DOE Topical Collaboration Meeting, Chapel Hill, Sept 6-7 2019

EFT approach to $0\nu\beta\beta$: an update

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Los Alamos National Laboratory

Outline

- Introduction: EFT for LNV and $0\nu\beta\beta$
- $0\nu\beta\beta$ from light Majorana ν exchange in chiral EFT
    - Summary of 2017-18 results
    - 2019 updates

Credits and references

- Chiral EFT approach for TeV-scale LNV (dim 7, dim 9)

Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

V. C. , W. Dekens, M. Graesser, E. Mereghetti, J. de Vries,
1806.02780, JHEP 1812 (2018) 097

- Chiral EFT approach for light Majorana neutrino (dim 5)

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud,
1710.01729, Phys.Rev. C97 (2018) no.6, 065501

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1907.11254

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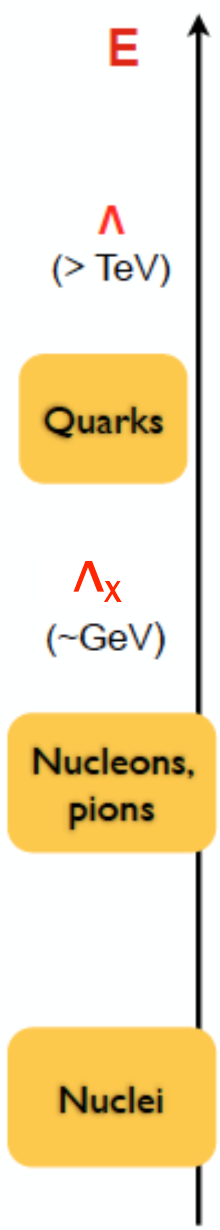
EFT framework for 0νββ



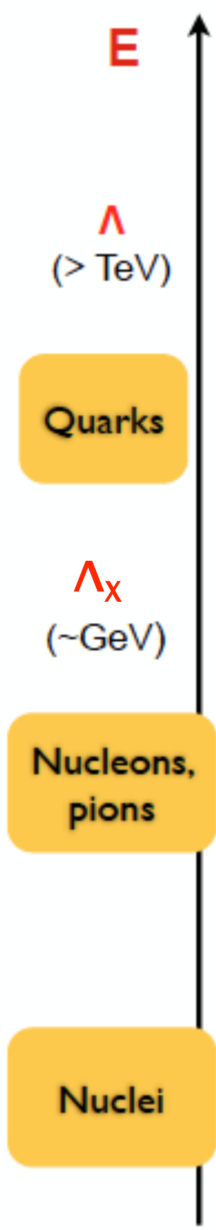
$\mathcal{L}_{\rm BSM}$

Integrate out heavy particles

$$\mathcal{L}_{\rm eff} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

LNV in the "Standard Model EFT": only dim=5,7,9,…

EFT framework for 0νββ



$$\mathcal{L}_{\text{BSM}}$$

↓ Integrate out heavy particles

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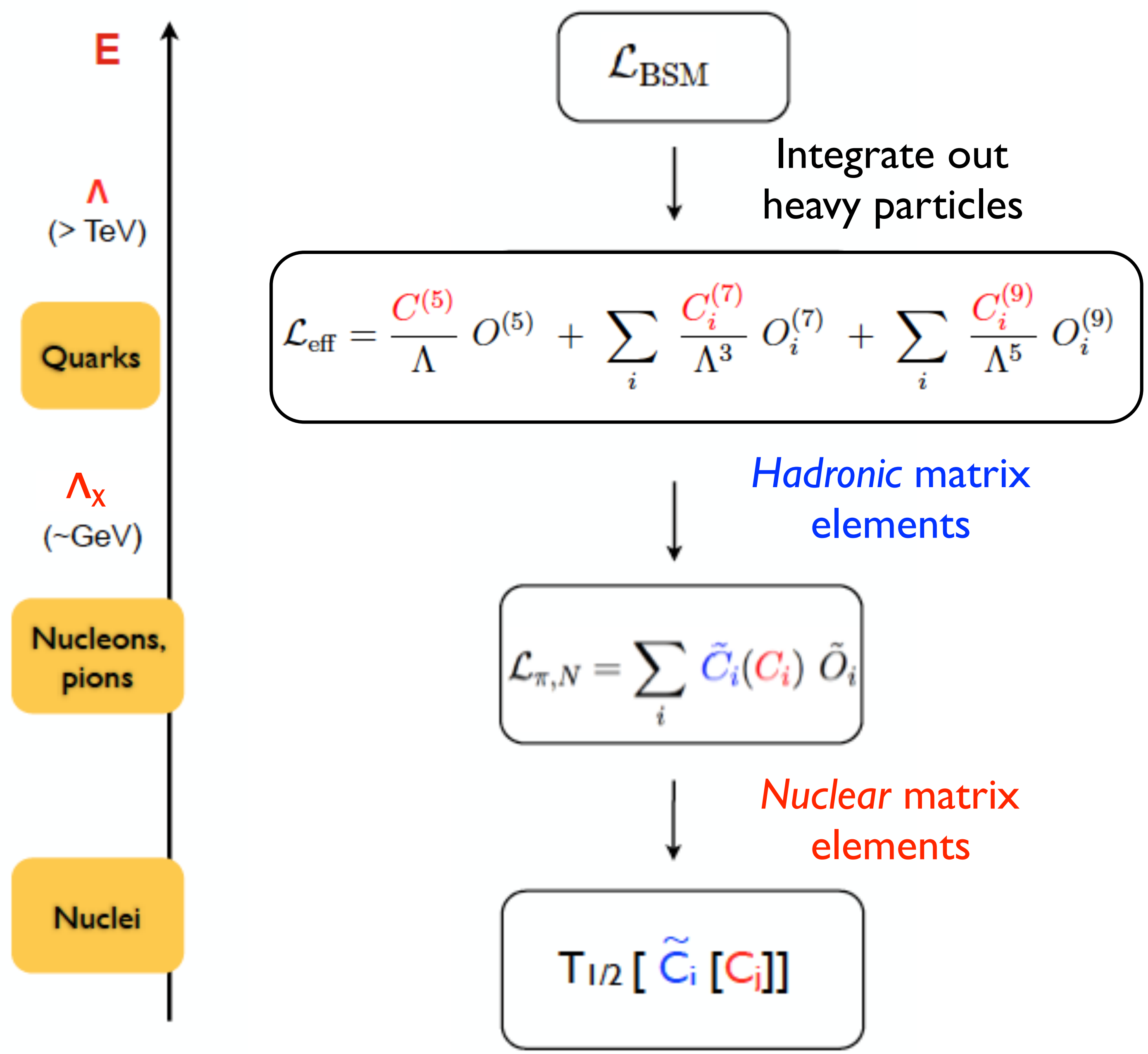
↓ *Hadronic* matrix elements

$$\mathcal{L}_{\pi,N} = \sum_i \tilde{C}_i(C_i)\, \tilde{O}_i$$

Chiral EFT:

Map ΔL=2 interactions onto π, N operators, organized according to power-counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$)

EFT framework for 0νββ



Chain of EFTs +

lattice QCD & many-body methods

$T_{1/2}[\,\tilde{C}_i\,[C_j]\,] \sim (m_W/\Lambda)^A\ (\Lambda_\chi/m_W)^B\ (k_F/\Lambda_\chi)^C$

$0\nu\beta\beta$ from light Majorana neutrino (dim-5 operator)

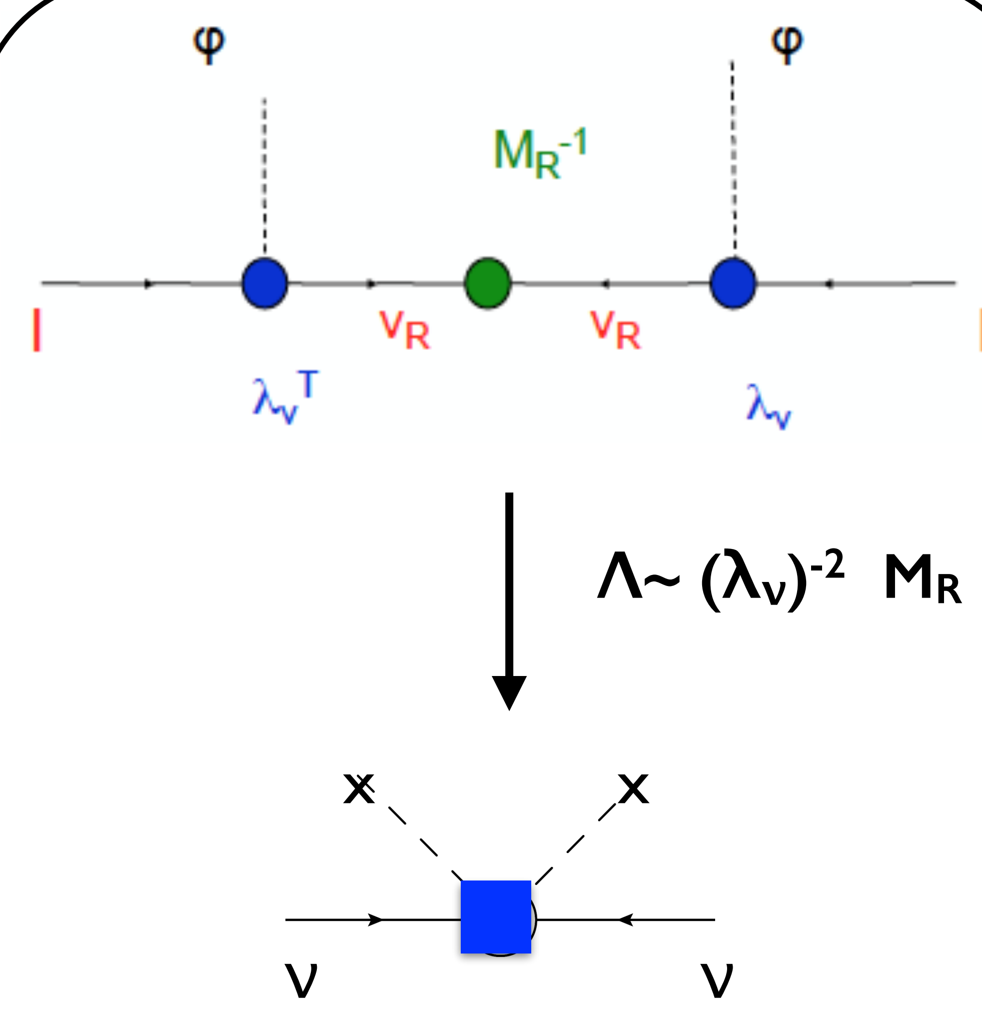
Underlying mechanism

- Assume that Lepton Number Violation originates at very high scale (e.g. GUT see-saw with heavy ν_R)

- Dominant low-energy footprint is the Weinberg operator (= Majorana mass for neutrinos written in $SU(2)_W$-invariant way)

- $0\nu\beta\beta$ mediated by light ν_M exchange

- Light ν_R states can be included (> 3 light Majorana eigenstates)



$$\mathcal{L}_5 = \frac{g_{\alpha\beta}}{\Lambda}\ \ell_\alpha^T C \epsilon \phi\ \phi^T \epsilon \ell_\beta$$

GeV-scale effective Lagrangian

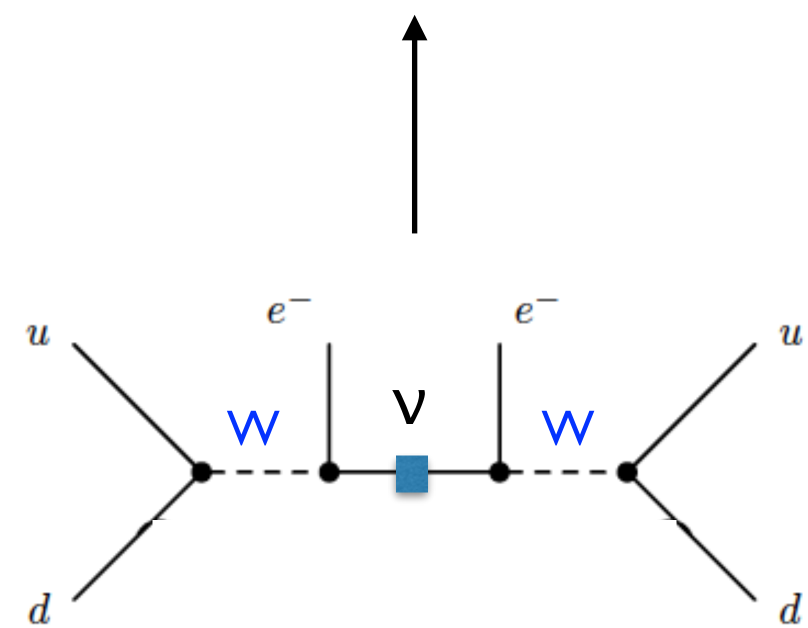
V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- QCD + Fermi theory + Majorana mass + local operator

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \left\{ 2\sqrt{2} G_F V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} + \frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL} - C_L\, O_L + \text{h.c.} \right\}$$

$$O_L = \bar{e}_L e_L^c\ \bar{u}_L \gamma_\mu d_L\ \bar{u}_L \gamma^\mu d_L \qquad C_L = (8 V_{ud}^2 G_F^2 m_{\beta\beta})/M_W^2 \times (1 + \mathcal{O}(\alpha_s/\pi))$$

- Effect of local operator highly suppressed at nuclear level ~ $O((k_F/M_W)^2)$



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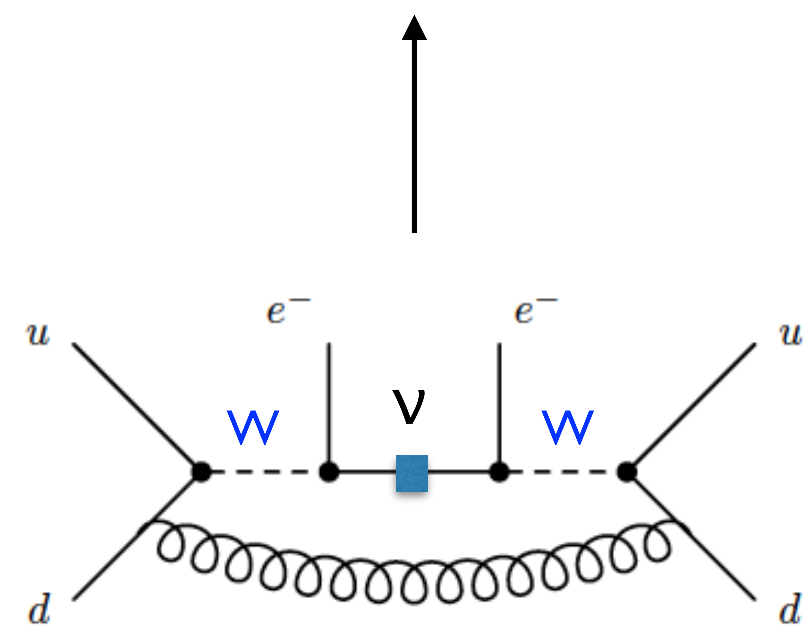


