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Title: An Effective Field Theory Approach to neutrinoless double beta decay

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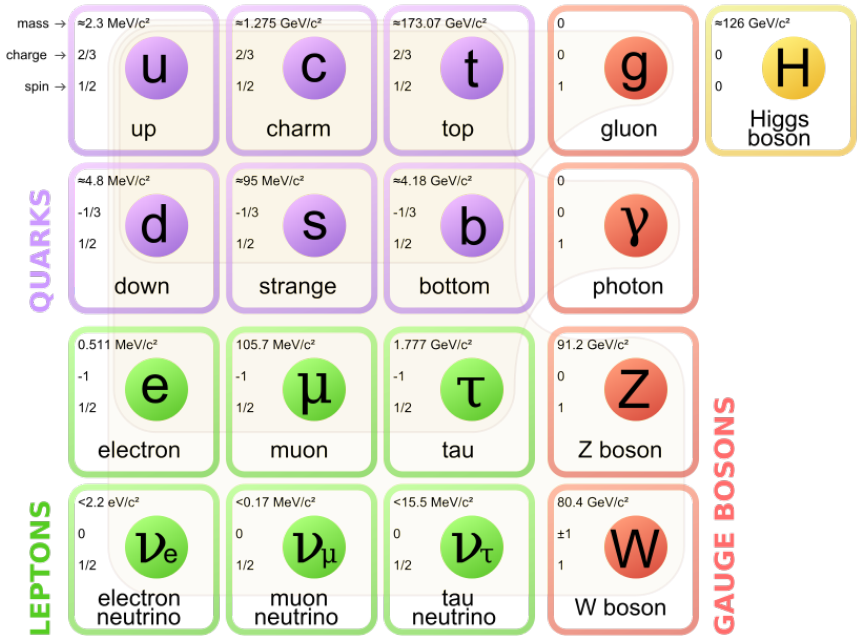
An Effective Field Theory approach to neutrinoless $\beta\beta$ decays

Emanuele Mereghetti

with V. Cirigliano, J. Carlson, W. Dekens, J. de Vries, M. Graesser, S. Pastore, M. Piarulli, U. van Kolck, A. Walker-Loud, R. Wiringa.

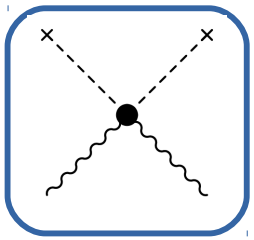
arXiv:1710.01729, 1802.10097, 1806.02780, 1907.xxxxx

Los Alamos NATIONAL LABORATORY EST. 1943

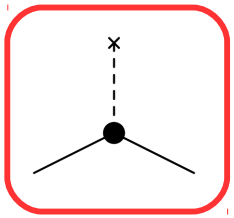


The Standard Model of Particle Physics

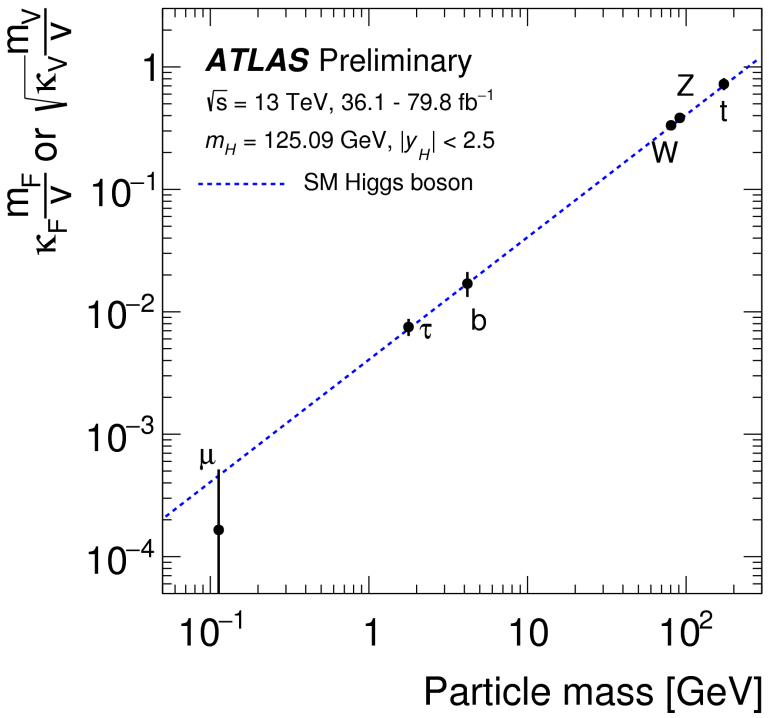
1. describes nature in a economic and elegant way
   (spontaneously broken) gauge symmetry



$$D_\mu \varphi D^\mu \varphi \to m_V^2 V_\mu V^\mu$$



$$\bar{q}_L \varphi d_R \to m_d \bar{d}_L d_R$$



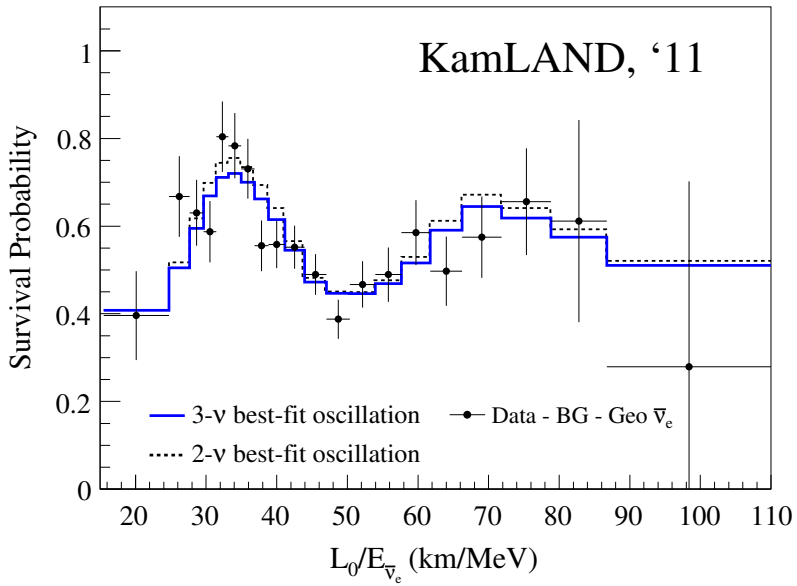
The Standard Model of Particle Physics

2. generates fermion and boson masses via the Higgs mechanism

confirmed at the LHC![1][2]

[1] ... for gauge bosons and heaviest fermions ...

[2] ... SM flavor structure is somewhat mysterious ...



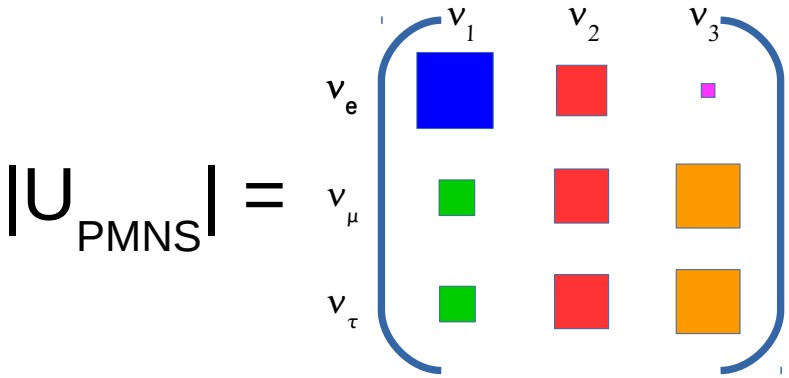
neutrino oscillation experiments:

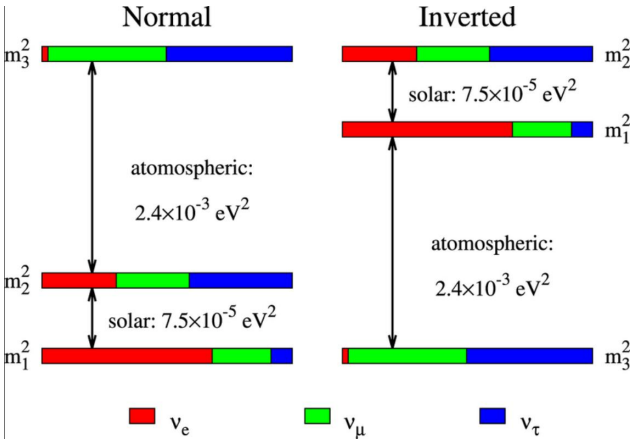
- neutrino have masses too!
- well described by 2 mass differences

& 3×3 unitary mixing matrix U_{PMNS}

Δm^2_{ij}, $|U_{li}|$ well known

CP (and Majorana) phases, mass ordering ?





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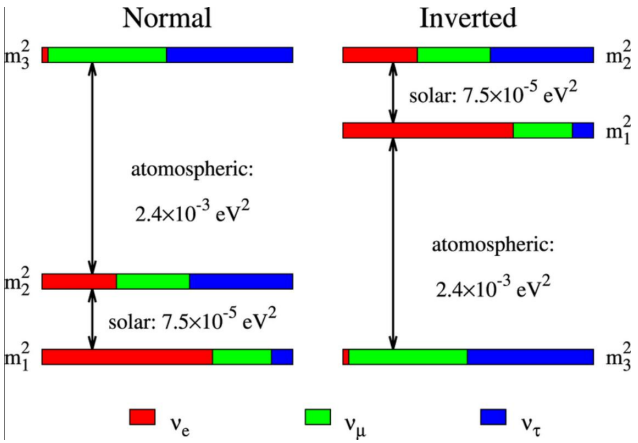
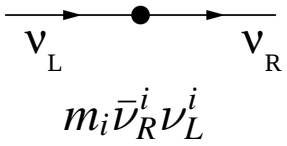
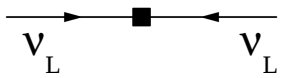




$m_i \bar{\nu}_R^i \nu_L^i$

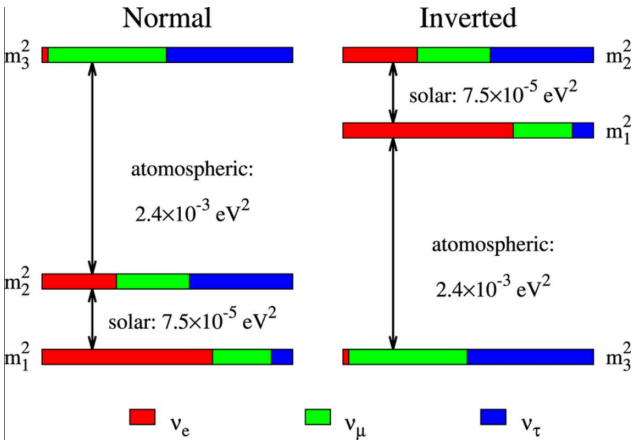
Dirac

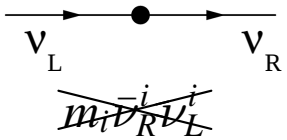


$m_i \nu^{T\,i}_L C \nu_L^i$

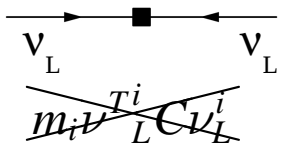
Majorana

- . . . but neutrinos are peculiar . . .
- two possible mass terms





Dirac



Majorana

- ...but neutrinos are peculiar ...
- two possible mass terms

Dirac:

- no ν_R in the SM
- if ν_R what forbids

$$m_{\nu_R} \nu_R^T C \nu_R ?$$

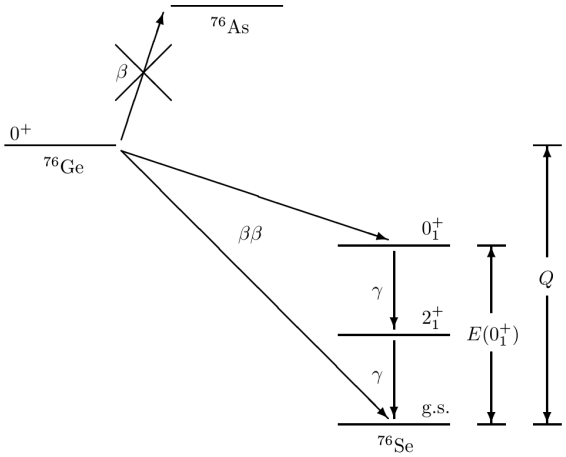
new mixings in oscillation exp.

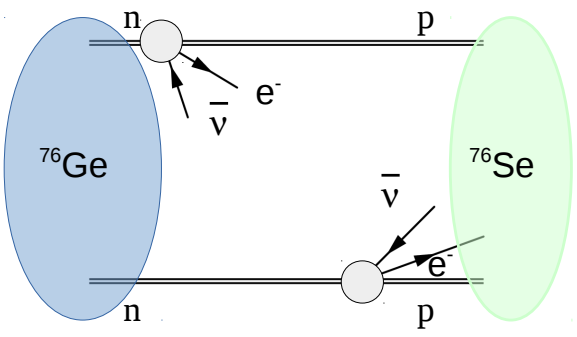
Majorana:

- break $SU(2)_L$
- restore $SU(2)_L$

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

at the price of heavy new physics



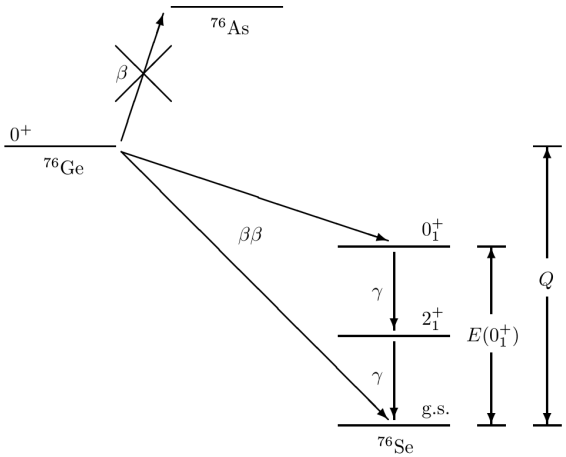


M. Duerr, M. Lindner, K. Zuber, '11

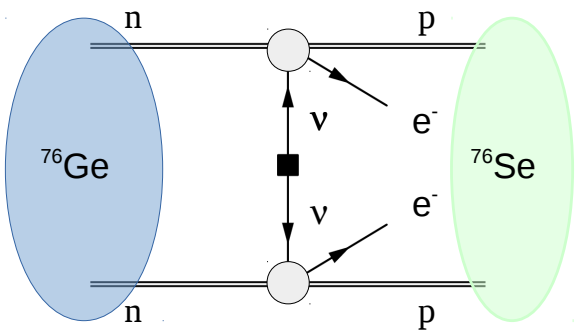
- double beta decay is rare doubly-weak decay process
- $2\nu\beta\beta$ allowed in SM

$$T_{1/2}^{2\nu}(^{76}\text{Ge} \rightarrow ^{76}\text{Se}) = (1.84^{+0.14}_{-0.10}) \times 10^{21}\ \text{yr}$$

GERDA coll., '15



M. Duerr, M. Lindner, K. Zuber, '11



- $0\nu\beta\beta$ violates lepton number L by two units

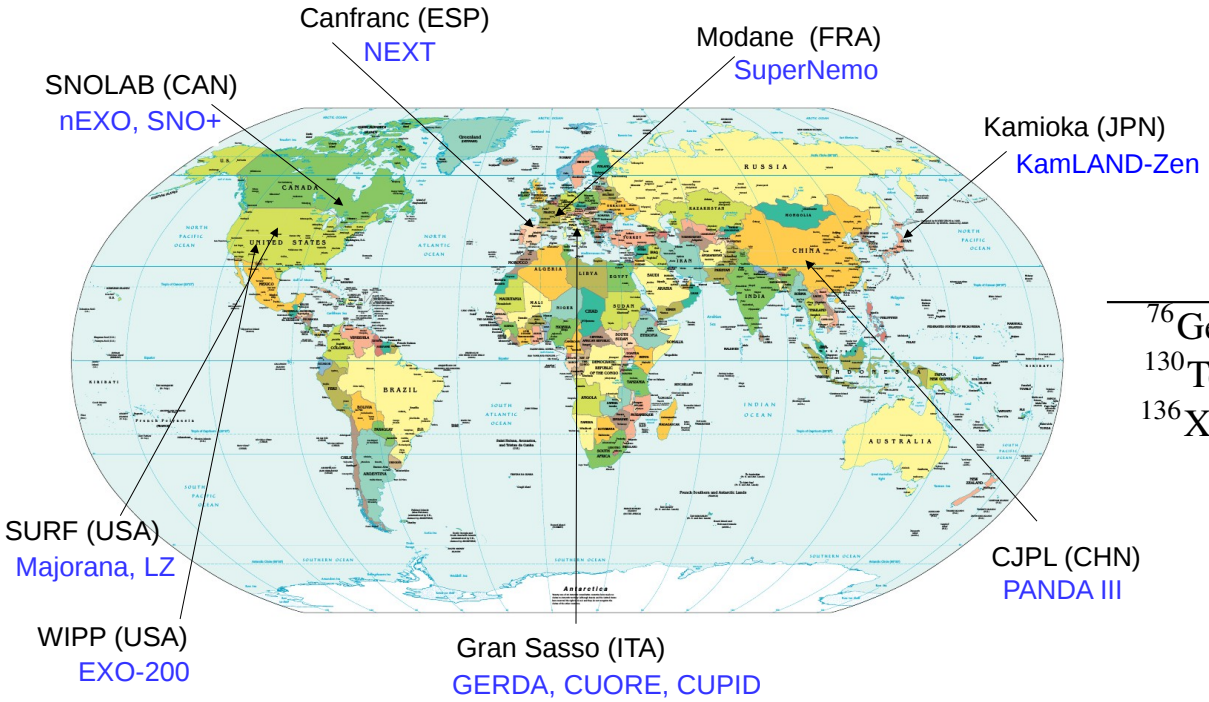
$$(A, Z) \to (A, Z+2) + e^- e^-$$

possible iff νs have a Majorana mass

- L conserved in the SM, $0\nu\beta\beta$ new physics!

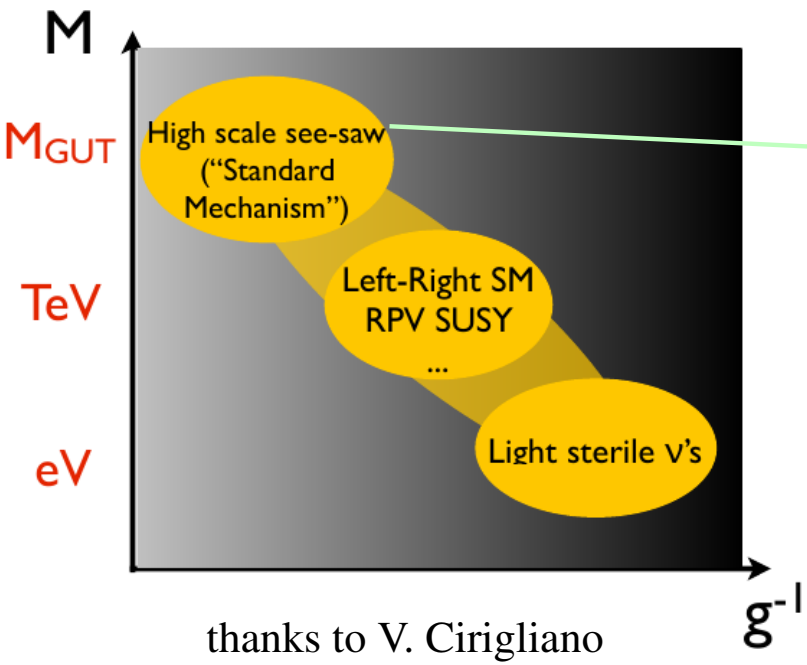
implications for ν mass, leptogenesis ...

