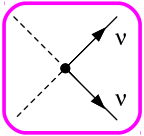
$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_{i,5}}{\Lambda}\mathcal{O}_{5\,i} + \sum \frac{c_{i,6}}{\Lambda^2}\mathcal{O}_{6\,i} \qquad + \sum \frac{c_{i,7}}{\Lambda^3}\mathcal{O}_{7\,i} + \dots$$

$$\Lambda \gg v = 246\,\mathrm{GeV}$$

- $\mathcal{O}$ have the same symmetries as the SM

gauge symmetry!
but not accidental symmetries as L

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

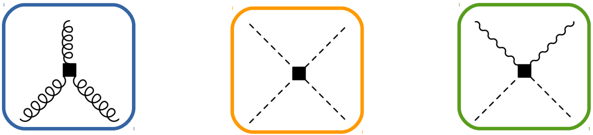


$$\frac{1}{\Lambda}\varepsilon_{ij}\varepsilon_{mn}L_i^T C L_m H_j H_n \to \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

neutrino masses and mixings

$\Lambda \sim 10^{14}$ GeV

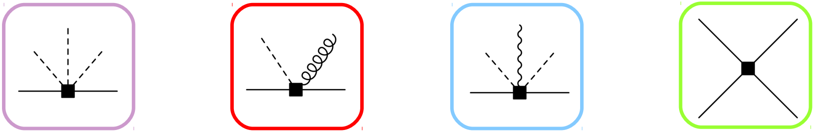
The Standard Model as an EFT



three/four bosons

h self-coupling

scalar-gauge



Yukawa

dipole

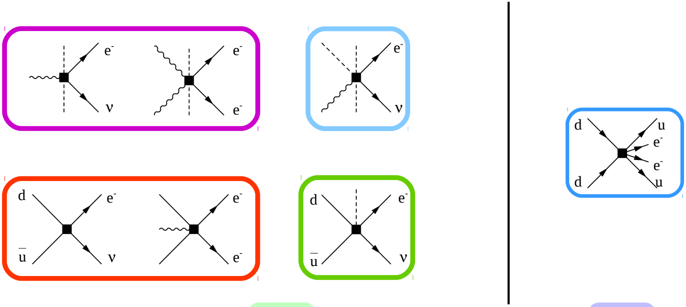
vector/axial currents

four-fermion

- **many** dimension 6, $\propto v^2/\Lambda^2$

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

LNV at dim. 7, dim. 9



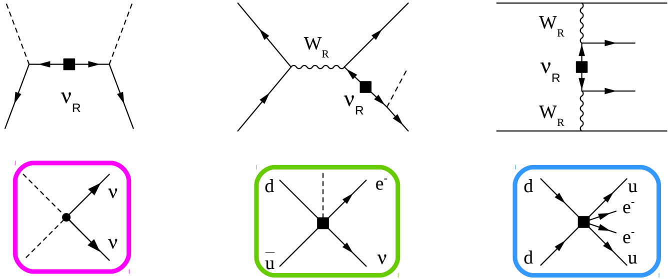
$\left(\frac{v}{\Lambda}\right)^3$ $\left(\frac{v}{\Lambda}\right)^5$

- dim.7 operators mostly induce β decay with "wrong" ν

  $\Longrightarrow$ long range contribs. to $0\nu\beta\beta$

- dim. 9 induce short-range contributions to $0\nu\beta\beta$

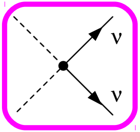
Connection to models



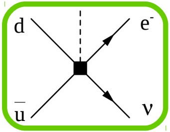
- specific models will match onto one or several operators
- e.g. LR symmetric model
  dim. 5, 7 & 9 (with different Yukawas)

can match any model to EFT

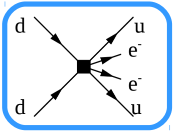
The low-energy LNV Effective Lagrangian



$\frac{v}{\Lambda}$



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



$\frac{v^3}{\Lambda^3}, \frac{v^5}{\Lambda^5}$

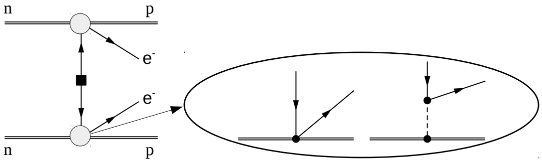
$$\mathcal{L}_{\Delta L=2}(\nu, e, u, d) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj}C\nu^i + C_\Gamma\, \nu^T C\, \Gamma e\, \mathcal{O}_\Gamma + C_{\Gamma'} e^T C\, \Gamma' e\, \mathcal{Q}_{\Gamma'}$$

quark bilinear — four-quark

1. write down π, N, NN, . . ., operators with same chiral properties as $\mathcal{L}_{\Delta L=2}$
2. estimate the low energy constants
   - ✓ well determined for nucleon bilinears
   - ✓ and for mesonic operators
   - × not so much for short-distance mechanisms
3. write down $0\nu\beta\beta$ transition operators

Revisiting the light Majorana-ν exchange mechanism

Chiral EFT approach to light-ν exchange mechanism



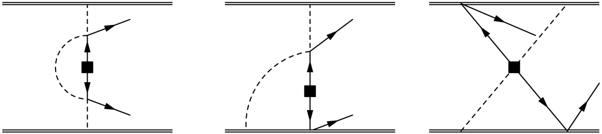
- weak currents are mainly one-body

$$
\begin{aligned}
J_V^\mu &= (g_V, \mathbf{0}) & g_V &= 1 \\
J_A^\mu &= -g_A \left(0, \boldsymbol{\sigma} - \frac{\mathbf{q}}{\mathbf{q}^2 + m_\pi^2}\, \boldsymbol{\sigma}\cdot\mathbf{q}\right) & g_A &= 1.27
\end{aligned}
$$

