Neutrinoless Double-Beta Decay in Chiral Effective Field Theory

Jordy de Vries

Mostly based on :

“A new leading contribution to $0\nu\beta\beta$”, 1802.10097, PRL
``A $0\nu\beta\beta$ Master formula from EFT“, 1806.02780 JHEP
“A renormalized approach to $0\nu\beta\beta$”, 1907.xxxxx

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

University of Massachusetts, Amherst
RIKEN BNL Research Center

The puzzle of the neutrino mass

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

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

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

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

- Nothing wrong with this!

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

$$L_\upsilon = -M_R \nu_R^T C \nu_R \qquad M_R$$ New mass scale not linked to EW scale

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

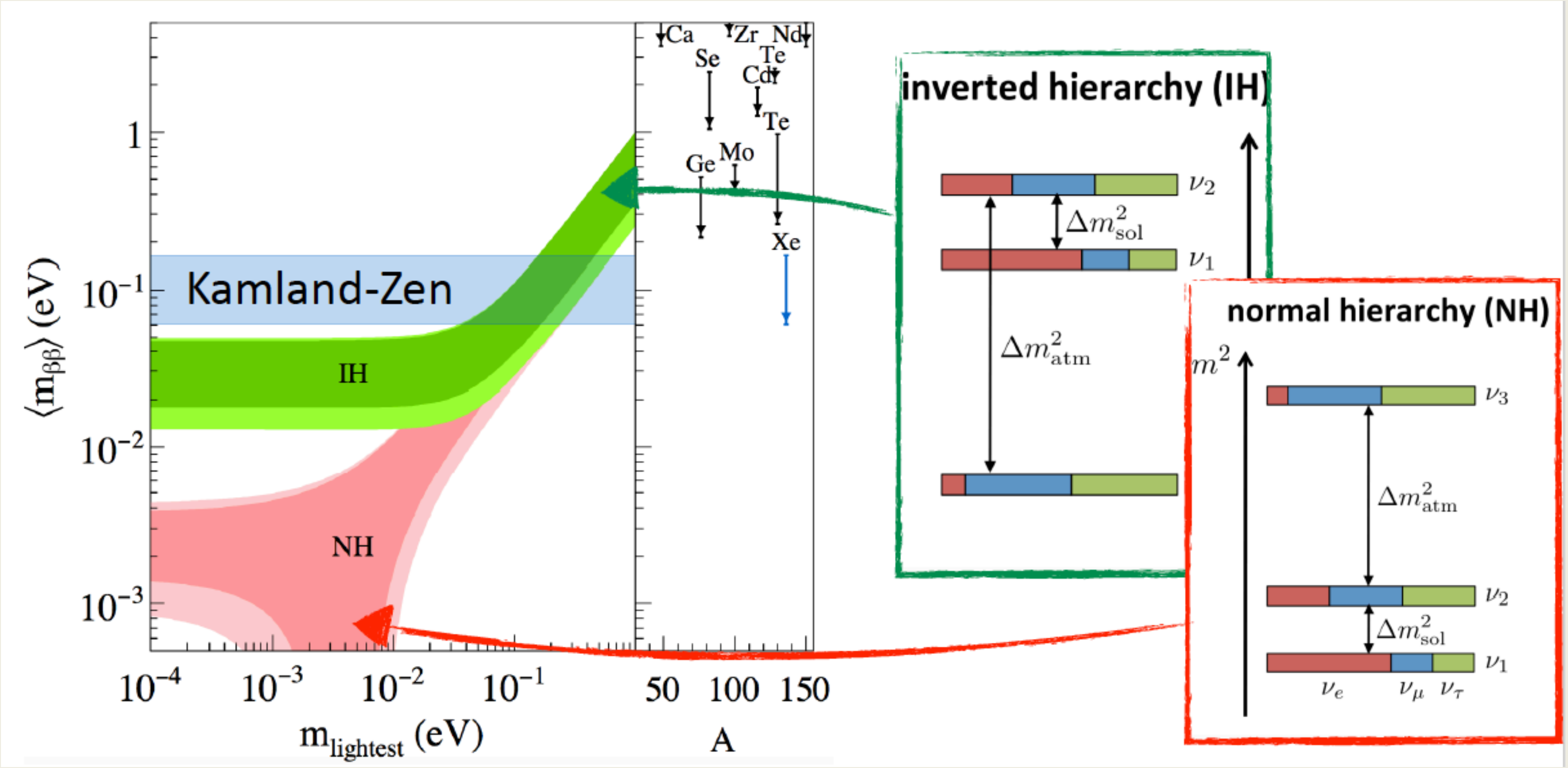
$$M_{diag} \approx \begin{pmatrix} (y_\nu v)^2 / M_R & 0 \\ 0 & M_R \end{pmatrix}$$

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

Standard interpretation

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

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

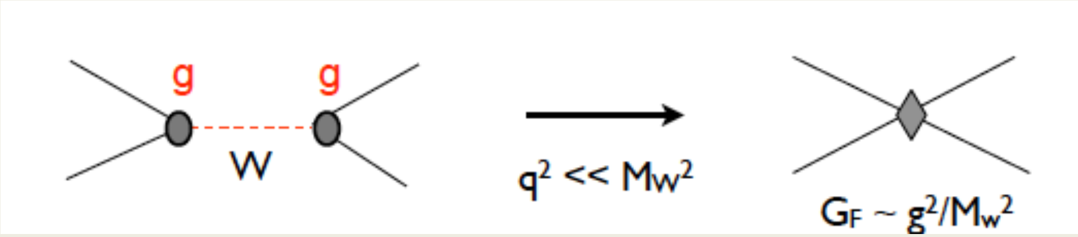


- Interpretation of experimental results requires theory

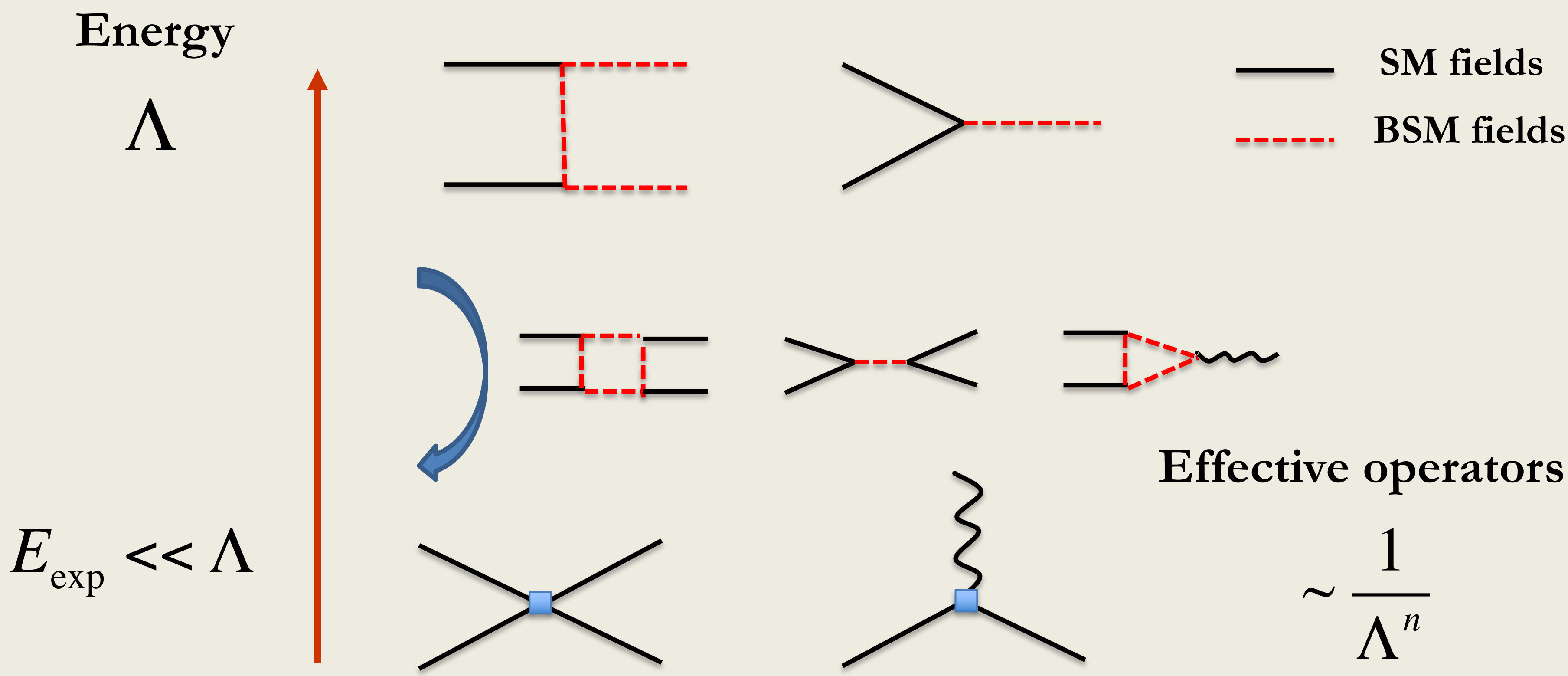
For this talk: SM-EFT framework

- Assume BSM physics exists but is heavy → **Integrate it out**

Fermi's theory:



- We don't need 'high-energy details', the W boson, at low energies !