Introduction

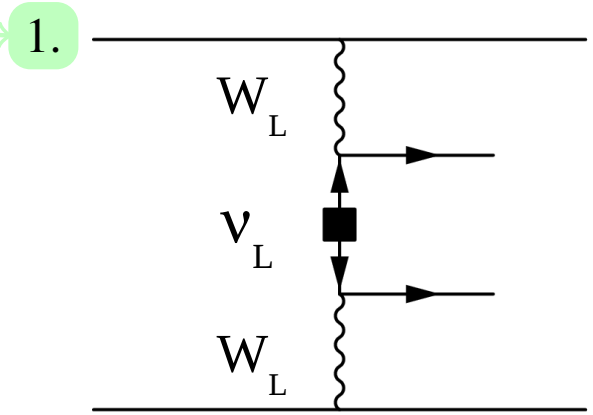


	$T^{0\nu}_{1/2}$ (yr)	
^{76}Ge	$8.0 \cdot 10^{25}$	GERDA
^{130}Te	$1.5 \cdot 10^{25}$	CUORE
^{136}Xe	$1.1 \cdot 10^{26}$	KamLAND-Zen

- current bounds already impressive
- next-generation tonne-scale experiments will improve by 1-2 orders

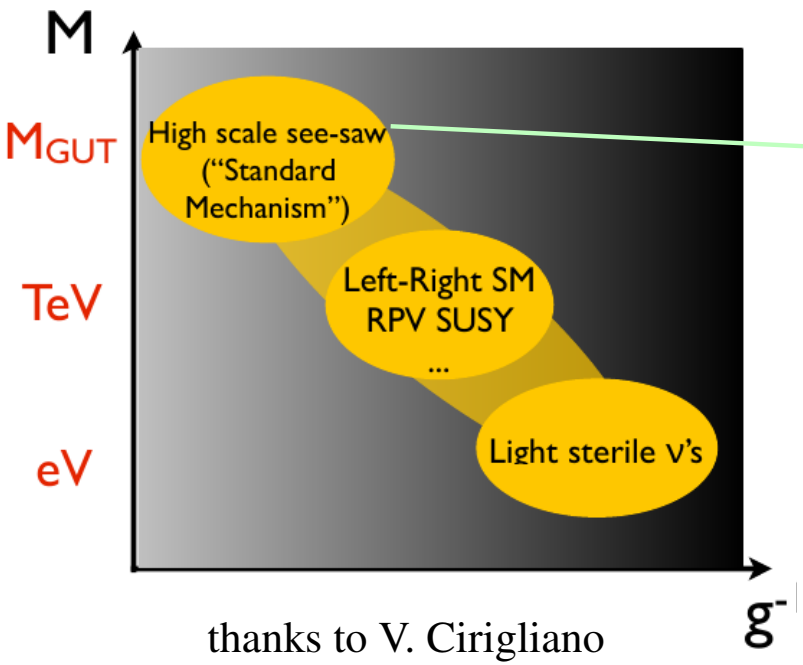


thanks to V. Cirigliano



Next generation of experiments sensitive to a variety of LNV scenarios

1. LNV originates at very high scales
   direct connection between ν oscillations and $0\nu\beta\beta$



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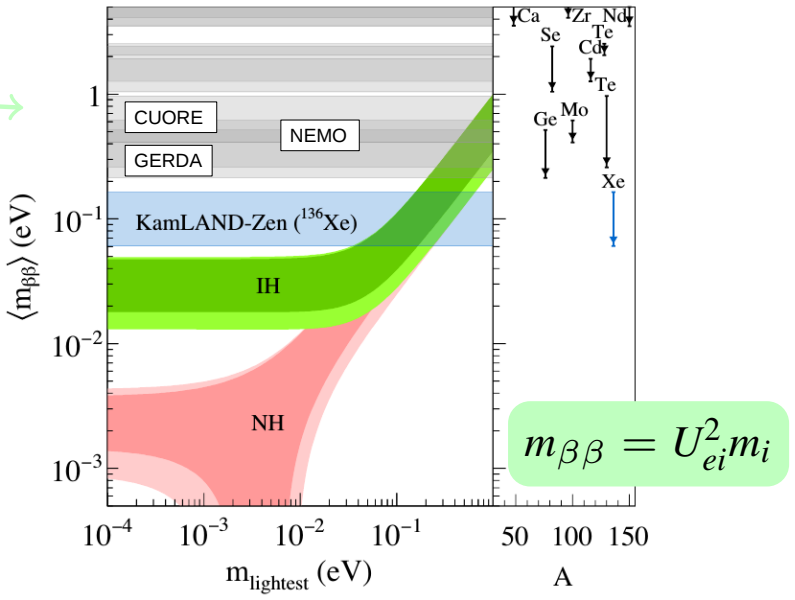
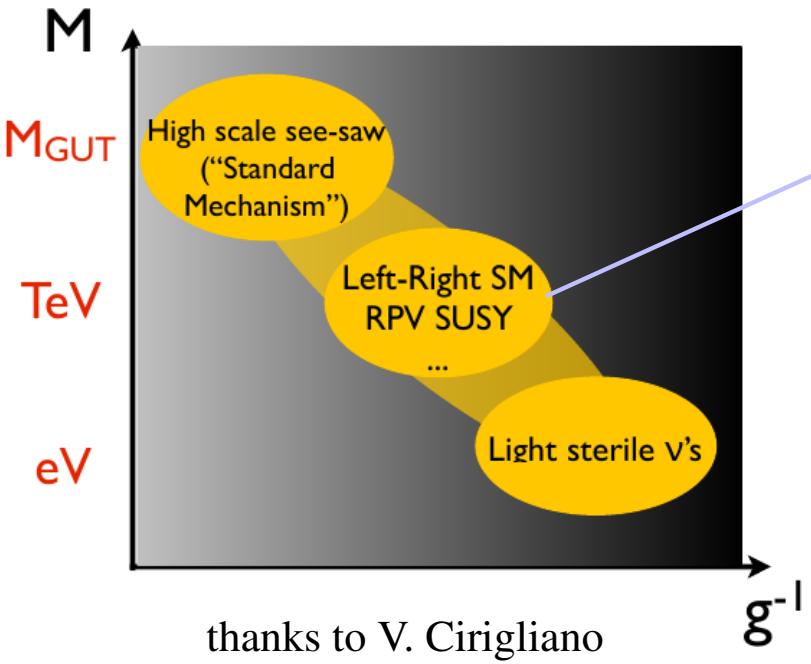


Next generation of experiments sensitive to a variety of LNV scenarios

1. LNV originates at very high scales
   direct connection between ν oscillations and $0\nu\beta\beta$
   clear interpretative framework and goals
   e.g. rule out inverted hierarchy



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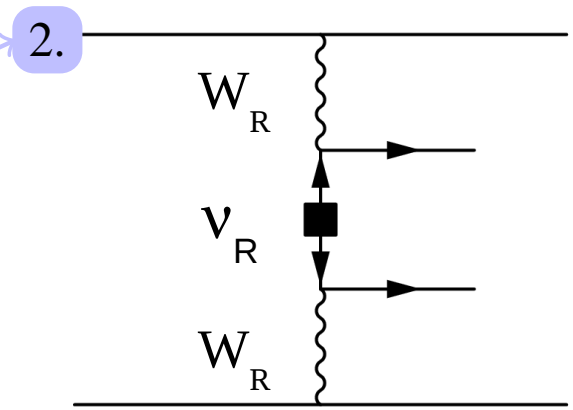
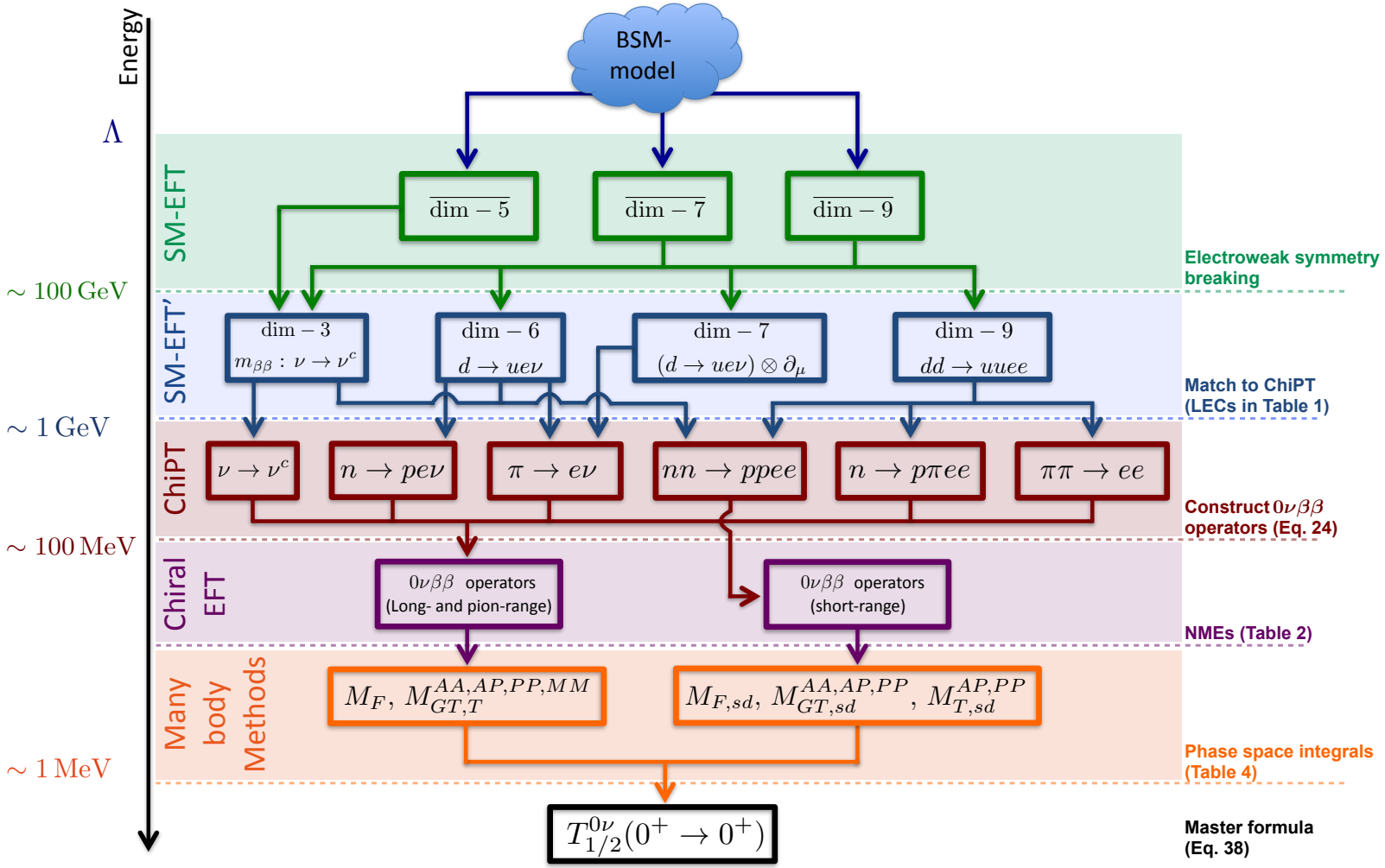


Next generation of experiments sensitive to a variety of LNV scenarios

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.?
with controlled uncertainties ?

EFT approach to LNV



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EFT approach to LNV

- half-life anatomy

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

What EFTs can do:

- fundamental LNV parameter

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

- "phase space factors"
  leptonic structure of LNV operators

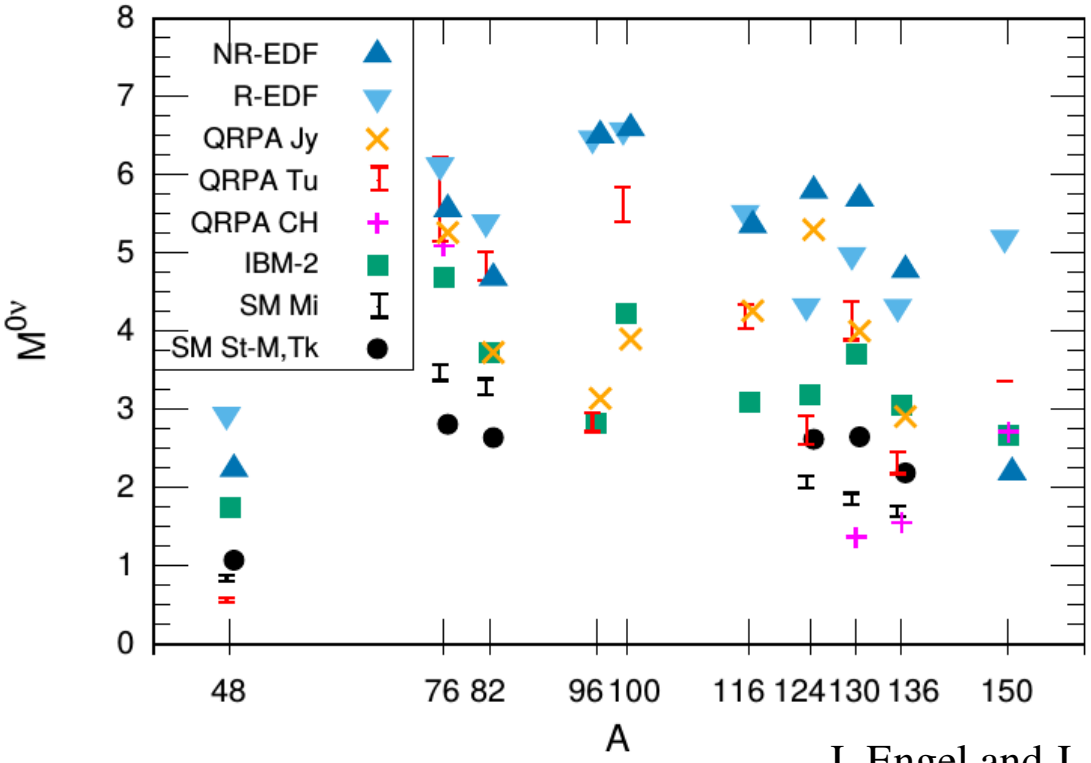
- from quarks to hadrons

identify QCD input & its uncertainty

- nuclear matrix elements of "ν potentials"

systematically derive the ν potentials

check NMEs in simpler systems



J. Engel and J. Menéndez, '16

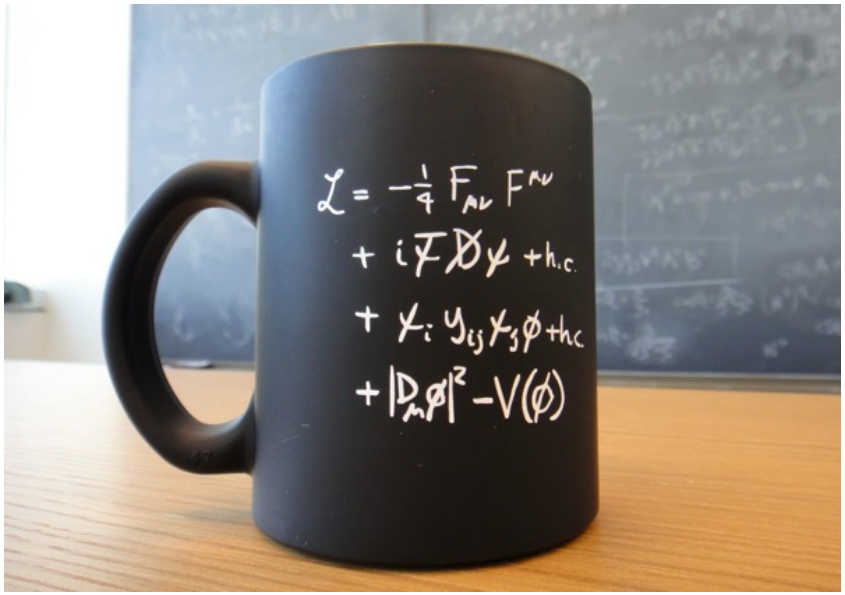
Final goal:

- help reduce theory uncertainties on $M^{0\nu}$

. . . not quite there yet . . .

The Standard Model as an EFT

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

- why stop at dim=4?

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

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

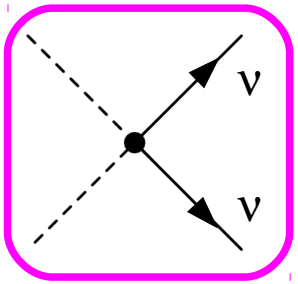
- $\mathcal{O}$ are gauge invariant
- no need to impose accidental symmetries as L

- why stop at dim=4?

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

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

- $\mathcal{O}$ are gauge invariant
- no need to impose accidental symmetries as L
- **one** dimension 5 operator S. Weinberg, '79

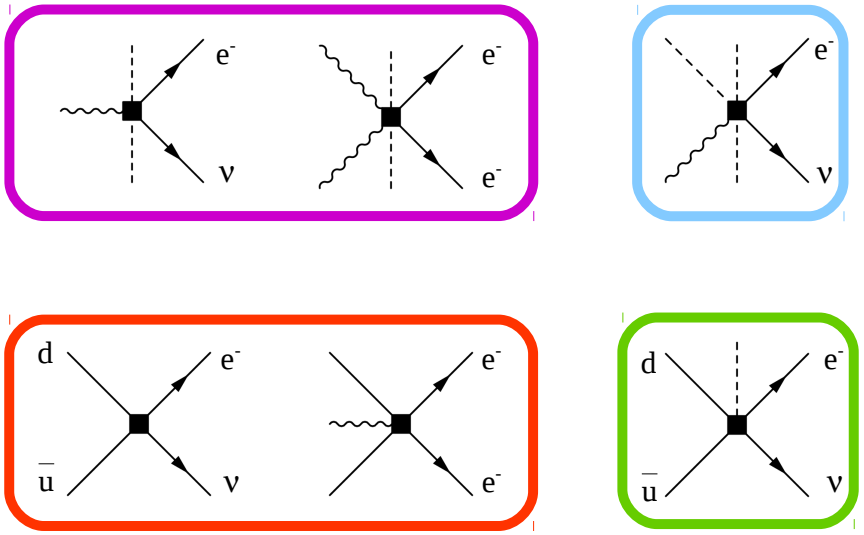


$$\frac{1}{\Lambda}\varepsilon_{ij}\varepsilon_{mn}L_i^T C L_m H_j H_n \to \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

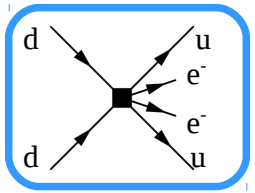
neutrino masses and mixings

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

LNV at dim. 7, dim. 9



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



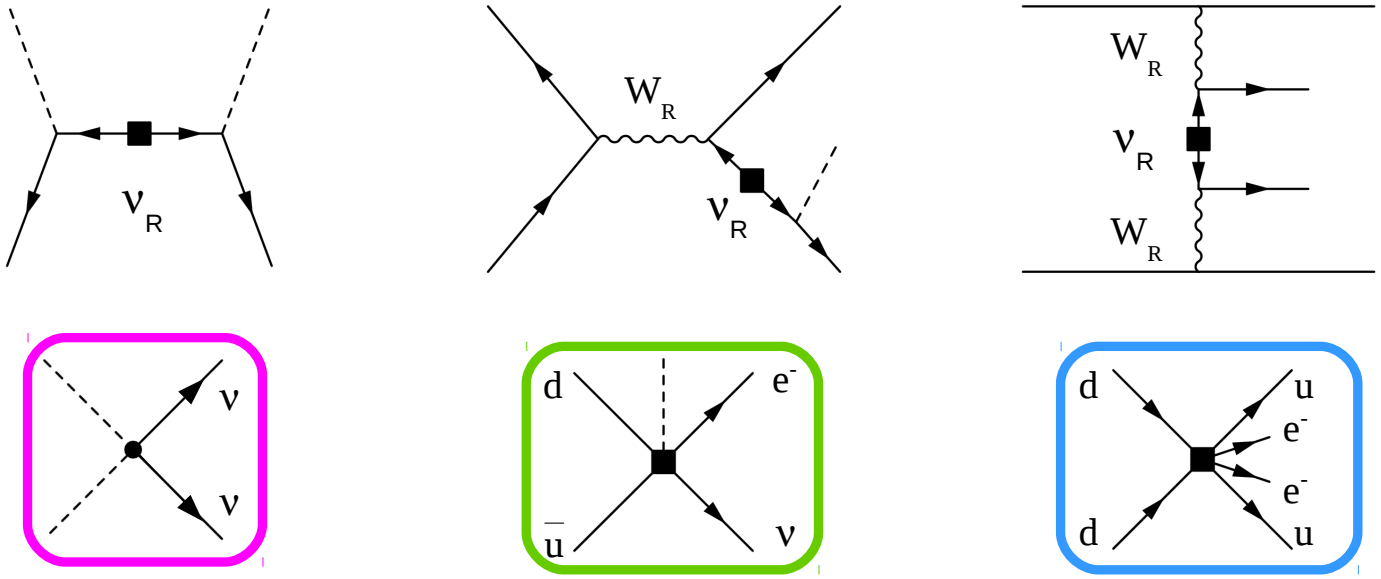
$\left(\frac{v}{\Lambda}\right)^5$

- 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 $0\nu\beta\beta$

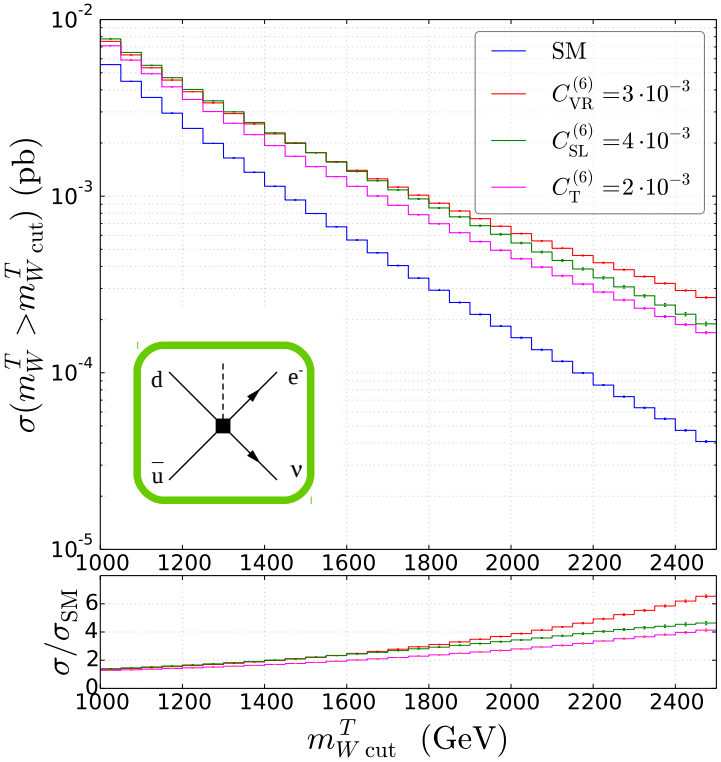
Connection to models

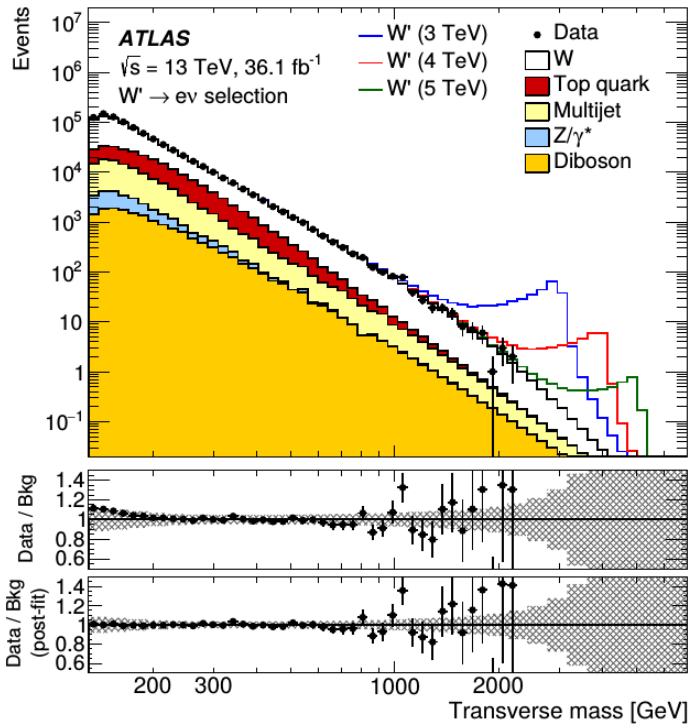


- specific models will match onto one or several operators
- e.g. LR symmetric model
  dim. 5, 7 & 9 (with different Yukawas)

can match any model to EFT

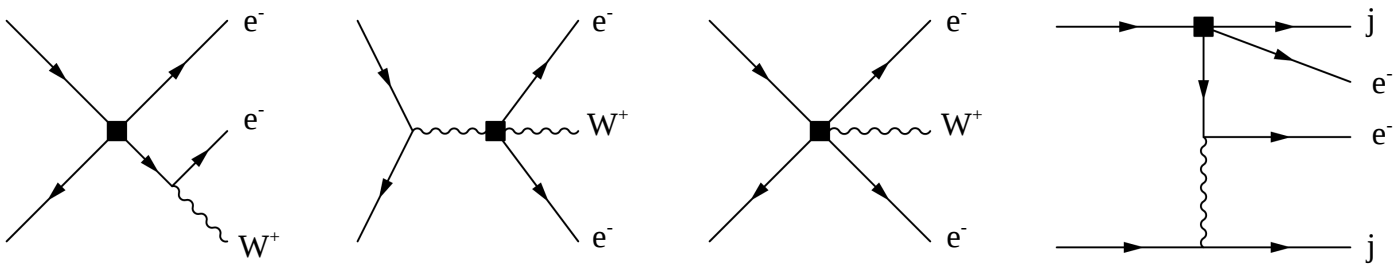
Dimension 7 at LHC





- some limits from $pp \to e\nu$: $\Lambda \lesssim 2.5$ 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