- $0\nu\beta\beta$ mediated by exchange of potential neutrinos

$$
\begin{aligned}
V_\nu &= \mathcal{A}\tau^{(1)+}\tau^{(2)+}\frac{1}{\mathbf{q}^2}\left\{\mathbf{1}^{(a)}\times\mathbf{1}^{(b)} - g_A^2\boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)}\left(\frac{2}{3}+\frac{1}{3}\frac{m_\pi^4}{(\mathbf{q}^2+m_\pi^2)^2}\right)+\dots\right\}. \\
\mathcal{A} &= 2G_F^2 m_{\beta\beta}\,\bar{e}_L C\,\bar{e}_L^T
\end{aligned}
$$

Standard mechanism. Higher orders



At N^{2}LO $\quad \mathcal{O}(\mathbf{q}^2/\Lambda_\chi^2)$, $\qquad \Lambda_\chi = 4\pi F_\pi \sim 1$ GeV

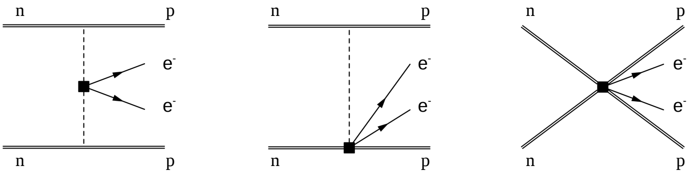
1. correction to the one-body currents (magnetic moment, radii, ...)

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

2. two-body corrections to V and A currents
3. pion-neutrino loops & local counterterms

UV divergences signal short-range sensitivity at N^{2}LO

Standard mechanism. Higher orders



At N^{2}LO $\quad \mathcal{O}(\mathbf{q}^2/\Lambda_\chi^2)$, $\qquad \Lambda_\chi = 4\pi F_\pi \sim 1$ GeV

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

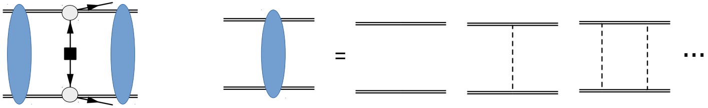
$$g_A(\mathbf{q}^2) = g_A \left(1 - r_A^2 \frac{\mathbf{q}^2}{6} + \dots\right) \qquad r_A = 0.47(7)\text{fm}$$

2. two-body corrections to V and A currents
3. pion-neutrino loops & local counterterms

UV divergences signal short

WARNING: based on naive dimensional analysis “Weinberg’s counting”

Is the Weinberg counting consistent for $0\nu\beta\beta$?



- Weinberg's counting fails in $^1S_0$ channel

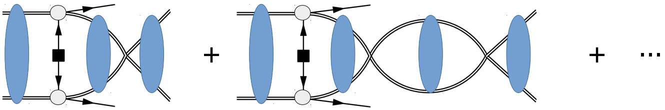
D. Kaplan, M. Savage, M. Wise, '96

- study $nn \to ppe^- e^-$ with LO χEFT strong potential

$$V_{\rm strong}(r) = \tilde{C}\,\delta^{(3)}(\mathbf{r}) + \frac{g_A^2 m_\pi^2}{16\pi F_\pi^2}\,\frac{e^{-m_\pi r}}{4\pi r}$$

- no problem with Yukawa potential

Is the Weinberg counting consistent for $0\nu\beta\beta$?



- Weinberg's counting fails in ${}^1S_0$ channel

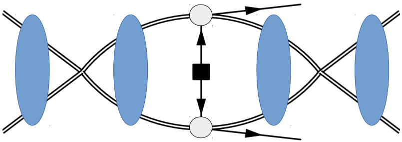
D. Kaplan, M. Savage, M. Wise, '96

- study $nn \to ppe^- e^-$ with LO χEFT strong potential

$$V_{\rm strong}(r) = \tilde{C}\,\delta^{(3)}(\mathbf{r}) + \frac{g_A^2 m_\pi^2}{16\pi F_\pi^2}\frac{e^{-m_\pi r}}{4\pi r}$$

- no problem with Yukawa potential
- and one insertion of short-range potential

Inconsistency of the Weinberg counting

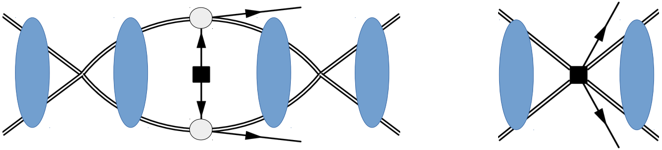


$$\frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2\left(\frac{1}{\varepsilon}+\log\mu^2\right)$$

- two-loop diagrams w. two insertions of $\tilde{C}$ have UV log divergence

need a local LNV counterterm at LO!

Inconsistency of the Weinberg counting



- two-loop diagrams w. two insertions of $\tilde{C}$ have UV log divergence

need a local LNV counterterm at LO!

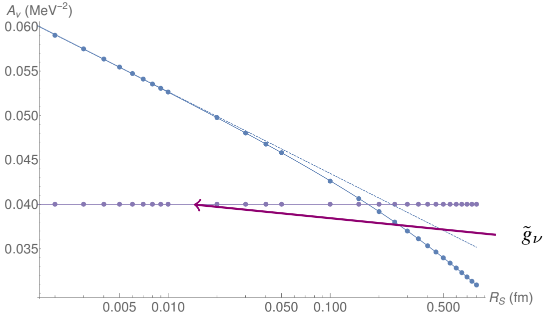
- renormalization requires to modify the LO ν potential

$$V_{\mathrm{LNV}} = V_\nu - 2 g_\nu \tau^{(1)+} \tau^{(2)+} \mathcal{A}$$

- the coupling g_ν is larger than NDA

$$g_\nu \sim \frac{1}{F_\pi^2} \gg \frac{1}{(4\pi F_\pi)^2}$$

Inconsistency of the Weinberg counting



$$g_\nu = \left(\frac{m_N \tilde{C}}{4\pi}\right)^2 \tilde{g}_\nu$$

$$\tilde{g}_\nu \sim b - \frac{1}{2}(1 + 2g_A^2) \log R_S$$

- divergence is not an artifact of dim. reg.