ΔL=2 amplitudes

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

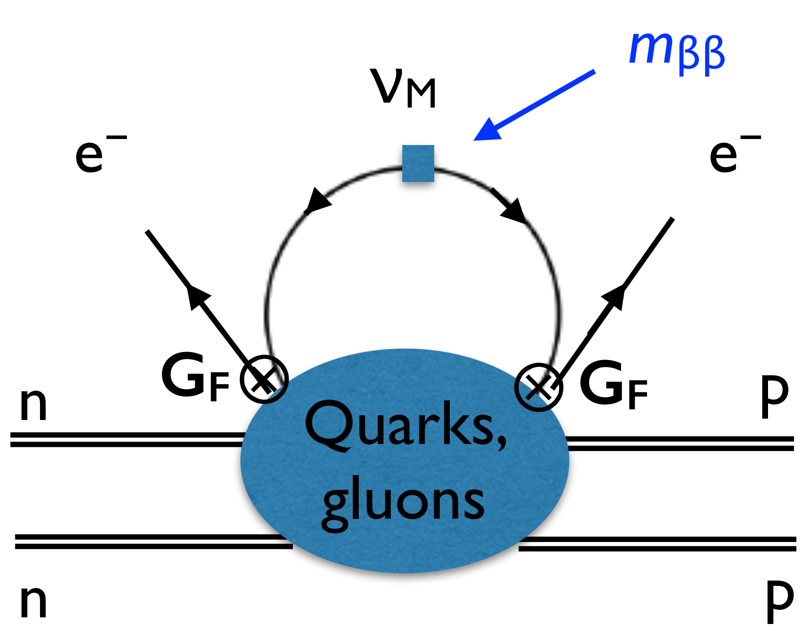
- Determined by neutrino-less non-local effective action

$$S_{\rm eff}^{\Delta L=2} = \frac{8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x d^4y \; S(x-y) \times \bar{e}_L(x)\gamma^\mu\gamma^\nu e_L^c(y) \times T\Big(\bar{u}_L\gamma_\mu d_L(x)\; \bar{u}_L\gamma_\nu d_L(y)\Big)$$

Scalar massless propagator

$|p_1 - p_2|/k_F \ll 1.$

$g^{\mu\nu}\; \bar{e}_L(x) e_L^c(x) + \dots$



ΔL=2 amplitudes

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

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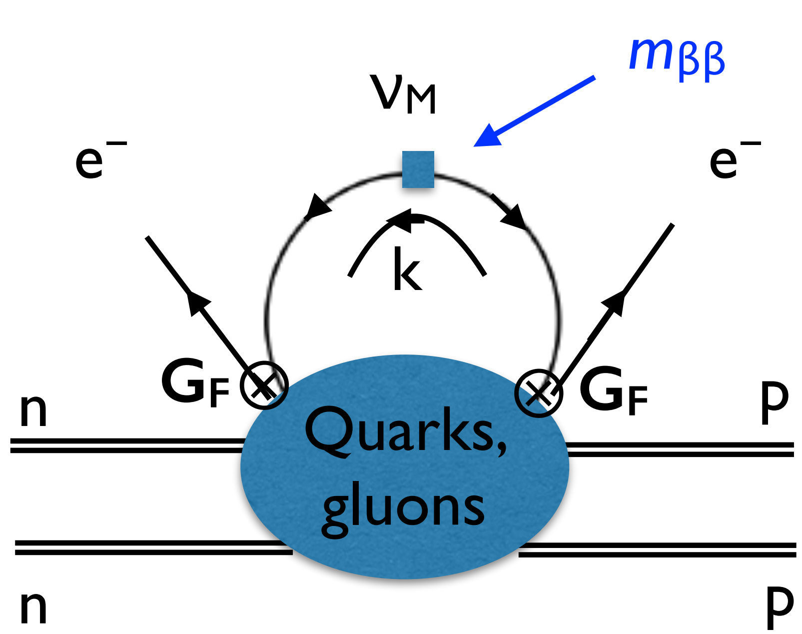
$$\langle e_1 e_2 h_f | S_{\text{eff}}^{\Delta L=2} | h_i \rangle = \frac{8 G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x \, \langle e_1 e_2 | \bar{e}_L(x) e_L^c(x) | 0 \rangle \int \frac{d^4k}{(2\pi)^4} \frac{g^{\mu\nu} \hat{\Pi}_{\mu\nu}^{++}(k,x)}{k^2 + i\epsilon},$$

$$\hat{\Pi}_{\mu\nu}^{++}(k,x) = \int d^4r \, e^{ik\cdot r} \, \langle h_f | T\Big(\bar{u}_L \gamma_\mu d_L(x + r/2) \; \bar{u}_L \gamma_\mu d_L(x - r/2) \Big) | h_i \rangle \, .$$

Momentum space representation

LNV hadronic amplitudes such as nn → ppee receive contributions from all neutrino virtual momenta (k)



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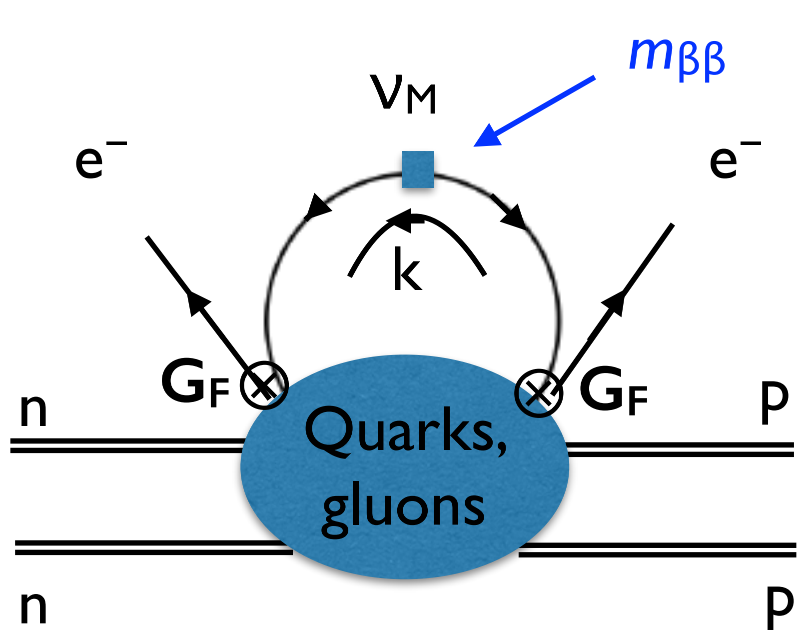
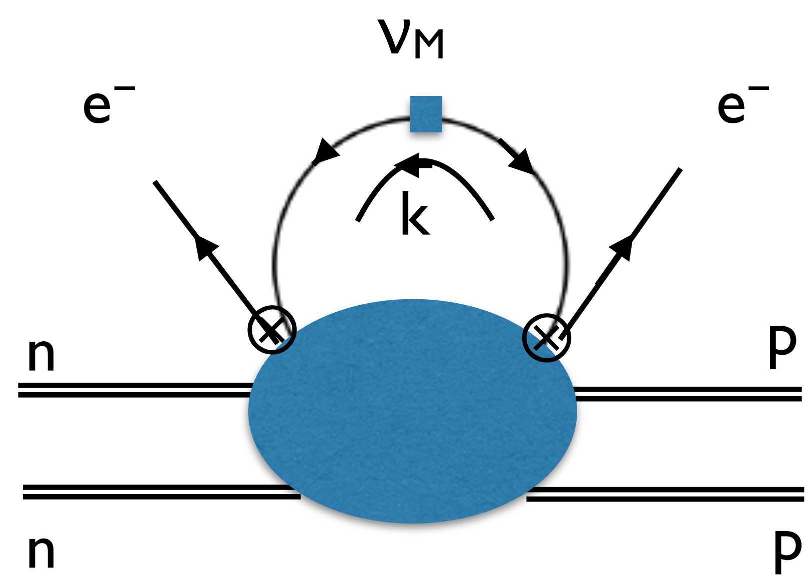
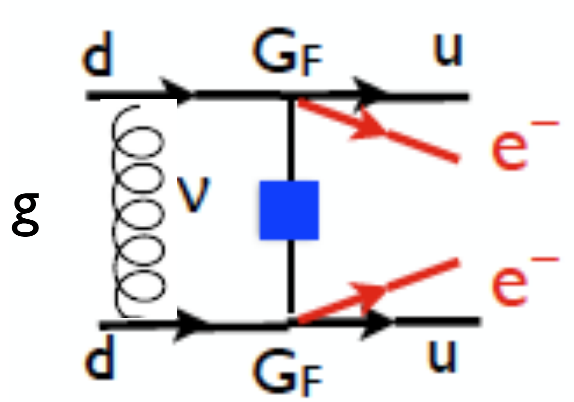


Chiral EFT captures contributions from all relevant momentum regions

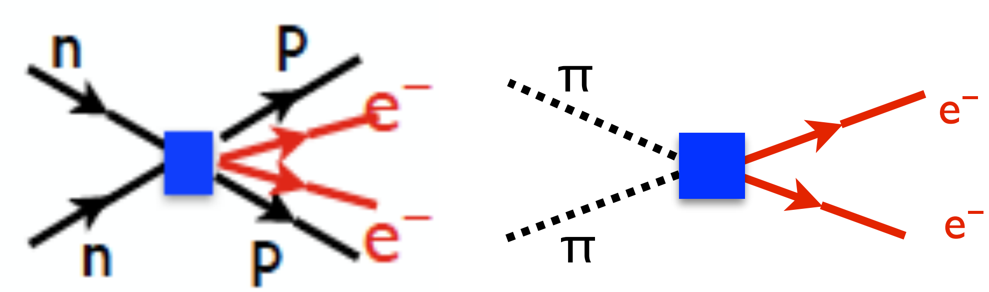
ΔL=2 amplitudes in EFT



"Hard neutrinos":
E, |**k**| > Λ_χ ~ m_N ~ GeV

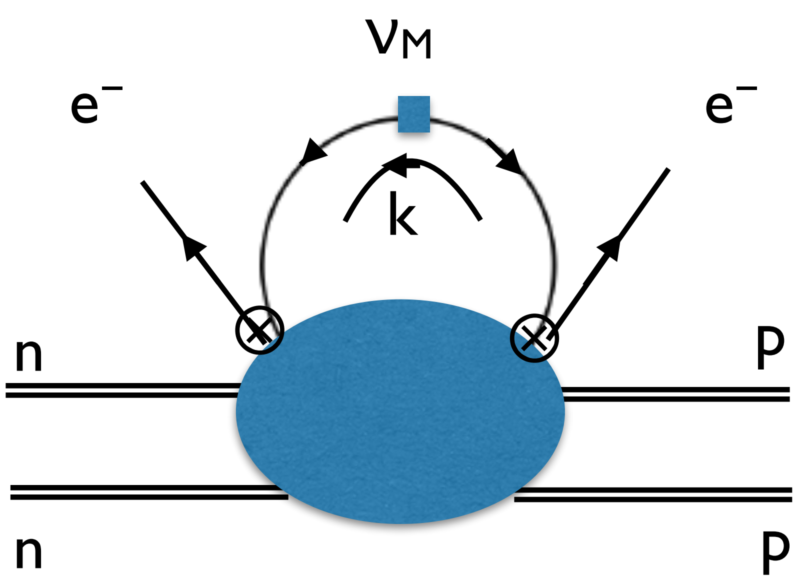


Short-range ΔL=2 operators at the hadronic level, *still proportional to $m_{\beta\beta}$*



Short- and pion-range contributions to "Neutrino potential" mediating nn→pp

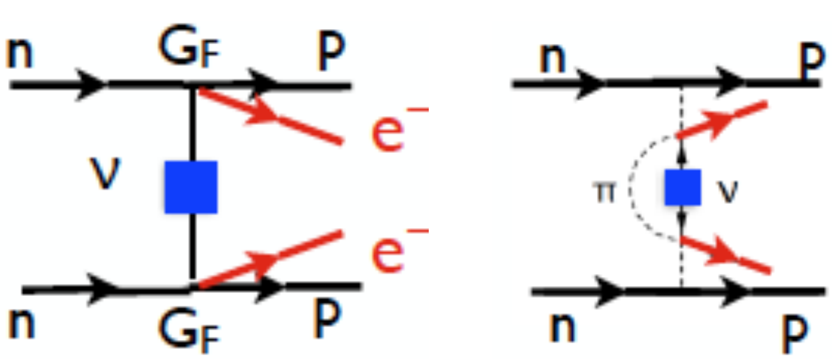
ΔL=2 amplitudes in EFT

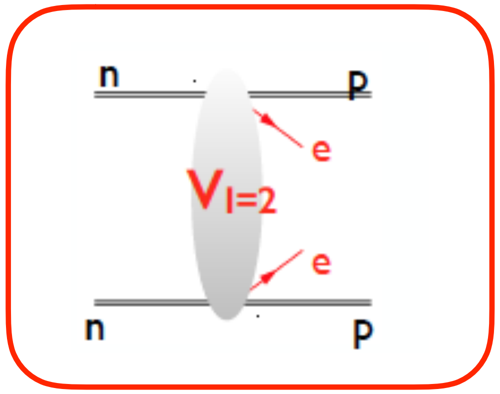


"Soft" & "Potential" neutrinos:

(E, |**k**|) ~ Q ~ k_F ~ m_π

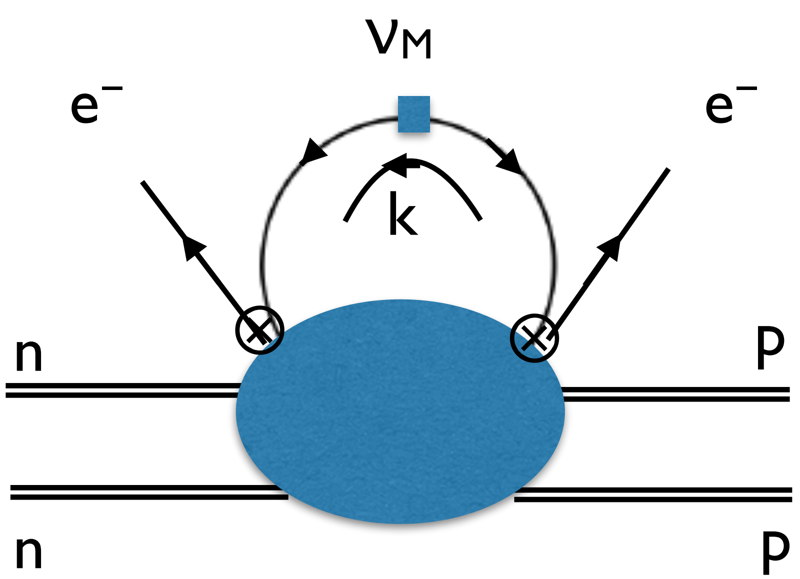
(E,|**k**|) ~ (Q^2/m_N, Q)



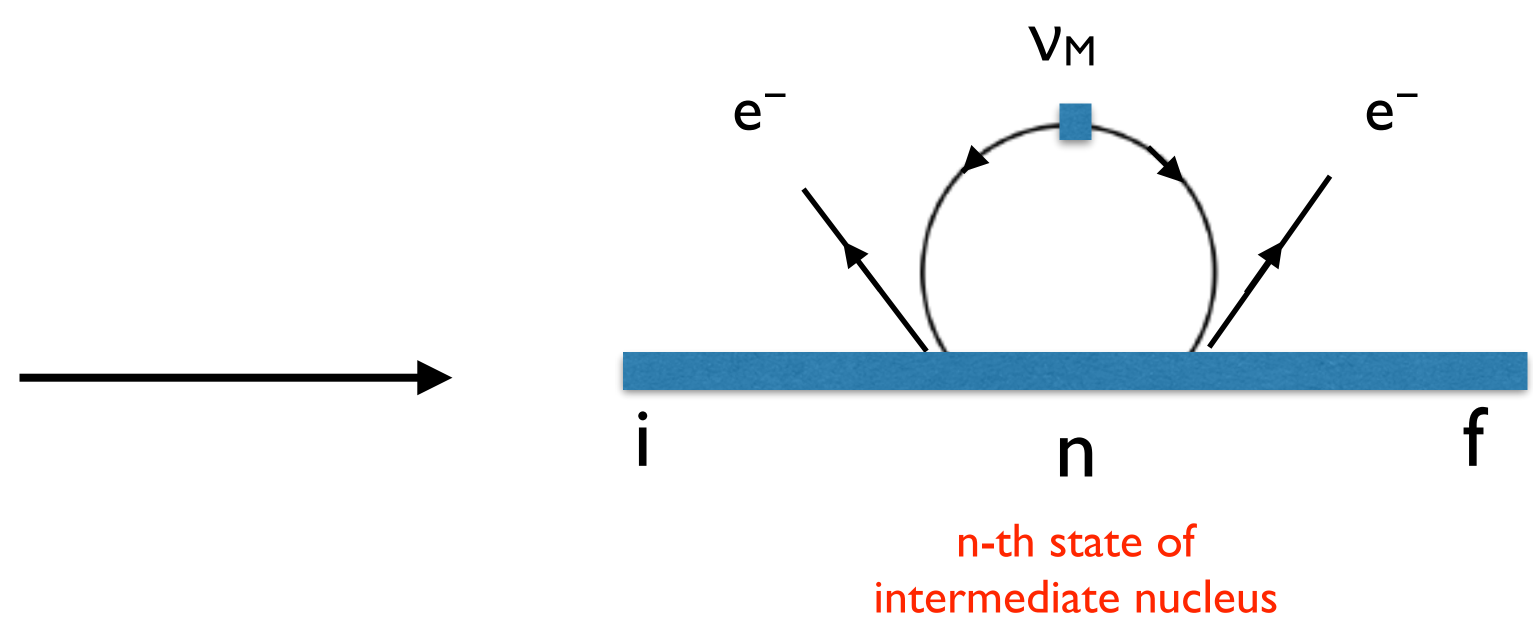


Calculable long- and pion-range contributions to "Neutrino potential" mediating nn→pp