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

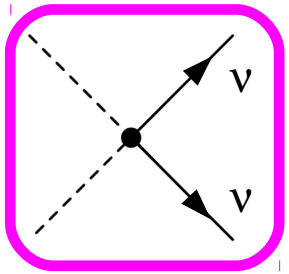
  $pp \to e^- e^- W^+ (jj)$

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

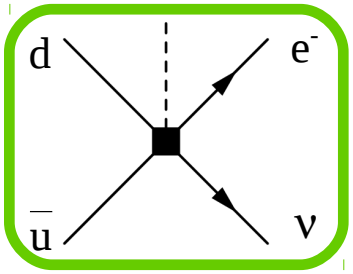
- non competitive for dim. 7 operators
- study for dim. 9

Low-energy EFT for LNV

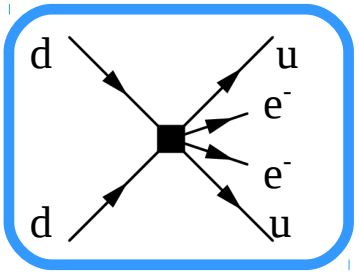
$\Delta L = 2$ Lagrangian at 1 GeV



$\frac{v}{\Lambda}$



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



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

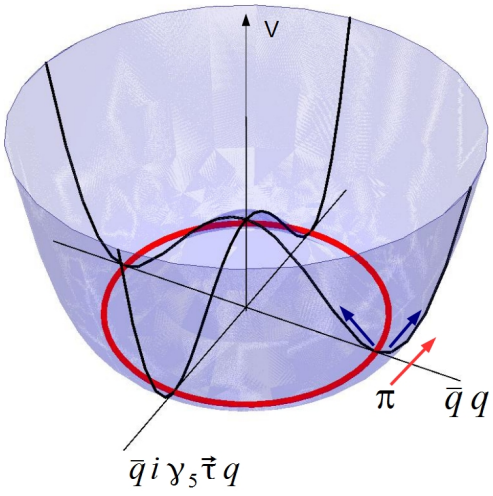
$$\mathcal{L}_{\Delta L=2}(\nu, e, u, d) = -\frac{1}{2}(m_\nu)_{ij}\nu^{Tj}C\nu^i + C_\Gamma\, \nu^T C\,\Gamma e\, \mathcal{O}_\Gamma + C_{\Gamma'} e^T C\,\Gamma' e\, \mathcal{Q}_{\Gamma'}$$

quark bilinear

four-quark

- match onto a EFT for nucleons?

Interlude: Chiral Effective Field Theory

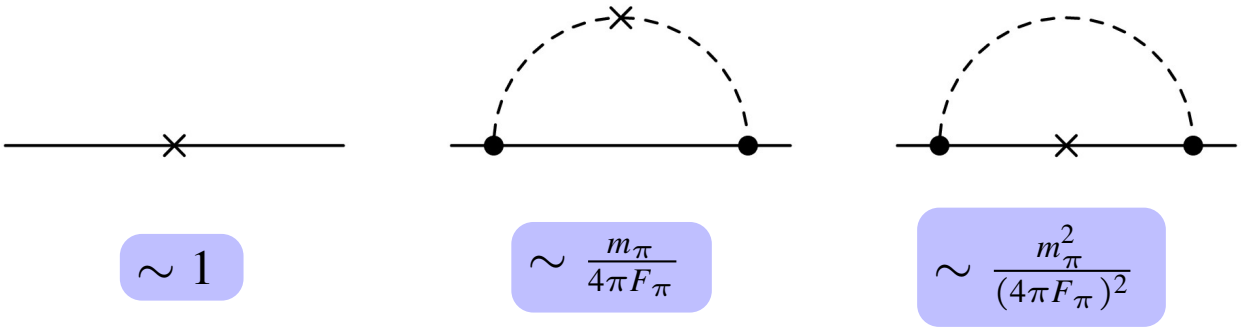


$$\mathcal{L} = -\frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} + \bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R - \bar{q}_L \mathcal{M} q_R - \bar{q}_R \mathcal{M} q_L + \mathcal{L}_{\Delta L=2} + \ldots$$

Chiral symmetry & its spontaneous breaking:

- pions are pseudo-Goldstone
  a. light, $m_\pi \ll \Lambda_\chi = 4\pi F_\pi \sim 1$ GeV
  b. and weakly coupled
- EFT expansion in powers of $\{Q, m_\pi\}/\Lambda_\chi$

$$\frac{dm_N}{dm_\pi^2} =$$



- only one relevant scale $Q \sim m_\pi$

  "HQET"-like w. "soft" pion & nucleon modes $p \sim (m_\pi, m_\pi)$
- perturbative expansion of χEFT Lagrangian

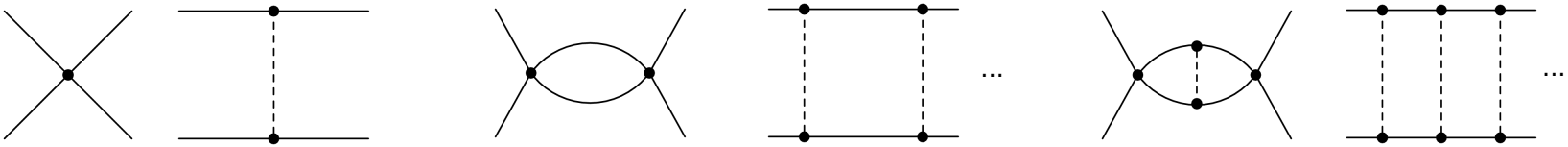
$$\mathcal{L} = \mathcal{L}^{(0)} + \frac{1}{\Lambda_\chi}\mathcal{L}^{(1)} + \frac{1}{(\Lambda_\chi)^2}\mathcal{L}^{(2)} \ldots$$

- and amplitudes

$$\mathcal{A} = \sum a_n \left(\frac{Q}{\Lambda_\chi}\right)^n$$

derivatives, pion masses & loops suppressed by Q/Λ_χ

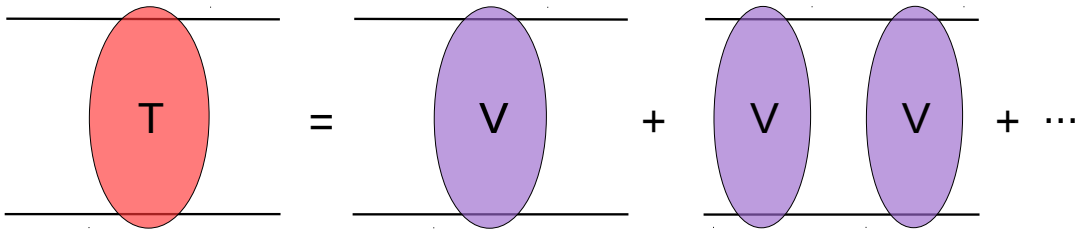
Chiral EFT. $A \geq 2$



$\sim \frac{1}{F_\pi^2}$ $\sim \frac{1}{F_\pi^2}\frac{Q}{F_\pi}$ $\sim \frac{1}{F_\pi^2}\frac{Q^2}{F_\pi^2}$

1. another scale in the problem: Q^2/m_N
   "NRQCD"-like with "potential" $p \sim (Q^2/m_N, Q)$ modes

   - resum an infinite class of diagrams
   - equivalent to solving Lippmann-Schwinger equation



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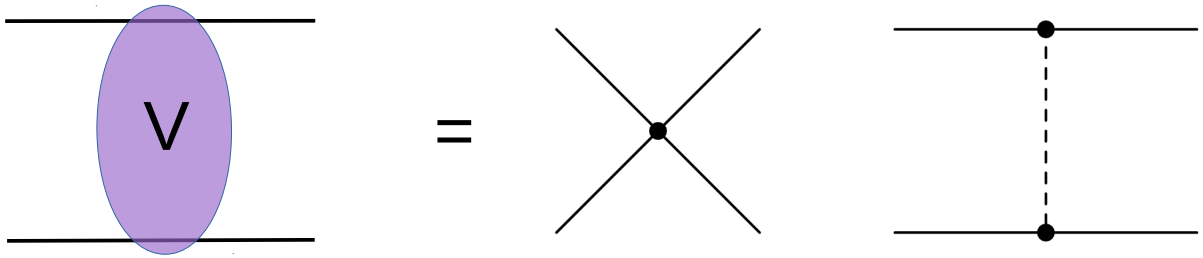
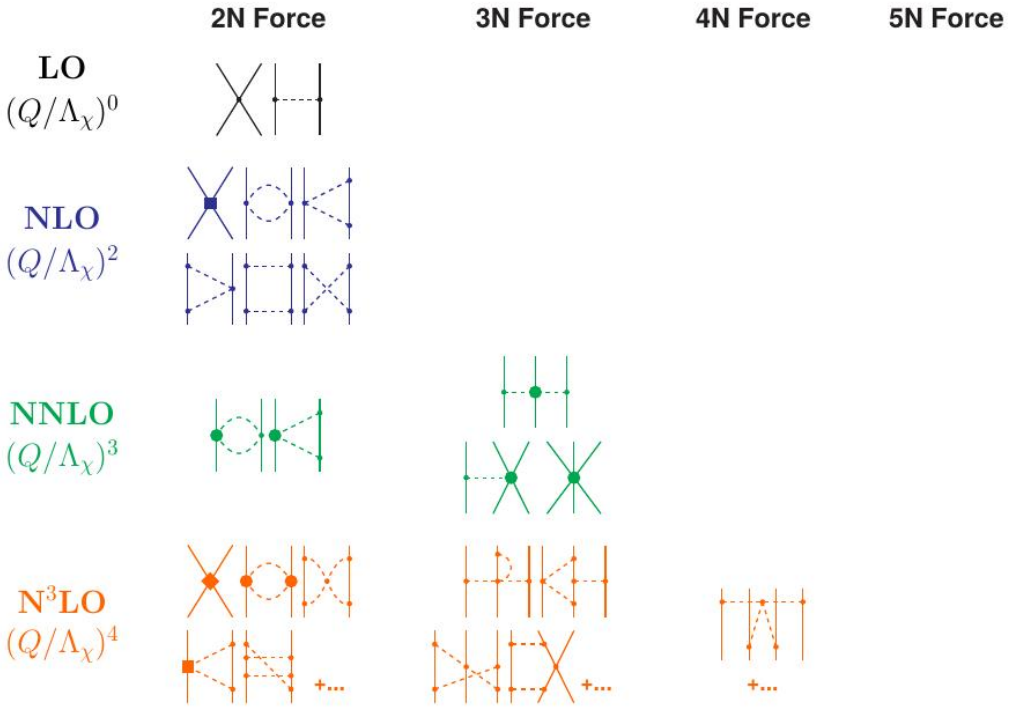


$+\mathcal{O}\left(\frac{Q}{\Lambda_\chi}\right)$

1. another scale in the problem: Q^2/m_N
   "NRQCD"-like with "potential" $p \sim (Q^2/m_N, Q)$ modes
   - resum an infinite class of diagrams
   - equivalent to solving Lippmann-Schwinger equation
2. V is organized in powers of $\frac{Q}{\Lambda_\chi}$
3. the LO potential is singular ("short-range core")
   - new divergences in solution of LS
   - can invalidate power counting based on NDA

Nuclear EFT(s)



from D. R. Entem and R. Machleidt, ‘17

see also:

P. Reinert, H. Krebs, E. Epelbaum, ‘18

M. Piarulli *et al*, ‘16

M. Piarulli *et al*, ‘14

A. Nogga, R. Timmermans, B. van Kolck, ‘05

D. Kaplan, M. Savage, M. Wise, ‘96

- LECs are fit to data in 2- and 3-nucleon systems
- and predict light-nuclear observables

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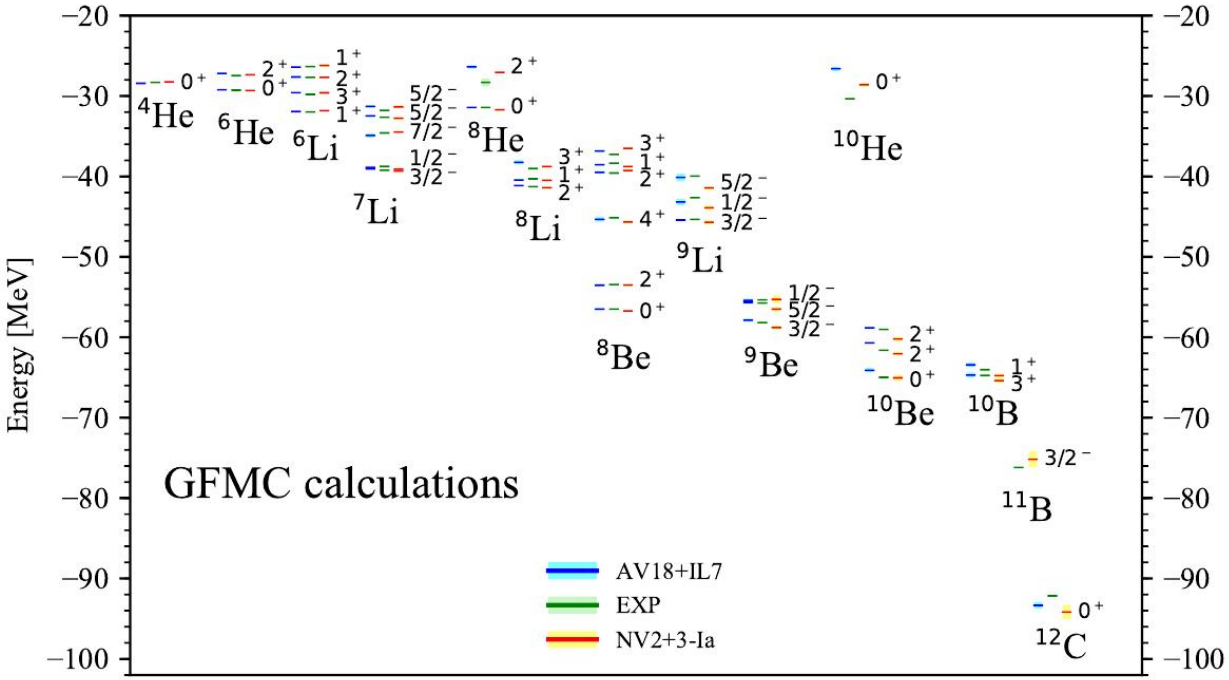


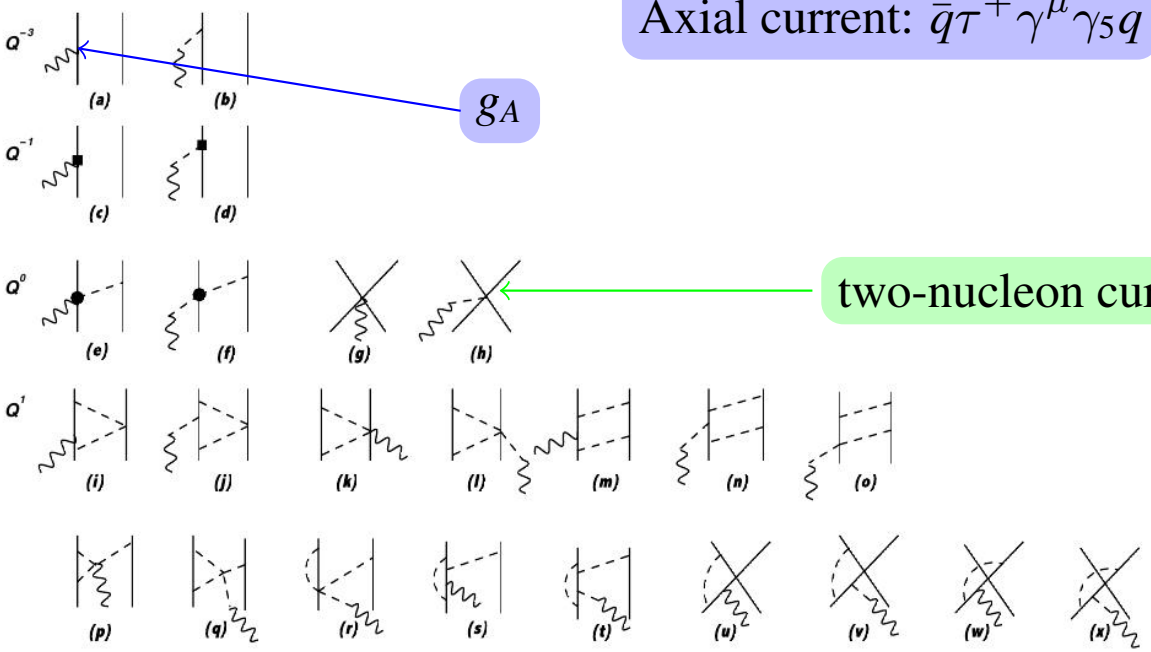
M. Piarulli *et al*, '17

- LECs are fit to data in 2- and 3-nucleon systems
- and predict light-nuclear observables

WARNING: unresolved issues with power counting

External currents in chiral EFT

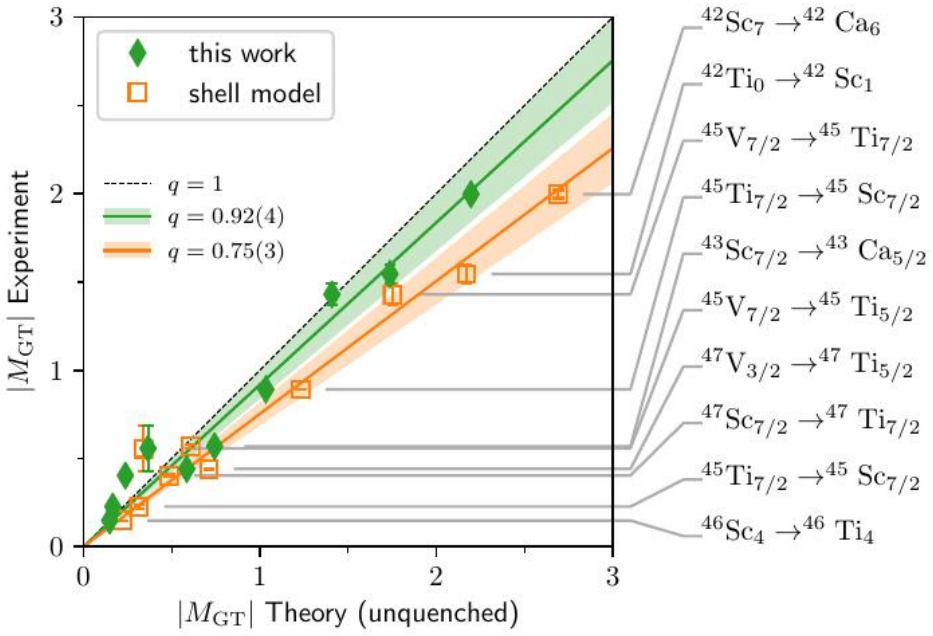
Axial current: $\bar{q}\tau^{+}\gamma^{\mu}\gamma_5 q$



from A. Baroni *et al*, '16

- similar expansions for external currents
- consistent interactions & currents:
  ab initio solution to long-standing problem in β decays
  "g_A quenching"

External currents in chiral EFT

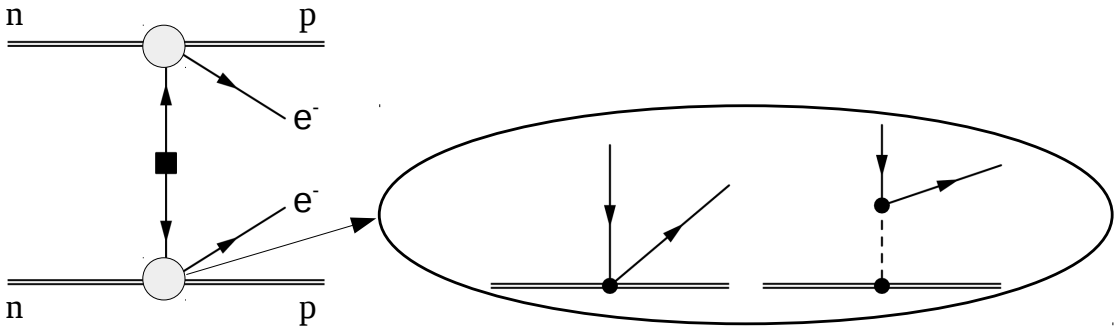


P. Gysbers *et al*, '19

- similar expansions for external currents
- consistent interactions & currents:
  ab initio solution to long-standing problem in β decays
  "g_A quenching"

Revisiting the light Majorana-ν exchange mechanism

Chiral EFT approach to light-ν exchange mechanism



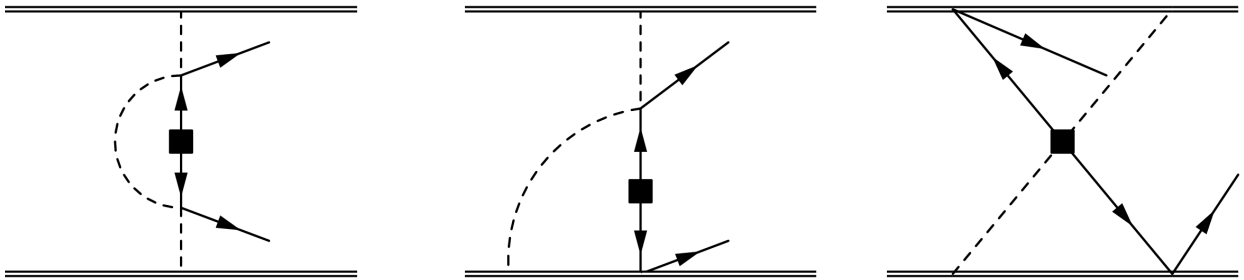
$$\mathcal{L} = \mathcal{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}} \bar{u}_L \gamma^\mu d_L \, \bar{e}_L \gamma_\nu \nu_L - \frac{m_{\beta\beta}}{2} \nu_L^T C \nu_L$$

- weak currents are mainly one-body
- $0\nu\beta\beta$ mediated by exchange of "potential" neutrinos

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

agrees with all $0\nu\beta\beta$ literature

Standard mechanism. Higher orders



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

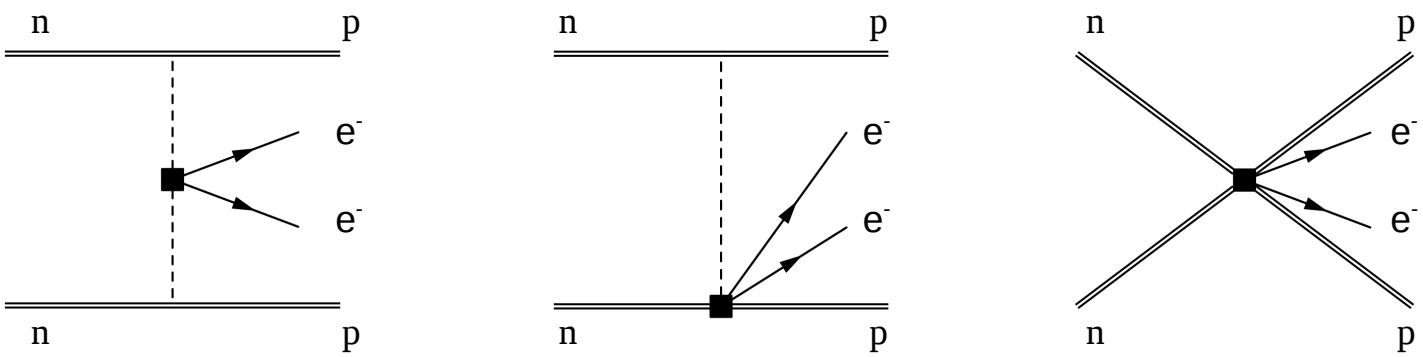
1. correction to the one-body currents (magnetic moment, radii, ...)