Effective lepton number violation

- Lepton number = **accidental** symmetry in Standard Model (at zero T)
- But no longer once we allow for operators of dim>4
- Consider the SM as an EFT $$L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$
- Contain SM fields only and obey SM gauge and Lorentz symmetry
- Note: framework is not suitable for light sterile neutrinos
- **At energy E, operators of dimension (4+n) contribute as** $\left(\frac{E}{\Lambda}\right)^n$

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Weinberg '79

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

$$L_5 = \frac{c_5}{\Lambda}(L^T C \tilde{H})(\tilde{H}^T L) \quad \rightarrow c_5 \frac{v^2}{\Lambda} \nu_L^T C \nu_L$$ → **Majorana neutrino mass**

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

Higher-order in the SM-EFT

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

Dimension-five

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

- One operator
- Induces Majorana mass

Dimension-seven

Lehman '14

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

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

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

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

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

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

- 12 ΔL=2 operators

Dimension-nine

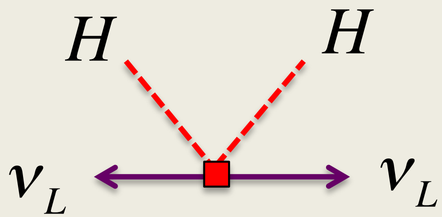
Prezeau et al '03
Graesser et al '17 '18

Full basis not known

19 4-quark 2-lepton operators after EWSB

- Seems crazy to go to dim-7 if expansion parameter is $\left(\frac{v}{\Lambda}\right)^2 \sim 10^{-24}$
- Example: in LR symmetry $c_5 \sim y_e^2 \sim 10^{-10}$ $c_7 \sim y_e \sim 10^{-5}$ $c_9 \sim y_e^0 \sim 1$
- Then if scale is low ~ $\Lambda \sim (10-100)\,TeV$ dim5 ~ dim7~ dim 9
- **I will focus on dim-5. See Wouter's + Lukas' talks on Thursday.**

Crossing the electroweak scale



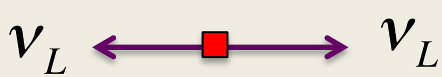
$$\frac{c_5}{\Lambda}(L^T C\tilde{H})(\tilde{H}^T L)$$

M_{EW}

100 GeV

Higgs takes vev

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



Neutrino Majorana Mass ~ dim-3

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

1 GeV

Integrate out ‘hard’ neutrinos and gluons/quarks

Match to effective hadronic operators

The anatomy of the decay

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

Energy

$> TeV$	$m_{\beta\beta}^2$	Lepton-number-violating (LNV) source *(not necessarily neutrino mass)*
$\sim GeV$	g_A^4	Hadronic ME: quarks → hadrons (domain of ChPT and lattice-QCD)
$\sim 100 MeV$	$\|M\|^2 = \left\|\langle 0^+ \| V_\upsilon \| 0^+ \rangle\right\|^2$	Depends on 'neutrino-potential' (ChEFT) and many-body calculations
$\sim 10 MeV$	G	Phase space factor, depends on Q value $\sim Q^5$ (of order 2-5 MeV for experimental targets)

Chiral perturbation theory

- Use the symmetries of QCD to obtain **chiral Lagrangian**

$$L_{QCD} \rightarrow L_{chiPT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots$$

- Quark masses = 0 → QCD has $SU(2)_L x SU(2)_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions are Goldstone)
  - Explicit breaking (quark mass) → pion mass
- ChPT gives systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\Lambda_\chi \cong 1\,GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)
  - LECs are related to nonperturbative QCD matrix elements
  - **Fit LECs or use lattice QCD or chiral symmetry arguments**

Weinberg, Gasser, Leutwyler, and many many others

Chiral effective field theory

~ GeV $L = L_{QCD}$ light quarks and gluons + electrons + neutrinos

---

~100 MeV Chiral limit $L_\chi = L_{kin} - m_N \bar{N}N + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N + C_0\ \bar{N}N\bar{N}N$

Nucleon mass, g_A, C_0 are 'LECs' and must be **measured** or **lattice QCD**

Quark mass $L_m = -\frac{m_\pi^2}{2}\pi^2 - \delta m_N\ \bar{N}\tau^3 N$

Small quark masses → Small pion mass and small nucleon mass splitting

Chiral effective field theory

~ GeV $L = L_{QCD} + L_{Fermi}$ light quarks and gluons + electrons + neutrinos

~100 MeV Chiral limit

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

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Quark mass

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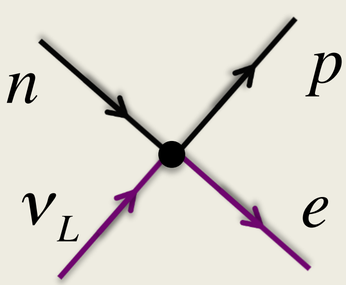
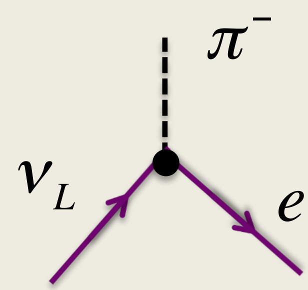
Weak interactions

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

$$+ G_F \ \bar{p}\left(\gamma^\mu - g_A \gamma^\mu \gamma^5\right) n \ \bar{e}_L \gamma^\mu \nu_L + \cdots$$



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



Prezeau et al '03

Chiral effective field theory

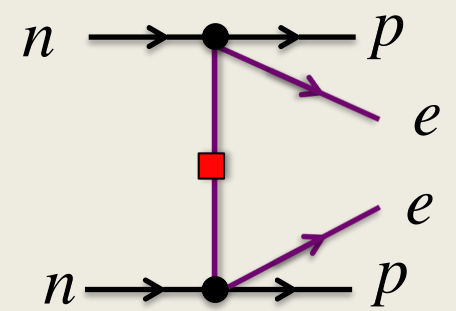
~ GeV $L = L_{QCD} + L_{Fermi} - m_{\beta\beta}\nu_L^T C \nu_L$ light quarks and gluons + electrons + neutrinos

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

LO interaction : ν_L ⟵■⟶ ν_L $\sim m_{\beta\beta}$

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

$q \sim k_F \sim m_\pi$



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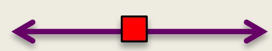
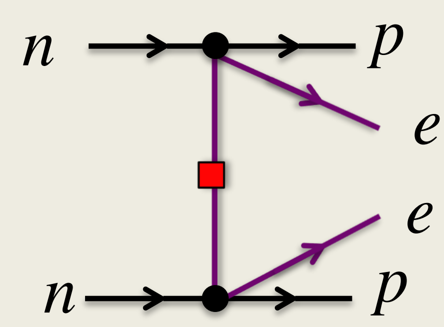
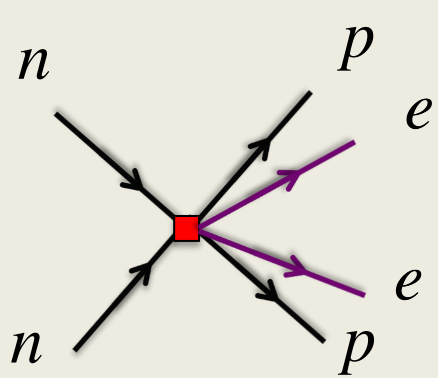
LO interaction : ν_L  ν_L $\quad \sim m_{\beta\beta}$



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

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

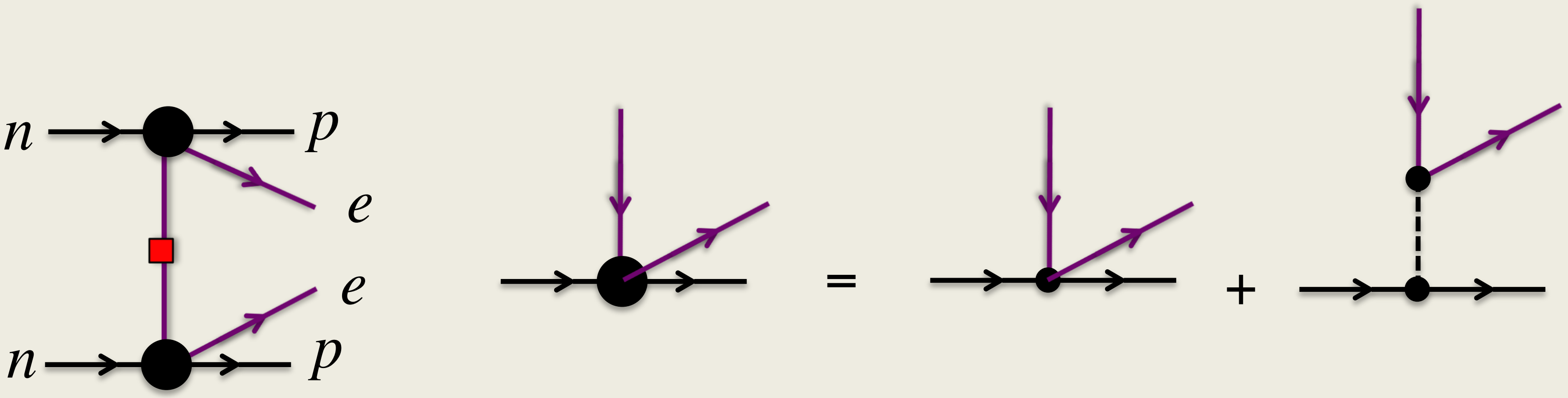
\`Hard' neutrino exchange $(E, |\vec{p}| > \Lambda_\chi)$ → short-range operators



Expected at N²LO
(Weinberg counting) $\quad \sim \dfrac{m_{\beta\beta}}{\Lambda_\chi^2}$

Majorana mass contribution

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



In $^1S_0$ $\quad V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\vec{q}^{\,2}}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{\left(\vec{q}^{\,2}+m_\pi^2\right)^2}\right] \otimes \bar{e}_L e_L^c$

- LO potential very simple and long-range ~ $1/q^2$
- All other contributions are higher order
- **Crucial: no unknown hadronic input (only unknown is $m_{\beta\beta}$)**