ΔL=2 amplitudes in EFT

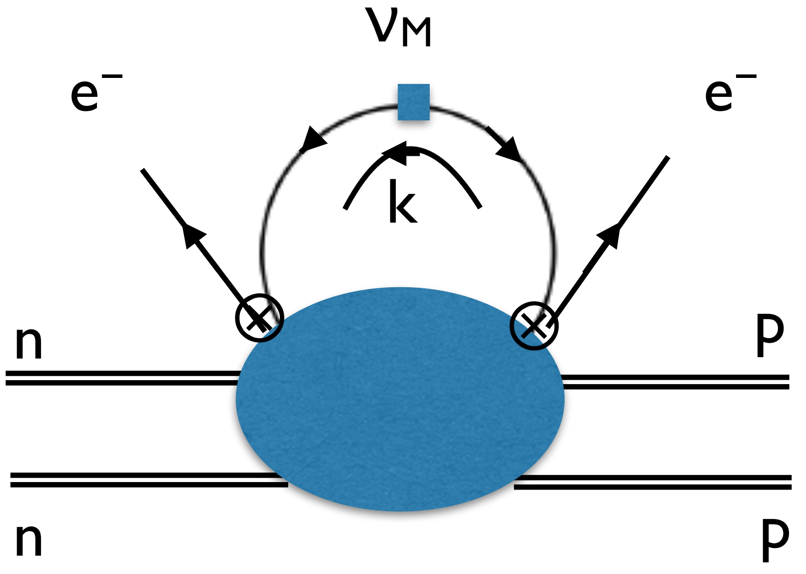


"UltraSoft" neutrinos:
$(E, |\mathbf{k}|) \ll k_F$



Double insertions of the weak current at the hadronic / nuclear level

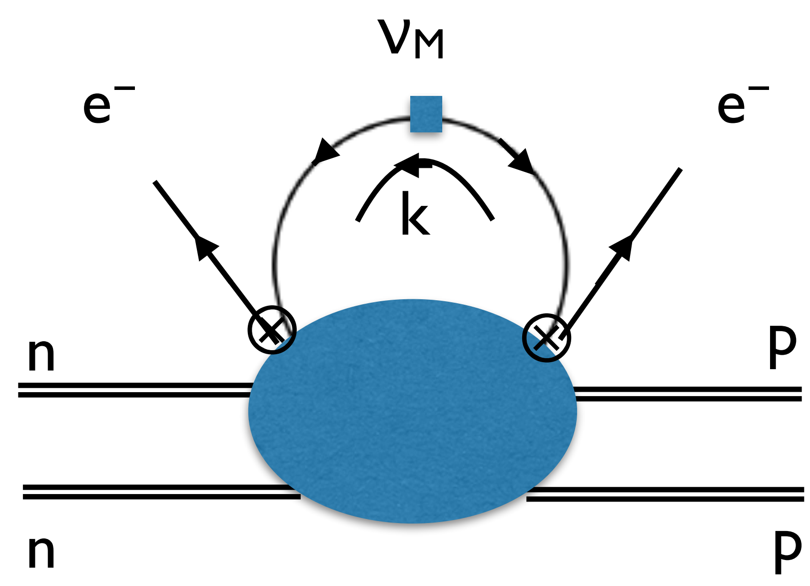
Nuclear scale effective Hamiltonian



Kinetic terms and strong NN potential

$$H_{\rm Nucl} = H_0 + \sqrt{2} G_F V_{ud}\, \bar{N} \left(g_V \delta^{\mu 0} - g_A \delta^{\mu i} \sigma^i \right) \tau^+ N\, \bar{e}_L \gamma_\mu \nu_L + 2 G_F^2 V_{ud}^2 m_{\beta\beta}\, \bar{e}_L e_L^c\, V_{I=2}$$

Nuclear scale effective Hamiltonian



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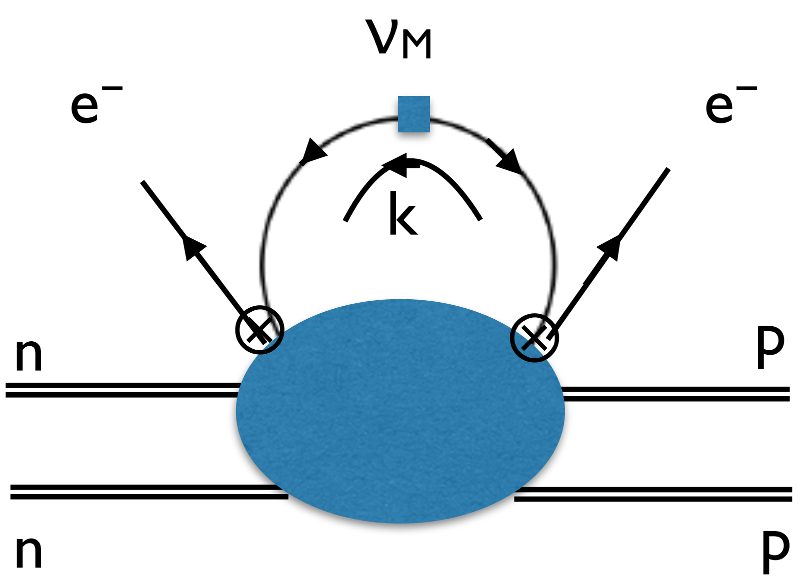
"Ultra-soft" (e, ν) with |**p**|, E << k_F
cannot be integrated out

Nuclear scale effective Hamiltonian



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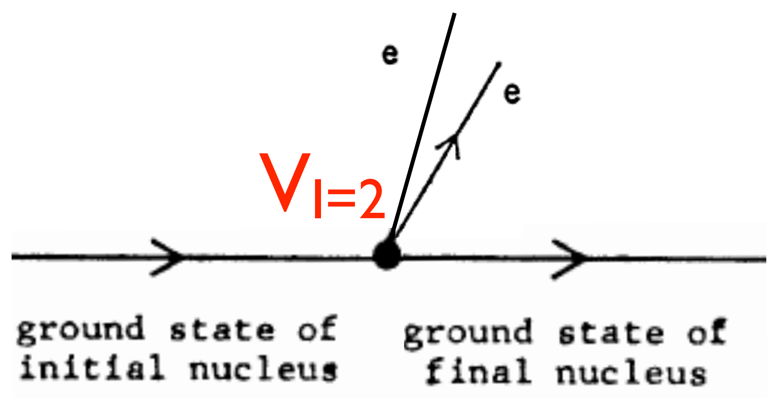
"Ultra-soft" (e, ν) with |**p**|, E << k_F cannot be integrated out

"Isotensor" 0νββ potential mediates nn→pp. It can be identified to a given order in Q/Λ_χ by computing 2-nucleon amplitudes

Anatomy of 0νββ amplitude

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a\neq b}\left(V^{(a,b)}_{\nu,0} + V^{(a,b)}_{\nu,2} + \dots\right)$$

$V_\nu \sim 1/Q^2\,,\ 1/(\Lambda_\chi)^2, \dots$

↑ LO ↑ N^2LO

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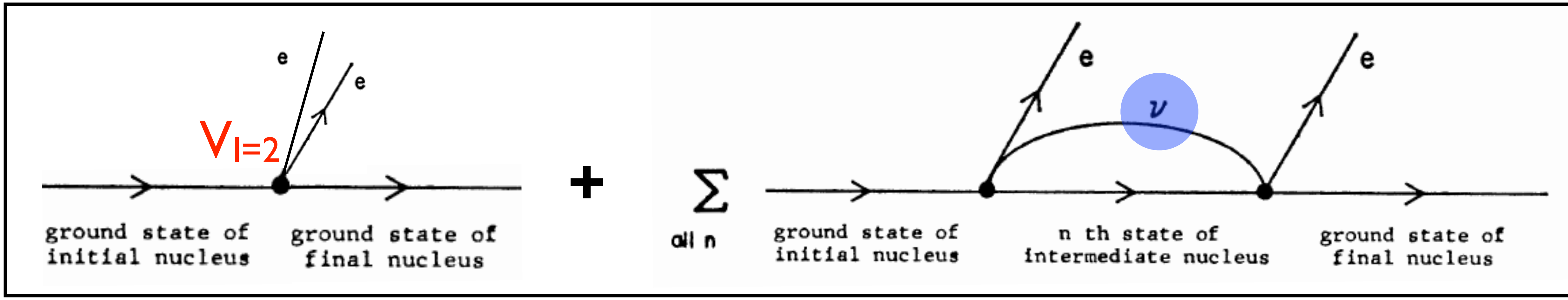
Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a \neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \dots \right)$$

$V_\nu \sim 1/Q^2$, $1/(\Lambda_\chi)^2$, …

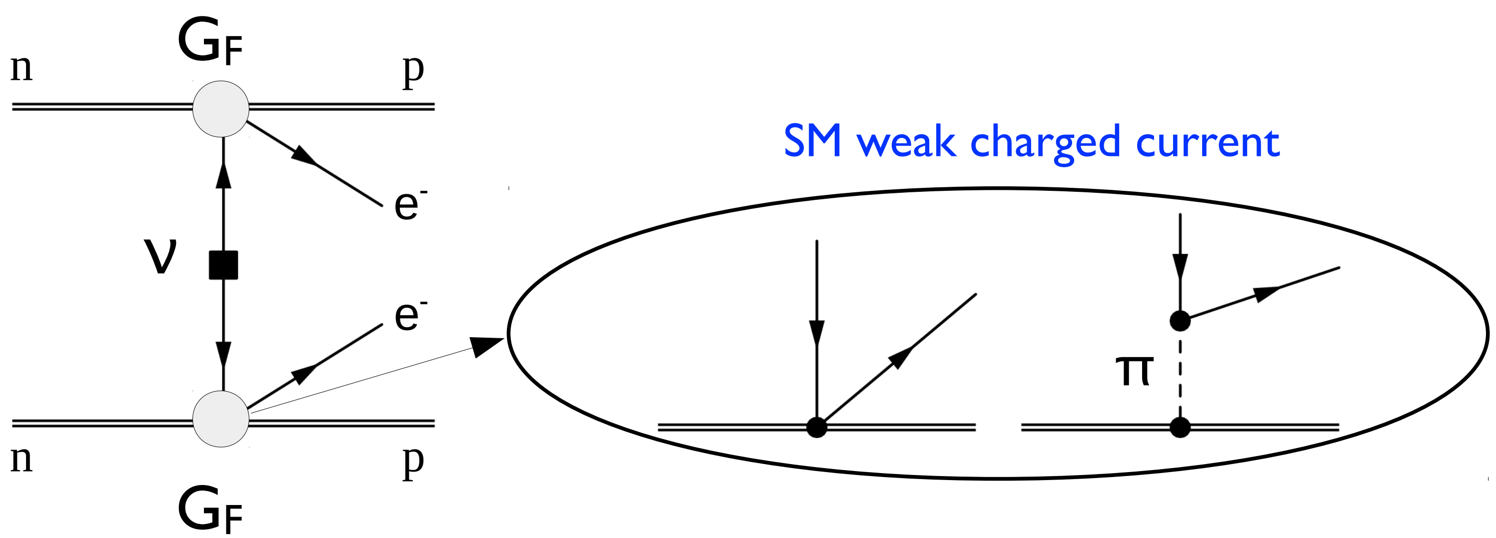
↑ LO ↑ N^2LO

Ultrasoft ν

Loop calculable in terms of $E_n - E_i$ and $\langle f\,|J_\mu|\,n\rangle\langle n\,|J^\mu|\,i\rangle$, that also control 2νββ.

Contributes to the amplitude at N^2LO

Leading order 0νββ potential

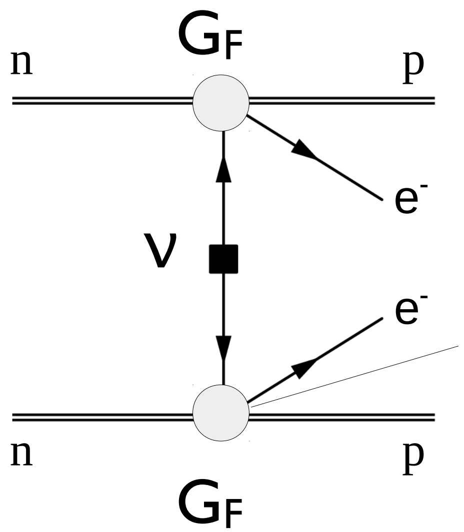


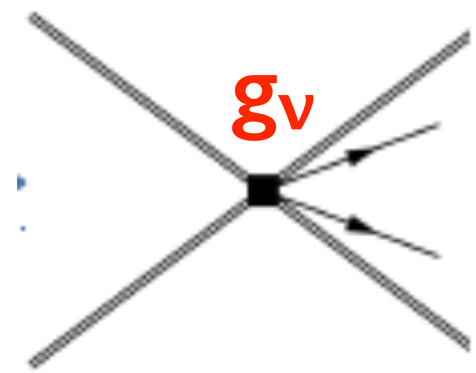
- Tree-level ν_M exchange

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\frac{1}{\mathbf{q}^2}\left\{1 - g_A^2\left[\boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(b)}\cdot\mathbf{q}\,\frac{2m_\pi^2+\mathbf{q}^2}{(\mathbf{q}^2+m_\pi^2)^2}\right]\right\}$$

Hadronic input: g_A

Leading order $0\nu\beta\beta$ potential





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Hadronic input: g_A

- Short-range coupling $g_\nu \sim 1/Q^2 \sim 1/k_F^2$ (only in $^1S_0$ channel) required by renormalization of $nn \to ppee$ amplitude

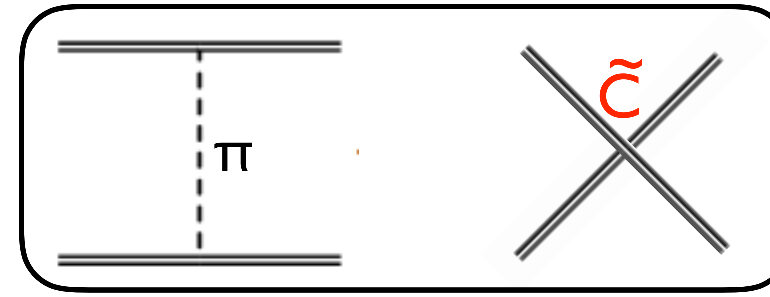
$$V_{\nu,CT}^{(a,b)} = -2\,g_\nu\,\tau^{(a)+}\tau^{(b)+}$$

$g_\nu \sim 1/\Lambda^2 \sim 1/(4\pi F_\pi)^2$ in NDA / Weinberg counting

Scaling of contact term

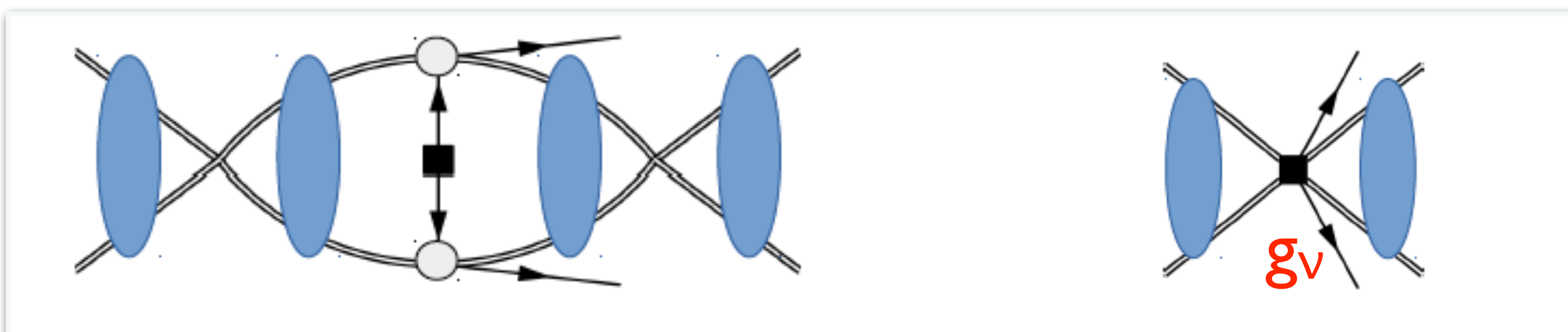
Weinberg 1991, Kaplan-Savage-Wise 1996

- Study nn→ppee amplitude (in $^1S_0$ channel) with LO strong potential



$\tilde{C} \sim 4\pi/(m_N Q) \sim 1/F_\pi^2$ from fit to a_{NN}

- Renormalization requires contact LNV operator at LO!