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

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



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2. two-body corrections to V and A currents
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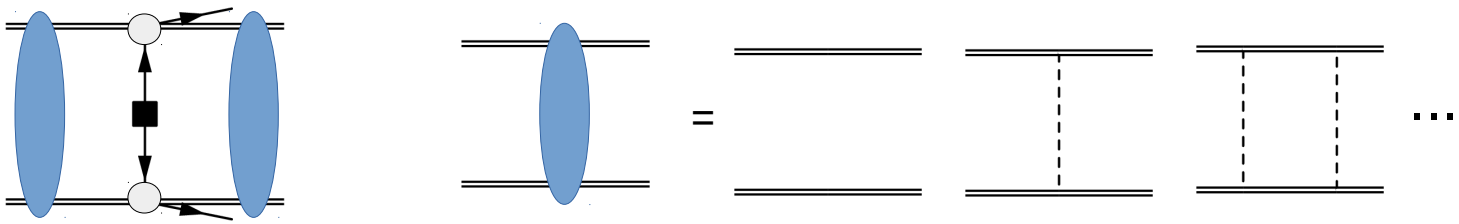
UV divergences signal short

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

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

$\tilde{C}$ fit to ${}^1S_0$ scattering length

- no problem with Yukawa potential

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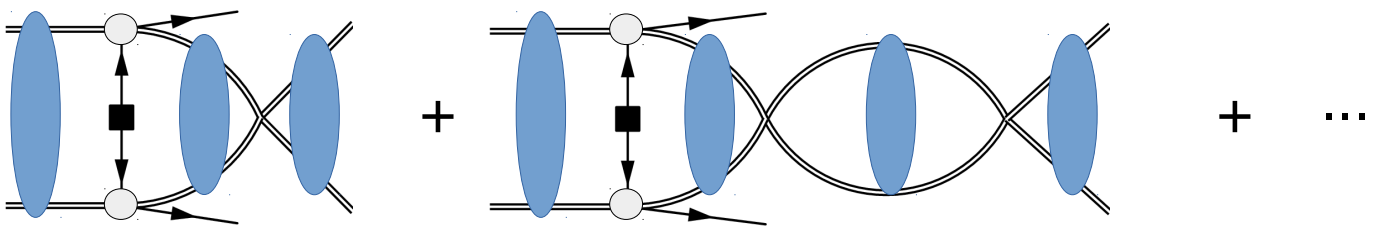

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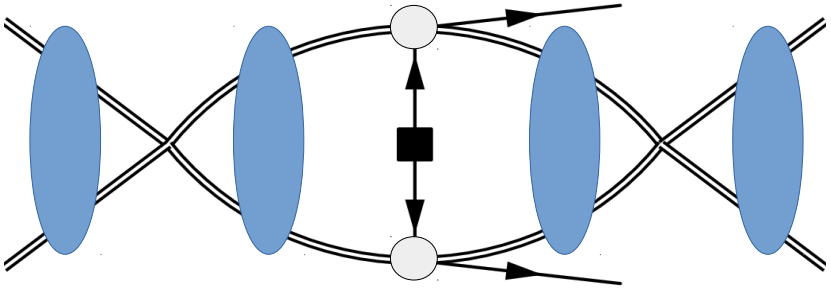
- no problem with Yukawa potential
- and one insertion of short-range potential

Inconsistency of the Weinberg counting

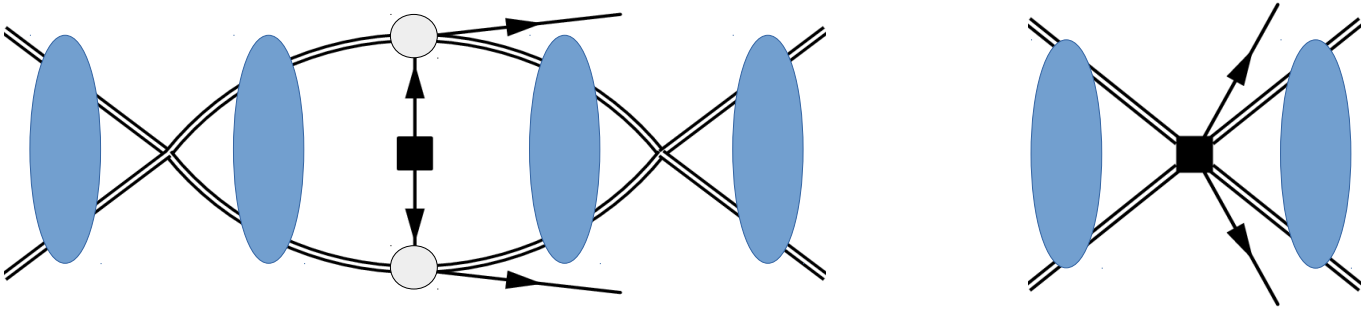


$$\frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2\left(\frac{1}{\varepsilon}+\log\mu^2\right)$$

- 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!

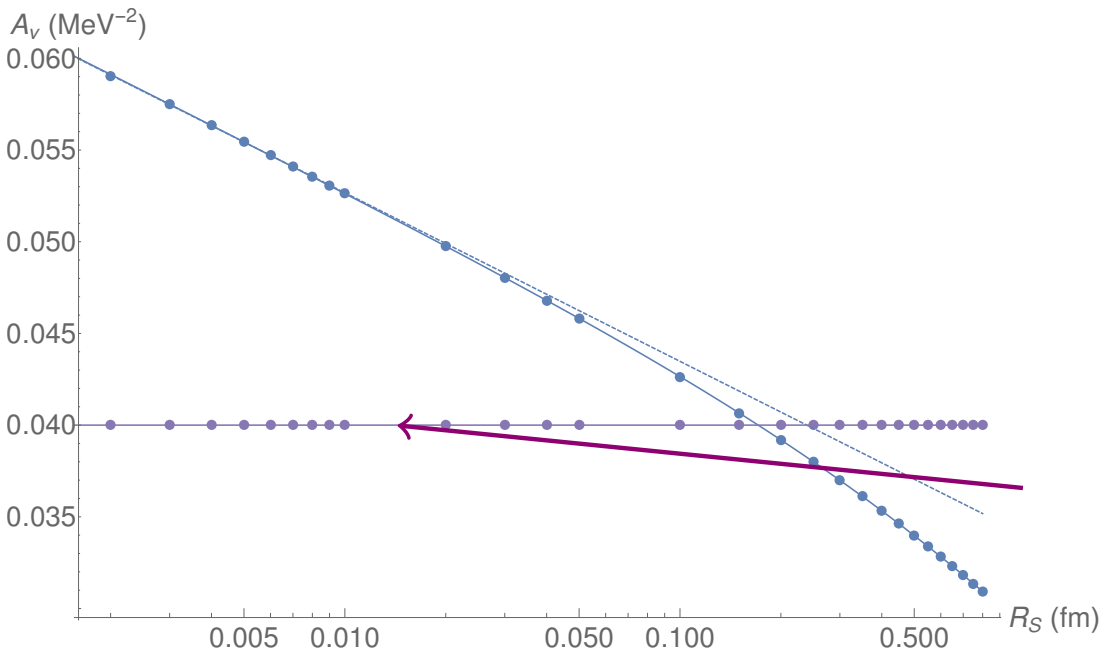
- renormalization requires to modify the LO ν potential

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

- 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



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

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

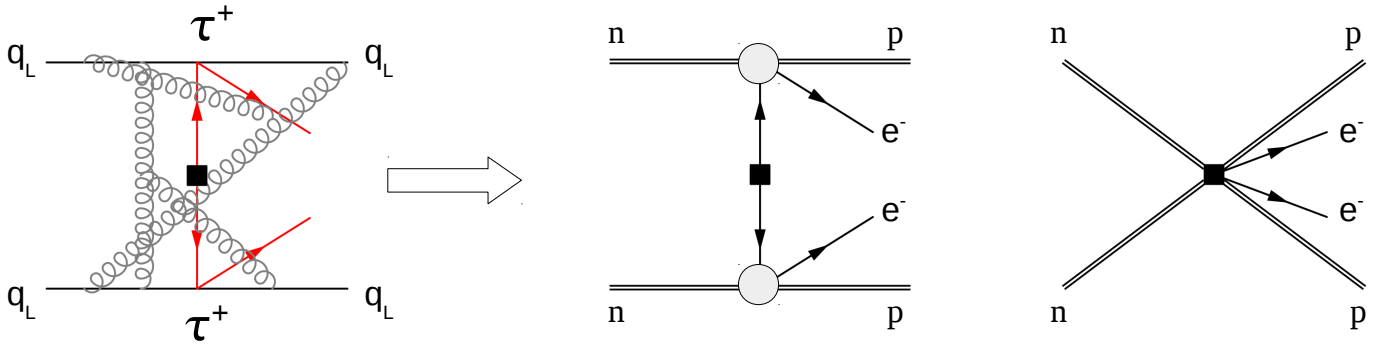
$$\tilde{g}_\nu \sim b - \tfrac{1}{2}(1+2g_A^2)\log R_S$$

- divergence is not an artifact of dim. reg.
  e.g use a gaussian cut-off

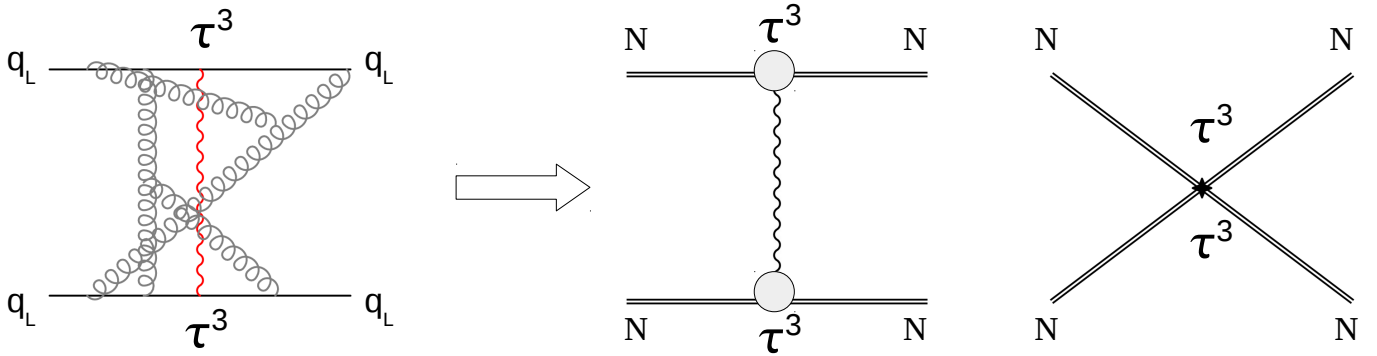
$$\tilde{C}\,\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}}{\pi^{3/2}R_S^3}e^{-r^2/R_S^2}$$

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

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



- the dynamics of QCD seems to imply a short-range component for V_ν
- does this happen anywhere else? How to fix finite piece of the coupling? Charge independence breaking in NN scattering



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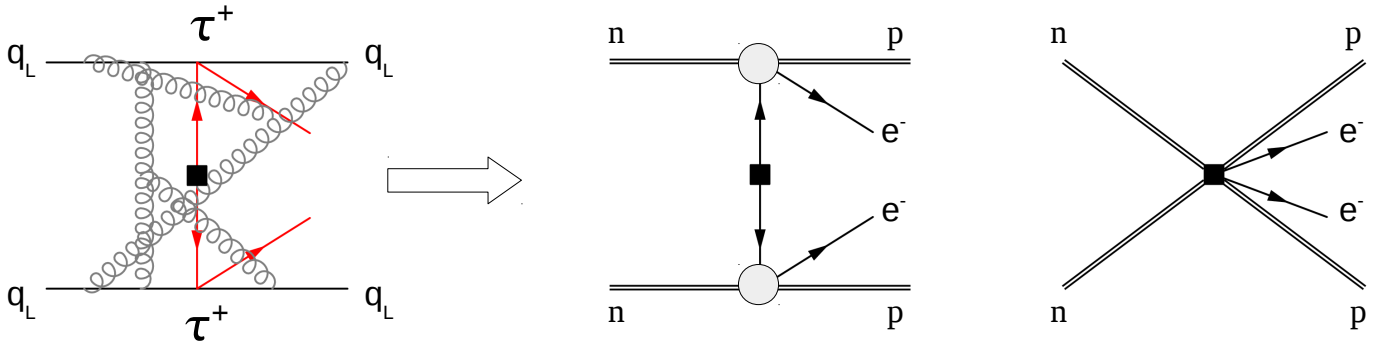

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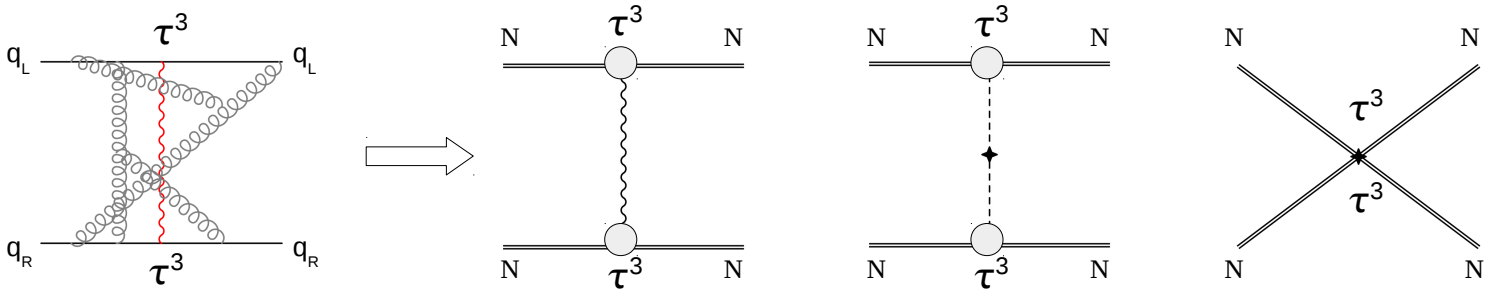

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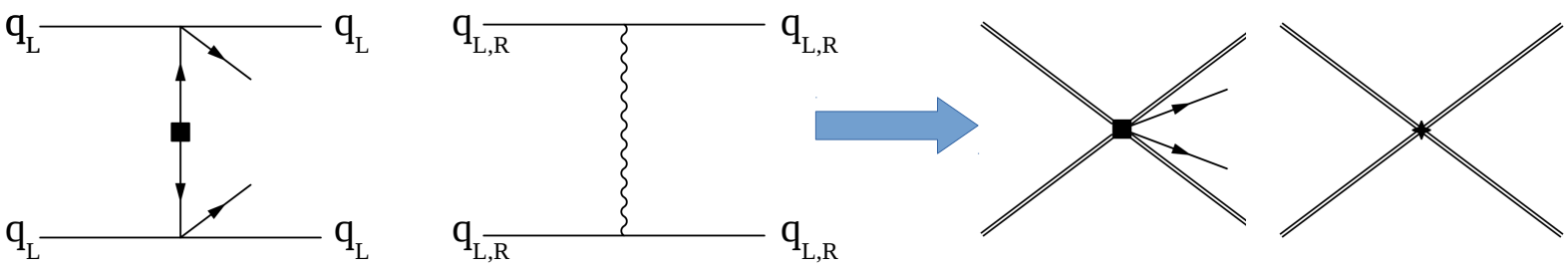
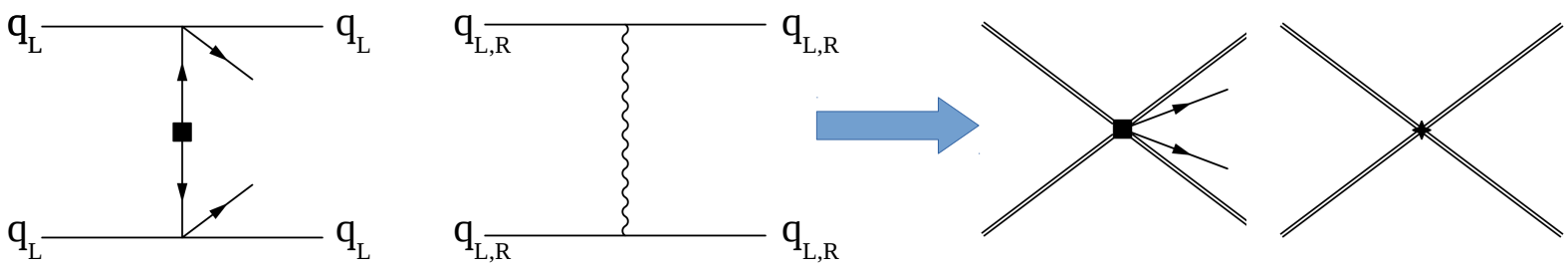


- only two $I = 2$ operators w. same properties as weak/EM currents

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

- 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



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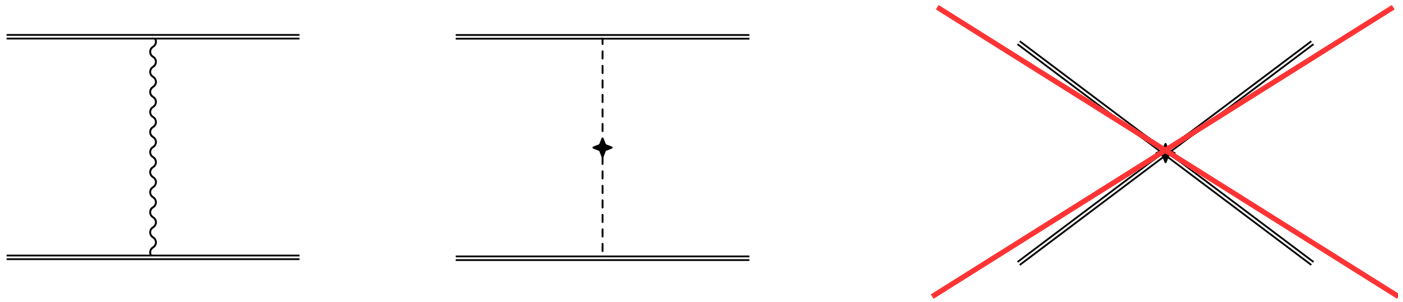
- $C_1 = g_\nu$ by chiral symmetry!
- C_1 and C_2 differ at multipion level