  regulate the short-range core as

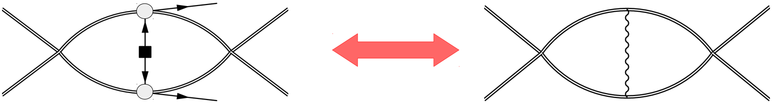
  $$\delta^{(3)}(\mathbf{r}) \to \frac{1}{\pi^{3/2} R_S^3} e^{-\frac{r^2}{R_S^2}}$$

  and calculate

  $$\mathcal{A}_\nu = \int d^3\mathbf{r}\, \psi^-_{\mathbf{p}'}(\mathbf{r}) V_\nu(\mathbf{r}) \psi^+_{\mathbf{p}}(\mathbf{r})$$

- $\mathcal{A}_\nu$ shows logarithmic dependence on R_S (+ power corrections)

Relation between $0\nu\beta\beta$ and EM isospin breaking

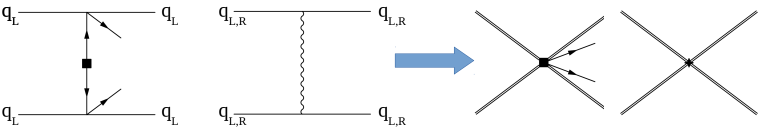


$$G_F^2 \tau^{(1)+} \tau^{(2)+} \frac{m_{\beta\beta}}{\mathbf{q}^2}$$

$$\left(\tau^{(1)z} \tau^{(2)z} - \frac{1}{3} \boldsymbol{\tau}^{(1)} \cdot \boldsymbol{\tau}^{(2)} \right) \frac{e^2}{\mathbf{q}^2}$$

- can we determine g_ν ?
- ν potential very similar to $I = 2$ piece of Coulomb potential
- & chiral symmetry relates $I = 2$ short-range operators in $0\nu\beta\beta$ and NN scattering

Relation between $0\nu\beta\beta$ and EM isospin breaking

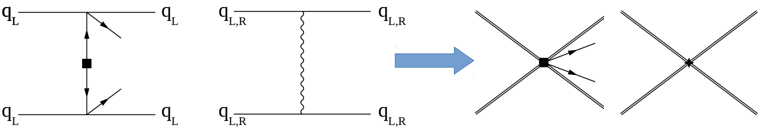


- only two $I = 2$ operators w. same properties as weak/EM currents

$$\mathcal{L}_{I=2} = c\,C_1 \left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6} \bar{N}\boldsymbol{\tau}N \cdot \bar{N}\boldsymbol{\tau}N + L \to R \right)$$
$$+\ c\,C_2 \left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L\mathcal{Q}_R]}{6} \bar{N}\boldsymbol{\tau}N \cdot \bar{N}\boldsymbol{\tau}N + L \to R \right)$$
$$\mathcal{Q}_L = u^\dagger Q_L u \quad \mathcal{Q}_R = u Q_R u^\dagger, \qquad u = 1 + \frac{i\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{2F_\pi} + \ldots$$

- weak interactions: $Q_L = \tau^+,\ Q_R = 0, \qquad c_{LNV} = 2G_F^2 m_{\beta\beta}\, \bar{e}_L C \bar{e}_L^T$
- EM interactions: $Q_L = \frac{\tau^z}{2},\ Q_R = \frac{\tau^z}{2}, \qquad c_{e^2} = \frac{e^2}{4}$

Relation between $0\nu\beta\beta$ and EM isospin breaking



- only two $I = 2$ operators w. same properties as weak/EM currents

$$\mathcal{L}_{I=2} = c\,C_1\left(\bar{N}\mathcal{Q}_L N\bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$

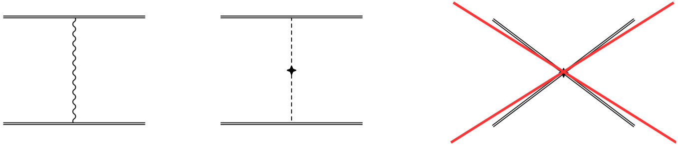
$$+\ c\,C_2\left(\bar{N}\mathcal{Q}_L N\bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L\mathcal{Q}_R]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$

$$\mathcal{Q}_L = u^\dagger Q_L u \quad \mathcal{Q}_R = u Q_R u^\dagger, \qquad u = 1 + \frac{i\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{2F_\pi} + \ldots$$

- $C_1 = g_\nu$ by chiral symmetry!
- C_1 and C_2 differ at multipion level

cannot disentangle in NN scattering
but give an idea of $0\nu\beta\beta$ counterterm

Weinberg counting for isospin breaking operators



- leading $I = 2$ potential in ${}^1S_0$ channel from γ exchange & pion mass splitting