V. C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

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

- The coupling flows to $g_\nu \sim 1/Q^2 \;>>\; 1/(4\pi F_\pi)^2$, same order as $1/q^2$ from tree-level neutrino exchange

Use different regulator and scheme

- Same conclusion obtained by solving the Schroedinger equation
  - Use smeared delta function to regulate short range strong potential: $\tilde{C} \to \tilde{C}\,(R_S)$

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

  - Compute amplitude

$$\mathcal{A}_\nu = \int d^3\mathbf{r}\ \psi^-_{\mathbf{p}'}(\mathbf{r})\, V_{\nu,0}(\mathbf{r})\, \psi^+_{\mathbf{p}}(\mathbf{r})$$

Scattering states "fully correlated" according to the leading order strong potential in the $^1S_0$ channel

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  - Compute amplitude

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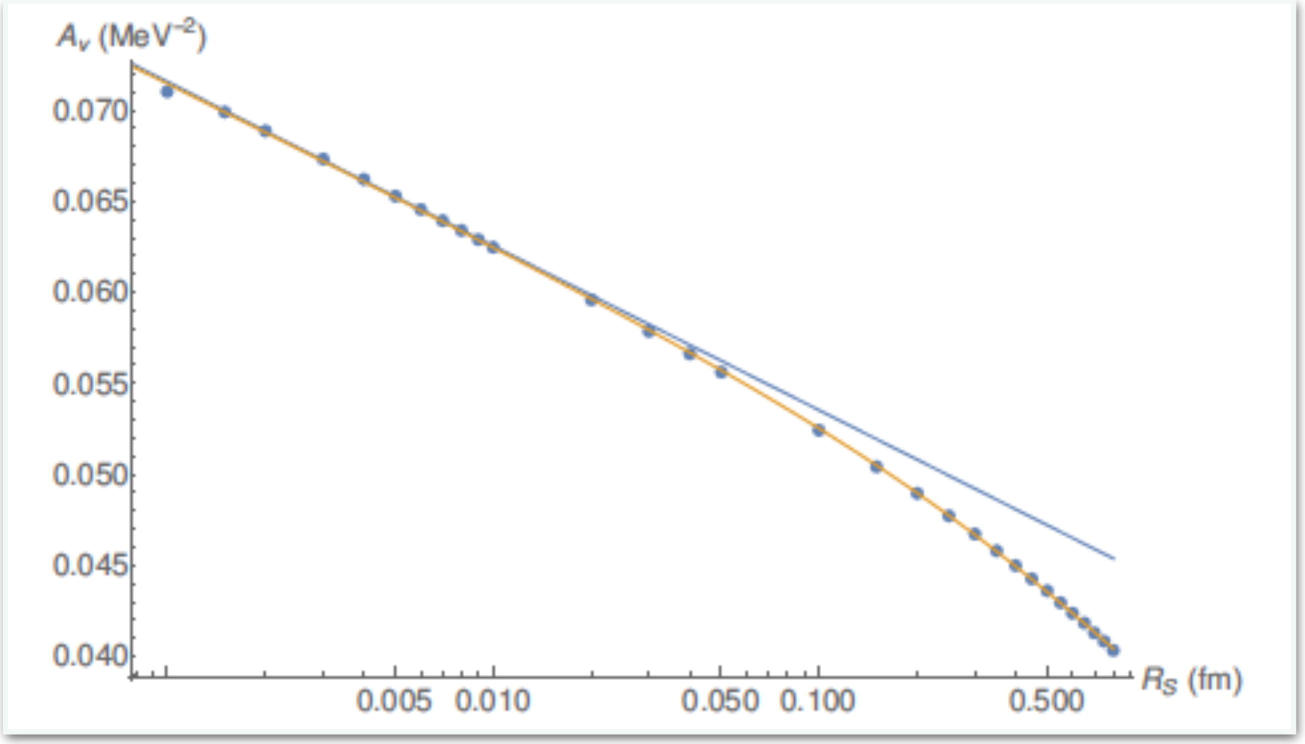
- Logarithmic dependence of A_ν on R_S $\Rightarrow$

  need LO counterterm to obtain physical, regulator-independent result



LO contact in higher waves?

- In $^3P_0$, renormalization of pion potential requires a LO contact term

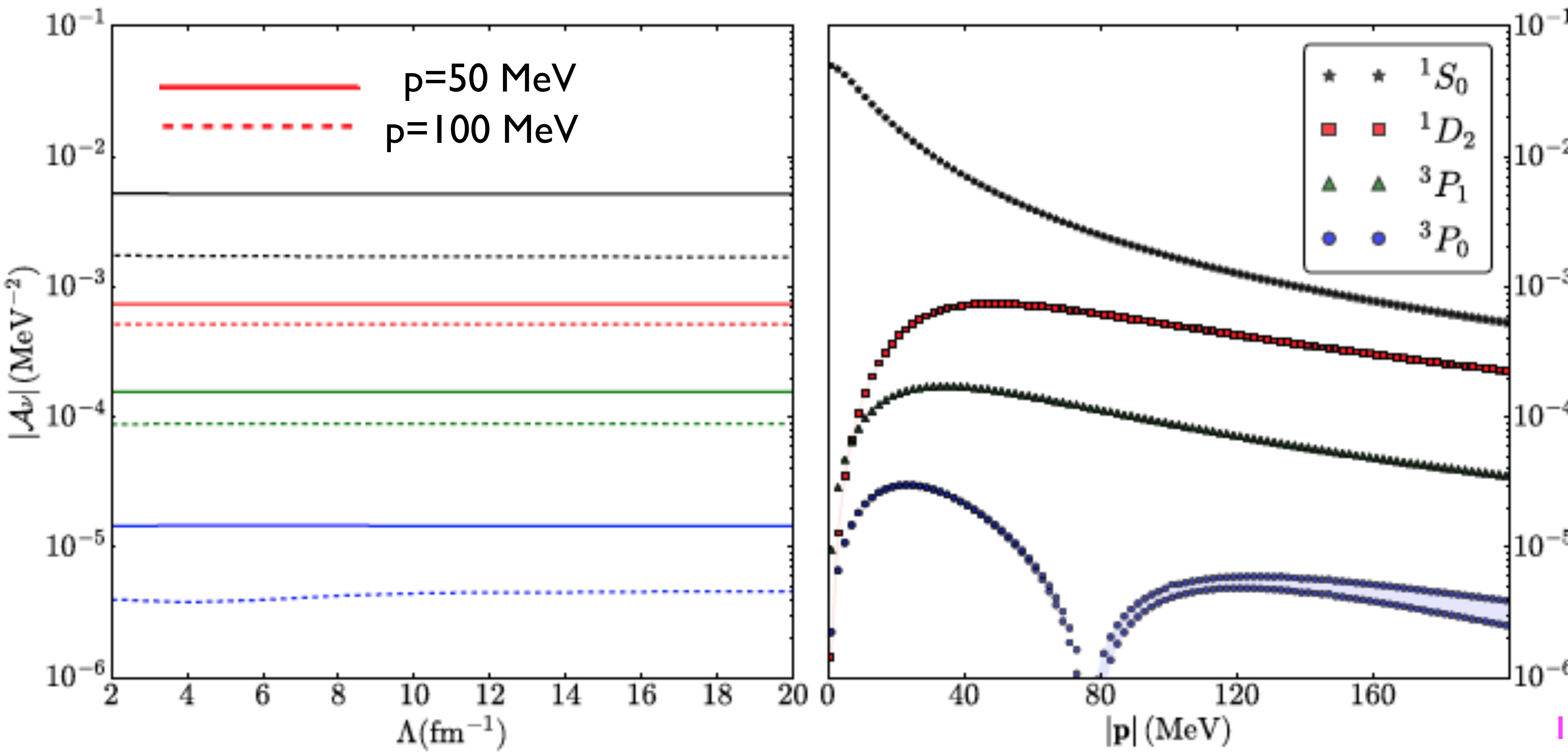
Nogga et al, nucl-th/0506005

$$C_{^3P_0}\left(N^T\vec{P}_{^3P_0}N\right)^\dagger\cdot\left(N^T\vec{P}_{^3P_0}N\right)$$

$$\vec{P}_{^3P_0}=-\frac{i}{\sqrt{8}}\sigma_2\boldsymbol{\sigma}\cdot\overleftrightarrow{\nabla}\tau_2\vec{\tau}$$

$$C_{^3P_0}=\mathcal{O}(4\pi/(m_N Q^3))$$

- Once strong NN force is renormalized, no cutoff dependence in neutrino-mediated nn→pp



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NLO contact in $^1S_0$ channel?

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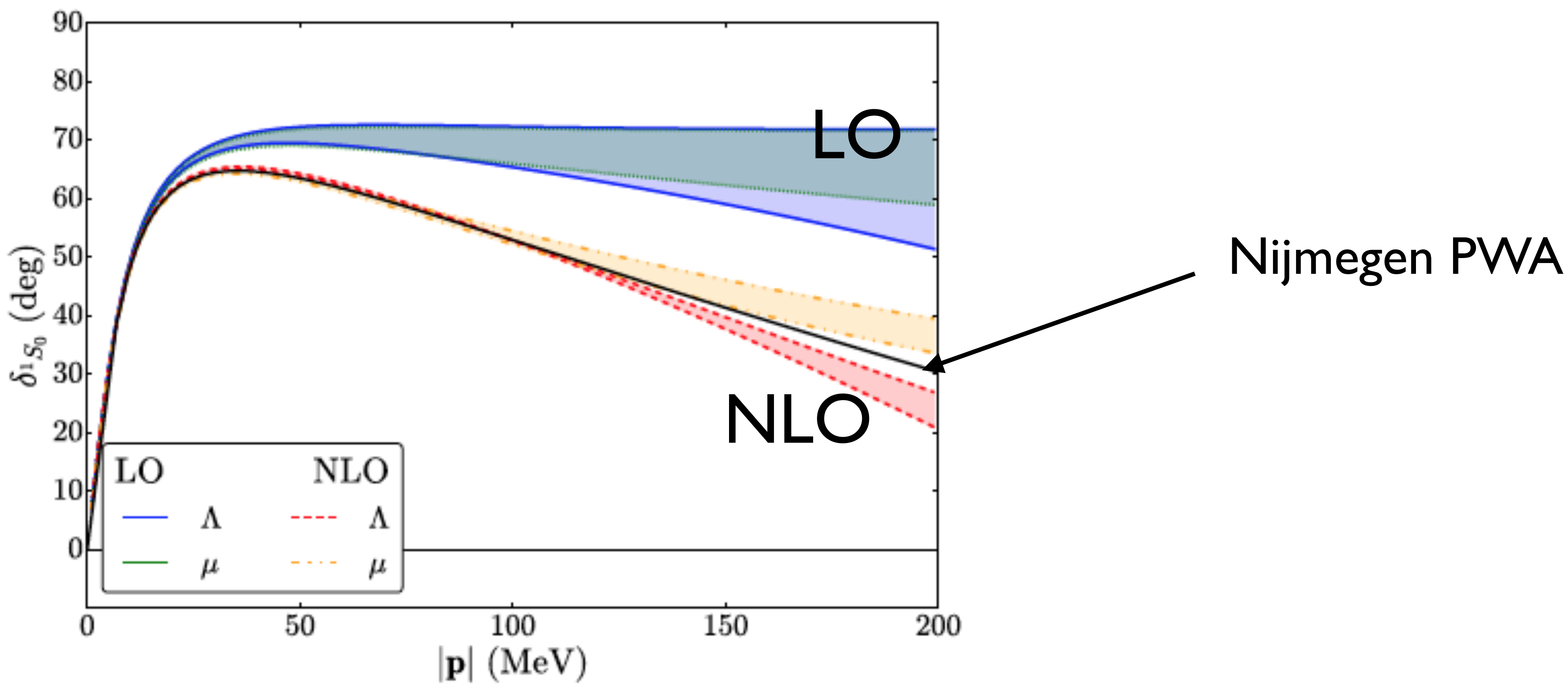
- Introduce $V_{Strong,1} \sim C_2\ N D^2 N\ NN$ with $C_2 \sim 4\pi/(MQ^2\Lambda)$

Long-Yang 1202.4053

Improved description of phase shifts



NLO contact in $^1S_0$ channel?

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254

- Introduce $V_{\text{Strong},1} \sim C_2\ N D^2 N\ NN$ with $C_2 \sim 4\pi/(MQ^2\Lambda)$

Long-Yang 1202.4053

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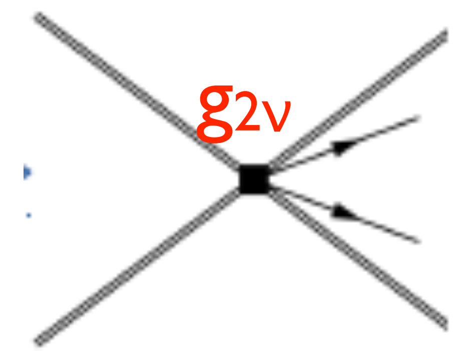
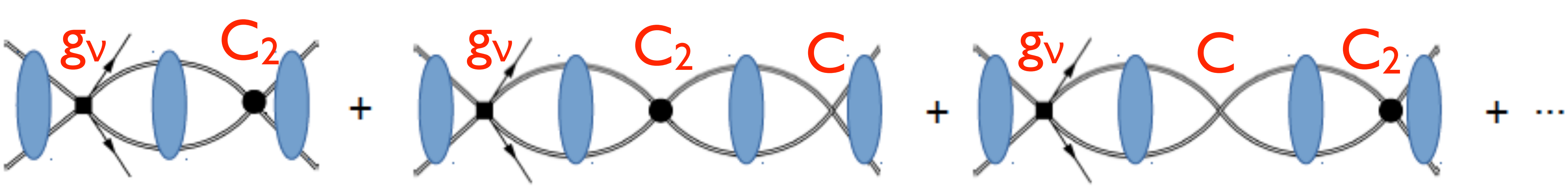


- RGE imply that $g_{2\nu}$ has an "NLO" term $\sim 1/(\Lambda Q^3)$ determined by LO couplings and effective range parameter + unknown N2LO piece



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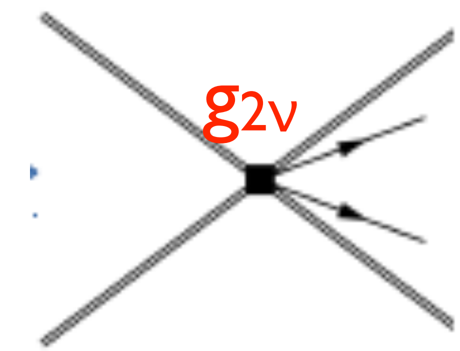