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

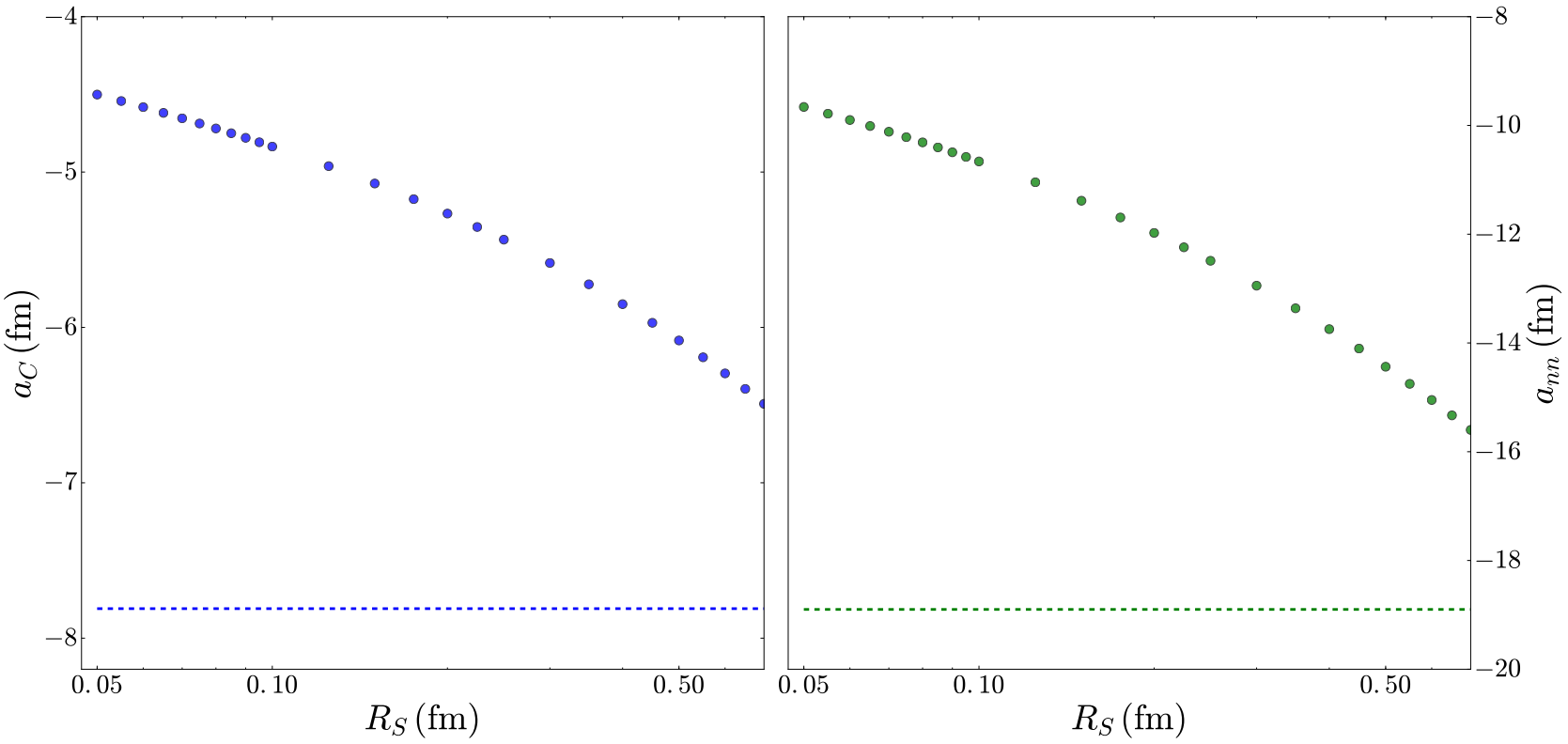
$$V_{\rm CIB} = \frac{e^2}{4}\left(\tau_3^{(1)}\tau_3^{(2)} - \frac{1}{3}\boldsymbol{\tau}^{(1)}\cdot\boldsymbol{\tau}^{(2)}\right)\frac{1}{\mathbf{q}^2}\left\{1 - \frac{g_A^2}{F_\pi^2}\frac{\Delta m_\pi^2}{e^2}\boldsymbol{\sigma}^{(1)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(2)}\cdot\mathbf{q}\frac{\mathbf{q}^2}{(\mathbf{q}^2+m_\pi^2)^2}\right\}.$$

$$\Delta m_\pi^2 = m_{\pi^\pm}^2 - m_{\pi^0}^2$$

- short-range contributions suppressed

$$V_{\rm CIB}^S = \frac{e^2}{2}\frac{C_1+C_2}{2}\left(\tau^{(1)\,z}\tau^{(2)\,z} - \frac{1}{3}\boldsymbol{\tau}^{(1)}\cdot\boldsymbol{\tau}^{(2)}\right) \qquad C_1 \sim C_2 \sim \frac{1}{(4\pi F_\pi)^2}$$

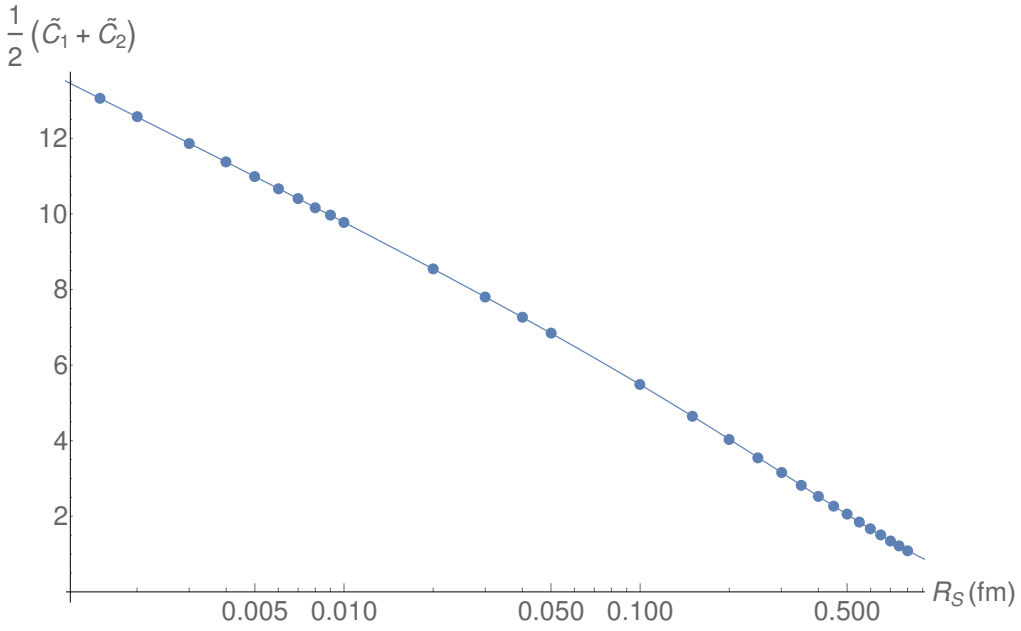
Relation to charge-independence breaking



- fit one charge-independent $\tilde{C}$ in np
- compute a_{nn} and a_C

log divergence! need a ct in each channel

Relation to charge-independence breaking



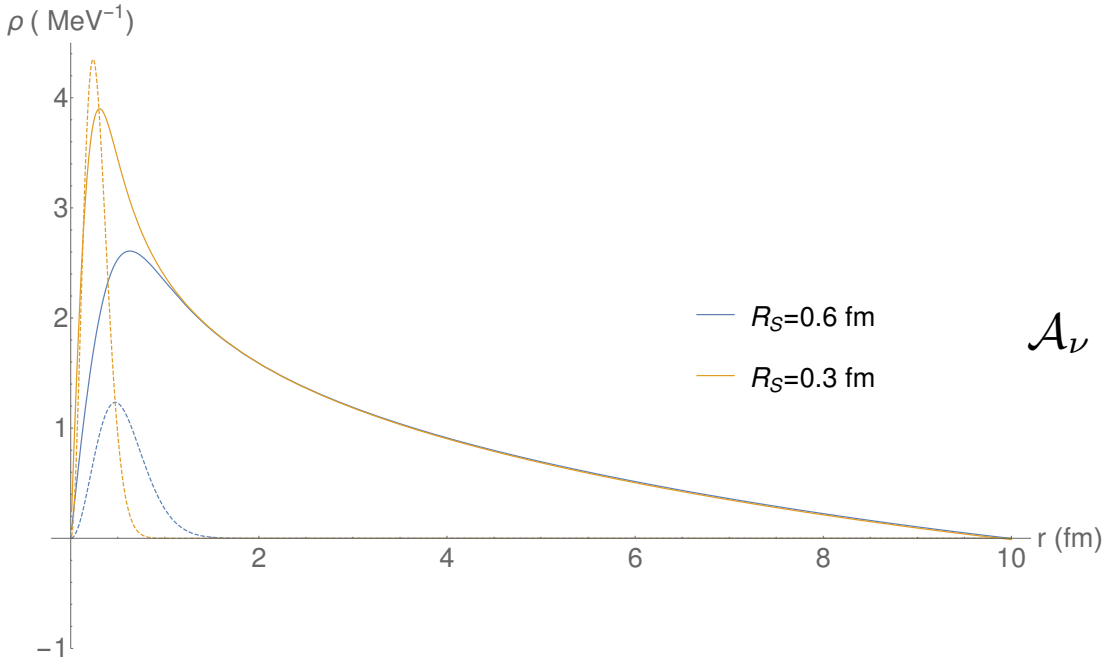
1. LO analysis of isospin breaking show log dependence

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

disagree with Weinberg's counting!

2. all high-quality chiral & pheno *NN* potentials include short-range CIB

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



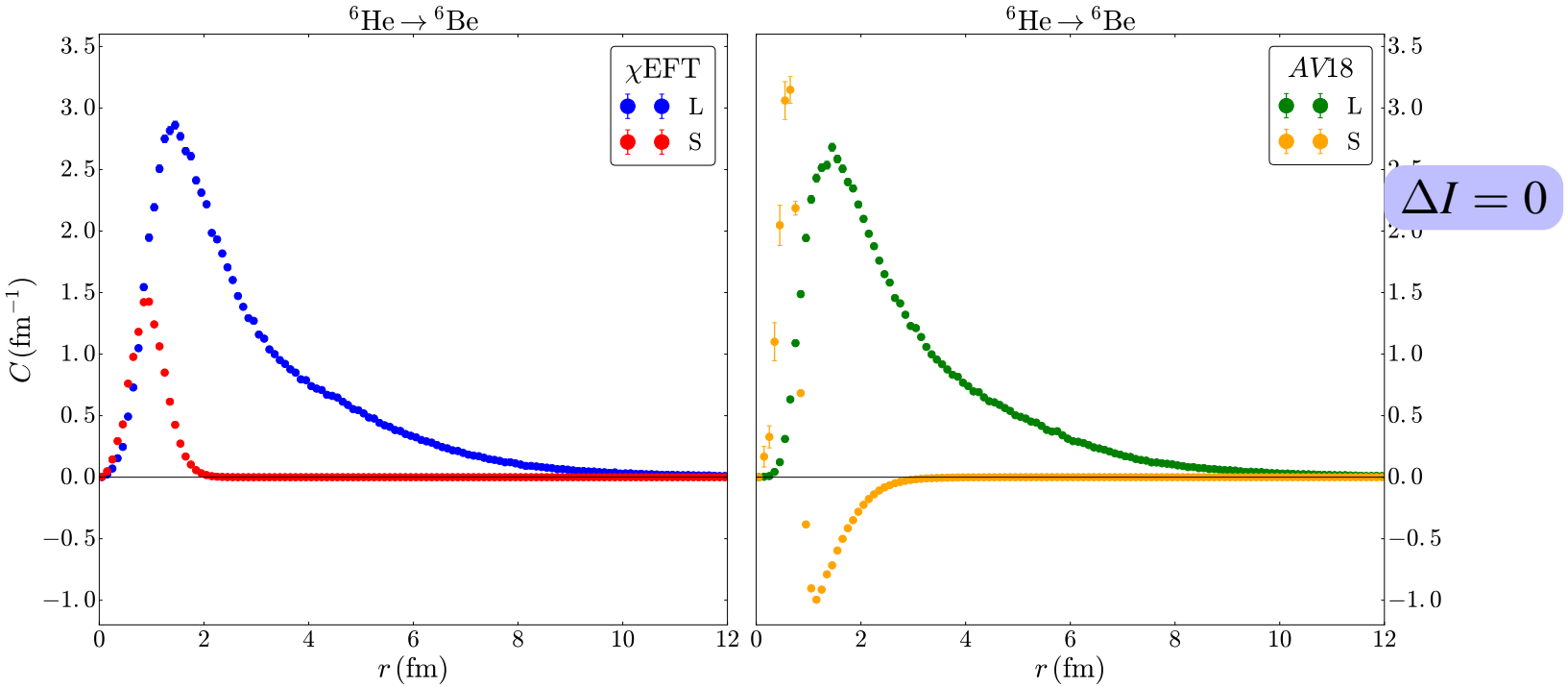
$$\mathcal{A}_\nu = \int dr \rho(r)$$

$nn \to pp$

- *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

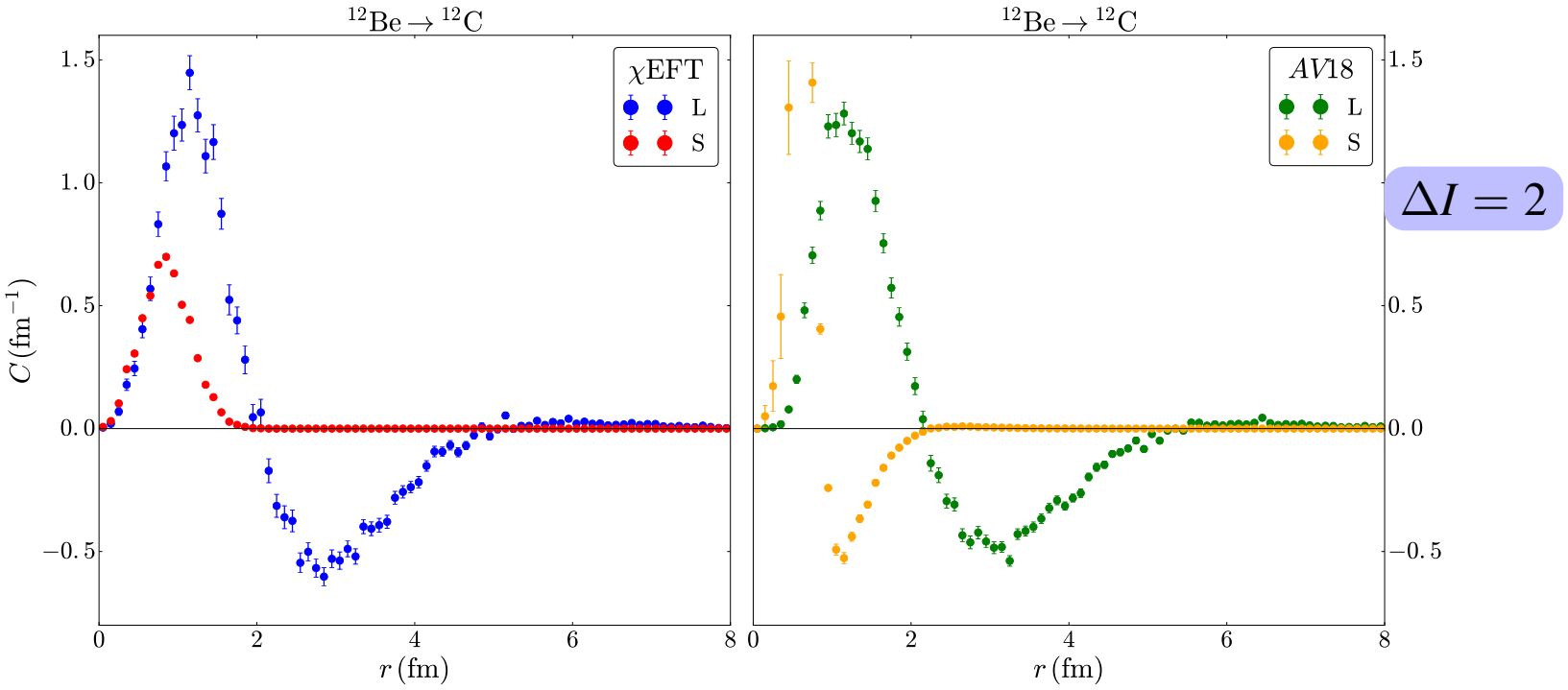


- extract CIB potential V^S_{CIB} from AV18 or χEFT (rescaled by c_{LNV}/c_{e^2})

$$\text{AV18:} \quad M_L = 7.45, \quad M_S = 0.48$$
$$\chi\text{EFT:} \quad M_L = 7.82, \quad M_S = 1.15$$

$\sim 10\%$ corrections

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



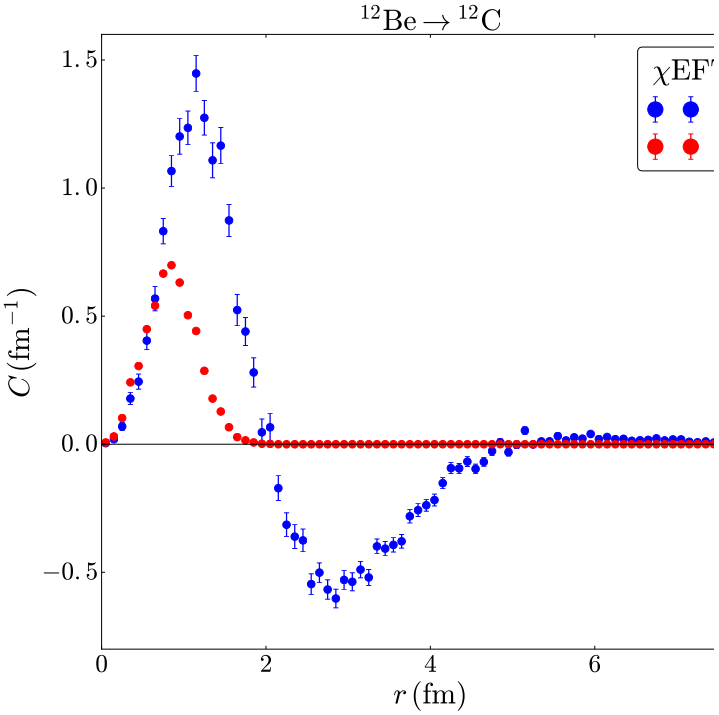
- larger corrections to $I = 2$ transitions

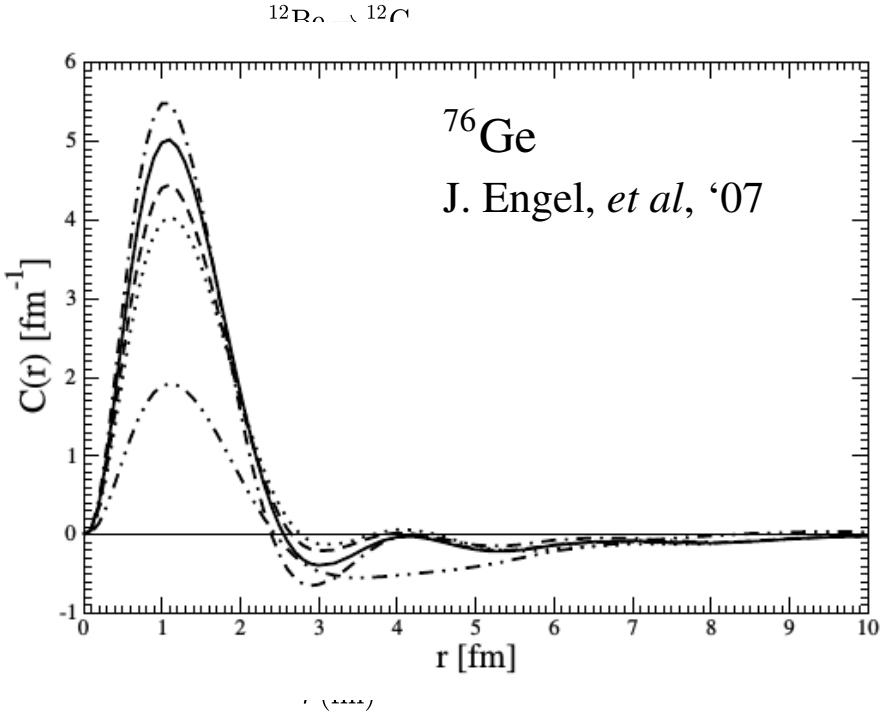
$$\begin{aligned} \text{AV18:} \quad & M_L = 0.653, \quad M_S = 0.518 \\ \chi\text{EFT:} \quad & M_L = 0.725, \quad M_S = 0.533 \end{aligned}$$

$> 50\%$ corrections

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

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





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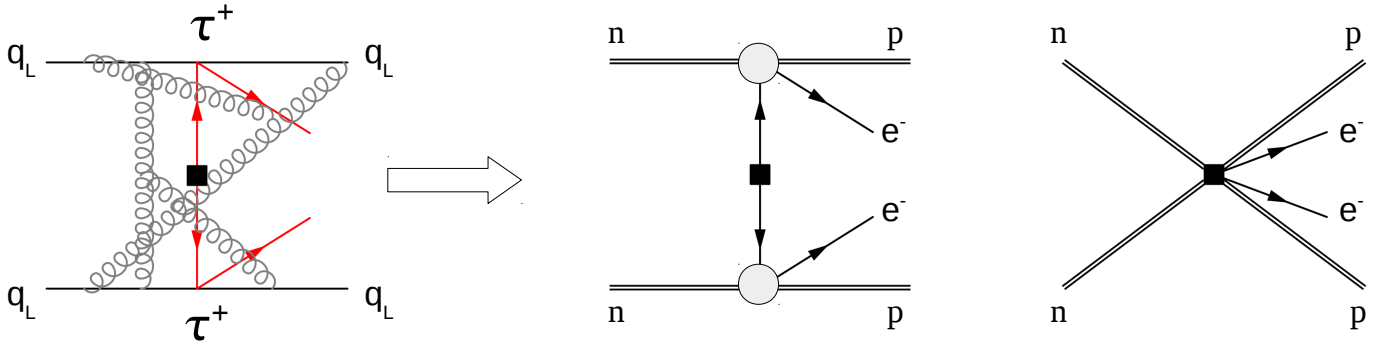
Partial summary: light Majorana exchange