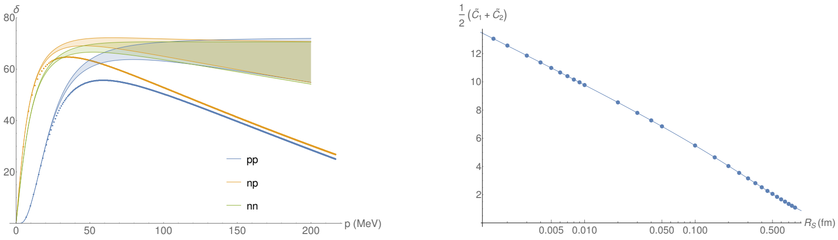
$$V^{\mathrm{lr}}_{I=2} = \frac{1}{4}\left(\frac{e^2}{\mathbf{q}^2} + \frac{g_A^2}{F_\pi^2}\frac{m^2_{\pi^\pm} - m^2_{\pi^0}}{\mathbf{q}^2 + m_\pi^2}\right)\left(\tau^{(1)\,z}\tau^{(2)\,z} - \frac{1}{3}\boldsymbol{\tau}^{(1)}\cdot\boldsymbol{\tau}^{(2)}\right)$$

$$m^2_{\pi^\pm} - m^2_{\pi^0} \sim e^2 F_\pi^2$$

- short-range contributions suppressed

$$V^{\mathrm{sr}}_{I=2} = \frac{e^2}{2}\frac{C_1 + C_2}{2}\left(\tau^{(1)\,z}\tau^{(2)\,z} - \frac{1}{3}\boldsymbol{\tau}^{(1)}\cdot\boldsymbol{\tau}^{(2)}\right) \qquad C_1 \sim C_2 \sim \frac{1}{(4\pi F_\pi)^2}$$

Relation to charge-independence breaking



Charge-independence breaking (CIB) observables, e.g.

$$a_{CIB} = \frac{a_{nn} + a_{pp}}{2} - a_{np}$$

1. LO analysis of isospin breaking show log dependence

$$\frac{C_1 + C_2}{2} = \left(\frac{m_N \tilde{C}}{4\pi}\right)^2 \frac{\tilde{C}_1 + \tilde{C}_2}{2} \sim_{R_S=0.5} \frac{16}{(4\pi F_\pi)^2}$$

disagree with Weinberg's counting!

Relation to charge-independence breaking

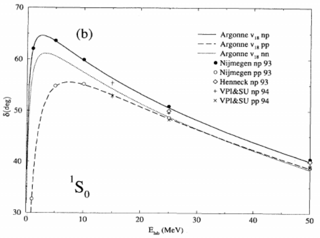


TABLE IX. Evolution of $^1S_0$ *pp* phase shifts from the charge-independent potential to the full interaction, as described in the text. Energies are in MeV.

$T_{\rm lab}$	CI	$+\,m_p$	$+$ CD v^π	$+$ CD v^R	$+\,v^{\rm EM}$
1	57.99	57.80	57.42	55.50	32.68
5	61.22	61.12	60.88	59.78	54.74
10	57.98	57.90	57.71	56.84	55.09
25	49.22	49.17	49.05	48.36	48.51
50	38.87	38.84	38.76	38.13	38.78
100	24.87	24.85	24.80	24.19	25.01
150	14.83	14.81	14.77	14.16	15.00
200	6.82	6.80	6.77	6.15	6.99
250	0.08	0.06	0.04	−0.60	0.23
300	−5.78	−5.79	−5.82	−6.47	−5.64
350	−10.99	−11.00	−11.01	−11.69	−10.86

AV18 potential, Phys. Rev. C51 (1995) 38-51

2. in realistic potentials (AV18, χ-EFT)
   $V^{\rm lr}_{I=2}$ and $V^{\rm sr}_{I=2}$ give effects of comparable size

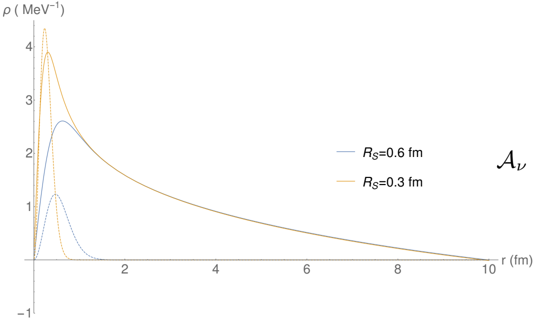
- e.g. large $C_1 + C_2$ in χ-EFT potentials

$$\frac{C_1 + C_2}{2} \sim \frac{50}{(4\pi F_\pi)^2}$$

M. Piarulli et al, '16

- same effect in isotensor energy coeff. of light nuclei

Impact on $0\nu\beta\beta$ nuclear matrix elements



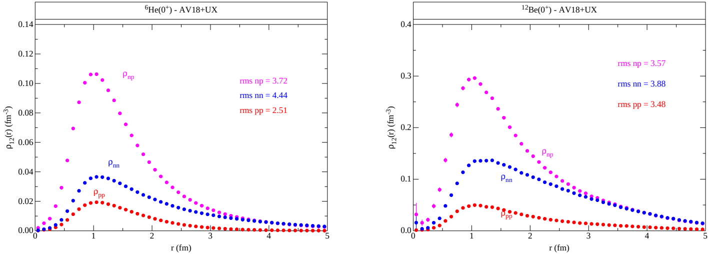
$$\mathcal{A}_\nu = \int dr \rho(r)$$

$nn \to pp$

- *assume* $C_1(R_S) = C_2(R_S)$
- LNV matrix element is scale independent
- effect of short-range potential $\sim 10\%$

$\Delta I = 0$ transition

Impact on $0\nu\beta\beta$ nuclear matrix elements

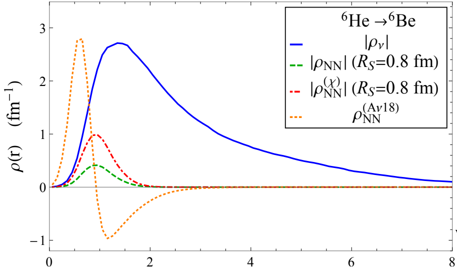


R. Wiringa, S. Pastore *et al.*
`http://www.phy.anl.gov/theory/research/density2/`

Ab initio calculation of ^{6}He $\rightarrow$ ^{6}Be and ^{12}Be $\rightarrow$ ^{12}C

- not a realistic double beta decay candidate
- ...but same spin/isospin as $0\nu\beta\beta$ emitters
- ...and fully controlled calculation