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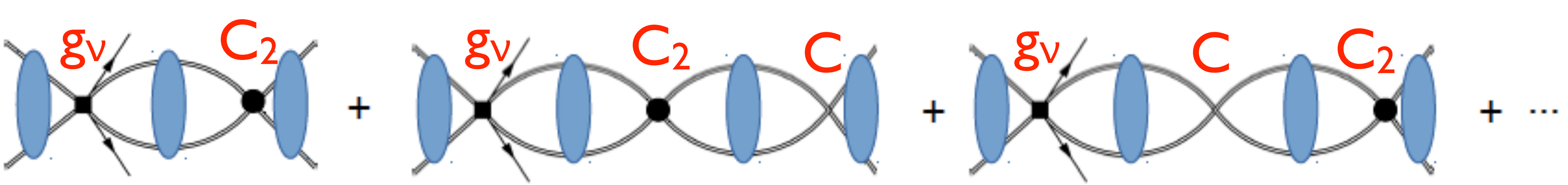
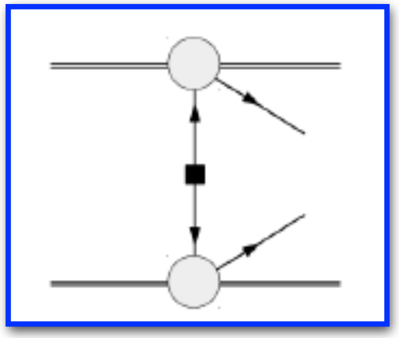


No new parameter needed at NLO

N^2LO $0\nu\beta\beta$ potential

- Known factorizable corrections
  to 1-body currents (radii, …)



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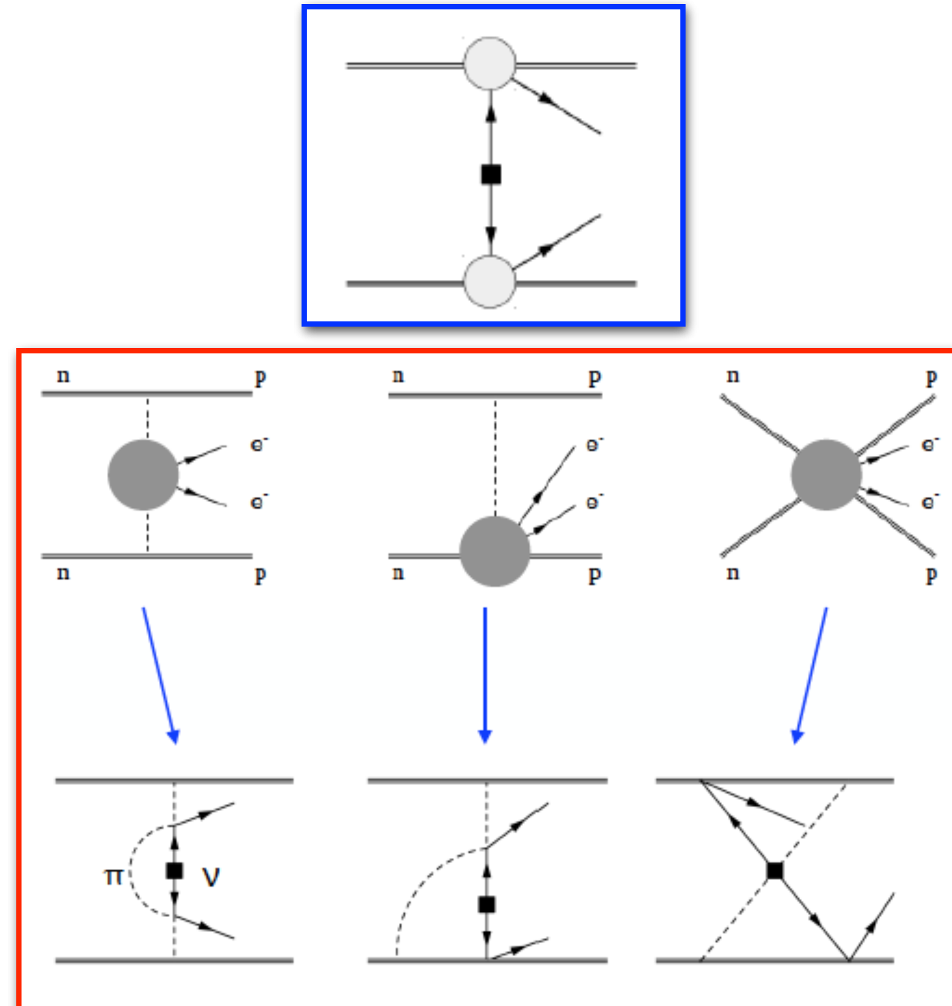

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

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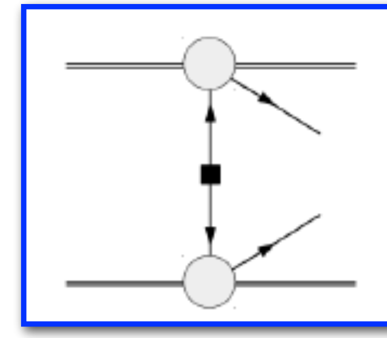

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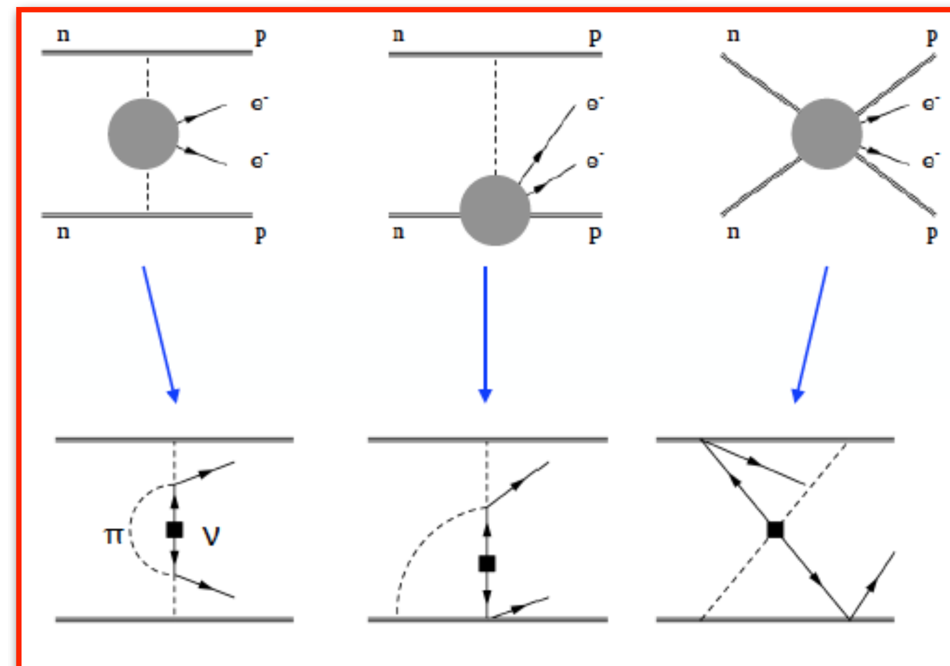

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- 2-body x 1-body current
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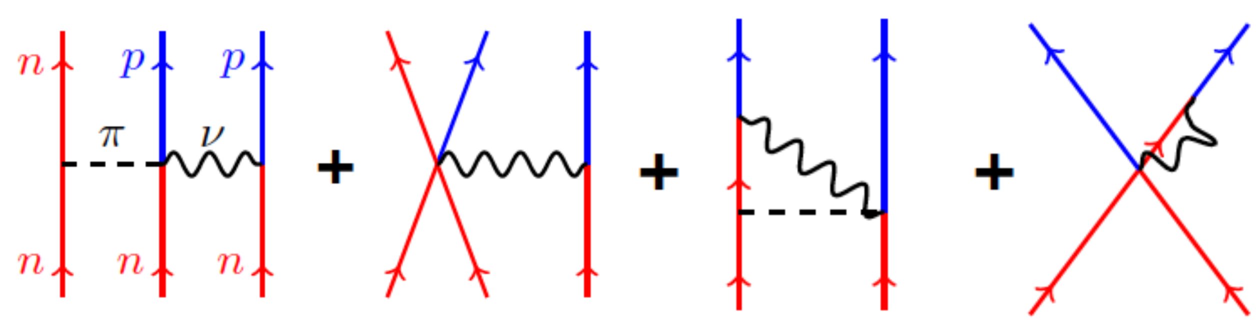

Wang-Engel-Yao 1805.10276

N^2LO $0\nu\beta\beta$ potential

Calculations of these effects in light and heavy nuclei show O(10%) corrections

S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026 V.C., J. Engel, E. Mereghetti, in preparation

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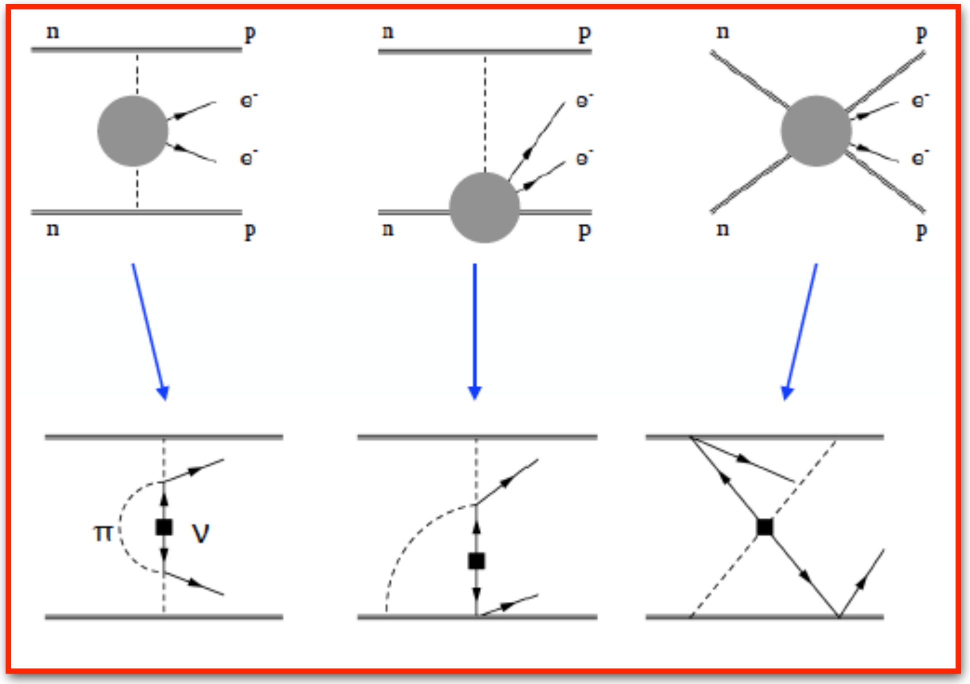

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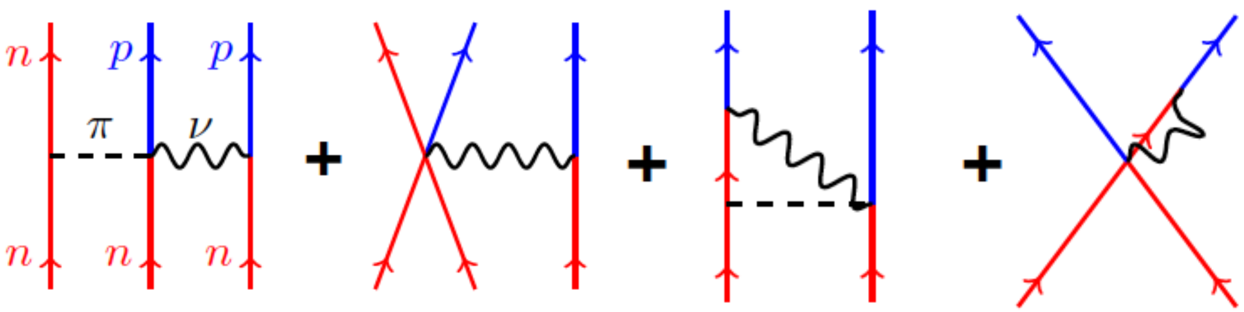

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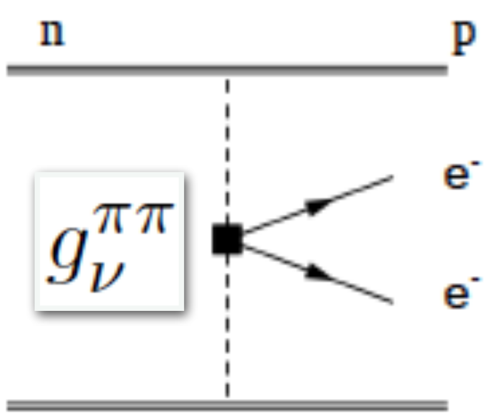
Estimating the LECs



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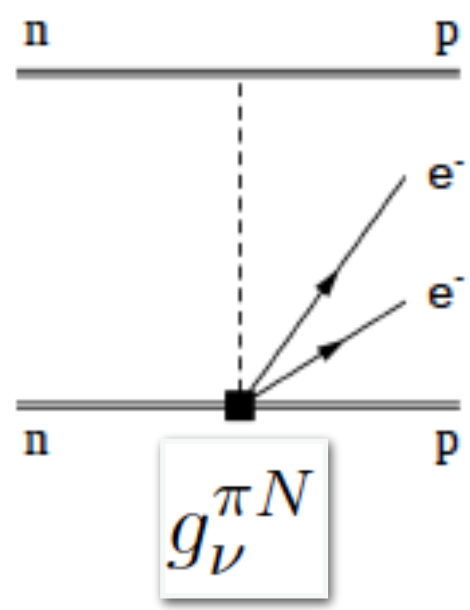

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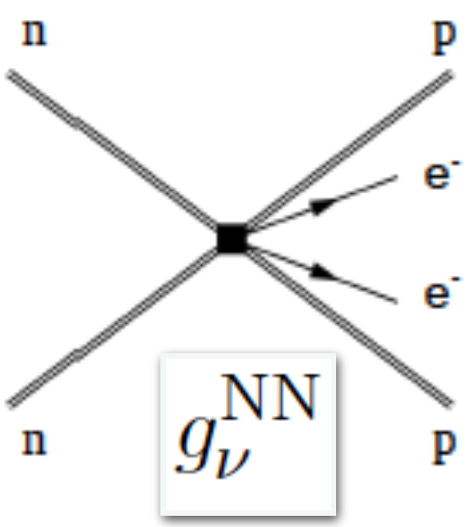


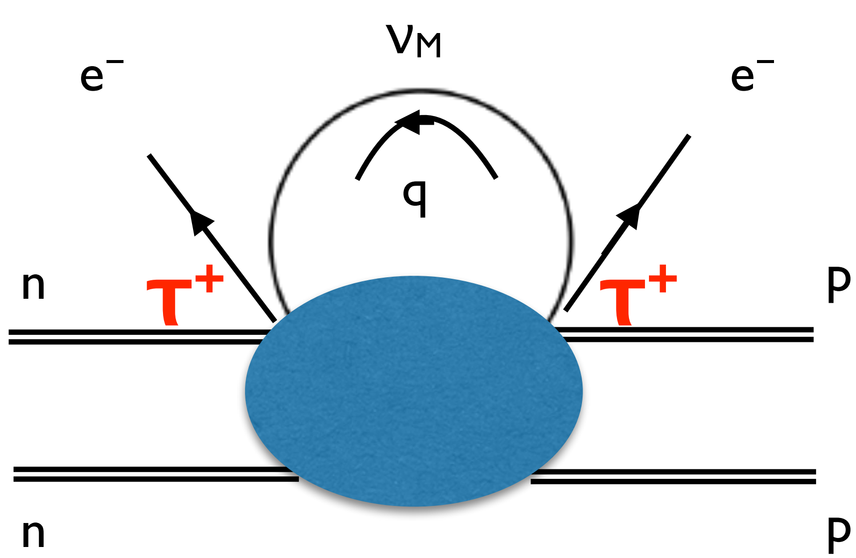
LO

Estimating the LECs

1. Compute $\pi^- \to \pi^+$, $nn \to pp$, … in lattice QCD and match to EFT

$$S_{\rm eff}^{\Delta L=2} = i4G_F^2 V_{ud}^2 m_{\beta\beta} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, g^{\mu\nu}\, T\Big(\bar{u}_L\gamma_\mu d_L(x)\, \bar{u}_L\gamma_\nu d_L(y)\Big)$$

