ECT* Workshop on "Exploring the role of electro-weak currents in Atomic Nuclei"
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Effective theory approach to neutrinoless double beta decay

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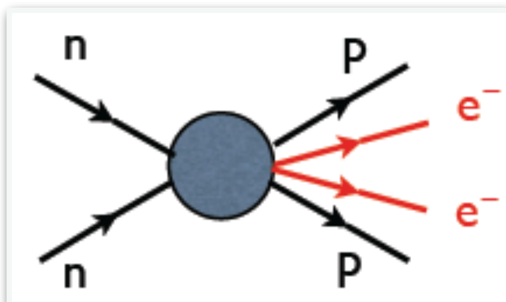
Outline

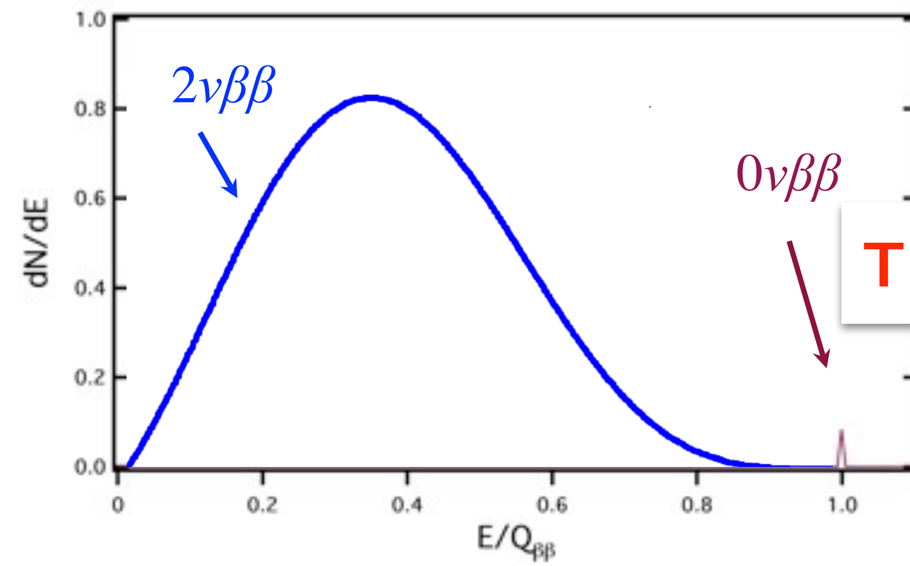
- Introduction: $0\nu\beta\beta$ decay and Lepton Number Violation (LNV)
- Effective Field Theory (EFT) framework for LNV
- $0\nu\beta\beta$ from light Majorana ν exchange in chiral EFT
    - "Neutrino potential" to LO and N2LO
    - *A new leading short-range contribution*
    - "Ultrasoft neutrinos" and closure approximation

0νββ and Lepton Number Violation

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



Lepton number changes by two units: ΔL=2

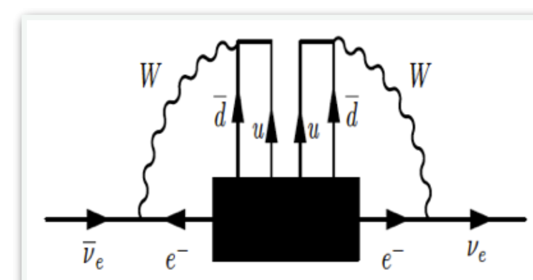


$T_{1/2} > 10^{25}$ yr

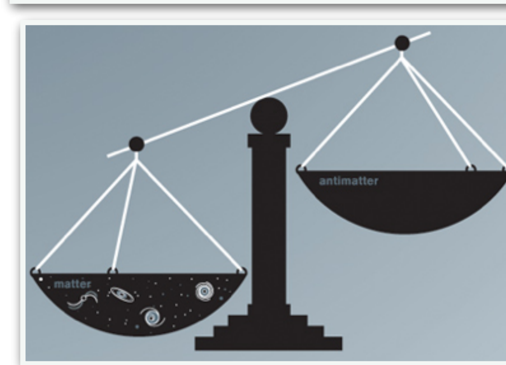
- B-L conserved in SM → 0νββ observation would signal new physics