- chiral EFT uncovers additional source of uncertainty

  QCD at $\Lambda \sim 1$ GeV gives non-negligible contributions to V_ν

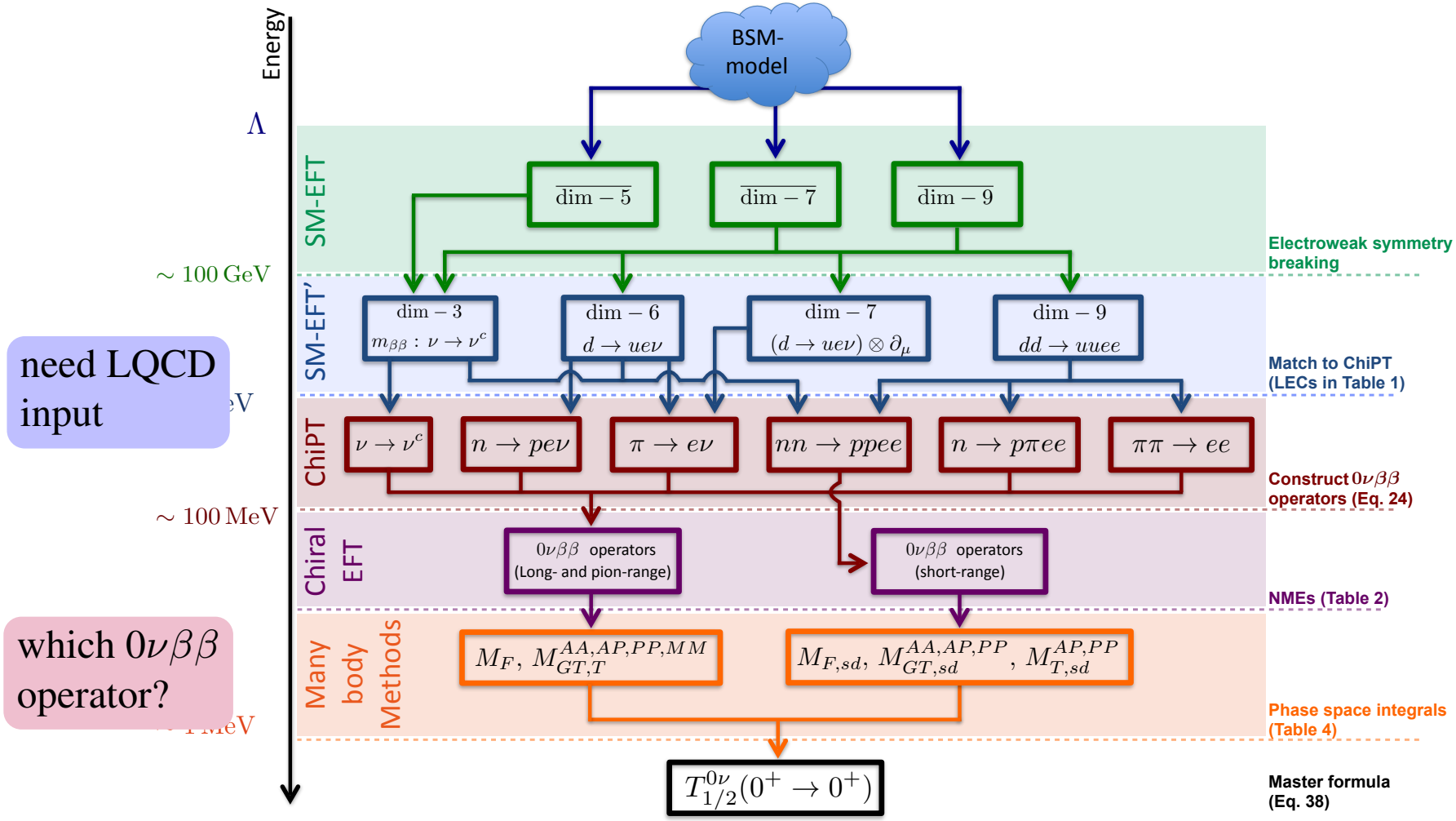
  confirmed by isospin breaking in NN scattering
- V_ν needs non-ptb matching between QCD & chiral EFT

  e.g. Lattice QCD calculation of $nn \to ppe^- e^-$

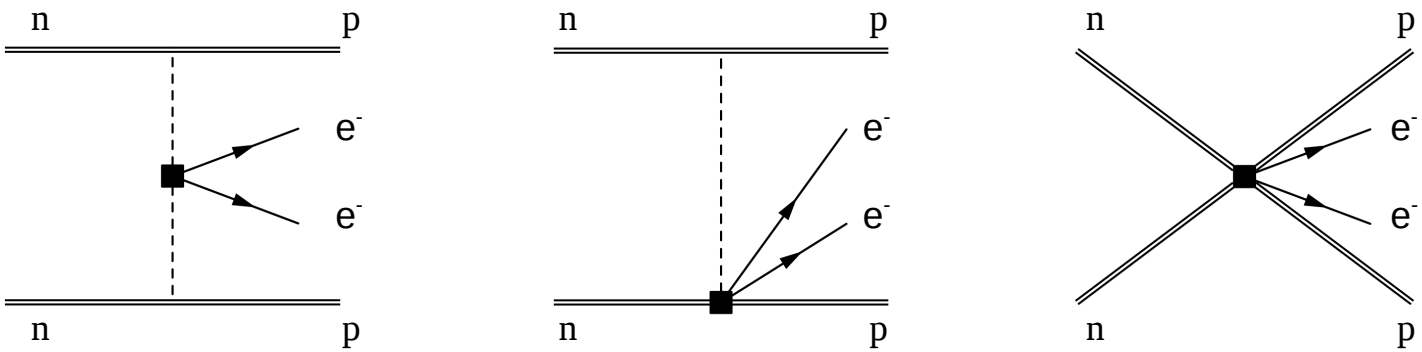
  first results on $\pi^- \to \pi^+ e^- e^-$ Xu Feng, *et al.* '18
- problem only in the $^1S_0$ channel
  Weinberg's counting ok in ^3P_J, $^1D_2$ channels

Chiral EFT for non-standard mechanisms

Chiral EFT for non-standard mechanisms



Dim. 9 operators



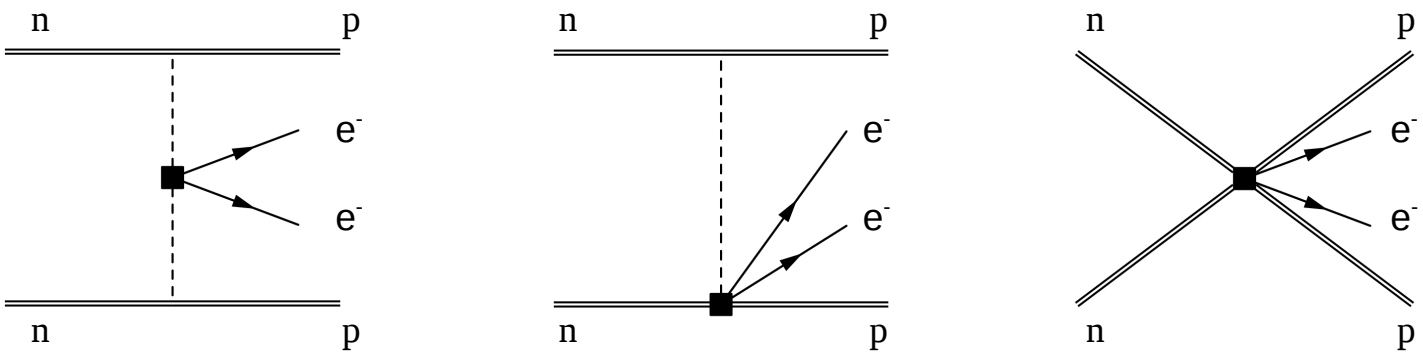
1. LL LL : $\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \, \gamma_\mu d_L$
2. LR LR : $\mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R, \qquad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha$
3. LL RR : $\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \,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

- several unjustified assumptions in the literature . . .

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

  inconsistent with QCD, miss chiral dynamics

LNV interactions from dim. 9 operators



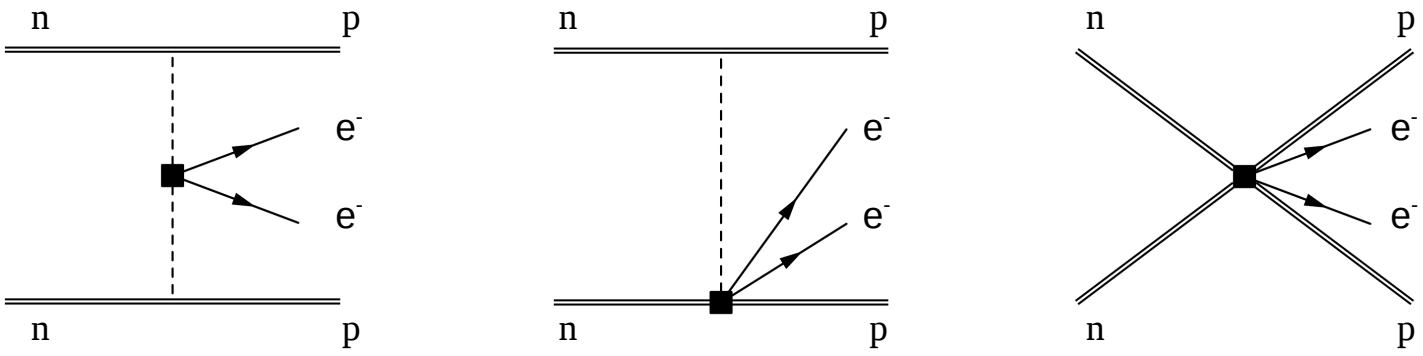
- $\pi\pi$ couplings

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

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

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

LNV interactions from dim. 9 operators



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

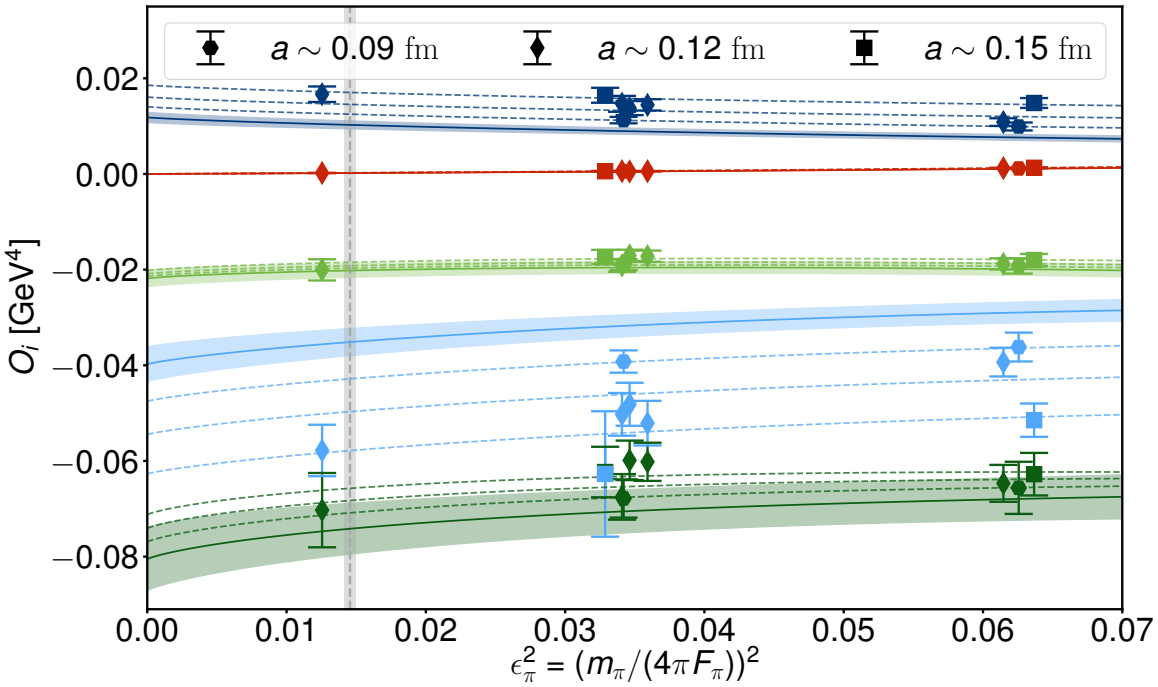
$$\mathcal{L}_{NN} = \left(g_1^{NN} C_{1\mathrm{L}}^{(9)} + g_2^{NN} C_{2\mathrm{L}}^{(9)} + g_3^{NN} C_{3\mathrm{L}}^{(9)} + g_4^{NN} C_{4\mathrm{L}}^{(9)} + g_5^{NN} C_{5\mathrm{L}}^{(9)}\right) (\bar{p}n)\ (\bar{p}n)\ \frac{\bar{e}_L C \bar{e}_L^T}{v^5}$$

- 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



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

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

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

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

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

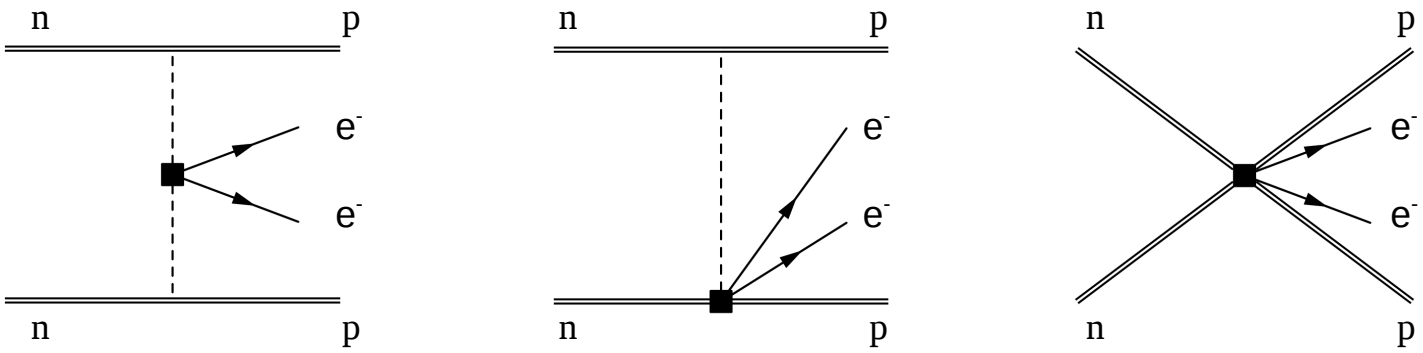
A. Nicholson *et al.*, CalLat collaboration, '18

- $\pi\pi$ 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

$0\nu\beta\beta$ potential



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

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

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

bigger error than from NMEs ...

Master Formula

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4 \Big\{ G_{01} \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04}) \mathrm{Re} \mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02} |\mathcal{A}_E|^2$$
$$+2G_{04} \left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^* (\mathcal{A}_\nu + \mathcal{A}_R)\right)\right] - 2G_{03} \,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right]$$
$$+G_{09} |\mathcal{A}_M|^2 + G_{06} \,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\} .$$

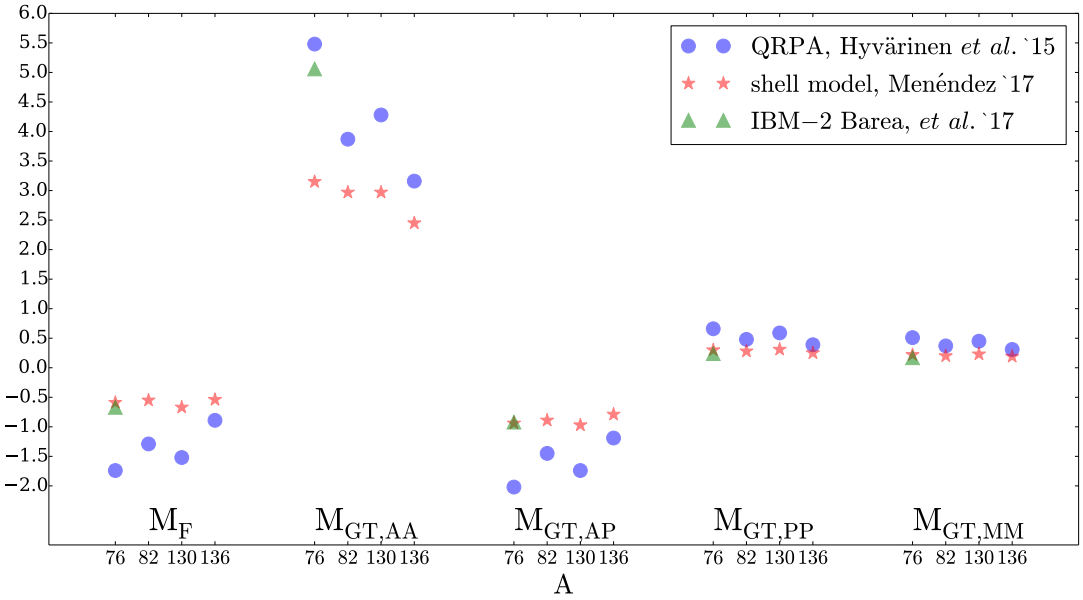
- $G_{01}, \ldots, G_{09}$: phase space factors
  leptonic structure of the operators
- $\mathcal{A}_\nu, \ldots, \mathcal{A}_M$: combinations of NME and couplings

$$\mathcal{A}_\nu = \frac{m_{\beta\beta}}{m_e} \mathcal{M}_\nu^{(3)} + \frac{m_N}{m_e} \mathcal{M}_\nu^{(6)} + \frac{m_N^2}{m_e v} \mathcal{M}_\nu^{(9)}$$

- organized in powers of Λ_χ/Λ and Q/Λ_χ

$$\mathcal{M}_\nu^{(9)} = -\frac{1}{2m_N^2} C^{(9)}_{\pi\pi\,\mathrm{L}} \left(\frac{1}{2} M^{AP}_{GT,sd} + M^{PP}_{GT,sd} + \frac{1}{2} M^{AP}_{T,sd} + M^{PP}_{T,sd}\right) + \ldots$$

Nuclear matrix elements



calculations differ by factor of 2-3

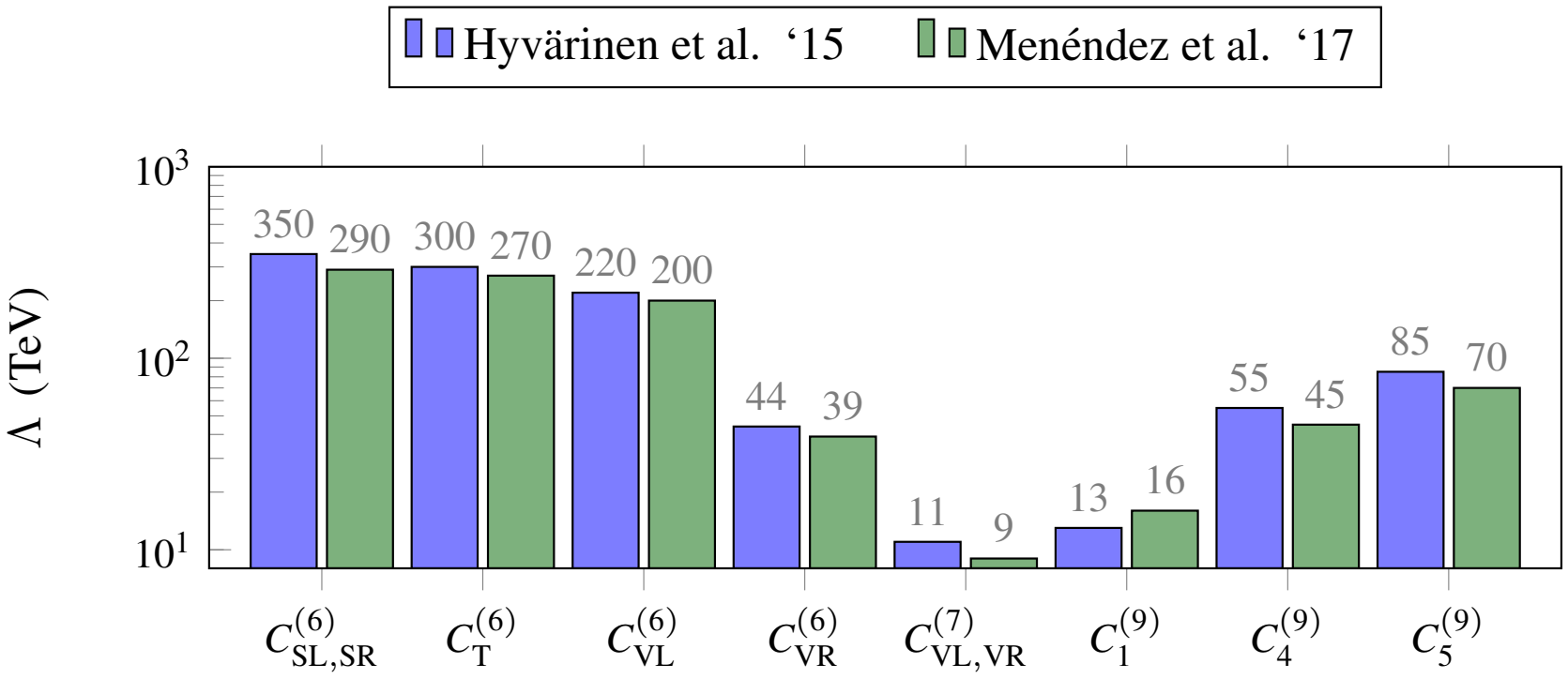
- at LO in χEFT, **all** nuclear matrix elements (NME) can be expressed in terms of existing calculations
- 8 long-range NME

contribute to light ν exchange

- 6 short-range NME

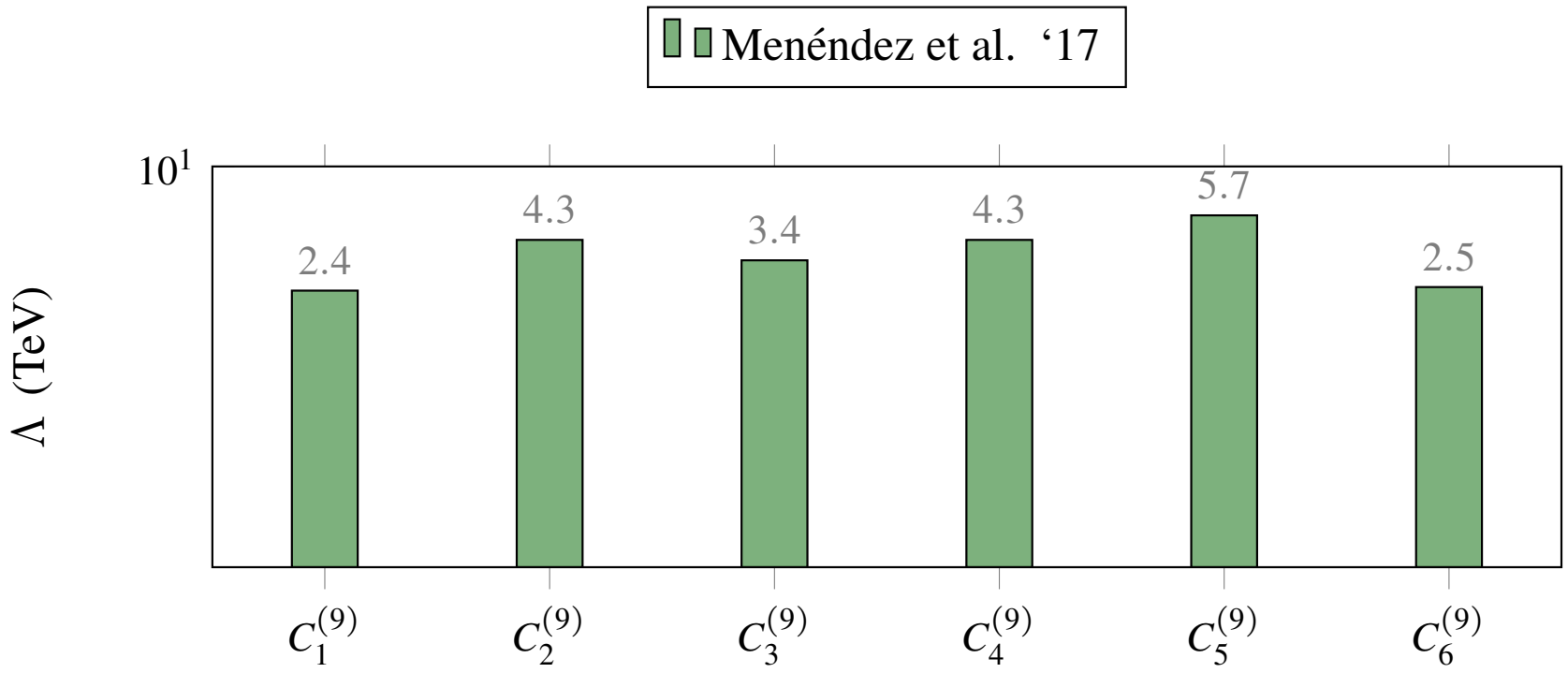
contribute to heavy Majorana ν exchange

Phenomenology



- $0\nu\beta\beta$ put strong limits on dim. 7 operators
- dim. 9 in the TeV range

pattern can be understood from effective dimension
& chiral properties of $0\nu\beta\beta$ operator