Impact on $0\nu\beta\beta$ nuclear matrix elements



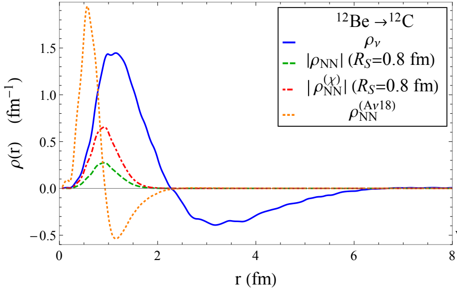
$\Delta I = 2$

VMC calculation
w. AV18 potential

- extract CIB potential $V^{\rm sr}_{I=2}$ from AV18, rescaled by c_{LNV}/c_{e^2}
- $\sim$ 10% corrections to $\Delta I = 0$ transitions

$$\frac{M_{F\nu}}{g_A^2} = 0.93 \quad M_{GT\nu} = 3.58 \quad \frac{M_{F,NN}}{g_A^2} = 0.30$$

Impact on $0\nu\beta\beta$ nuclear matrix elements



$\Delta I = 2$

VMC calculation
w. AV18 potential

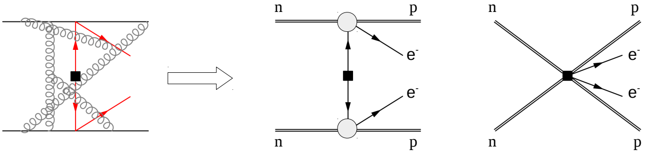
- extract CIB potential $V^{\rm sr}_{\Delta I=2}$ from AV18
- larger corrections to $I = 2$ transitions

$$\frac{M_{F\nu}}{g_A^2} = 0.191 \quad M_{GT\nu} = 0.400 \quad \frac{M_{F,NN}}{g_A^2} = 0.29$$

$\mathcal{O}(1)$ correction!

- …but uncontrolled theory error from assuming $C_1 = C_2$!

Standard mechanism: summary



how to relate $0\nu\beta\beta$ to the neutrino masses?

- power counting & analogy to EM isospin breaking:

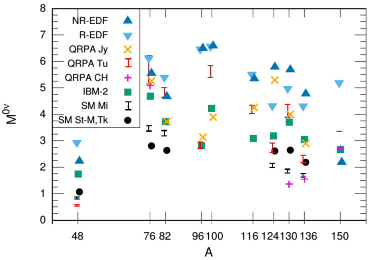
  strong indication that $0\nu\beta\beta$ operator has significant short-range components

- need Lattice QCD calculation of $nn \to ppe^- e^-$
  & matching to nuclear EFTs !

CalLat, NPLQCD
see Z. Davoudi's talk last week

- can pinpoint C_1 via pion double charge exchange?

Standard mechanism: summary



J. Engel and J. Menéndez, '16

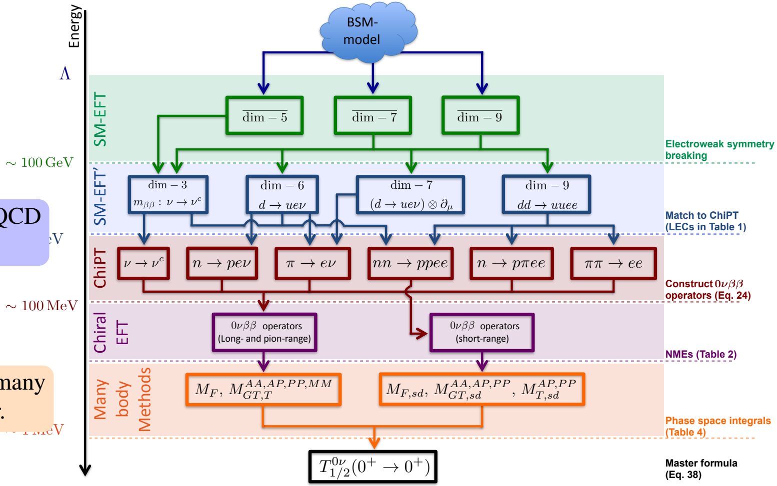
- . . . just another uncertainty on top of many-body

see J. Menéndez's talk

- mimicked by short-range correlations?

Chiral EFT for non-standard mechanisms

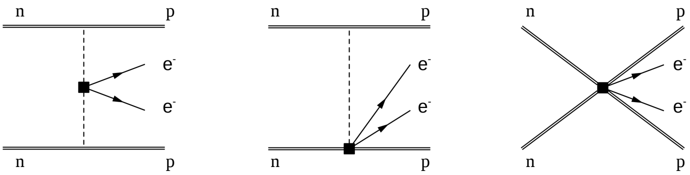
Chiral EFT for non-standard mechanisms



need LQCD input

sizable many body err.

Dim. 9 operators



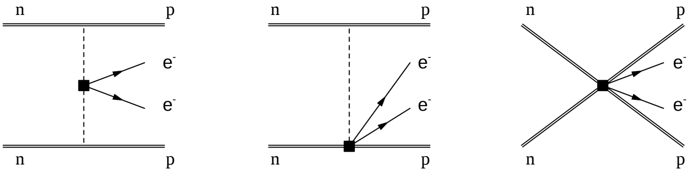
1. LL LL : $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \, \gamma_\mu d_L$
2. LR LR : $\mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R,$ $\mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha$
3. LL RR : $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \, \gamma_\mu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

- several unjustified assumptions in the literature . . .