Quick look at higher orders

Cirigliano et al '17

- The EFT approach allows for systematic corrections

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

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

Quick look at higher orders

Cirigliano et al '17

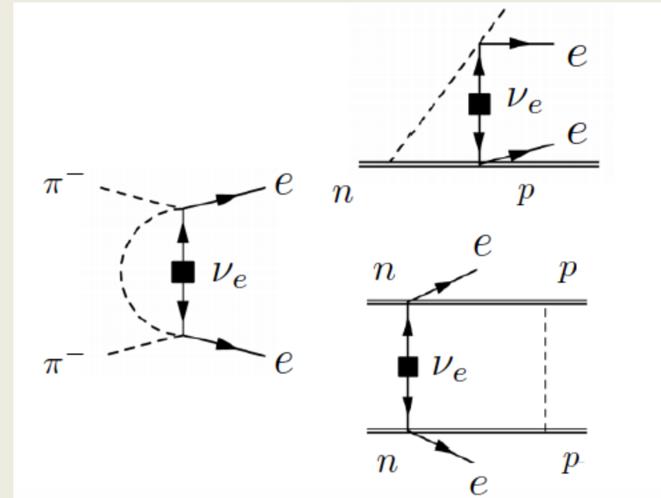
- The EFT approach allows for systematic corrections

  1. Factorizable 'one-body' corrections

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

  2. New non-factorizable pieces

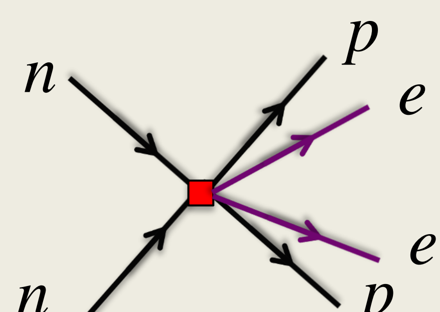
     + associated **counter terms**



Some diagrams are UV divergent…..

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

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



- **As expected: short-range at N^2LO**

Quick look at higher orders

Cirigliano et al '17

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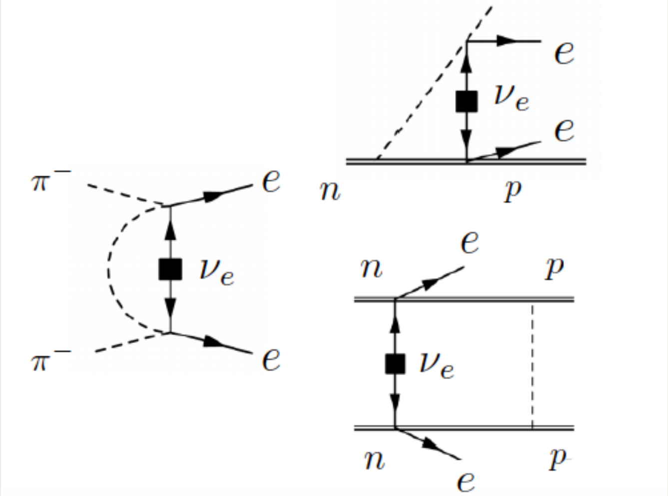
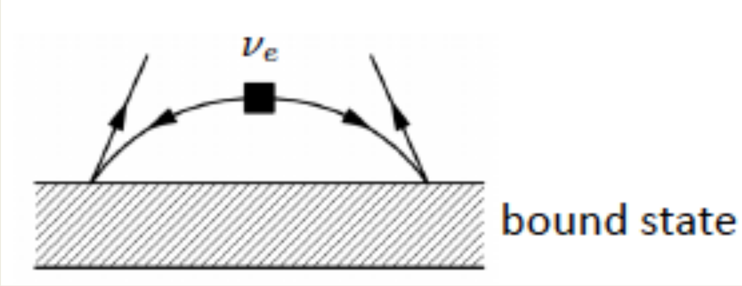


- Closure corrections from ultrasoft neutrino exchange
- Depends on **nuclear excited states**

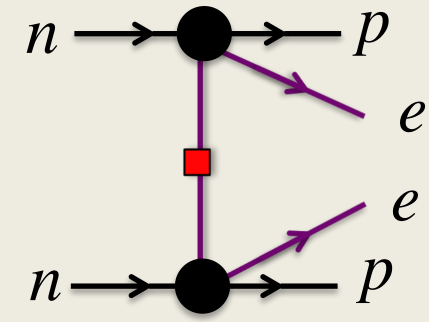
- Appear at N^{2}LO ~ $\dfrac{(E_n - E_0)}{(4\pi k_F)} \sim \dfrac{q^2}{\Lambda_\chi^2}$



- Correspond to so-called 'closure corrections'

Review by Doi et al '83

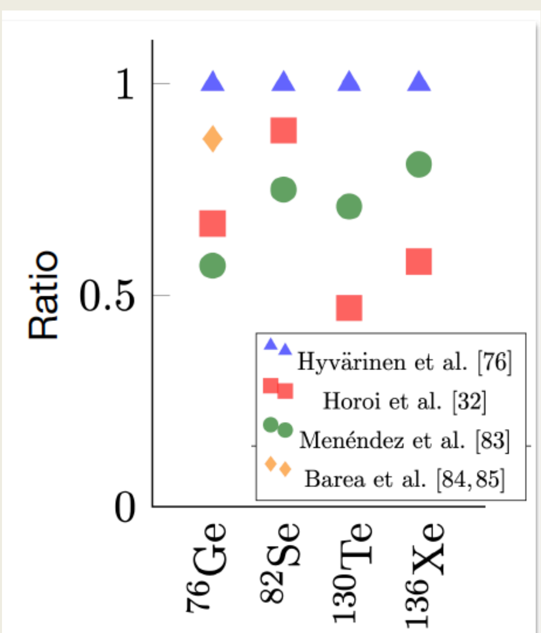
The neutrino amplitude



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

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

- Now insert this in nuclear wave functions
- **Different methods have roughly a factor 2 to 3 `many-body spread'**



Nuclear structure problem ?

Other problems ?

QPRA (Hyvarinen/Suhonen '15)

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

IBM (Barea et al '15 '18)

Back to the basics

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

“A new leading contribution to $0\nu\beta\beta$”, 1802.10097, PRL 120

Back to the basics

- Size of short-range piece was estimated by perturbation theory (NDA)
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"A new leading contribution to 0νββ", 1802.10097, PRL 120

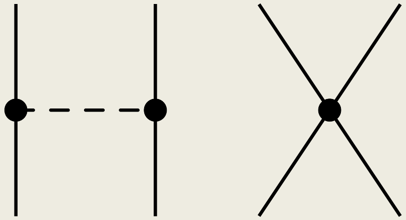
- First describe NN scattering by solving LS equation

$$T = V + VG_0T$$

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

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

LO



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

Nucleon-nucleon scattering

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

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

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

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

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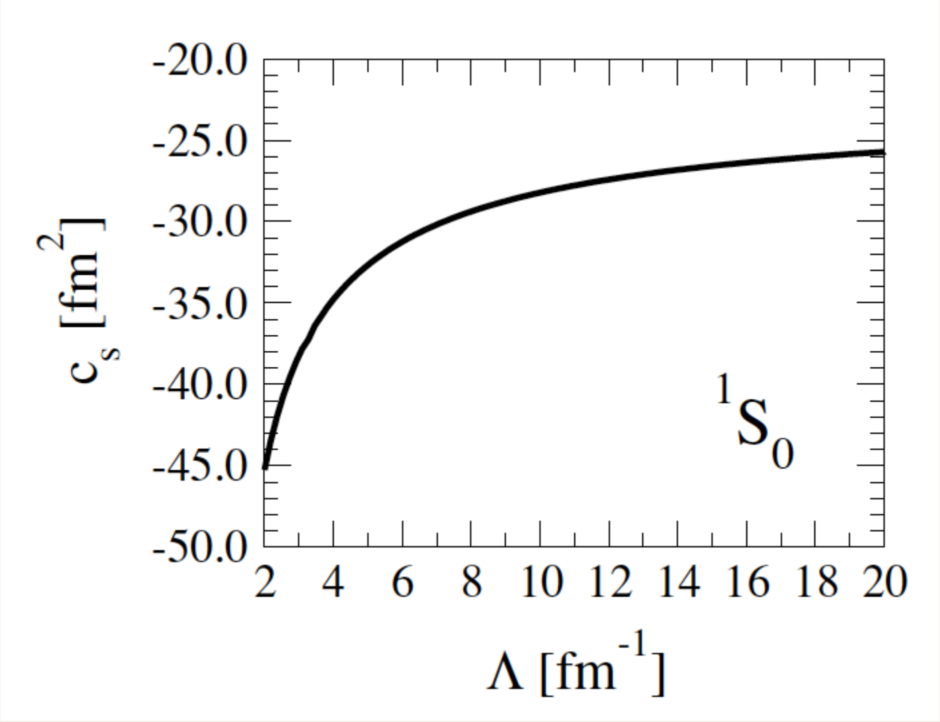
EFT breakdown scale $\sim \Lambda_\chi$