Remnant of ν propagator



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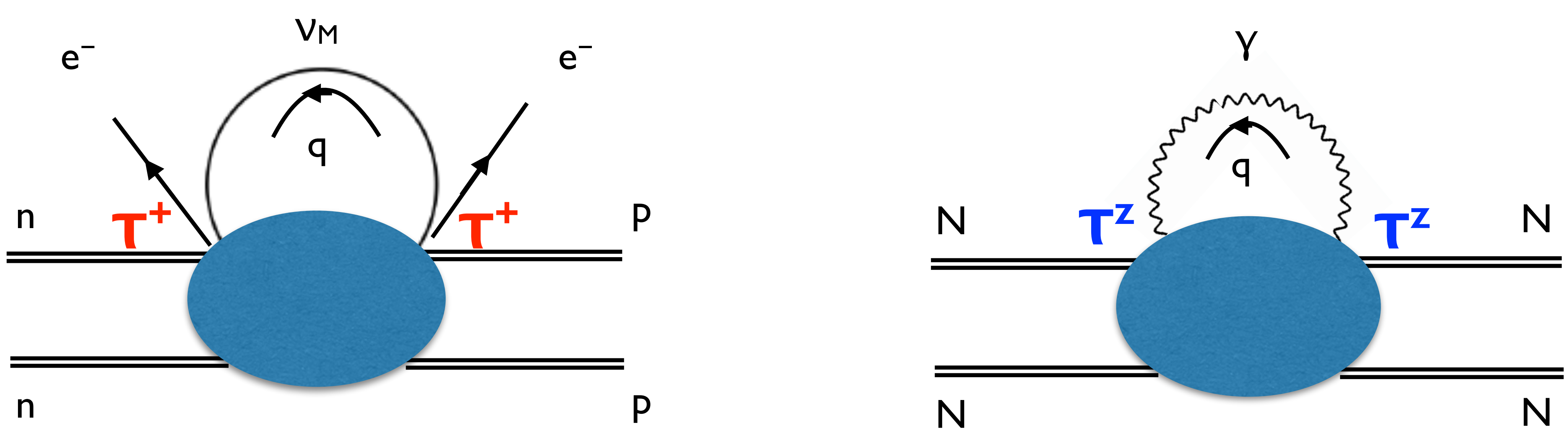
Remnant of ν propagator
~ γ propagator in Feynman gauge

$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2. Chiral symmetry relates $(g_\nu)^{AB}$ to one of two I=2 EM LECs (hard γ's vs ν's)



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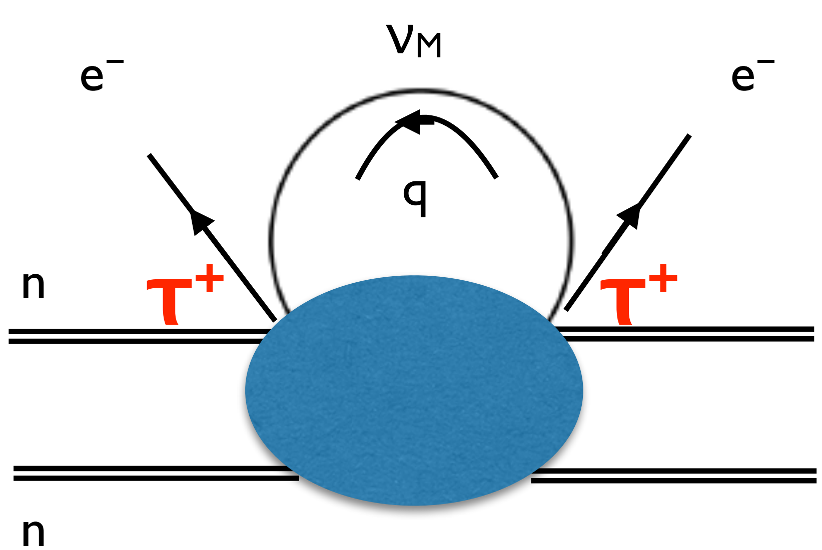
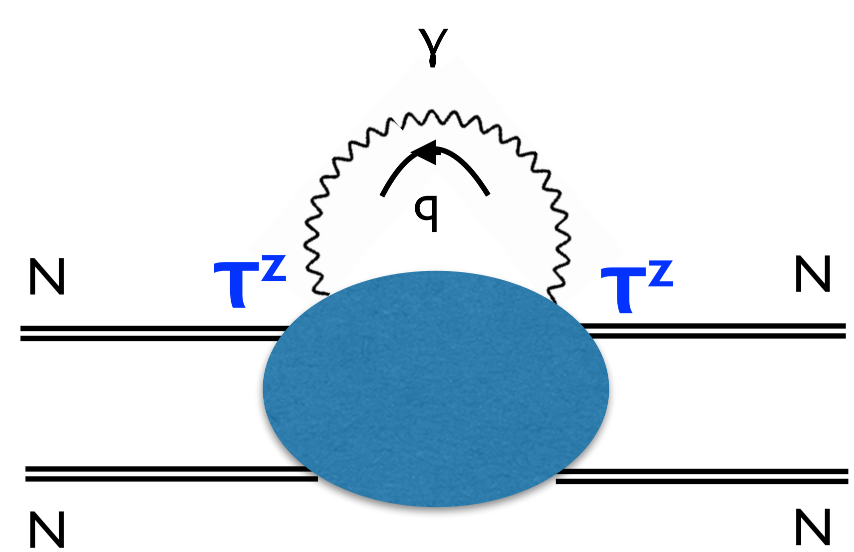




g_ν | $g_\nu = C_1$ | C_1 $(J_L J_L)$ | C_2 $(J_L J_R)$

ππ contact

- Estimates of I=2 pion coupling in large-N_C inspired resonance approach ⇒

Ananthanarayan & Moussallam hep-ph/0405206

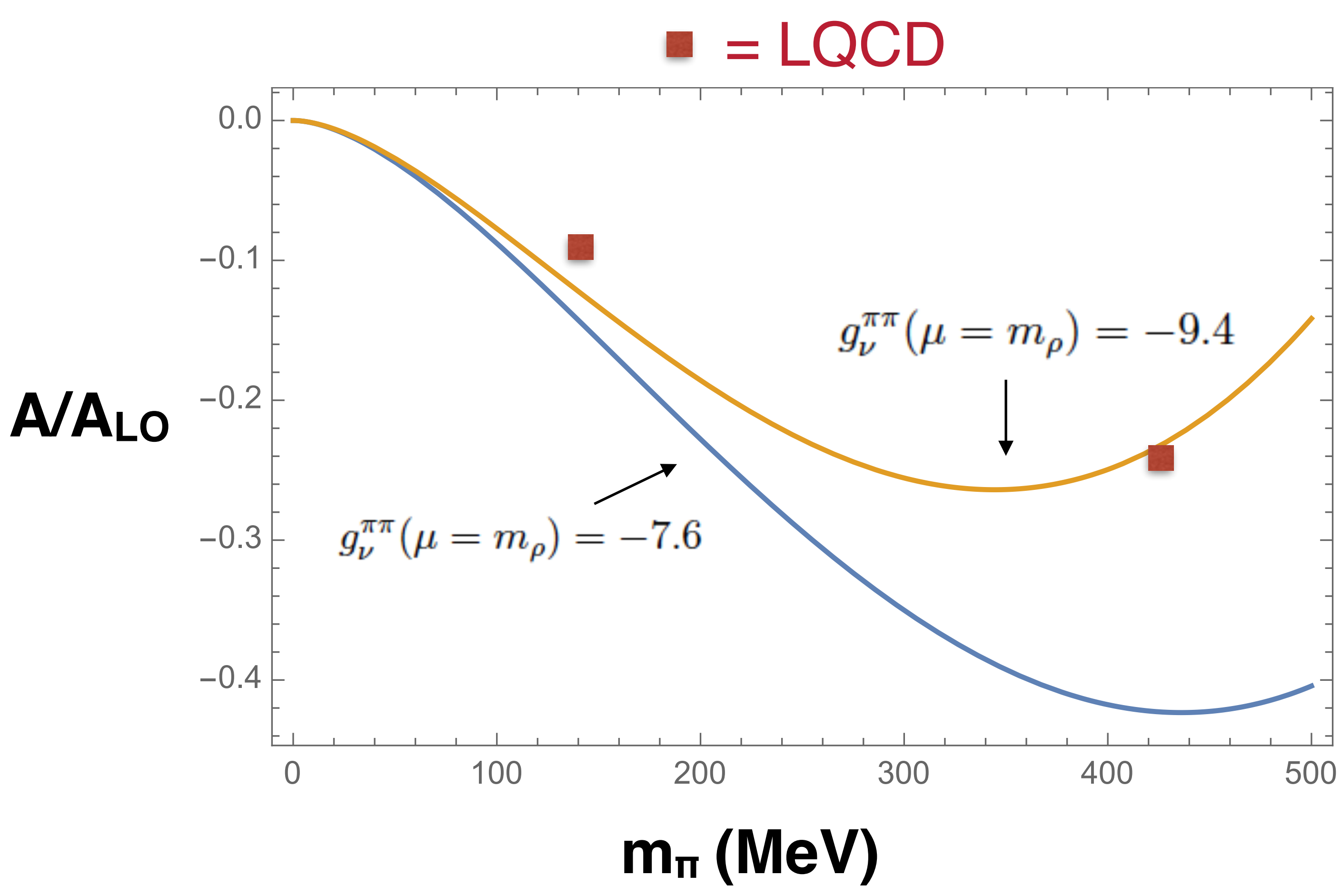
$$g_\nu^{\pi\pi}(\mu = m_\rho) = -7.6$$

~30% uncertainty

- Good agreement with matching 1-loop ChPT $\pi^-\pi^- \to e^-e^-$ to LQCD calculation*

* Xu Feng et al., 1809.10511

For related work see Detmold-Murphy 1811.0554



NN contact

- Two I=2 operators involving four nucleons

(See also Walzl-Meiβner-Epelbaum nucl-th/0010109)

EM case

$Q_L = \frac{\tau^z}{2}, Q_R = \frac{\tau^z}{2}$

$$\frac{e^2 C_1}{4}\left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

$$\frac{e^2 C_2}{4}\left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L \mathcal{Q}_R]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

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

ΔL=2 case

$Q_L = \tau^+, Q_R = 0$

$$8G_F^2 V_{ud}^2 m_{\beta\beta}\bar{e}_L e_L^c \, \frac{g_\nu}{4}\left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

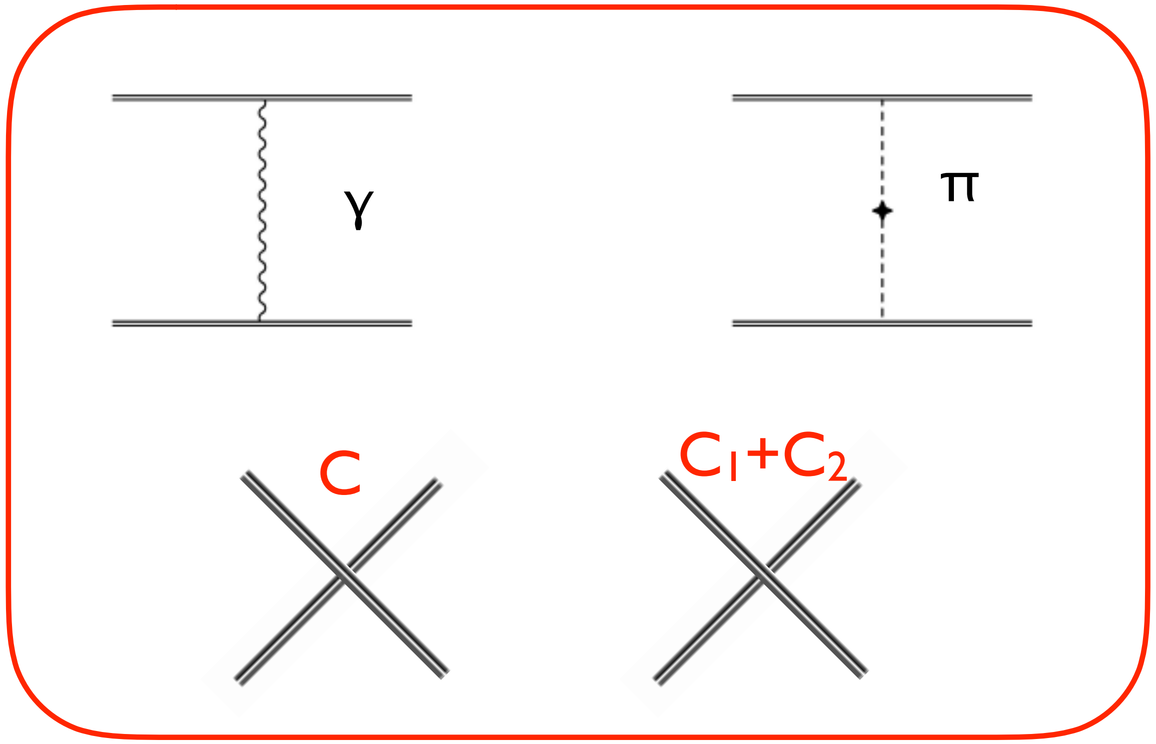
- Chiral symmetry ⇒ $g_\nu = C_1$

- NN observables *cannot* disentangle C_1 from C_2 (need pions), but provide data-based estimate of C_1+C_2

Connection with data

$$a_{np} = -23.7 \pm 0.02 \text{ fm}, \qquad a_{nn} = -18.90 \pm 0.40 \text{ fm}, \qquad a_C = -7.804 \pm 0.005 \text{ fm}.$$

- $C_1 + C_2$ controls CIB combination of $^1S_0$ scattering lengths $a_{nn} + a_C - 2\, a_{np}$



1907.11254

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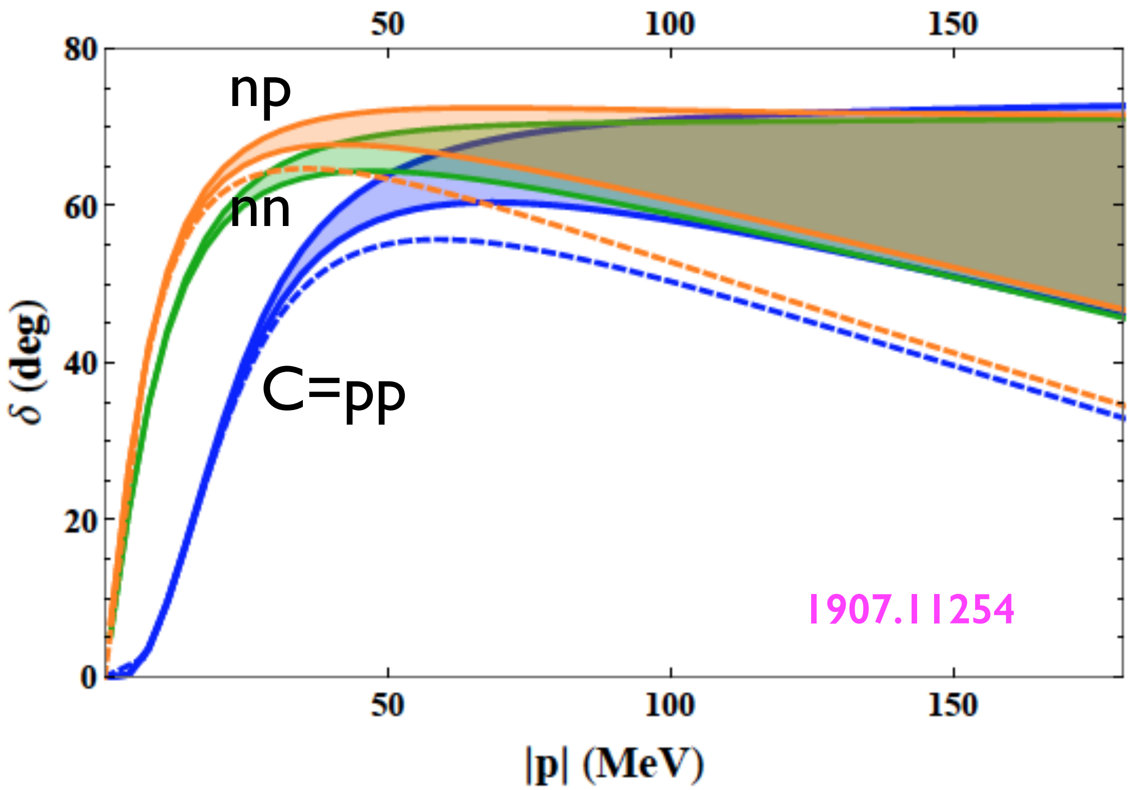

$$\frac{\mathcal{C}_1 + \mathcal{C}_2}{2} \equiv \left(\frac{m_N C}{4\pi}\right)^2 \left(2.5 - 1.8\,\ln(m_\pi/\mu)\right)$$

$$C = -\frac{1}{\tilde{\Lambda}^2}$$

$$\tilde{\Lambda}(\mu = m_\pi) = O(100 \text{ MeV})$$

MS-bar scheme analysis [1907.11254]