e.g. $\langle pp | \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \, \gamma_\mu d_R | nn \rangle = \langle p | \bar{u}_L \gamma^\mu d_L | n \rangle \, \langle p | \bar{u}_R \, \gamma_\mu d_R | n \rangle = (1 - 3 g_A^2)$

inconsistent with QCD, miss chiral dynamics

LNV interactions from dim. 9 operators



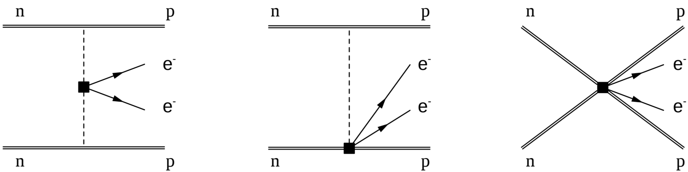
- $\pi\pi$ couplings

$$\mathcal{L}_\pi = \frac{F_0^2}{2}\left[\frac{5}{3} g_1^{\pi\pi} C_{1L}^{(9)}\, \partial_\mu \pi^- \partial^\mu \pi^- + \left(g_4^{\pi\pi} C_{4L}^{(9)} + g_5^{\pi\pi} C_{5L}^{(9)} - g_2^{\pi\pi} C_{2L}^{(9)} - g_3^{\pi\pi} C_{3L}^{(9)}\right) \pi^- \pi^- \right] \times \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots$$

- size depends on chiral properties of $\mathcal{O}_{1,\dots,5}$

$$g_1^{\pi\pi} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{\pi\pi} \sim \mathcal{O}(\Lambda_\chi^2)$$

LNV interactions from dim. 9 operators



- πN couplings, only important for $\mathcal{O}_1$
- NN couplings

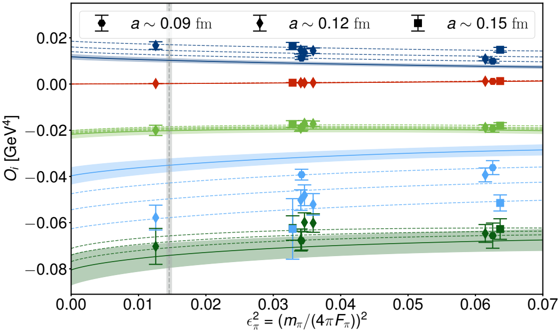
$$\mathcal{L}_{NN} = \left(g_1^{NN} C_{1\mathrm{L}}^{(9)} + g_2^{NN} C_{2\mathrm{L}}^{(9)} + g_3^{NN} C_{3\mathrm{L}}^{(9)} + g_4^{NN} C_{4\mathrm{L}}^{(9)} + g_5^{NN} C_{5\mathrm{L}}^{(9)}\right) (\bar{p}n)\ (\bar{p}n)\ \frac{\bar{e}_L C \bar{e}_L^T}{v^5}$$

- size depends on chiral properties of $\mathcal{O}_{1,\ldots,5}$

$$g_1^{NN} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{NN} \sim \mathcal{O}\left(\frac{\Lambda_\chi^2}{F_\pi^2}\right)$$

enhanced w.r.t NDA!

$\pi\pi$ matrix elements



$g_1^{\pi\pi} = +0.4$

$g_2^{\pi\pi} = -(1.8\,\text{GeV})^2$

$g_3^{\pi\pi} = +(1.0\,\text{GeV})^2$

$g_4^{\pi\pi} = -(1.7\,\text{GeV})^2$

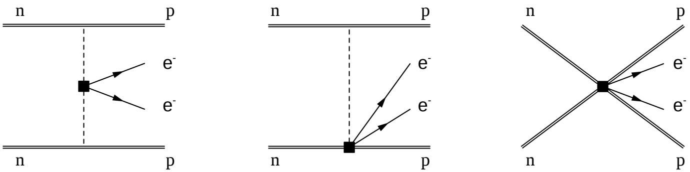
$g_5^{\pi\pi} = -(3.6\,\text{GeV})^2$

A. Nicholson *et al.*, CalLat collaboration, '18

- $\pi\pi$ matrix elements well determined in LQCD

good agreement with NDA

- $nn \to pp$ will allow to determine g_i^{NN}
  and test the chiral EFT power counting



- NME differ dramatically from factorization
  e.g $C_4^{(9)}$

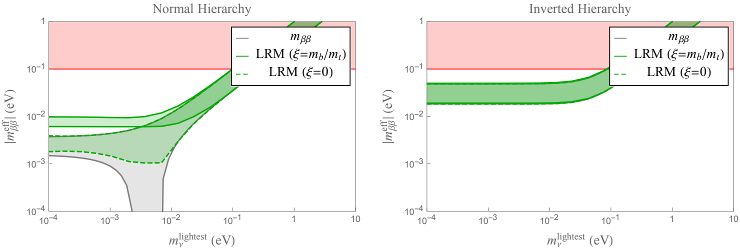
$$M = -\frac{g_4^{\pi\pi} C_4^{(9)}}{2m_N^2}\left(\frac{1}{2}M^{GT}_{AP,sd} + M^{GT}_{PP,sd}\right) \sim -0.60 C_4^{(9)}$$

$$M_{\rm fact} = -\frac{3g_A^2 - 1}{2g_A^2}\frac{m_\pi^2}{m_N^2} C_4^{(9)} M_{F,sd} \sim -0.04 C_4^{(9)}$$

bigger error than from NMEs ...