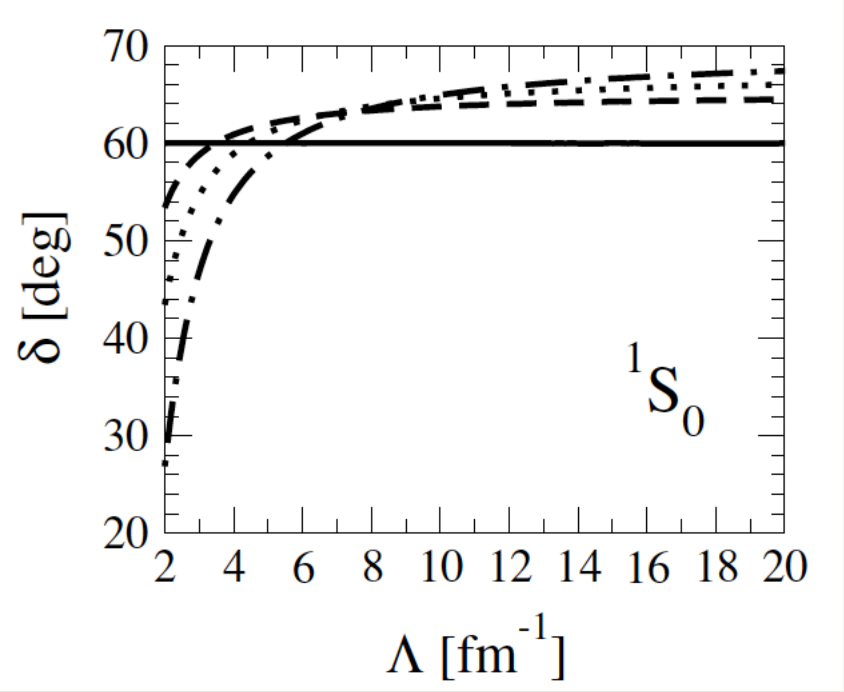
- Λ is a momentum cut-off. It should be $\Lambda \geq M_{high}$ so that we do not miss soft physics. **In practice** $\Lambda \cong M_{high}$ **is often useful.**
- **But we can in principle use** $\Lambda >> M_{high}$

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

Nucleon-nucleon scattering

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





Fit to 10 MeV data

50 MeV

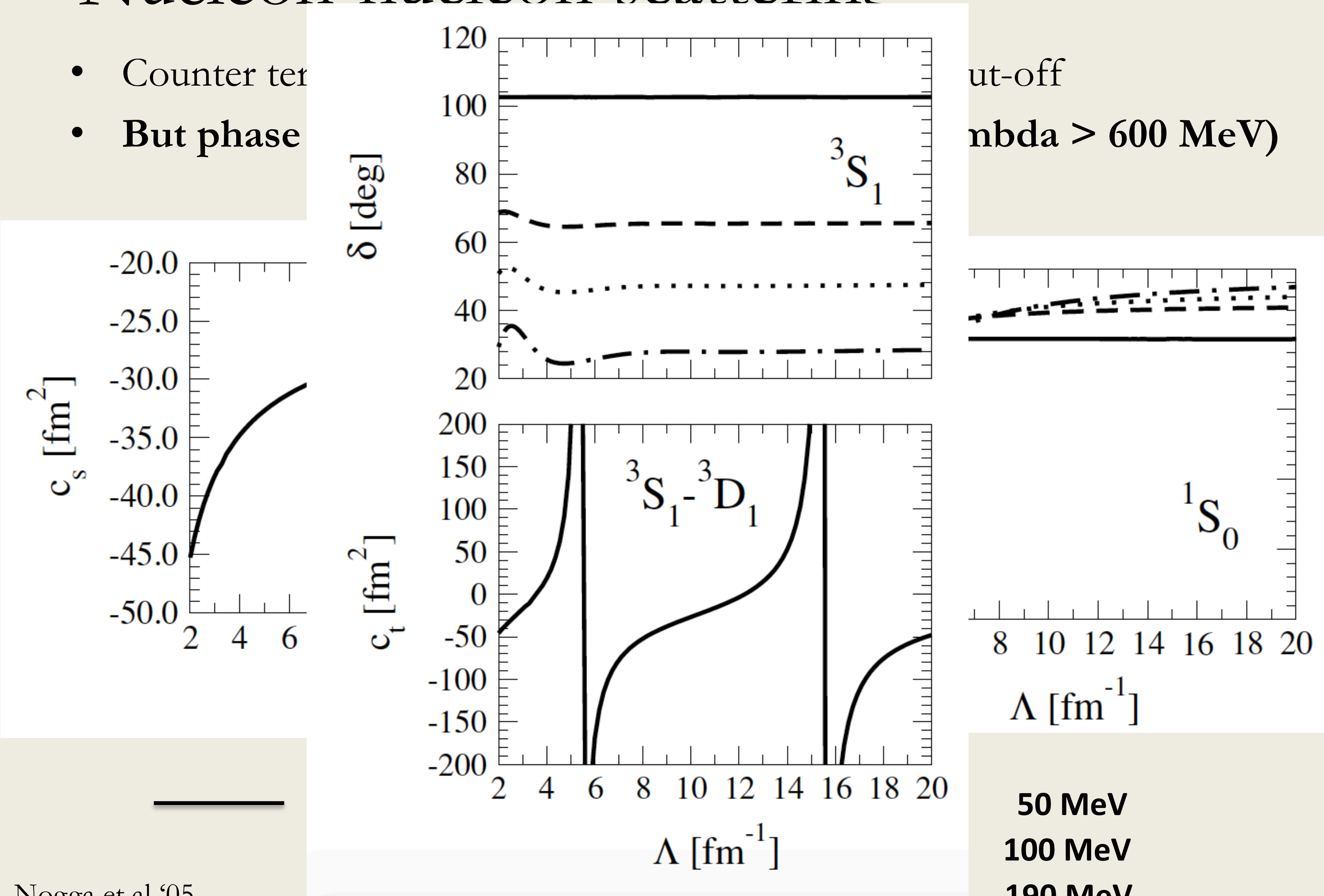
100 MeV

190 MeV

Nogga et al '05

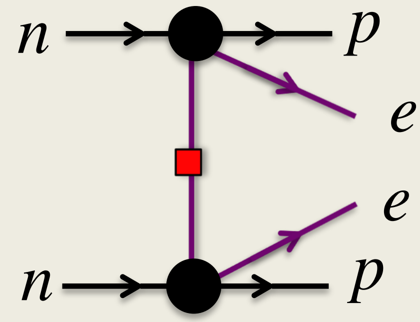
Nucleon-nucleon scattering

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



Nogga et al ‘05

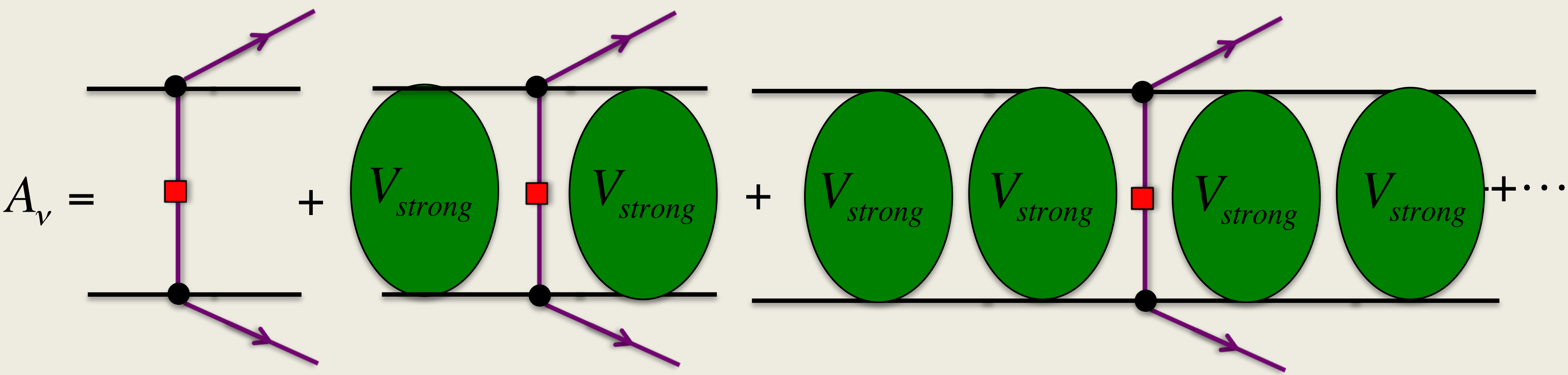
The neutrino amplitude



- Now insert the neutrino potential

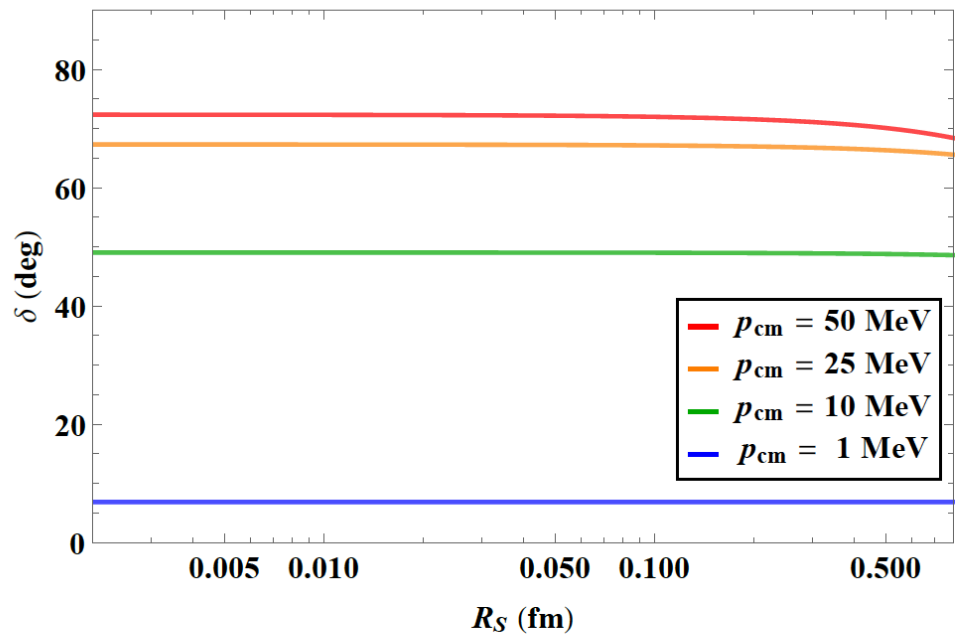
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\vec{q}^2}\left[(1+2g_A^2)+\frac{g_A^2 m_\pi^4}{\left(\vec{q}^2+m_\pi^2\right)^2}\right] \otimes \bar{e}_L e_L^c$$