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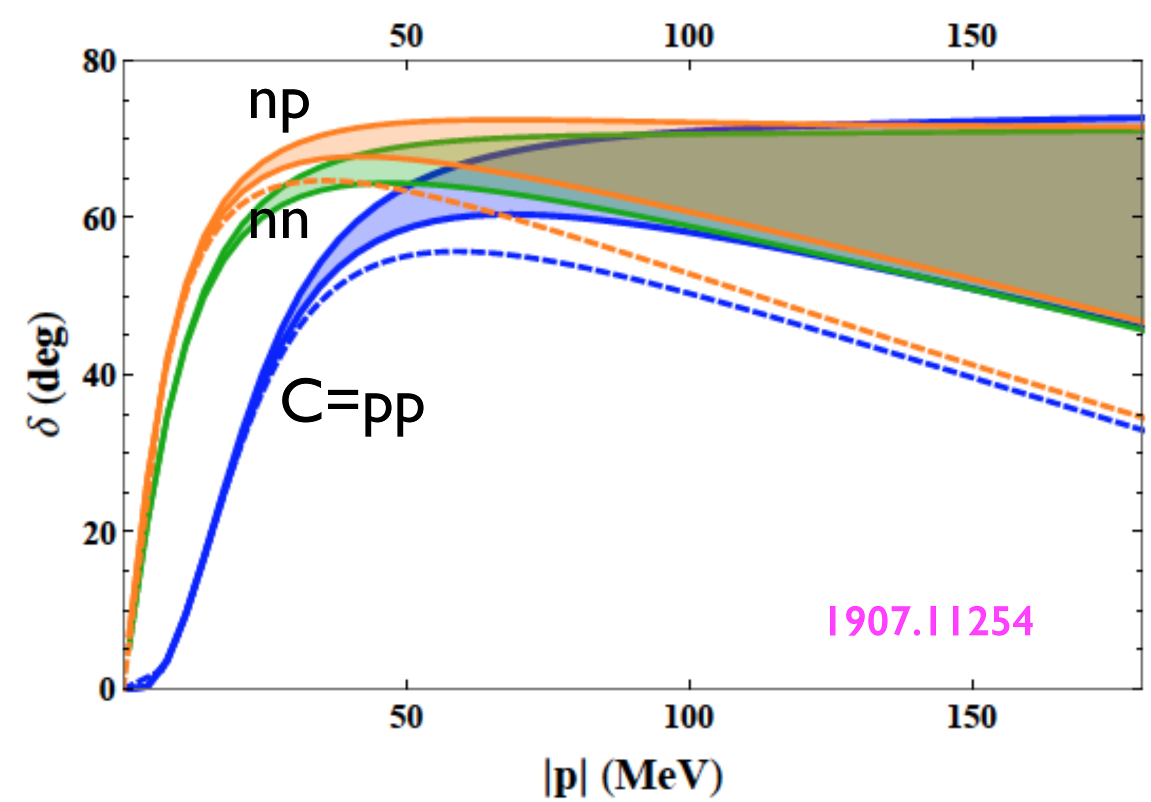


The EFT analysis survives comparison with data

The analog of $e^2(C_1+C_2)$ is included in all high-quality potentials (AV18, CD-Bonn, chiral, …)

MeV)

C_1+C_2 in "high-quality" NN potentials

1907.11254

$$V_{\rm CIB,S} = -\frac{e^2}{6}\frac{\mathcal{C}_1+\mathcal{C}_2}{2}\,T^{(12)}\,\delta^{(3)}_{R_S}(\mathbf{r})$$

$$T^{(12)} = 3\,\tau_3^{(1)}\tau_3^{(2)} - \vec{\tau}^{(1)}\cdot\vec{\tau}^{(2)}$$

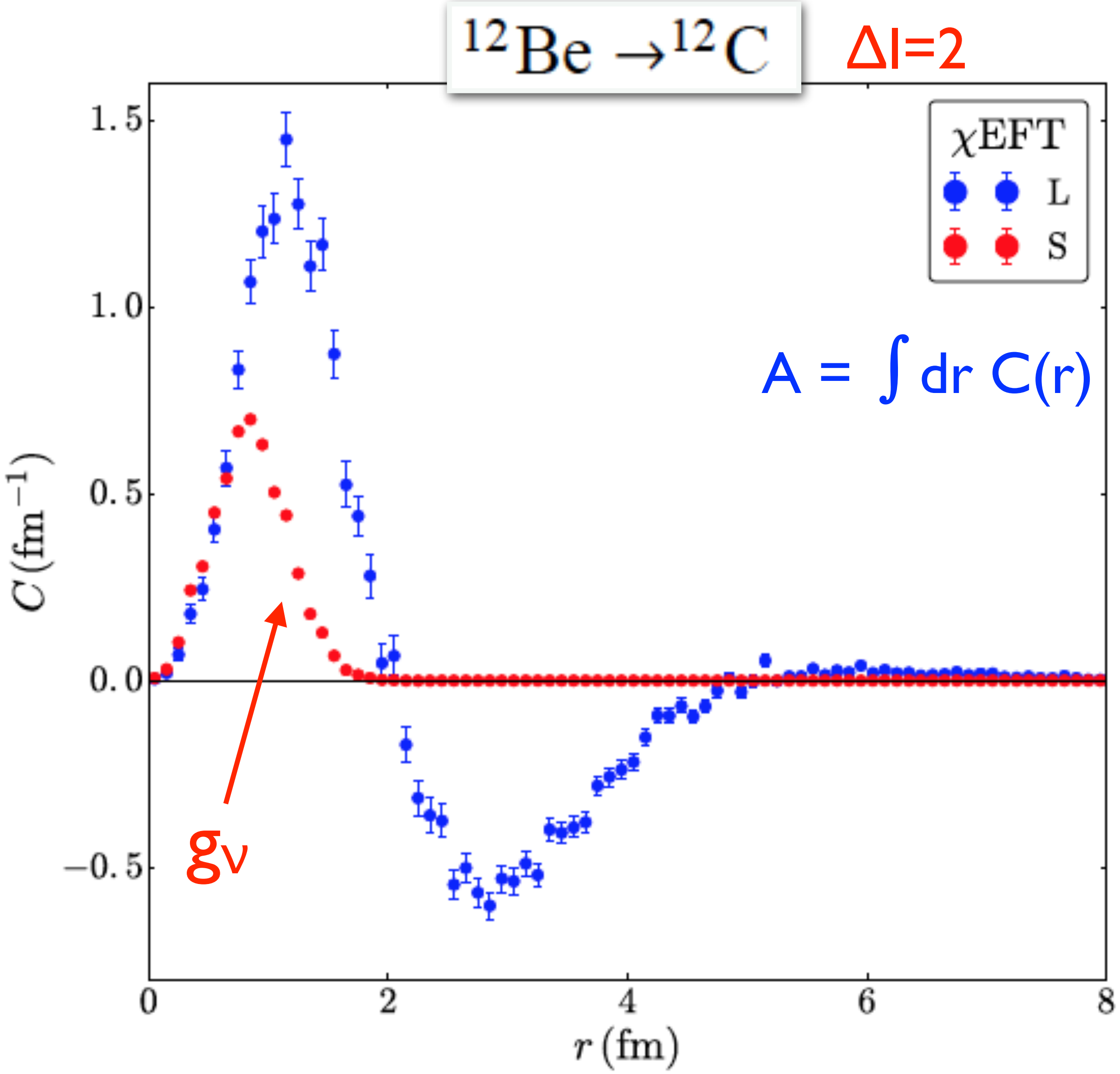
Model	Ref.	R_S (fm)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[37]	0.8	−1.03
NV-IIa*	[37]	0.8	−1.44
NV-Ic	[37]	0.6	−1.44
NV-IIc	[37]	0.6	−0.91

Model	Ref.	Λ (MeV)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)
Entem-Machleidt	[33]	500	−0.47
Entem-Machleidt	[33]	600	−0.14
Reinert *et al.*	[38]	450	−0.67
Reinert *et al.*	[38]	550	−1.01
$\rm NNLO_{sat}$	[36]	450	−0.39

- The above fits include higher order chiral terms
- Our LO fit gives $(C_1+C_2)/2 = 0.71$ fm^2 @ $R_S = 0.8$ fm
- All confirm strong violation of Weinberg counting

Guesstimating numerical impact

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254



Assume $g_\nu \sim (C_1+C_2)/2$ with $(C_1+C_2)/2$ taken from fit to NN data

Evaluate impact in light nuclei using Variational Monte Carlo, with wavefunctions corresponding to the Norfolk chiral potential NV-Ia* [1606.06335]

g_ν contribution sizable in ΔI=2 transition (due to node): for A=12, $A_S/A_L = 0.75$

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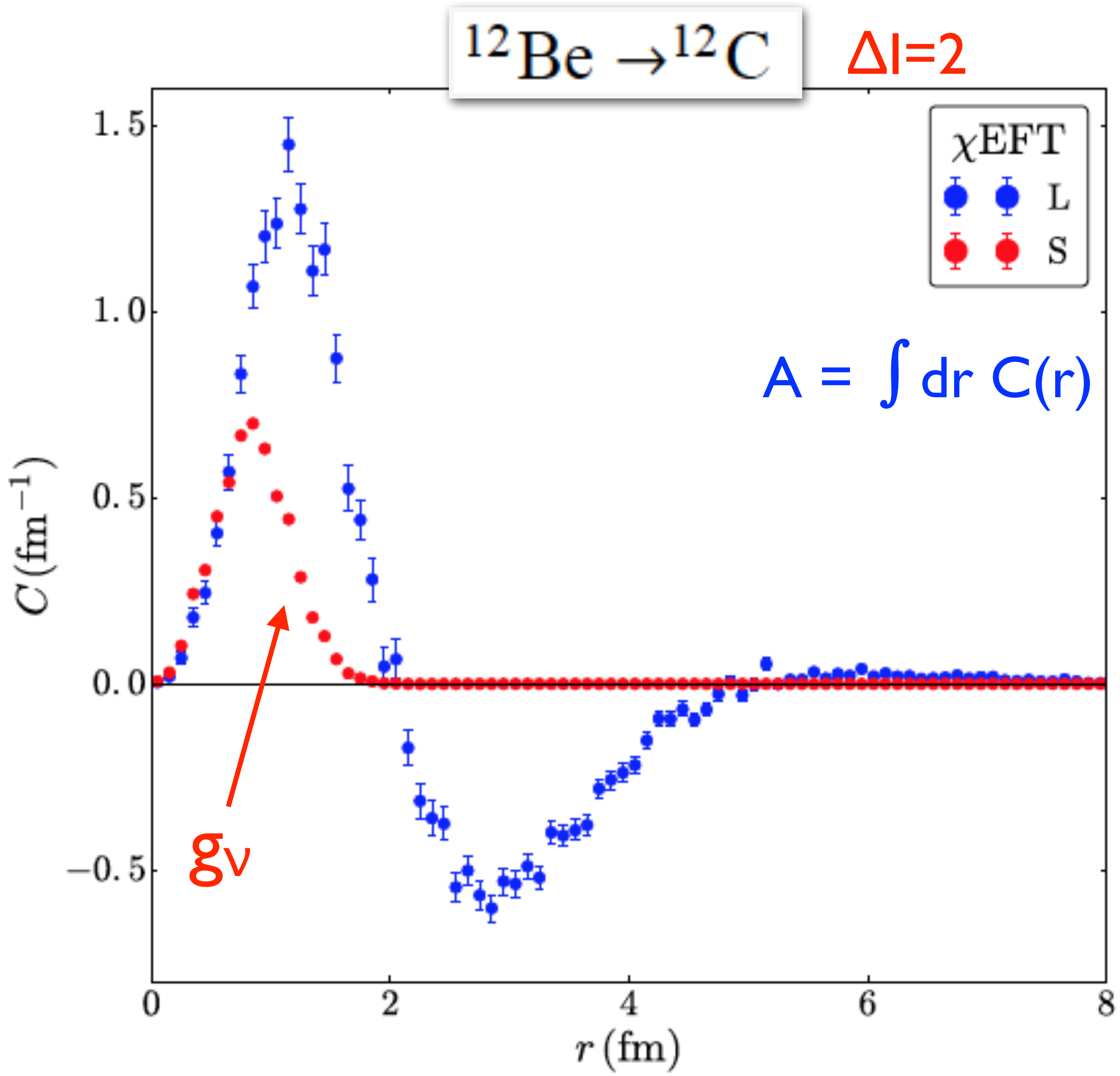

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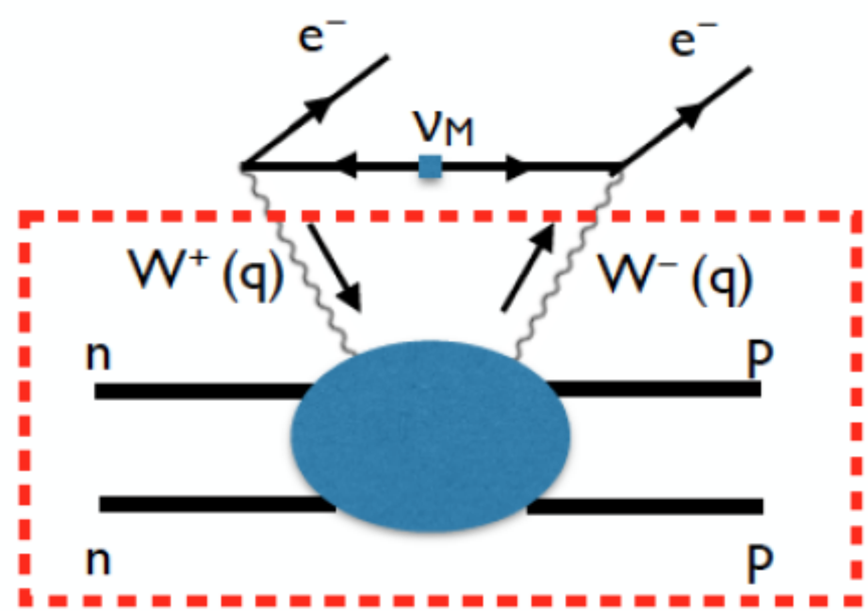
Transitions of experimental interest (^{76}Ge→ ^{76}Se, …) have ΔI=2 (and node) ⇒ expect significant effect!