Phenomenology

$0\nu\beta\beta$ in the Left-Right Symmetric Model



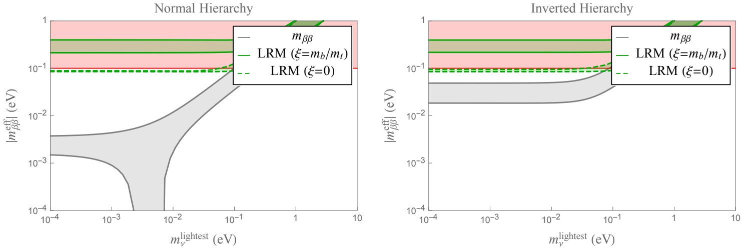
- generate dim. 5, 7 and 9
- dim. 7 and dim. 9 are chirally suppressed

Case 1 $m_{W_R} = 4.5$ TeV, $m_{\Delta_R} = 10$ TeV, $U_R = U_{\mathrm{PMNS}}$,

$m_{\nu_R} \sim m_{W_R}$

- strong collider bounds on m_{W_R} suppress dim. 7 and dim. 9 contribs.
- light-ν Majorana mass dominates in IH
- dim. 9 sizable in NH, but not in reach

$0\nu\beta\beta$ in the LRSM

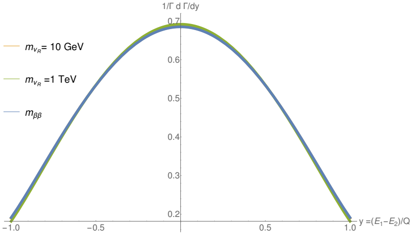


Case 2 $m_{W_R} = 4.5$ TeV, $m_{\Delta_R} = 10$ TeV, $U_R = U_{\rm PMNS}$,

$m_{\nu_R} \sim 10$ GeV

- not ruled out by LEP, LHC searches
- dim. 9 contribution becomes dominant
- in conflict with current $0\nu\beta\beta$ limits

$0\nu\beta\beta$ in the LRSM



- disentangle LRSM from standard mechanism?
- different isotopes are largely degenerate
- electron energy and angular distributions as well

- need interplay with LHC searches!

Conclusion

- BSM searches with nuclei are complementary
  & very competitive with the energy frontier

$0\nu\beta\beta$, EDMs, DM, ...

- but need to control QCD & nuclear theory !

EFTs

- model independent link to collider phenomenology
- identify non-perturbative QCD input

Lattice QCD

- calculate few nucleon observables

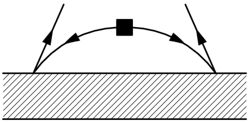
d_n, EDMs of light nuclei, $^6\mathrm{He} \to ^6\mathrm{Li}\, e^- \bar{\nu}$

- provide input for many-body calculations

$0\nu\beta\beta$ potentials, DM-nucleon currents, ...

Backup

Usoft contribution to the amplitude



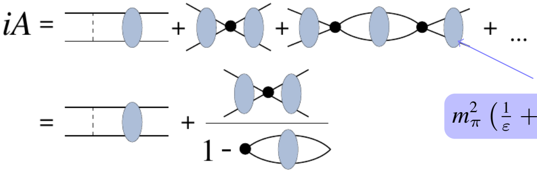
overlap $\langle n|J_\mu|i\rangle$ same as in $2\nu\beta\beta$!

4. soft neutrinos, which couple to the nuclear bound states

$$T_{\rm usoft}(\mu_{\rm us}) = \frac{T_{\rm lept}}{8\pi^2} \sum_n \langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle \left\{ (E_2+E_n-E_i) \left(\log \frac{\mu_{\rm us}}{2(E_2+E_n-E_i)} + 1 \right) + 1 \leftrightarrow 2 \right\},$$

- corrections to the "closure approximation"
- suppressed by $E/(4\pi k_F)$

Is the Weinberg counting consistent?



$m_\pi^2 \left(\frac{1}{\varepsilon} + \log \mu^2\right)$

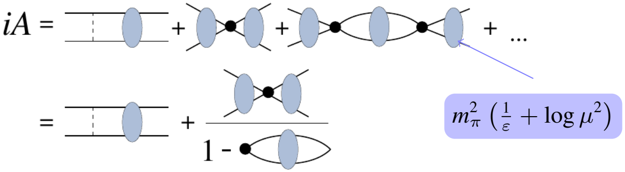
D. Kaplan, M. Savage, M. Wise, '96

- NDA does not work in *NN* scattering
- m_π dependence of short-range nuclear force should be subleading

$$\mathcal{L} = -\tilde{C}(N^T P^{{}^1S_0} N)(N^T P^{{}^1S_0} N)^\dagger - \frac{m_\pi^2}{(4\pi F_\pi)^2} D_2 (N^T P^{{}^1S_0} N)(N^T P^{{}^1S_0} N)^\dagger + \ldots$$

$$4\pi F_\pi = \Lambda_\chi \sim 1\,\mathrm{GeV}$$

Is the Weinberg counting consistent?



D. Kaplan, M. Savage, M. Wise, ‘96

- NDA does not work in *NN* scattering
- m_π dependence of short-range nuclear force should be subleading

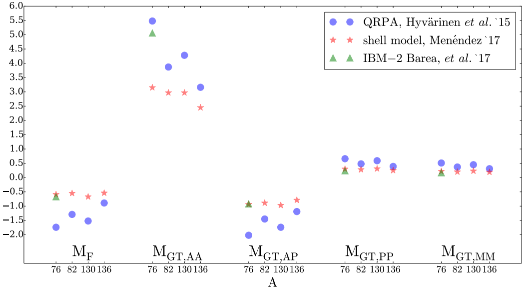
$$\mathcal{L} = -\tilde{C}(N^T P^{{}^1S_0} N)(N^T P^{{}^1S_0} N)^\dagger - \frac{m_\pi^2}{(\cancel{4\pi} F_\pi)^2} D_2 (N^T P^{{}^1S_0} N)(N^T P^{{}^1S_0} N)^\dagger + \ldots$$

$$4\pi F_\pi = \Lambda_\chi \sim 1\,\mathrm{GeV}$$

- …but UV divergences in the LO amplitude require a promotion …

conflict between NDA & short-range core of nuclear force

Nuclear matrix elements



calculations differ by factor of 2-3

- at LO in χEFT, **all** nuclear matrix elements (NME) can be expressed in terms of existing calculations
- 8 long-range NME