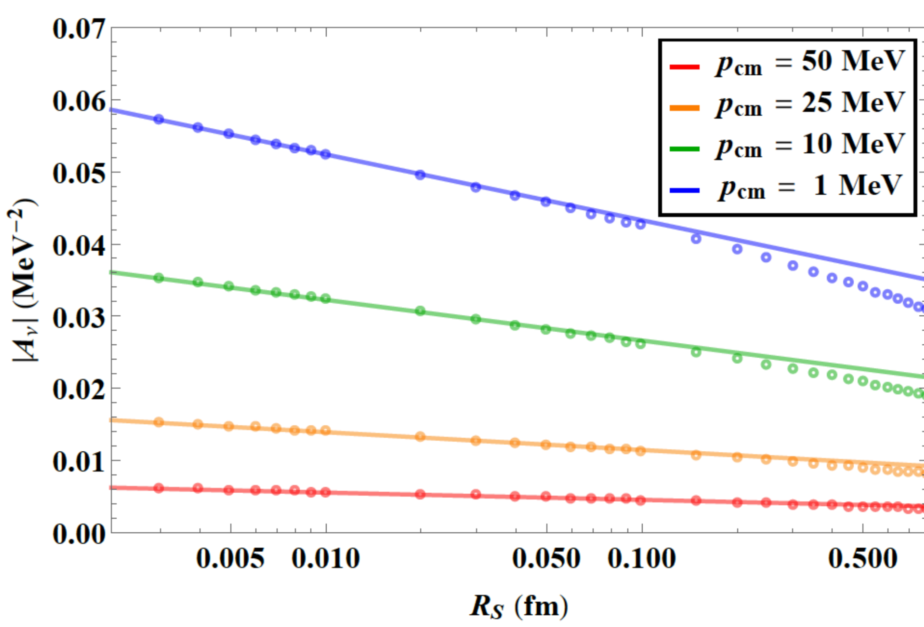
$$A_\nu = V_\nu + V_\nu G_0 T_{LO} + T_{LO} G_0 V_\nu + T_{LO} G_0 V_\nu G_0 T_{LO}$$



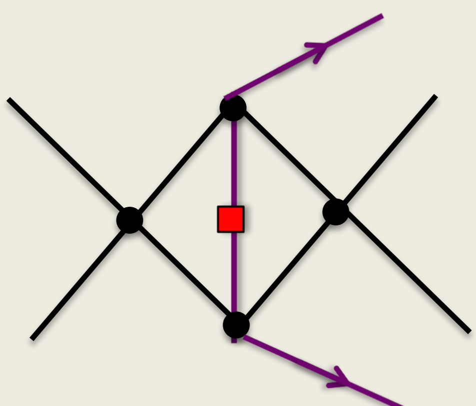
- **Can be measured in principle → should be independent of regulator !!**

The neutrino amplitude





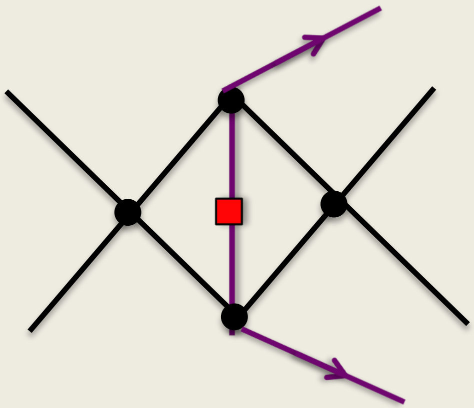
- But it is not... The amplitude depends logarithmically on the regulator.
- Note divergence is not NLO ! It is LO * $\log\Lambda$

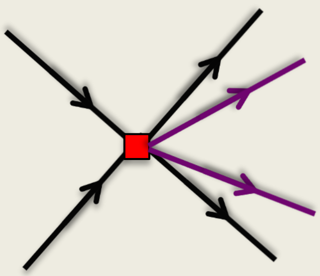


$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\varepsilon}+\log\frac{\mu^2}{p^2}\right)$$

Non-perturbative renormalization

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





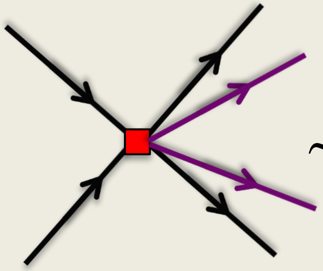
$\sim g_\nu^{NN}$

- Contact term comes with new LEC ~ QCD at lengths $< \left(\Lambda_\chi\right)^{-1}$
- The LO decay rate depends on unknown LEC → **hadronic uncertainty**
- Independent of short-range correlations (we use fully correlated NN wave functions)
- **It gets the job done though !**

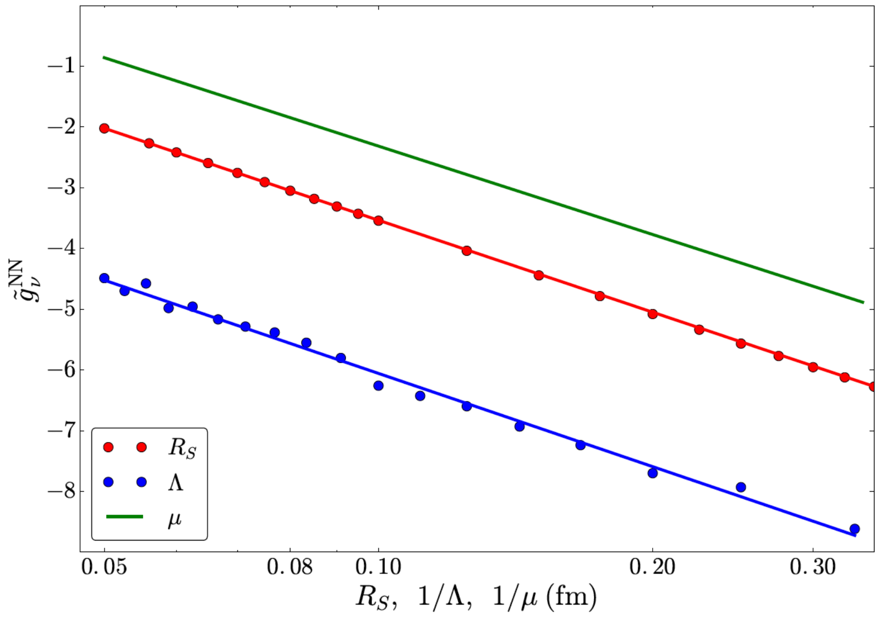
Non-perturbative renormalization

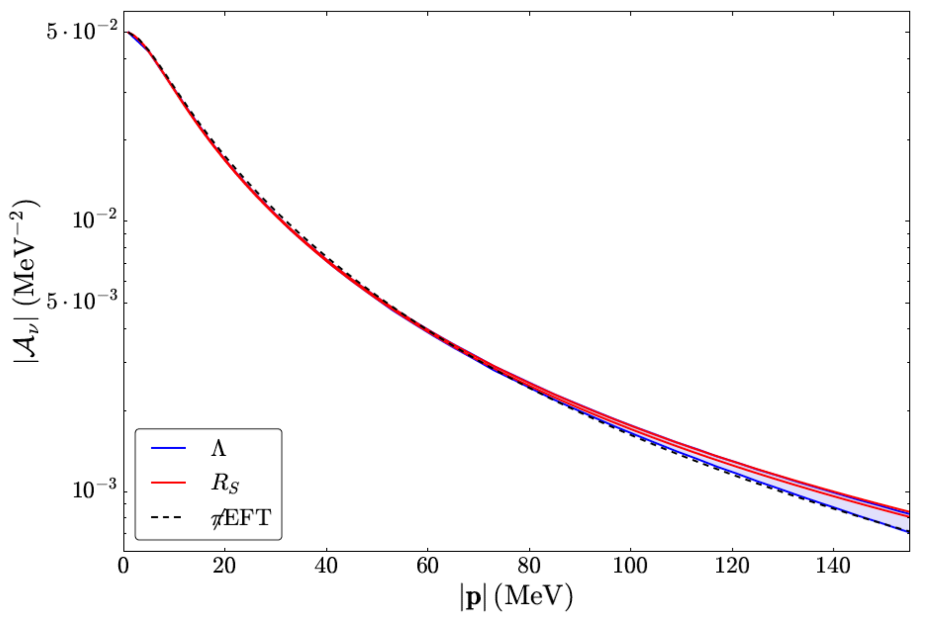
Fit the counter term to a ‘measurement’ at some kinematic point