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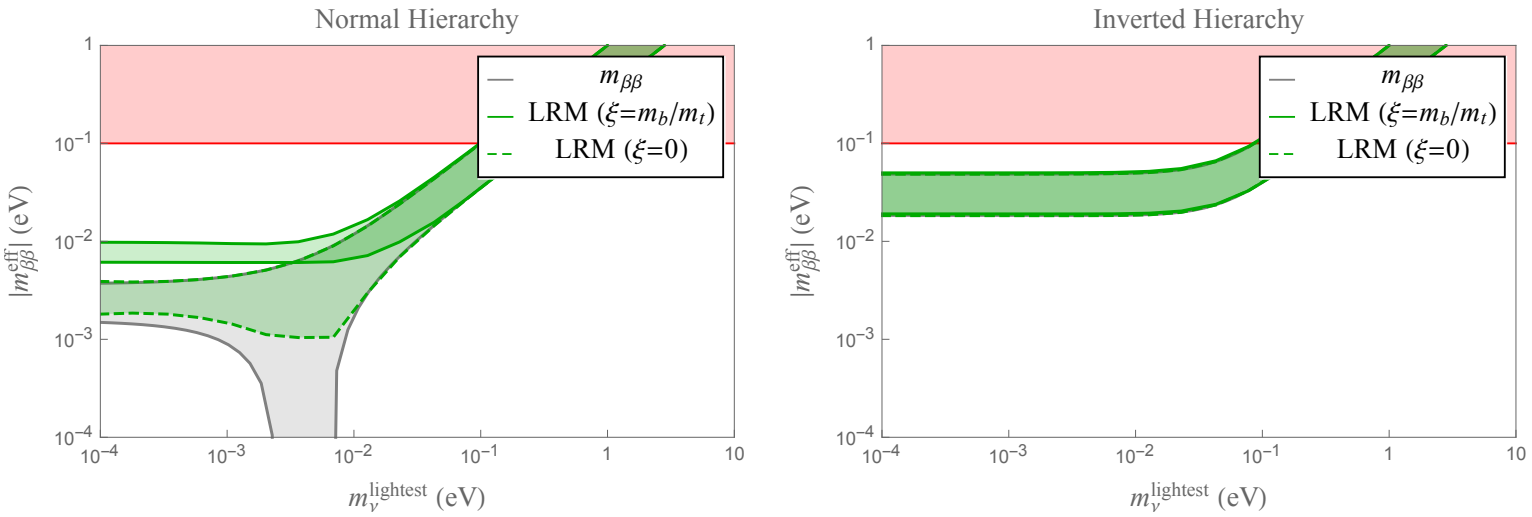
$0\nu\beta\beta$ in the Left-Right Symmetric Model



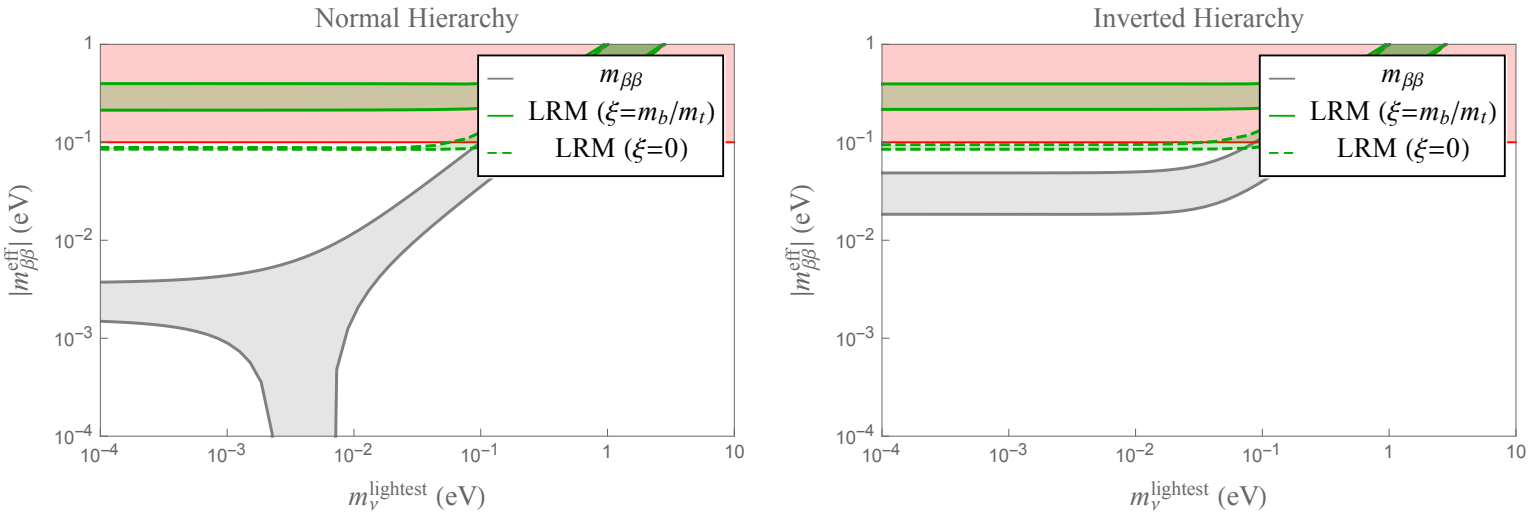
- generate dim. 5, 7 and 9
- dim. 7 and dim. 9 are chirally suppressed

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

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

- 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

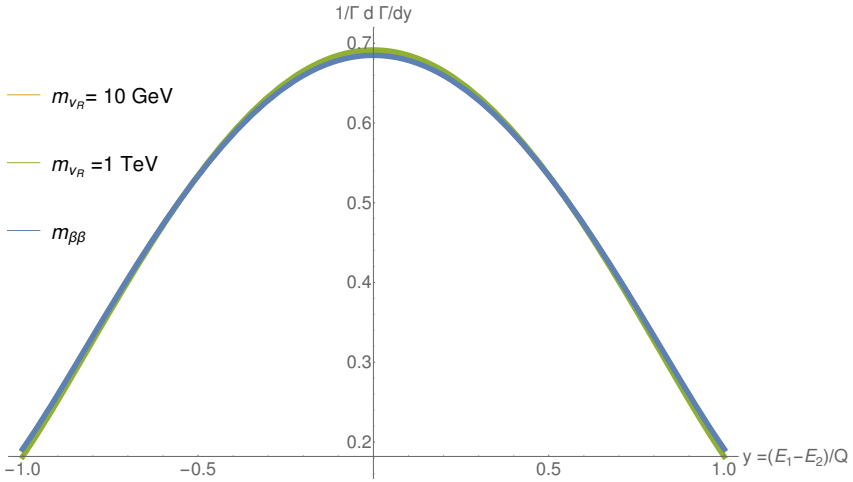


Case 2 $m_{W_R} = 4.5$ TeV, $m_{\Delta_R} = 10$ TeV, $U_R = U_{\rm PMNS}$,

$m_{\nu_R} \sim 10$ 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!

Summary

(χ)EFTs & $0\nu\beta\beta$ decay:

- connection with collider observables
- model-independent parameterization of low-energy $\Delta L = 2$ operators
- systematic organization of ν potentials

Standard mechanism:

- LO short-range potential missing from all existing calculations

additional $\mathcal{O}(1)$ contribution

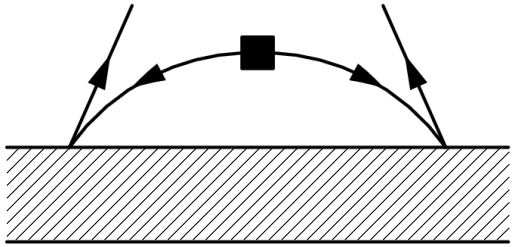
- g_ν can be guessed from isospin breaking in NN scattering
  new LQCD calculations required

Non Standard mechanisms:

- identify QCD input and hadronic uncertainties
- derive minimal sets on neutrino potentials & relate to existing calculations

Backup

Usoft contribution to the amplitude



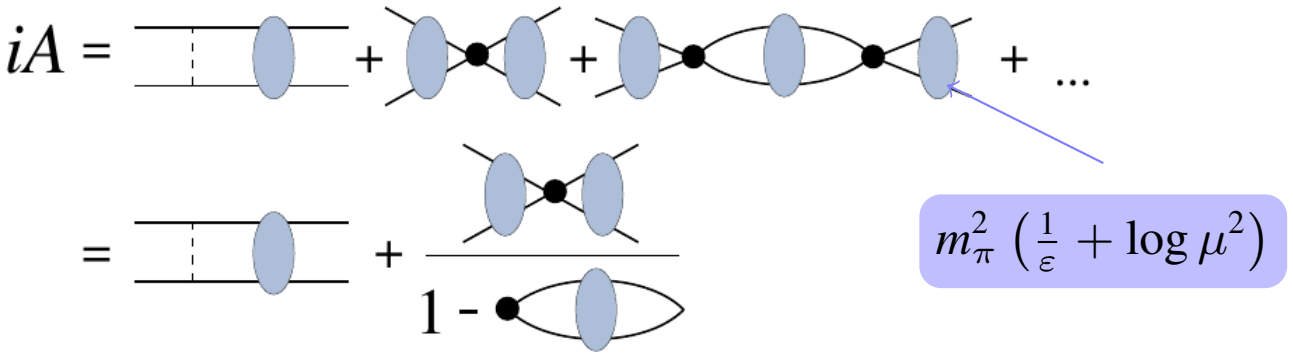
overlap $\langle n|J_\mu|i\rangle$
same as in $2\nu\beta\beta$!

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?



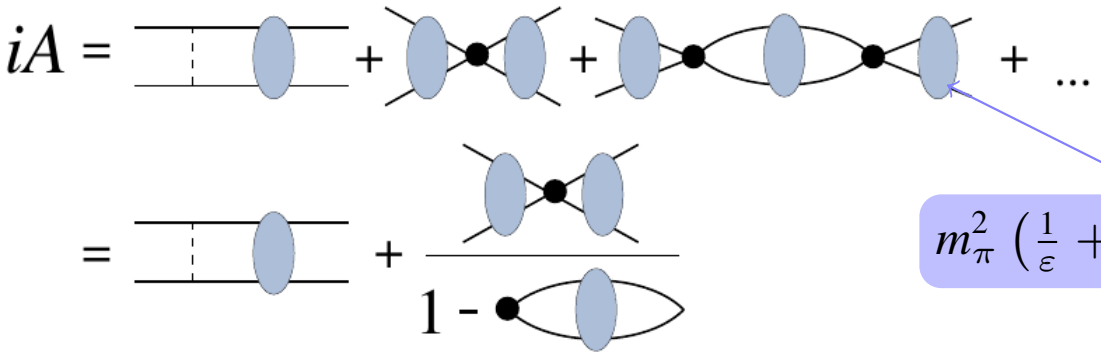
D. Kaplan, M. Savage, M. Wise, '96

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

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

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

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

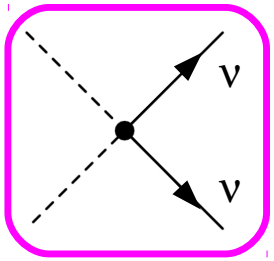
$$4\pi F_\pi = \Lambda_\chi \sim 1\,\text{GeV}$$

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

conflict between NDA & short-range core of nuclear force

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

$\Delta L = 2$ Lagrangian at 1 GeV

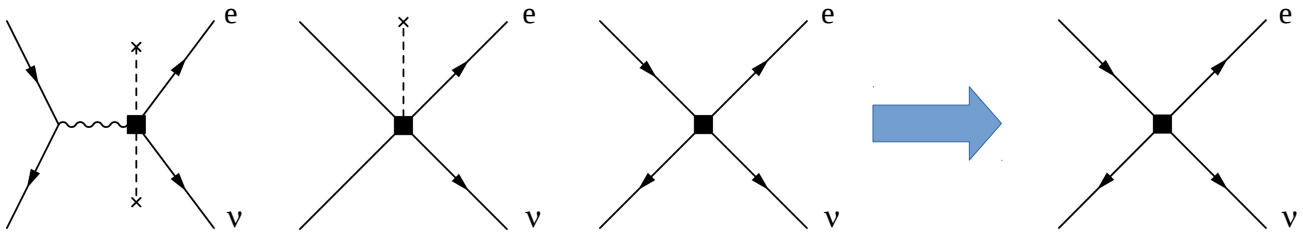


$$\mathcal{L}_{\Delta L=2} = \mathcal{L}_{\Delta L=2}^{\Delta e=0} + \mathcal{L}_{\Delta L=2}^{\Delta e=1} + \mathcal{L}_{\Delta L=2}^{\Delta e=2}$$

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

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

$\Delta L = 2$ Lagrangian at 1 GeV



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

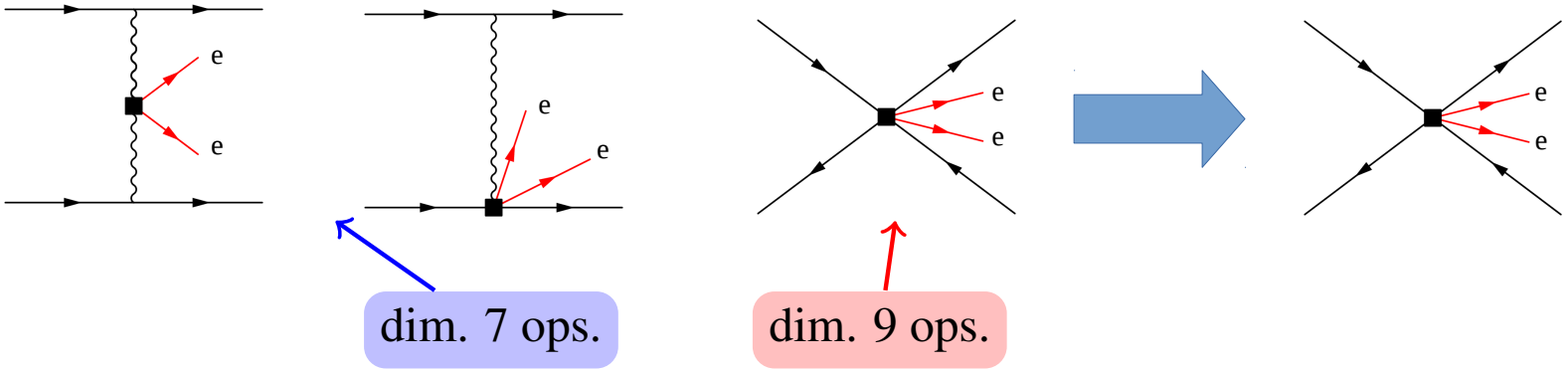
- $\mathcal{L}^{\Delta e=1}_{\Delta L=2}$ starts at dim. 6, $\quad C_i^{(6)} = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$

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

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

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

$\Delta L = 2$ Lagrangian at 1 GeV



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

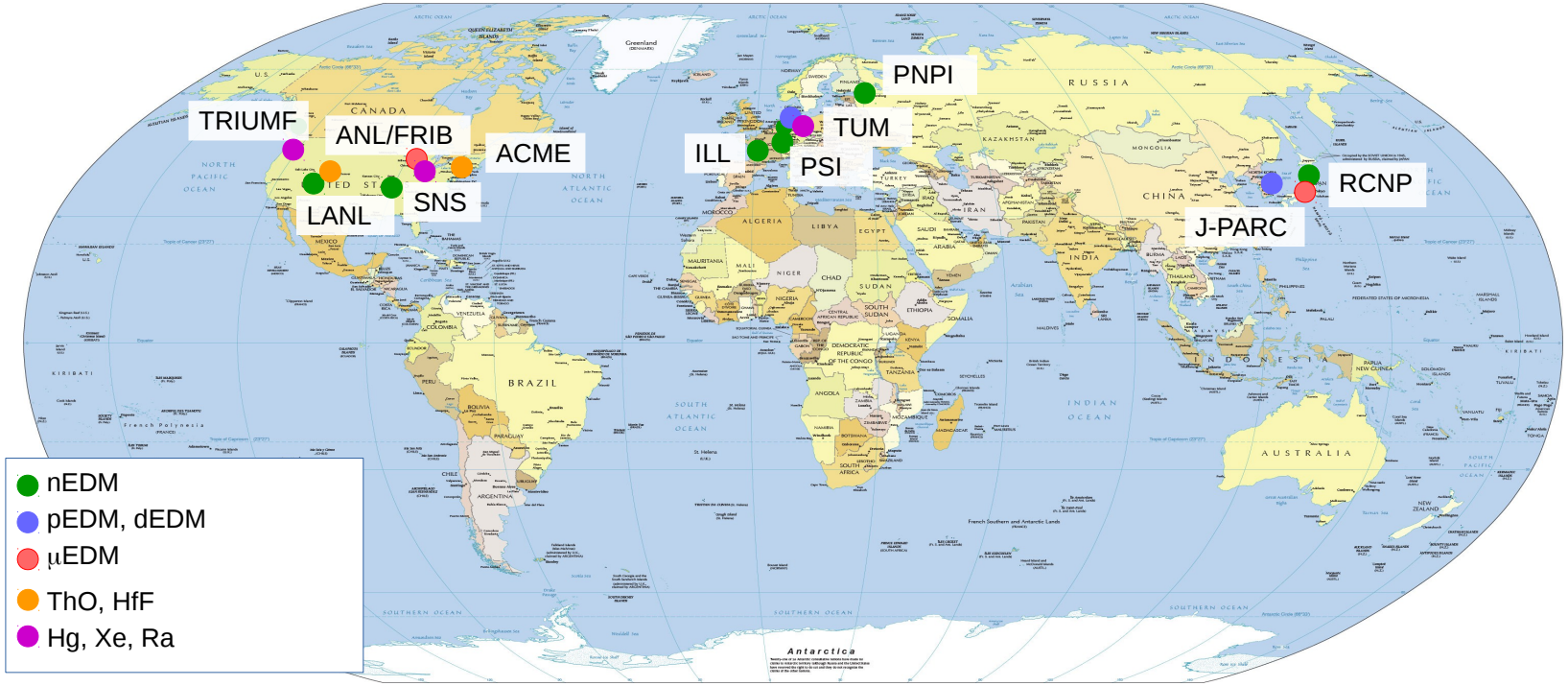
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{2G_F^2}{v}\left[\sum_{i=\text{scalar}}\left(C_i^{(9)}\,\bar{e}_L C\,\bar{e}_L^T + C_i^{(9)\prime}\,\bar{e}_R C\,\bar{e}_R^T\right)\,O_i \;+\; \bar{e}_R\gamma_\mu C\,\bar{e}_L^T \sum_{i=\text{vector}} C_{iV}^{(9)}\,O_i^\mu\right]$$

- 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



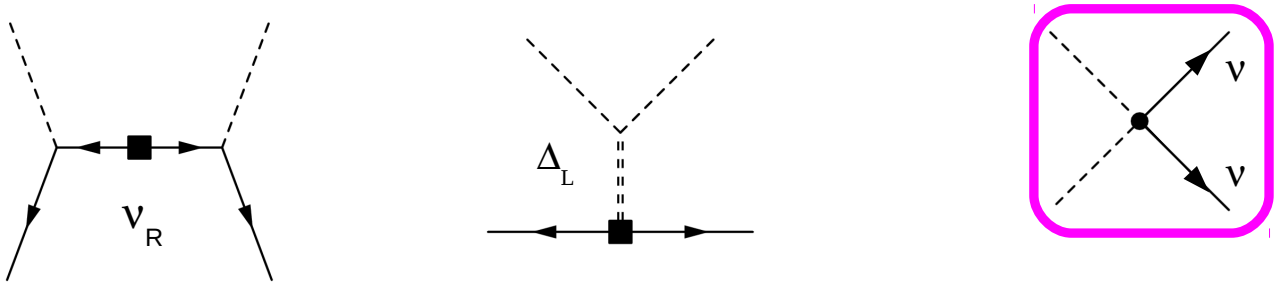
- current bounds

$$d_e < 8.7 \cdot 10^{-16}\ e\ \mathrm{fm}$$
$$d_n < 3.0 \cdot 10^{-13}\ e\ \mathrm{fm}$$
$$d_{^{199}\mathrm{Hg}} < 6.2 \cdot 10^{-17}\ e\ \mathrm{fm}$$
$$d_{^{225}\mathrm{Ra}} < 4.2 \cdot 10^{-17}\ e\ \mathrm{fm}$$

- future bounds

$$d_e < 5.0 \cdot 10^{-17}\ e\ \mathrm{fm}$$
$$d_n < 1.0 \cdot 10^{-15}\ e\ \mathrm{fm}$$
$$d_{^{199}\mathrm{Hg}} < 6.2 \cdot 10^{-17}\ e\ \mathrm{fm}$$
$$d_{^{225}\mathrm{Ra}} < 1.0 \cdot 10^{-14}\ e\ \mathrm{fm}$$