Non-LQCD strategy to determine g_ν

- Write full amplitude as convolution of a known kernel with forward amplitude $W^+(q)nn \rightarrow W^-(q)pp$

- Evaluate $W^+(q)nn \rightarrow W^-(q)pp$ in various momentum regions (q) using different techniques:



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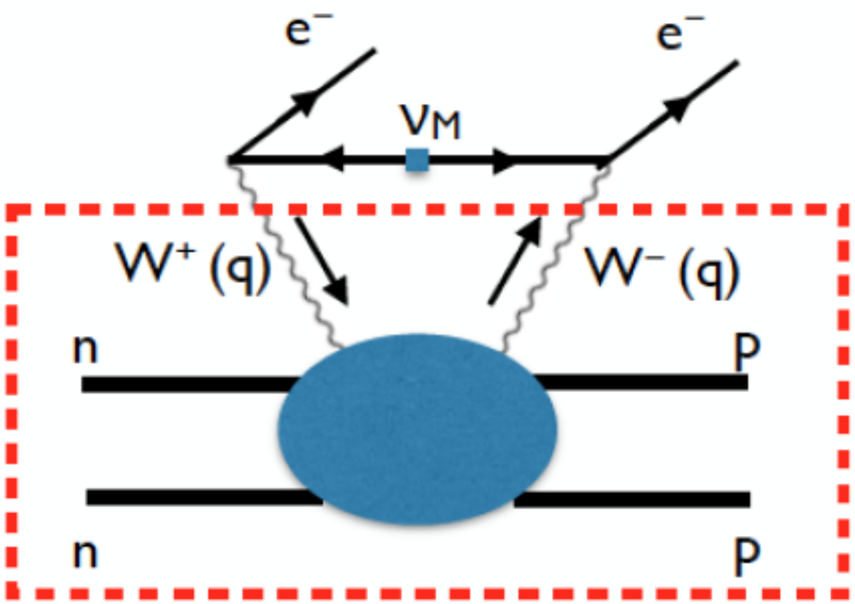

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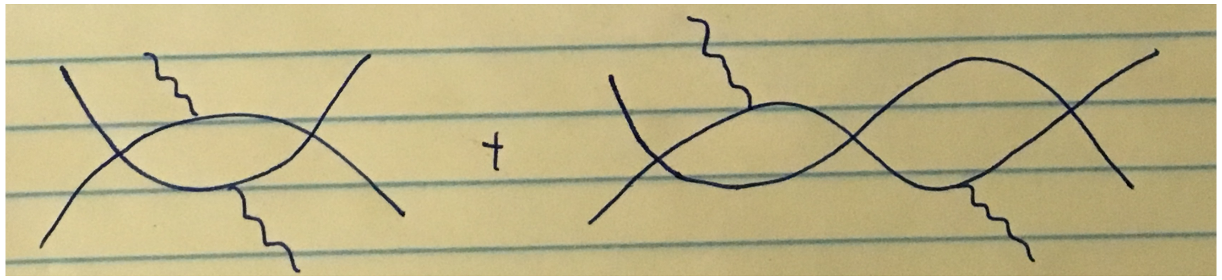

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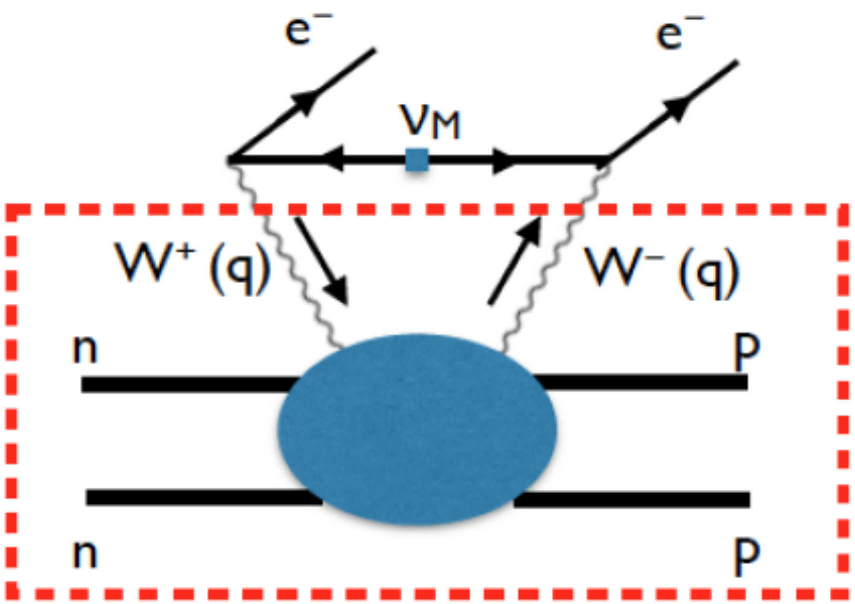

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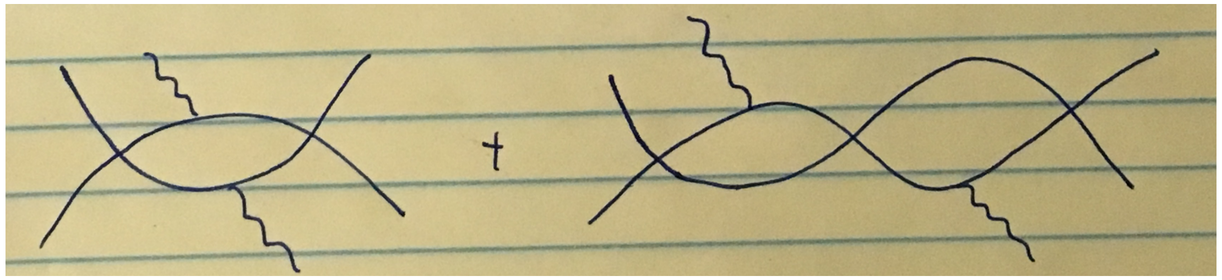
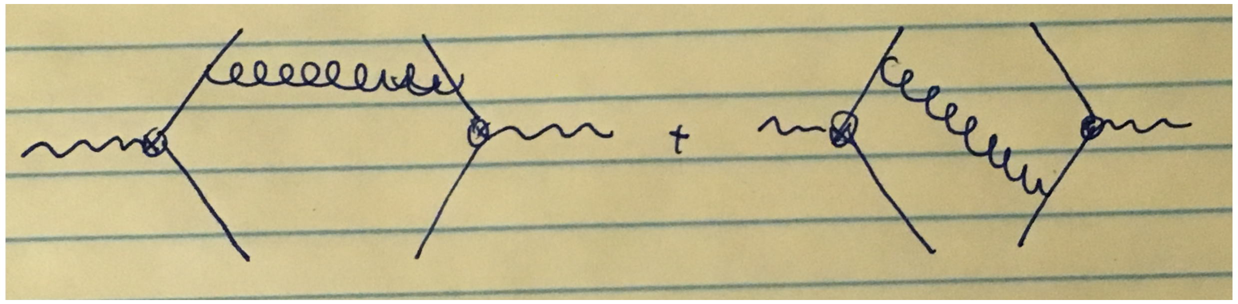


  - pQCD + local matrix element at $q_E^2 >> \text{GeV}^2$



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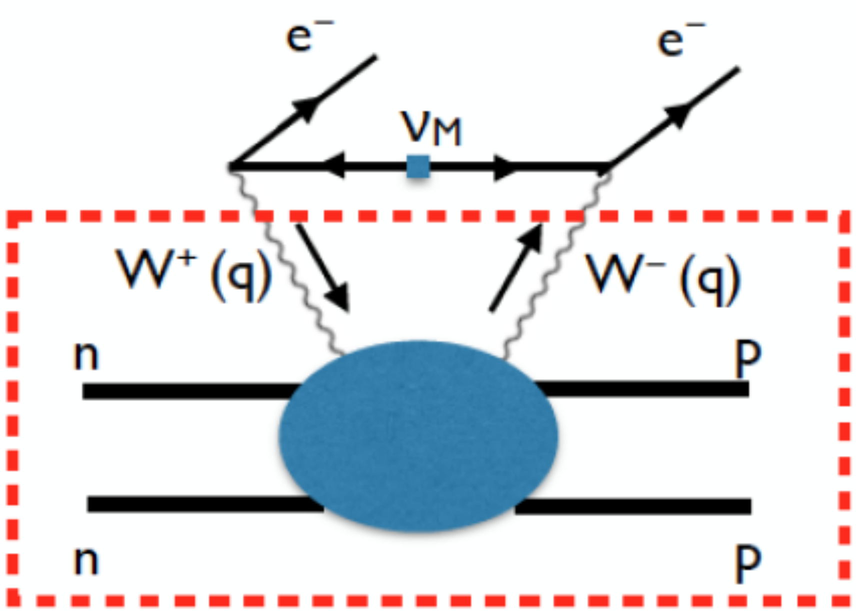

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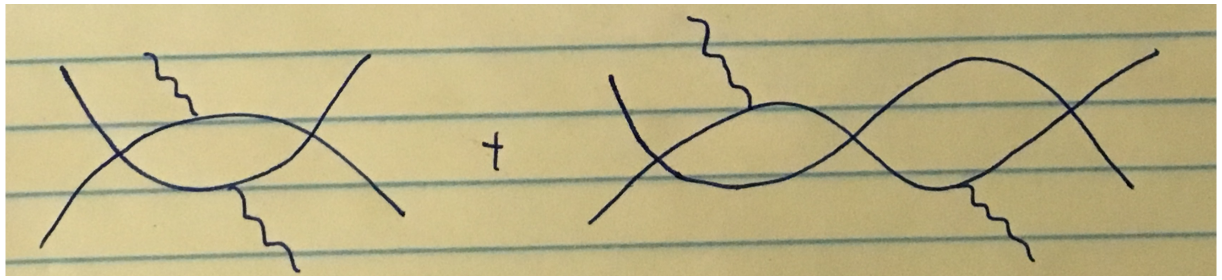

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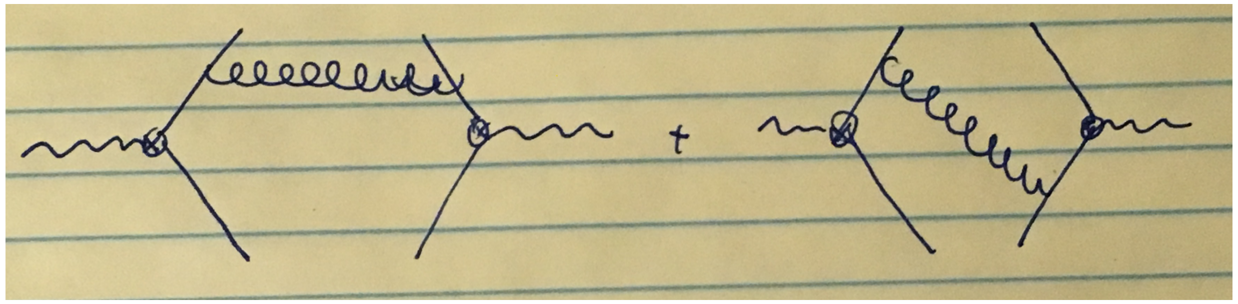


- Use electromagnetic I=2 contact term as a sanity check

Conclusions

- Chiral EFT analysis of light ν_M exchange contribution to $0\nu\beta\beta$
  - Contact nn → pp operator appears at leading order in the $^1S_0$ channel. Related to I=2 NN electromagnetic contact term.
  - First rough estimate of the coupling implies O(1) correction to matrix element in light nuclei
  - No new contact needed at NLO
  - At N2LO
    - new non-factorizable potential (O(10%) correction in light nuclei, same as form factor effects)
    - corrections to closure approximation due to"ultrasoft" ν's (not discussed today)
    - 2body x 1body currents

Backup

Details to be found in 1907.11254

- Analysis in both in pion-less and chiral EFT

- Chiral EFT with 3 regularizations / renormalization schemes
  - Dim reg (with scale μ) + minimal subtraction
  - Momentum-space cutoff Λ (in Lippmann-Schwinger eqs.)
  - Coordinate space gaussian regulator (R_S)

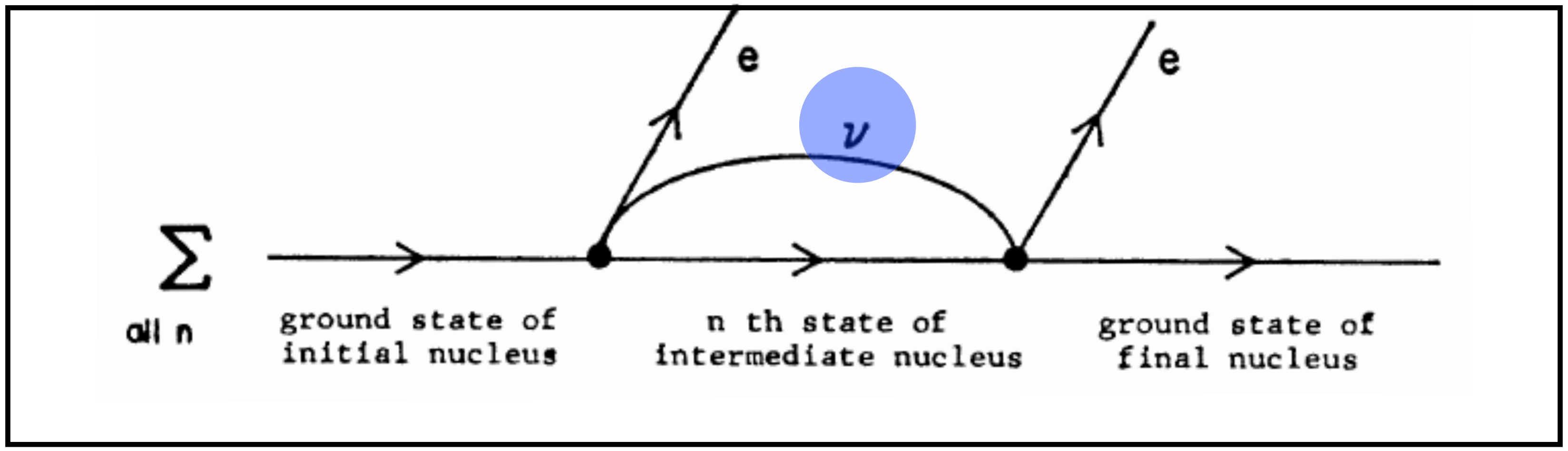
- Study of higher partial waves & NLO derivative operator

- Connection to electromagnetic I=2 operators worked out in detail

- Matrix elements in light nuclei using "Norfolk" chiral potentials

Ultrasoft neutrino contributions

Figure adapted from Primakoff-Rosen 1969



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

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- Ultrasoft ν's couple to *nuclear* states: sensitivity to $E_n - E_i$ and $\langle f\,|J_\mu|n\rangle\langle n|J^\mu|i\rangle$ that also determine $2\nu\beta\beta$ amplitude
- $T_{usoft}/T_0 \sim (E_n - E_i)/(4\pi k_F)$ → N2LO contribution
- μ_{us} dependence cancels with $V_{\nu,2.}$: consistency check

$T_{\rm usoft}$ and double commutator

$$\frac{dT_{\rm usoft}}{d\log\mu_{\rm us}} = -T_{\rm lept}\times\frac{1}{8\pi^2}\,\langle f|\,[J_\mu,[J^\mu,H_0]]\,|i\rangle = T_{\rm lept}\times\frac{1}{8\pi^2}\,\langle f|\,[\mathbf{A},[\mathbf{A},H_0]]\,|i\rangle$$

$$= -2\,T_{\rm lept}\times\sum_{a,b}\langle f|\tau^{(a)+}\tau^{(b)+}\,\tilde{\mathcal{V}}^{(a,b)}_{AA}\,|i\rangle\ ,$$

$$-T_{\rm lept}\frac{d(V_{\nu,2})_{fi}}{d\log\mu_{\rm us}} = +2T_{\rm lept}\times\sum_{a,b}\langle f|\tau^{(a)+}\tau^{(b)+}\,\tilde{\mathcal{V}}^{(a,b)}_{AA}\,|i\rangle\ ,$$

$$\tilde{\mathcal{V}}^{(a,b)}_{AA} = 2\,\frac{g_A^4}{(4\pi F_\pi)^2}\,\frac{\boldsymbol{\sigma}^{(a)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(b)}\cdot\mathbf{q}\ +\ \mathbf{q}^2\ \mathbf{1}^{(a)}\times\mathbf{1}^{(b)}}{\mathbf{q}^2+m_\pi^2} - \frac{g_A^2}{(4\pi)^2}\,48C_T\,\mathbf{1}^{(a)}\times\mathbf{1}^{(b)}$$