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



$\sim g_\nu^{NN}$





Urgent questions and some answers

1. Just a study of S-waves. Do higher waves need counter terms too?

2. Based a leading-order NN potential. What are the effects of higher-order corrections? More LNV counter terms ?

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

4. How to incorporate into realistic calculations of nuclear matrix elements? Not so easy to change regulators there.

5. Are there similar issues for non-standard LNV mechanisms?

   Yes, for mechanisms with LO $\pi\pi \to ee$

Higher waves

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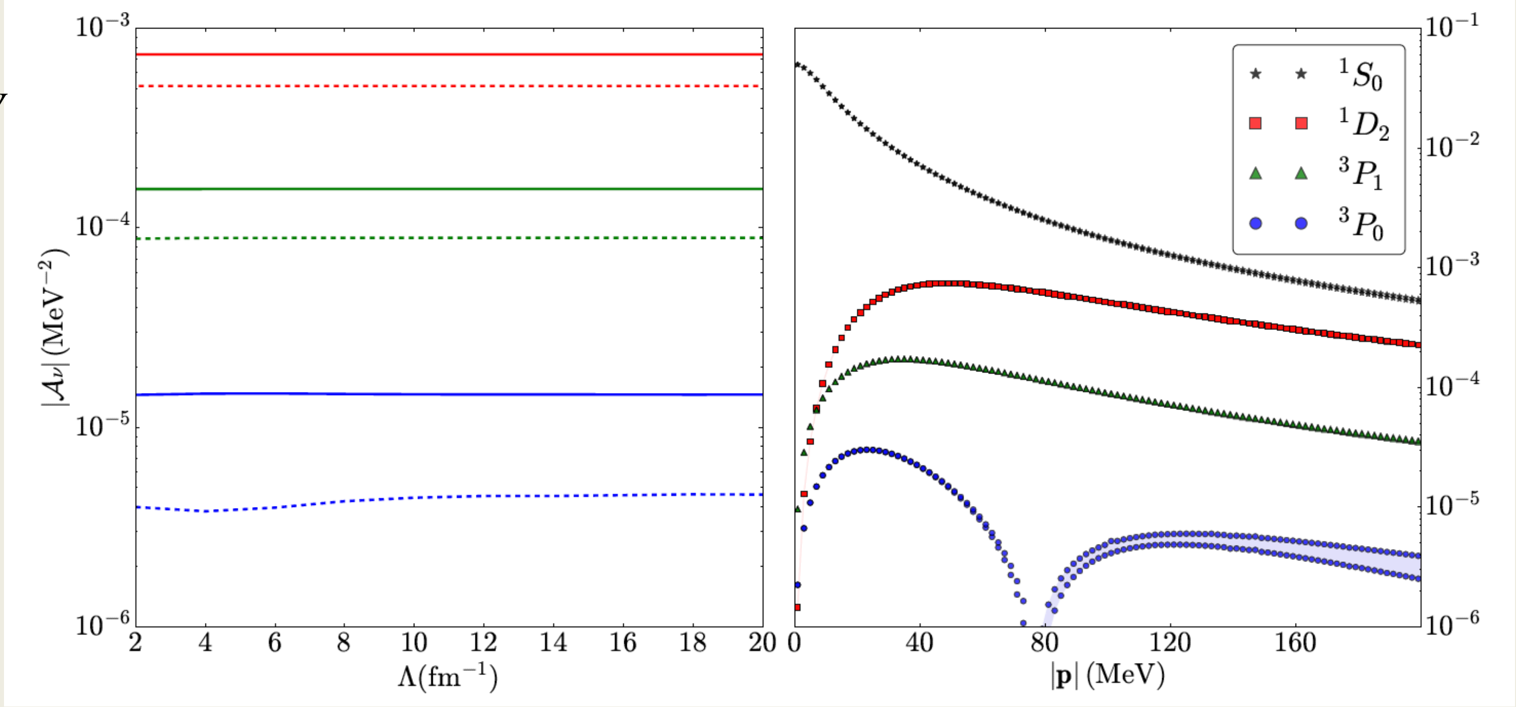
1. This was a study of S-waves. Do higher waves need counter terms too?
   - We studied P- and D-waves in similar fashion
   - Strong tensor force attractive in $^3P_0$ and an NN counter term is needed for the strong phase shifts   Nogga et al '05
   - But once NN force is renormalized so is nn → pp +ee

$p = 50\ MeV$

$p = 100\ MeV$



Higher-order corrections

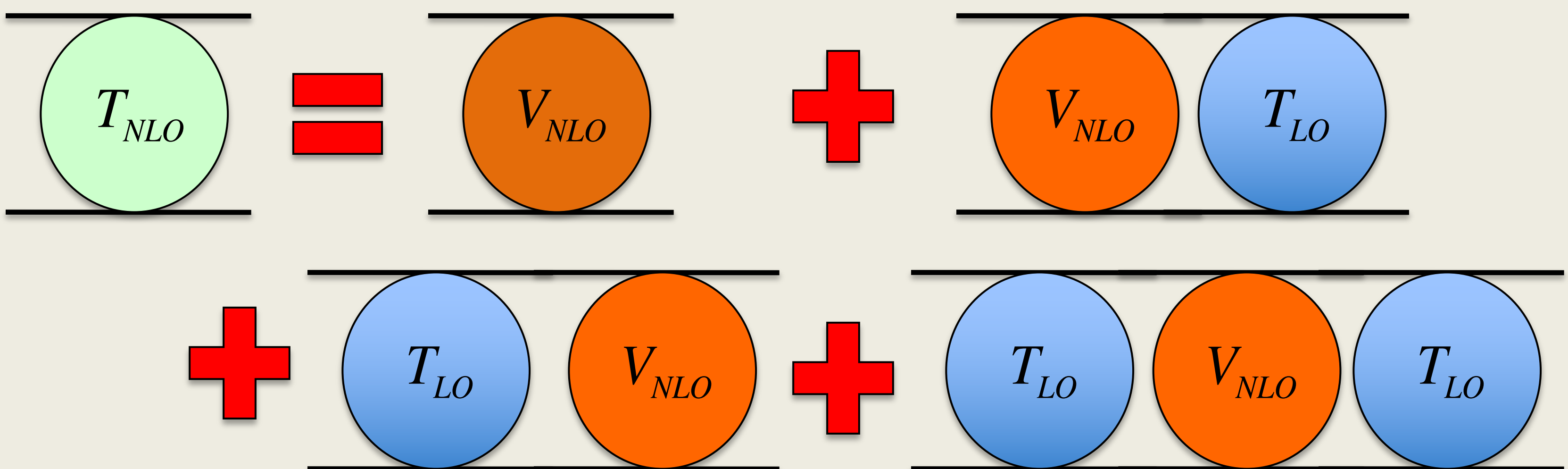
1. Effects of higher-order corrections? More LNV counter terms ?

   - At NLO the strong potential gets contributions from C_2 interaction

$$L_{NLO} = C_2\, \bar{N}\nabla^2 N\bar{N}N$$

Long & Yang '11 '12

   - Treat NLO in **perturbation theory** (not typically done in nuclear calculations where the whole potential is resummed).



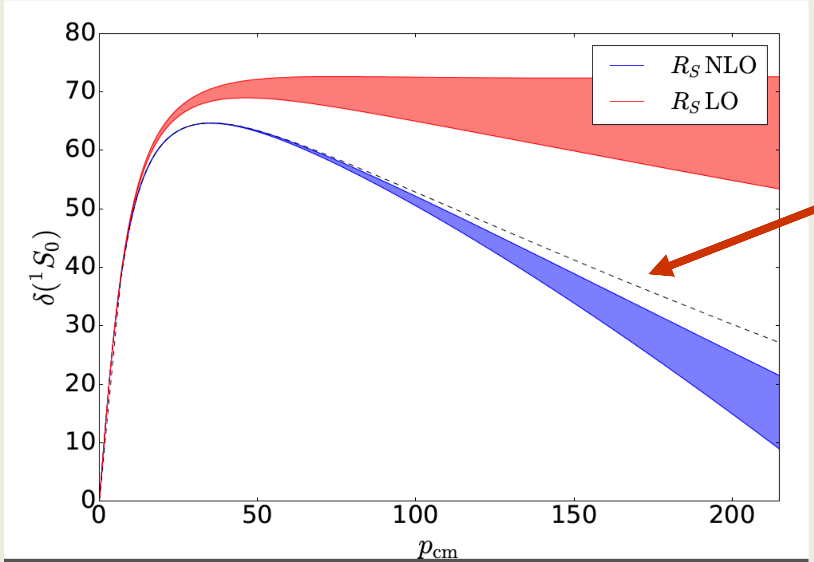
Higher-order corrections

1. This was based on a leading-order NN potential. What are the effects of higher-order corrections? More LNV counter terms ?
   - At NLO the strong potential gets contributions from C_2 interaction

$$L_{NLO} = C_2 \, \bar{N}\nabla^2 N\bar{N}N$$

Long & Yang ’11 ‘12

   - Treat NLO in **perturbation theory** (not typically done in nuclear calculations where the whole potential is resummed).
   - Fit C_2 to the effective range → much better description



Nijmegen PWA

Higher-order corrections

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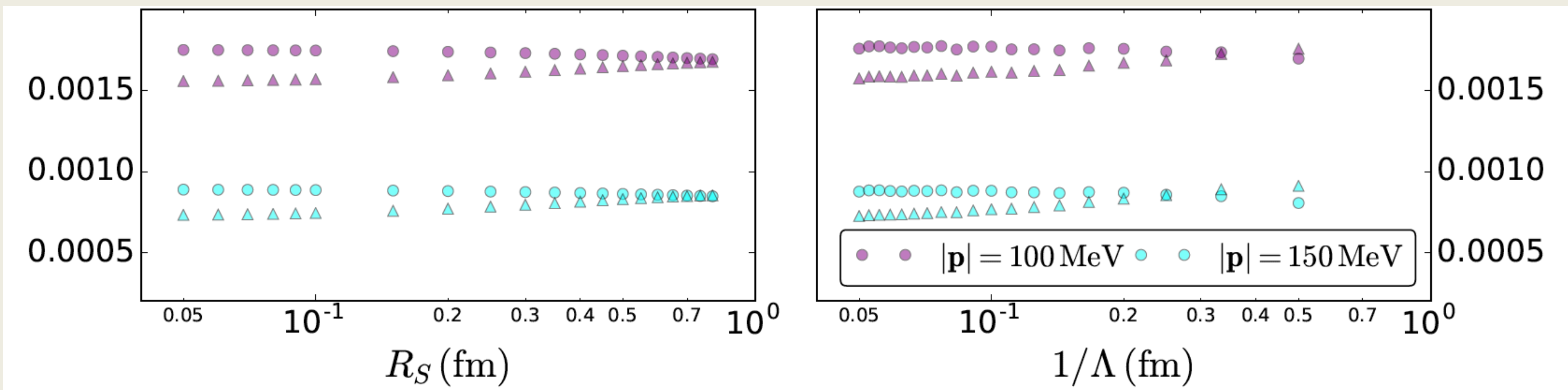
1. This was based on a leading-order NN potential. What are the effects of higher-order corrections? More LNV counter terms ?
   - We calculate NLO corrections to the neutrino amplitude
   - Semi-analytic calculations finds $\sim (\log \Lambda)/\Lambda$ dependence

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



- No problems at NLO and corrections ~ 10-20%. Everything ok !