Left-right symmetric model



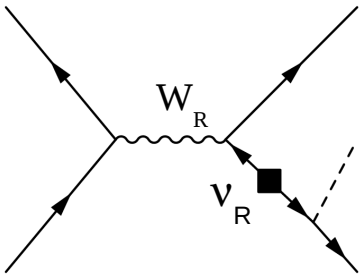
- model based on $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- broken to SM group at $v_R \gtrsim 10$ TeV

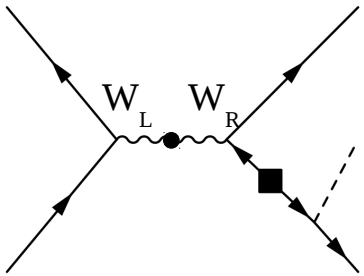
K-$\bar{K}$ oscillations and di-jet searches

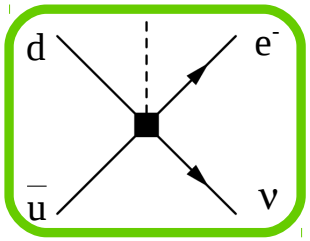
- generate ν masses via type-I and type-II see-saw

need small Yukawas

Left-right symmetric model







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

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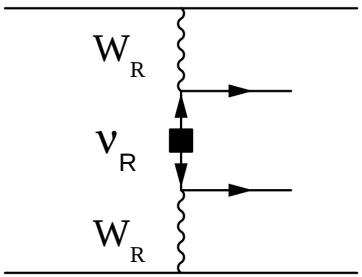
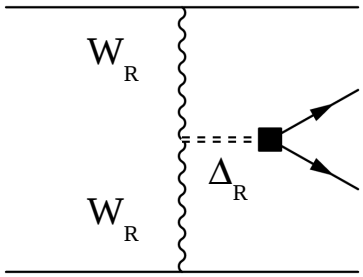
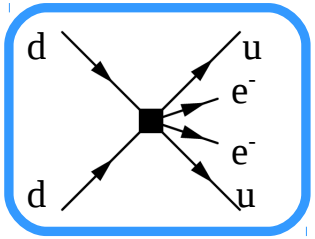
need small Yukawas

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

Left-right symmetric model







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

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Relation to charge-independence breaking

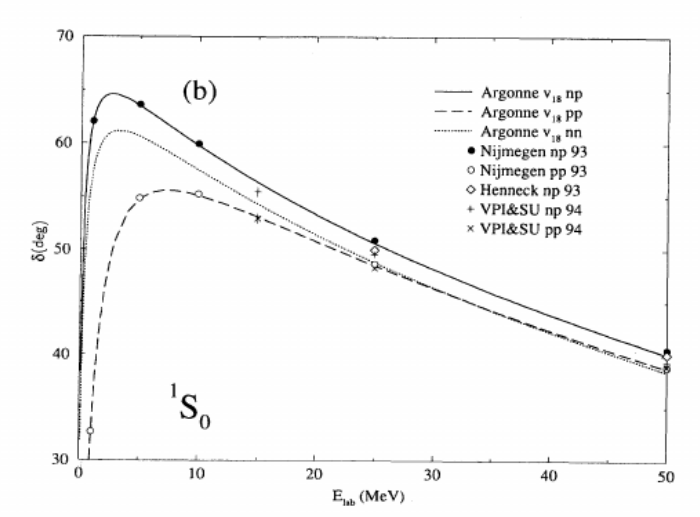


TABLE IX. Evolution of $^1S_0$ pp phase shifts from the charge-independent potential to the full interaction, as described in the text. Energies are in MeV.

$T_{\rm lab}$	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_{CIB} and V^S_{CIB} give effects of comparable size (when Coulomb is perturbative)

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

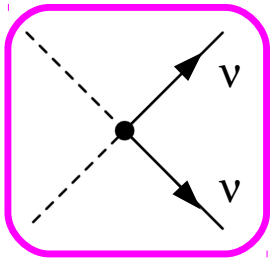
$$\frac{C_1 + C_2}{2} \sim \frac{50}{(4\pi F_\pi)^2}$$

M. Piarulli et al, ‘16

- same effect in isotensor energy coeff. of light nuclei

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

$\Delta L = 2$ Lagrangian at 1 GeV

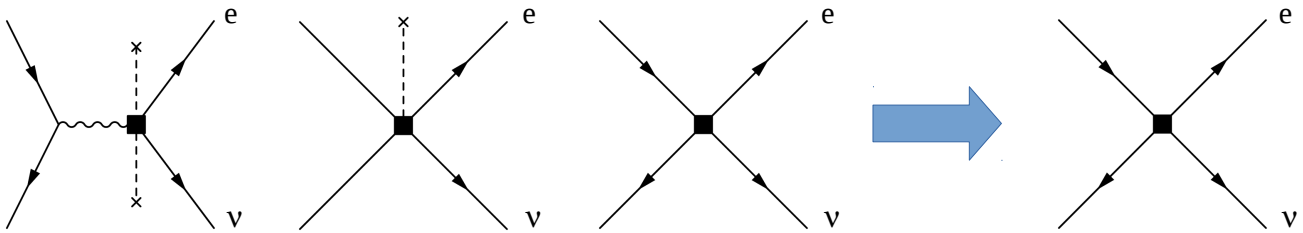


$$\mathcal{L}_{\Delta L=2} = \mathcal{L}_{\Delta L=2}^{\Delta e=0} + \mathcal{L}_{\Delta L=2}^{\Delta e=1} + \mathcal{L}_{\Delta L=2}^{\Delta e=2}$$

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

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

$\Delta L = 2$ Lagrangian at 1 GeV



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

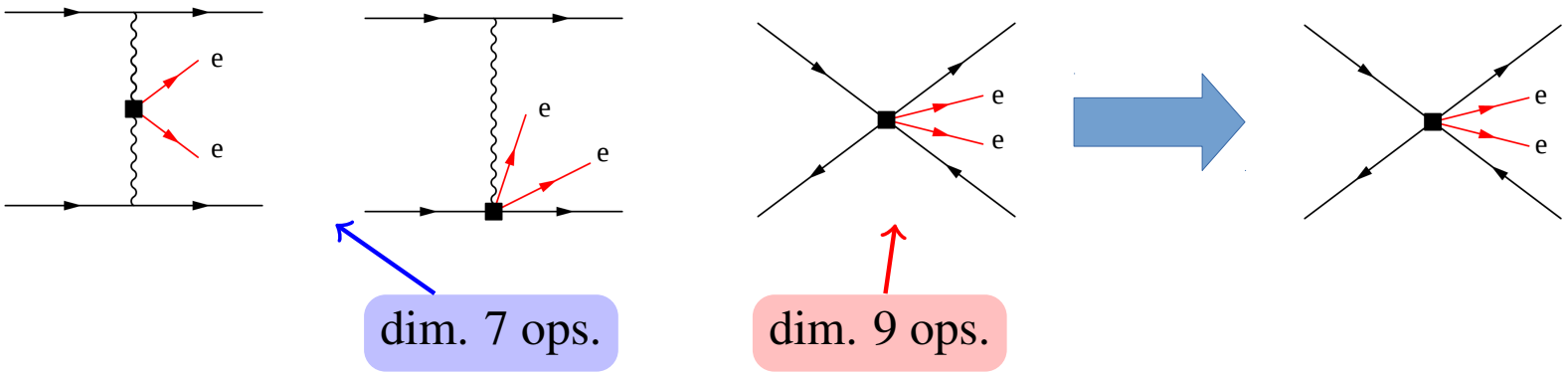
- $\mathcal{L}^{\Delta e=1}_{\Delta L=2}$ starts at dim. 6, $\quad C_i^{(6)} = \mathcal{O}\left(\frac{v^3}{\Lambda^3}\right)$

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

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

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

$\Delta L = 2$ Lagrangian at 1 GeV



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

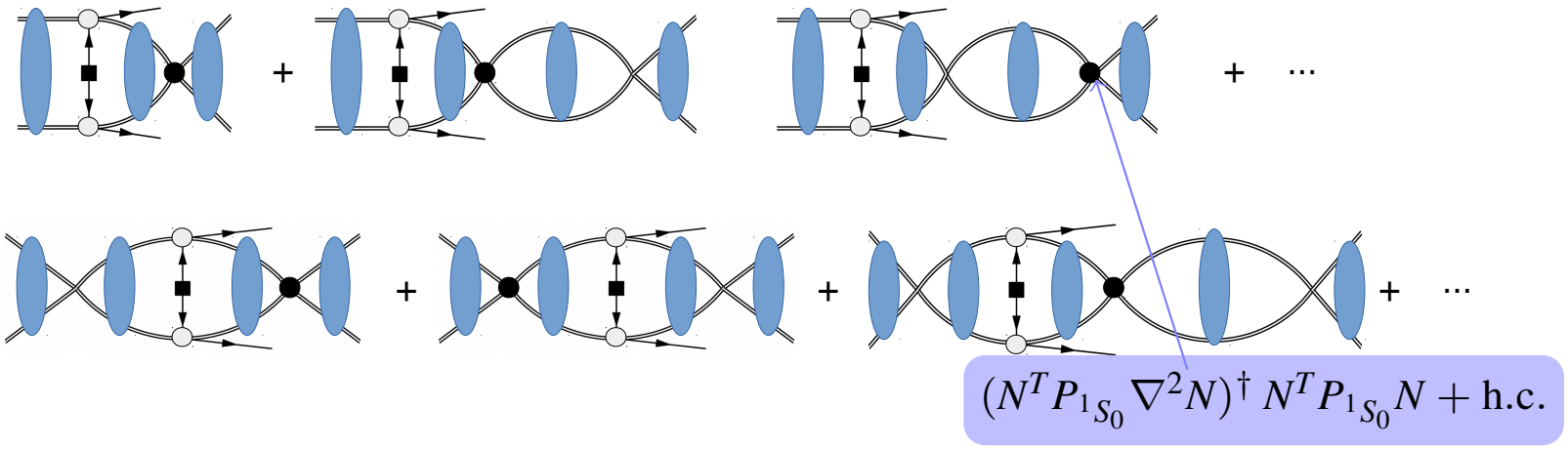
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{2G_F^2}{v}\left[\sum_{i=\text{scalar}}\left(C_i^{(9)}\,\bar{e}_L C\,\bar{e}_L^T + C_i^{(9)\prime}\,\bar{e}_R C\,\bar{e}_R^T\right) O_i \;+\; \bar{e}_R\gamma_\mu C\,\bar{e}_L^T \sum_{i=\text{vector}} C_{iV}^{(9)}\,O_i^\mu\right]$$

- a small set receives contributions from dim. 7 operators

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

- the remaining operators $\sim \mathcal{O}\left(\frac{v^5}{\Lambda^5}\right)$

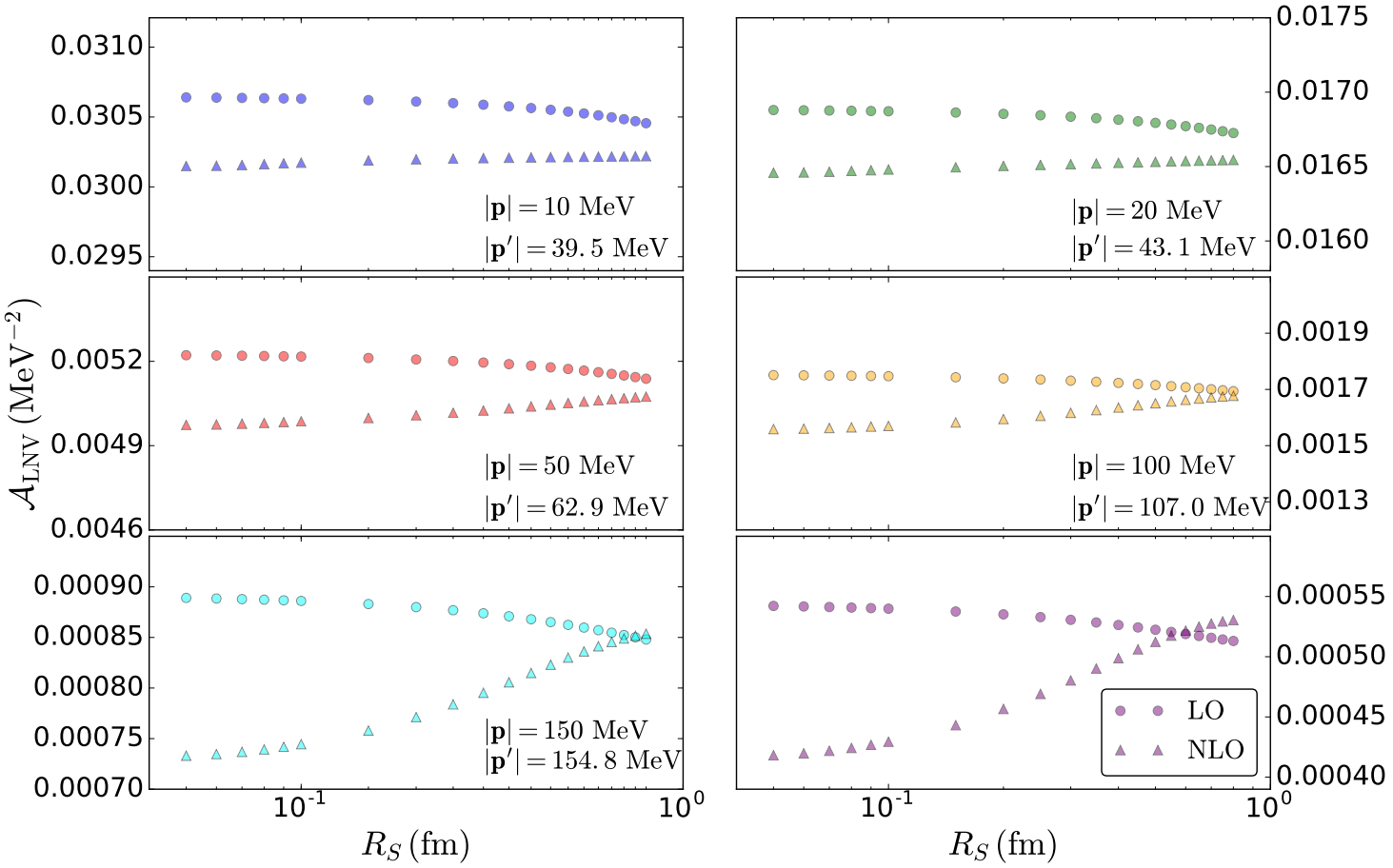
Next to leading order



- include $^1S_0$ derivative operator in ptb. theory
- compute

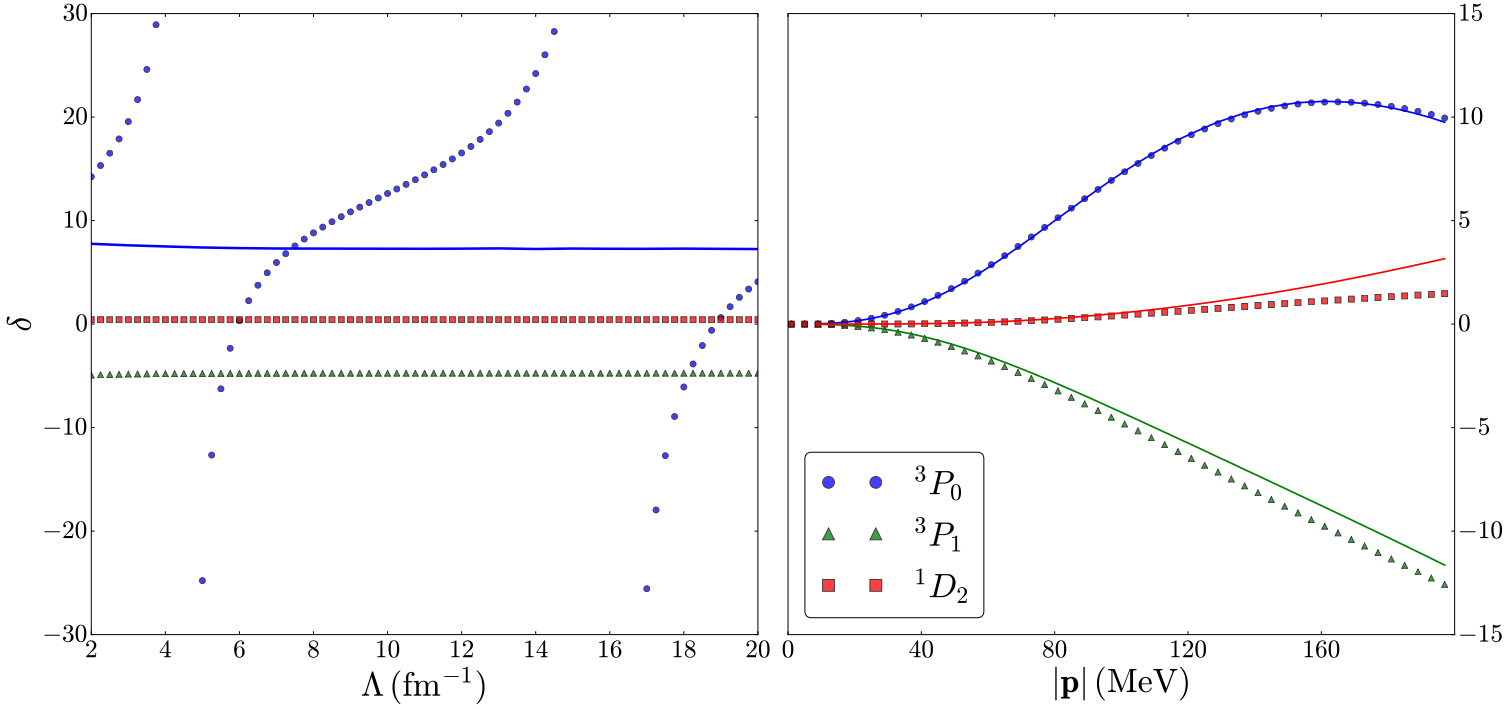
$$\mathcal{A}_\nu = -\int d^3\mathbf{r} \left(\psi_{\mathbf{p}'}^{-\,(0)\,*} + \psi_{\mathbf{p}'}^{-\,(1)\,*}\right)\left(V_\nu(\mathbf{r}) - 2g_\nu^{\mathrm{NN}}\delta_{R_S}^{(3)}(\mathbf{r})\right)\left(\psi_{\mathbf{p}}^{+\,(0)} + \psi_{\mathbf{p}}^{+\,(1)}\right),$$

Next to leading order



- small $\mathcal{O}(Q/\Lambda)$ corrections, no need for counterterm

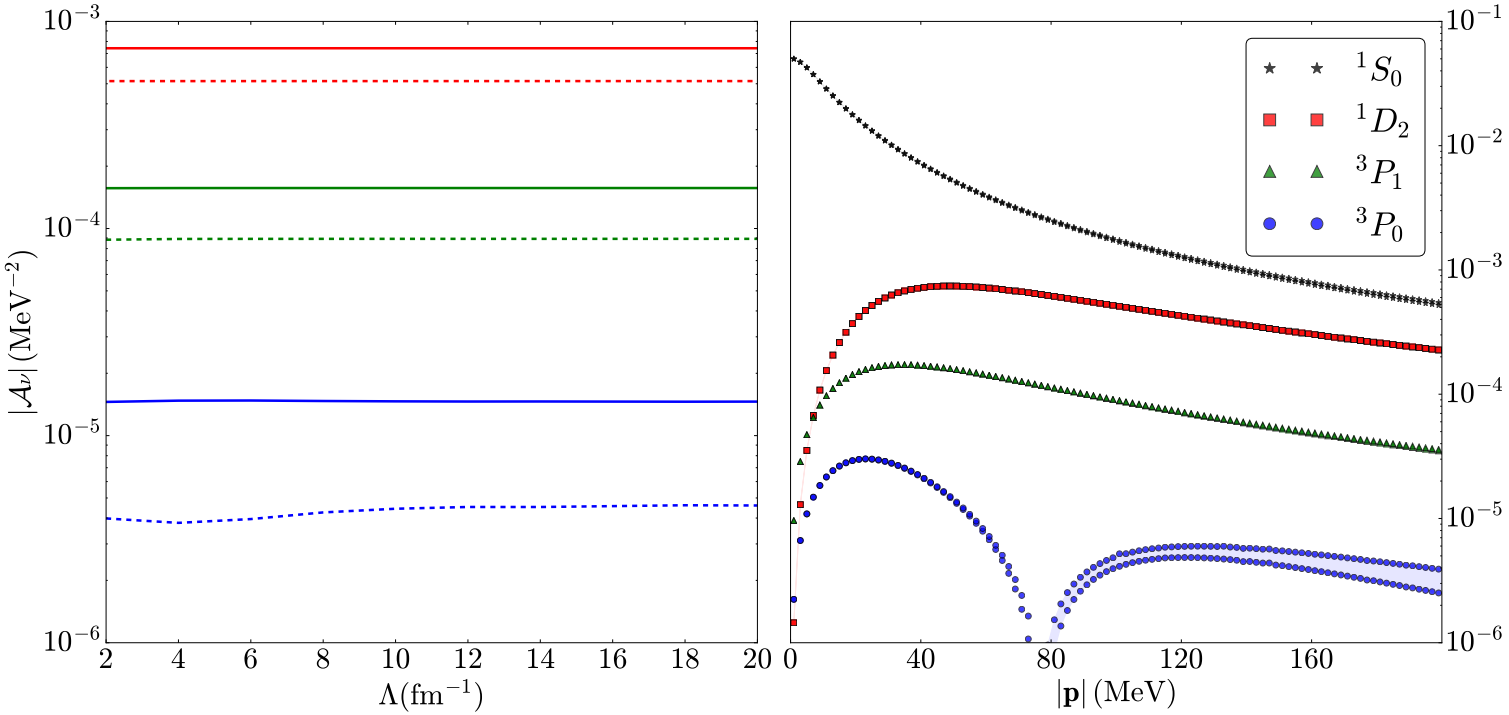
Higher partial waves



- Weinberg's counting lead to problems in $^3P_{0,2}$ waves

$\Longrightarrow$ need LO counterterms in the strong interaction

Higher partial waves



- Weinberg's counting lead to problems in $^3P_{0,2}$ waves

  $\Longrightarrow$ need LO counterterms in the strong interaction

- neutrino potential in P waves does not require further renormalization