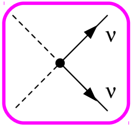
contribute to light ν exchange

- 6 short-range NME

contribute to heavy Majorana ν exchange

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

$\Delta L = 2$ Lagrangian at 1 GeV

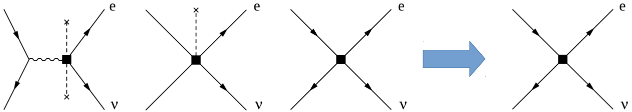


$$\mathcal{L}_{\Delta L=2} = \mathcal{L}_{\Delta L=2}^{\Delta e=0} + \mathcal{L}_{\Delta L=2}^{\Delta e=1} + \mathcal{L}_{\Delta L=2}^{\Delta e=2}$$

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

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2}(m_\nu)_{ij}\,\nu_L^{T\,j}\,C\nu_L^i + \ldots \qquad m_\nu \sim \mathcal{O}\left(\frac{v^2}{\Lambda}\right)$$

$\Delta L = 2$ Lagrangian at 1 GeV



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

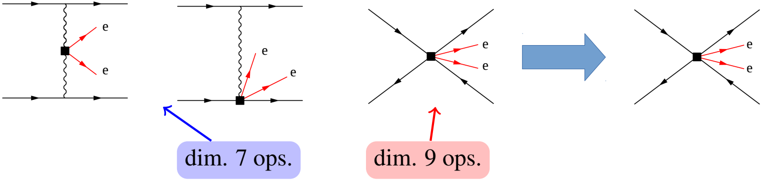
- $\mathcal{L}^{\Delta e=1}_{\Delta L=2}$ starts at dim. 6, $\quad C_i^{(6)} = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$

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

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

β decay w. the “wrong” neutrino & all possible Lorentz structures

$\Delta L = 2$ Lagrangian at 1 GeV



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

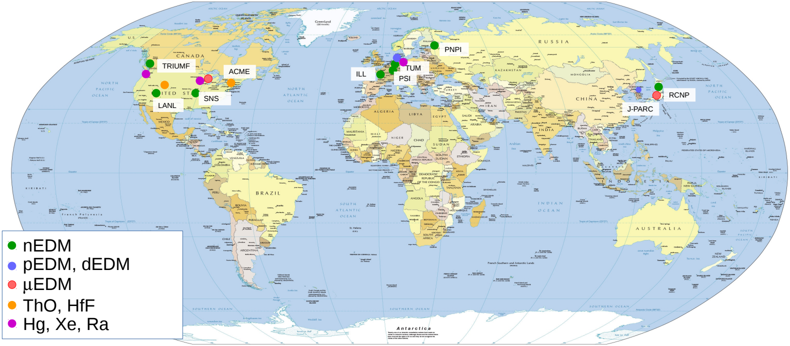
$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{2G_F^2}{v} \left[\sum_{i=\text{scalar}} \left(C_i^{(9)}\, \bar{e}_L C\, \bar{e}_L^T + C_i^{(9)\prime}\, \bar{e}_R C\, \bar{e}_R^T \right) O_i \;+\; \bar{e}_R \gamma_\mu C\, \bar{e}_L^T \sum_{i=\text{vector}} C_{iV}^{(9)}\, O_i^\mu \right]$$

- a small set receives contributions from dim. 7 operators

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

- straightforward to include pQCD corrections

CP violation



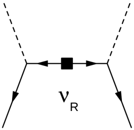
- current bounds

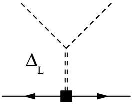
$$
\begin{aligned}
d_e &< 8.7 \cdot 10^{-16}\; e\,\text{fm} \\
d_n &< 3.0 \cdot 10^{-13}\; e\,\text{fm} \\
d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17}\; e\,\text{fm} \\
d_{^{225}\text{Ra}} &< 4.2 \cdot 10^{-17}\; e\,\text{fm}
\end{aligned}
$$

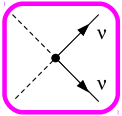
- future bounds

$$
\begin{aligned}
d_e &< 5.0 \cdot 10^{-17}\; e\,\text{fm} \\
d_n &< 1.0 \cdot 10^{-15}\; e\,\text{fm} \\
d_{^{199}\text{Hg}} &< 6.2 \cdot 10^{-17}\; e\,\text{fm} \\
d_{^{225}\text{Ra}} &< 1.0 \cdot 10^{-14}\; e\,\text{fm}
\end{aligned}
$$

Left-right symmetric model







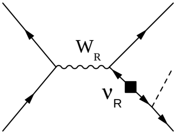
- model based on $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- broken to SM group at $v_R \gtrsim 10$ TeV

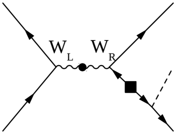
  K-$\bar{K}$ oscillations and di-jet searches

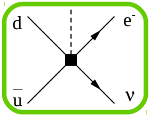
- generate ν masses via type-I and type-II see-saw

  need small Yukawas

Left-right symmetric model







- model based on $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- broken to SM group at $v_R \gtrsim 10$ TeV

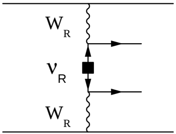
K-$\bar{K}$ oscillations and di-jet searches

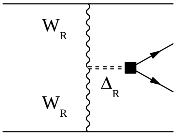
- generate ν masses via type-I and type-II see-saw

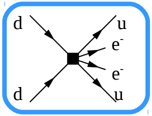
need small Yukawas

- also generate dim. 7, with one Yukawa
- and dim. 9, with no Yukawa suppression

Left-right symmetric model







- model based on $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- broken to SM group at $v_R \gtrsim 10$ TeV

K-$\bar{K}$ oscillations and di-jet searches

- generate ν masses via type-I and type-II see-saw

need small Yukawas

- also generate dim. 7, with one Yukawa
- and dim. 9, with no Yukawa suppression