Determining the LEC

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

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

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

   Interesting progress on ππ→ ee Nicholson et al '18, Feng et al '18

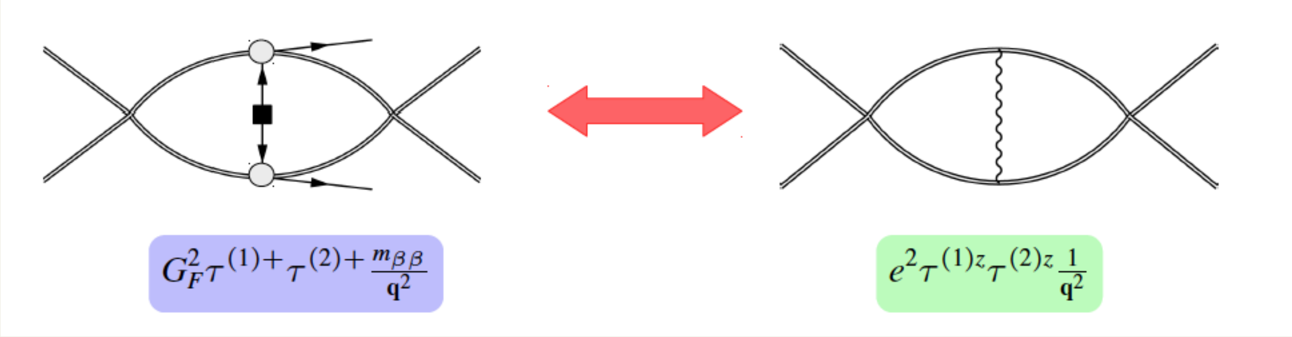
   This would be great if possible !

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

   - Convincingly (IMO) demonstrates the need for a LO counterterm
   - So far cannot give the full determination of

Using chiral symmetry

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



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

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

- **In Weinberg counting short-range operators at N^{2}LO**

Waltz, Epelbaum, Meißner ‘01

Charge-independence breaking

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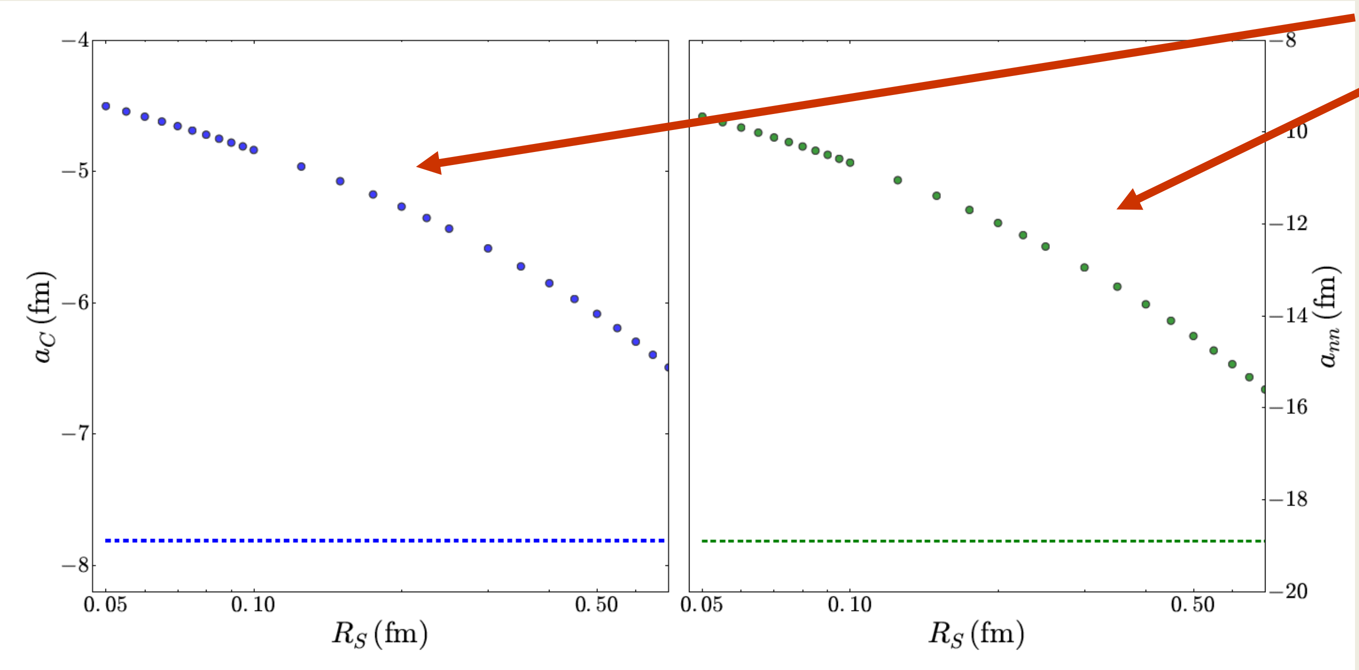
- We calculate the combination of scattering lengths

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

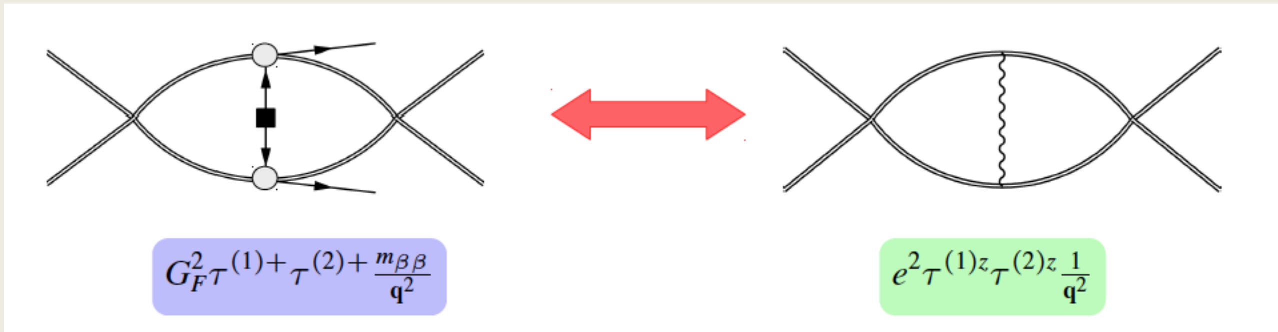
- Weinberg counting: once LO strong counter term is fitted to a_{np} then a_{nn} and a_{pp} are predicted. **They should be cut-off independent**
- We use as potentials: $V = V_{strong}^{LO} + V_{CIB}$

Log dependence !!!



Adding counter terms

- As we found for double beta, we need CTs for CIB



- Construct contact operators from EM I=2 operators

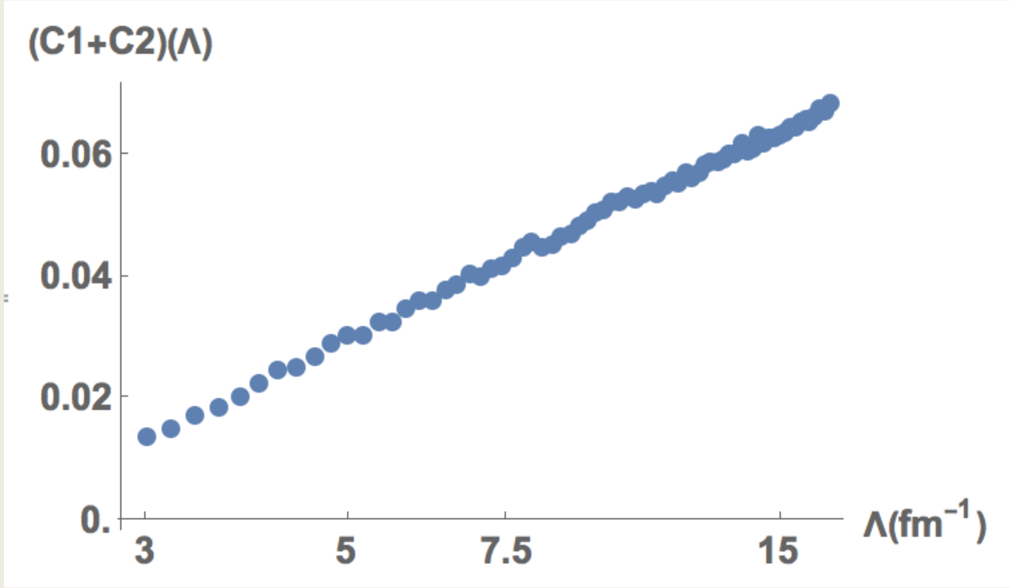
$$C_1\left(\bar{N}Q_L N\,\bar{N}Q_L N - \frac{Tr[Q_L^2]}{6}\bar{N}\vec{\tau}N\cdot\bar{N}\vec{\tau}N + L \leftrightarrow R\right) \qquad Q_{L,R} = u^{\dagger}Q_{L,R}u$$

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

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

A link to electromagnetism

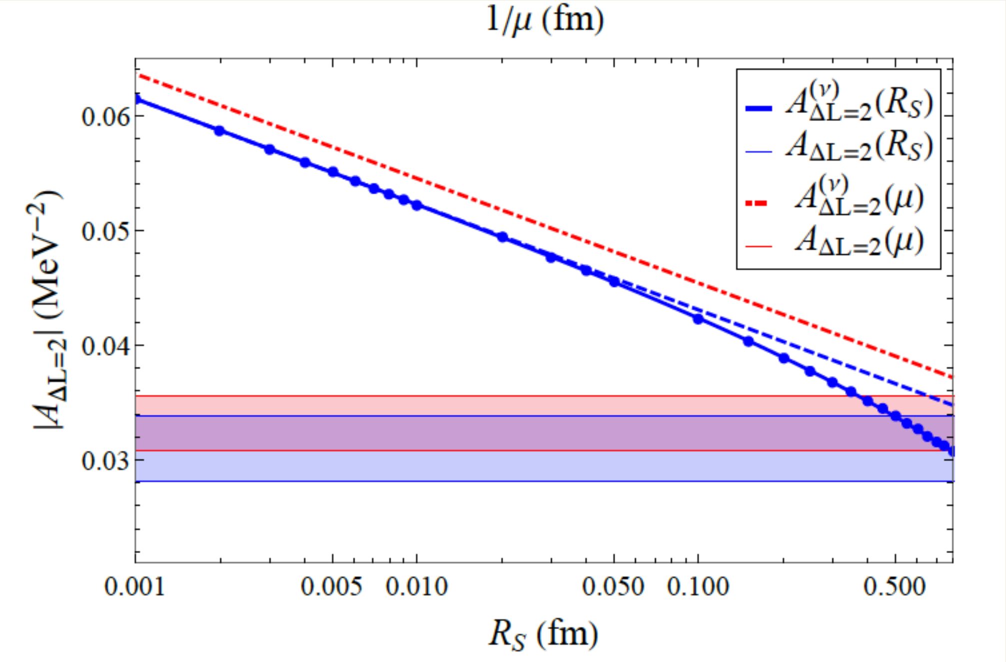
- We can extract C_1+C_2 from $\Delta I=2$ data $\quad \dfrac{a_{nn}+a_{pp}-2a_{np}}{2}$
- We calculate all scattering lengths and fit C_1+C_2
- Include isospin-breaking and Coulomb interactions



- **Clear log dependence:** Absorbs cut-off dependence in nn→ pp + ee
- Extract C1(Λ)+C2(Λ) as a function of the cut-off
- This then determines $g_\nu^{NN}(\Lambda)$

Partial success

- Recalculate amplitude with modified neutrino potential including CT



Cirigliano et al, PRL '18

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

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

Ab initio calculations of light nuclei

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- We study neutrinoless double beta decay in light nuclei

Pastore et al, PRC '17 '19

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

- Wave functions from QMC calculations with chiral potential Piarulli et al, PRC '14

- The CIB counter term extracted from potential → $g_{\nu}^{NN} = C_1 + C_2$
- **Study impact of short-range versus long-range neutrino potential**
- Note: these potentials all have $C_1 + C_2 \sim O(1)$ instead of N2LO

Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[35]	0.8	0.0158	−1.03	Entem-Machleidt	[31]	500	−0.47
NV-IIa*	[35]	0.8	0.0219	−1.44	Entem-Machleidt	[31]	600	−0.14
NV-Ic	[35]	0.6	0.0219	−1.44	Reinert *et al.*	[36]	450	−0.67
NV-IIc	[35]	0.6	0.0139	−0.91	Reinert *et al.*	[36]	550	−1.01
					NNLO$_{sat}$	[34]	450	−0.39

TABLE II. Values of $\mathcal{C}_1+\mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials

Ab initio calculations of light nuclei

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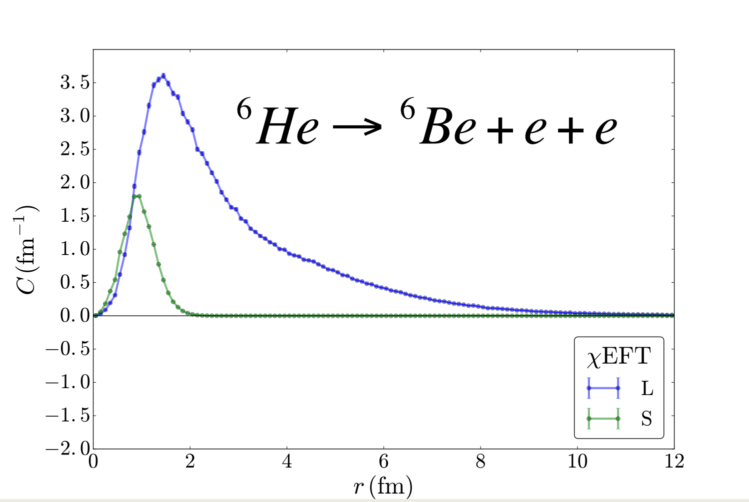
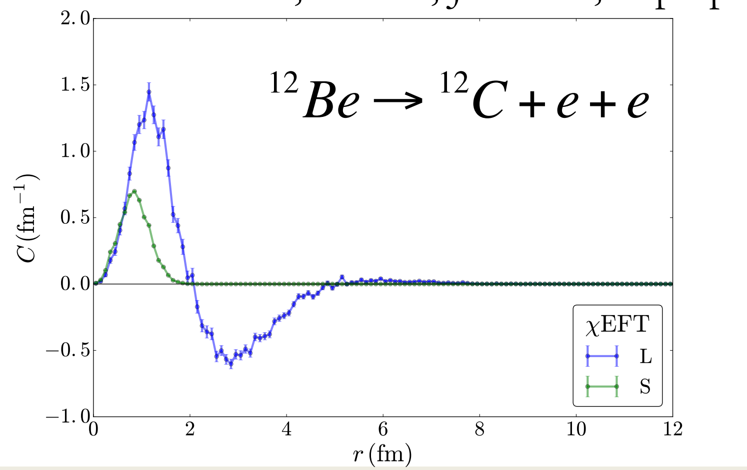
$$A_\nu = \int dr\, C(r) \qquad C(r) = C_{Long}(r) + C_{Short}(r)$$



Pastore, Piarulli, JdV et al, in prep

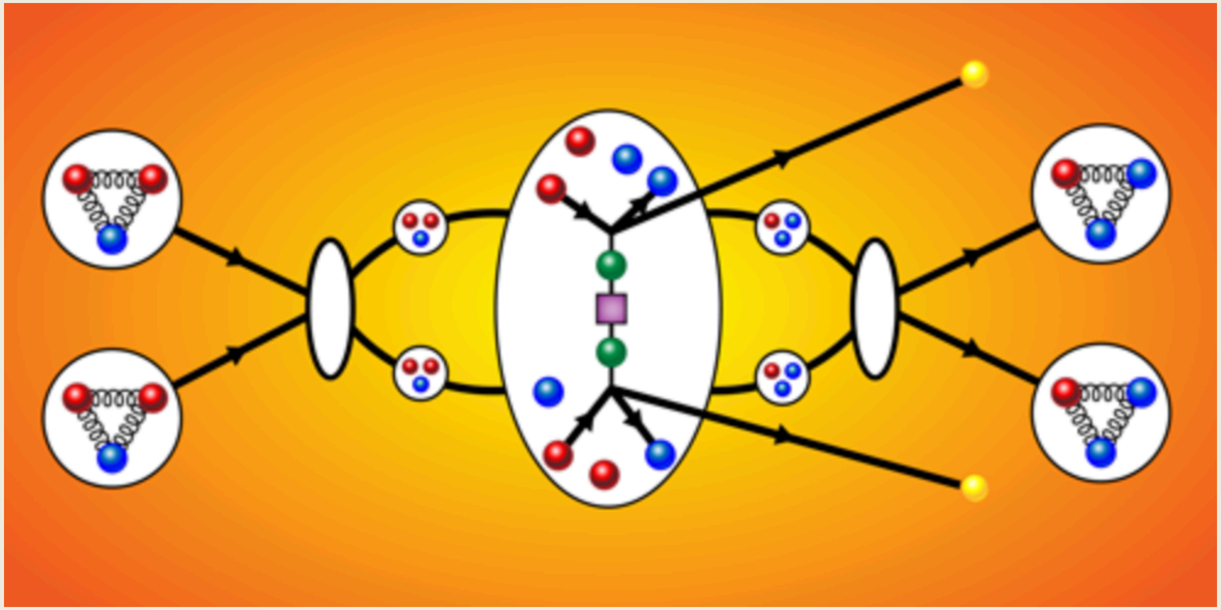


Dimensionless NME	Long range	Short range
$^6He \rightarrow {}^6Be + e + e$	7.8	1.2
$^{12}Be \rightarrow {}^{12}C + e + e$	0.7	0.55

- ΔI=2 transitions: orthogonal initial and final-state wave functions
- Feature of all isotopes of experimental interest
- **100% corrections to ΔI=2** transitions **from** g_ν^{NN}
- **If similar in heavier nuclei: large impact on neutrino mass extractions**

Summary of 'standard mechanism'

- Progress towards systematic derivation of $0\nu\beta\beta$ decay rate
- **Main result: a LO contact nn→pp + ee operator must be added**
- Potentially large impact on the neutrino mass limits
- Strong evidence for the need of the short-range currents
- **Lattice input needed to resolve + more ab initio calculations**
- **Not all bad!** Could enhance $0\nu\beta\beta$ decay rate and perhaps help align many-body calculations that are currently disagreeing?



Future developments

- Study three-nucleon double-beta decay processes in the same framework
- Some debate about role of two-nucleon weak currents

Menendez et al PRL '11
Engel et al PRC '15 '18

- **Can we disentangle C_1 and C_2 from CIB data ?**
- C_1 and C_2 are degenerate in pure nucleon processes
- Instead study associated interactions with 2 pions

Double charge exchange $\pi^{\pm} + A(N, Z) \rightarrow \pi^{\mp} + A(N \mp 2, Z \pm 2)$

CIB scattering $\sigma(\pi^{+} + A) + \sigma(\pi^{-} + A) - 2\sigma(\pi^{0} + A)$

CIB level splittings $E(\,^{6}He\,) + E(\,^{6}Be\,) - 2E(\,^{6}Li^{*}\,)$

- But not clear if this works….

- **Ideally, calculations on heavier nuclei**