    - Demonstrate that neutrinos are Majorana fermions

    - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



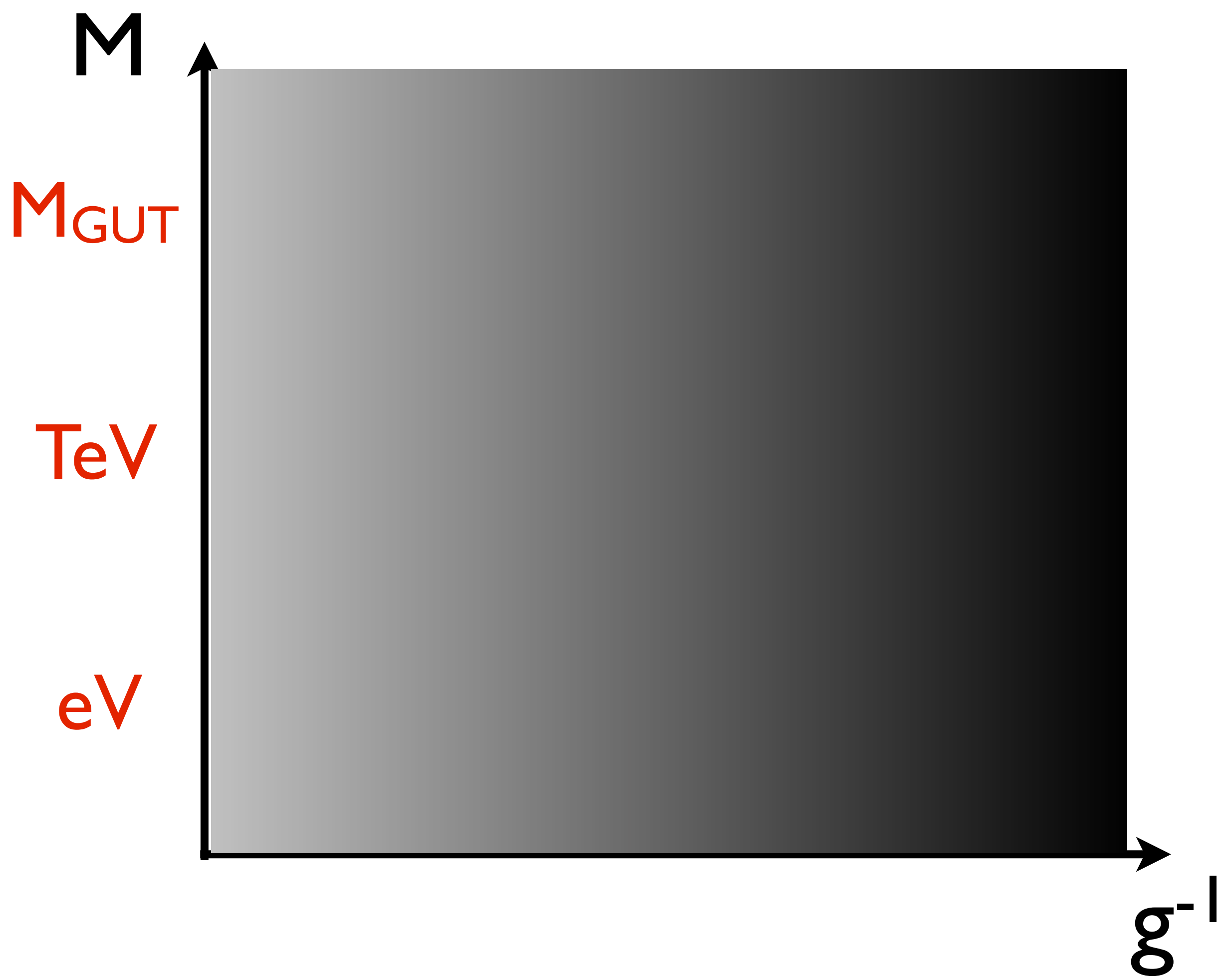
Shechter-Valle 1982

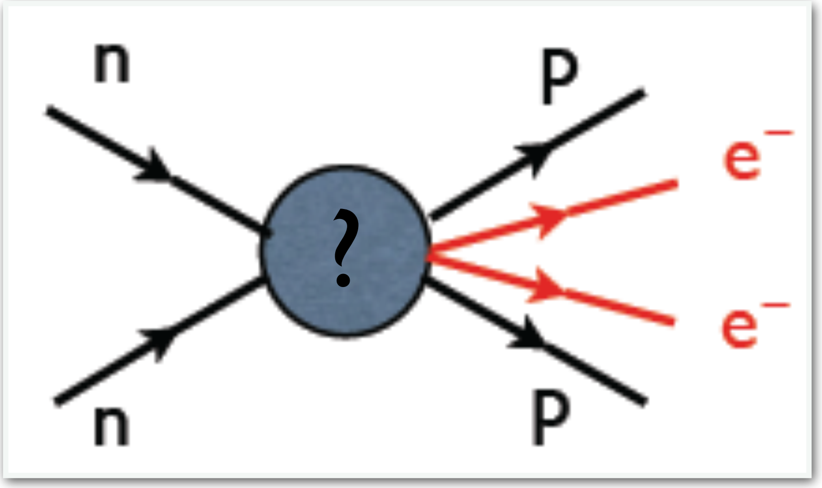


Fukujgita-Yanagida 1987

0νββ and Lepton Number Violation

- Ton-scale 0νββ searches will probe LNV from a variety of mechanisms





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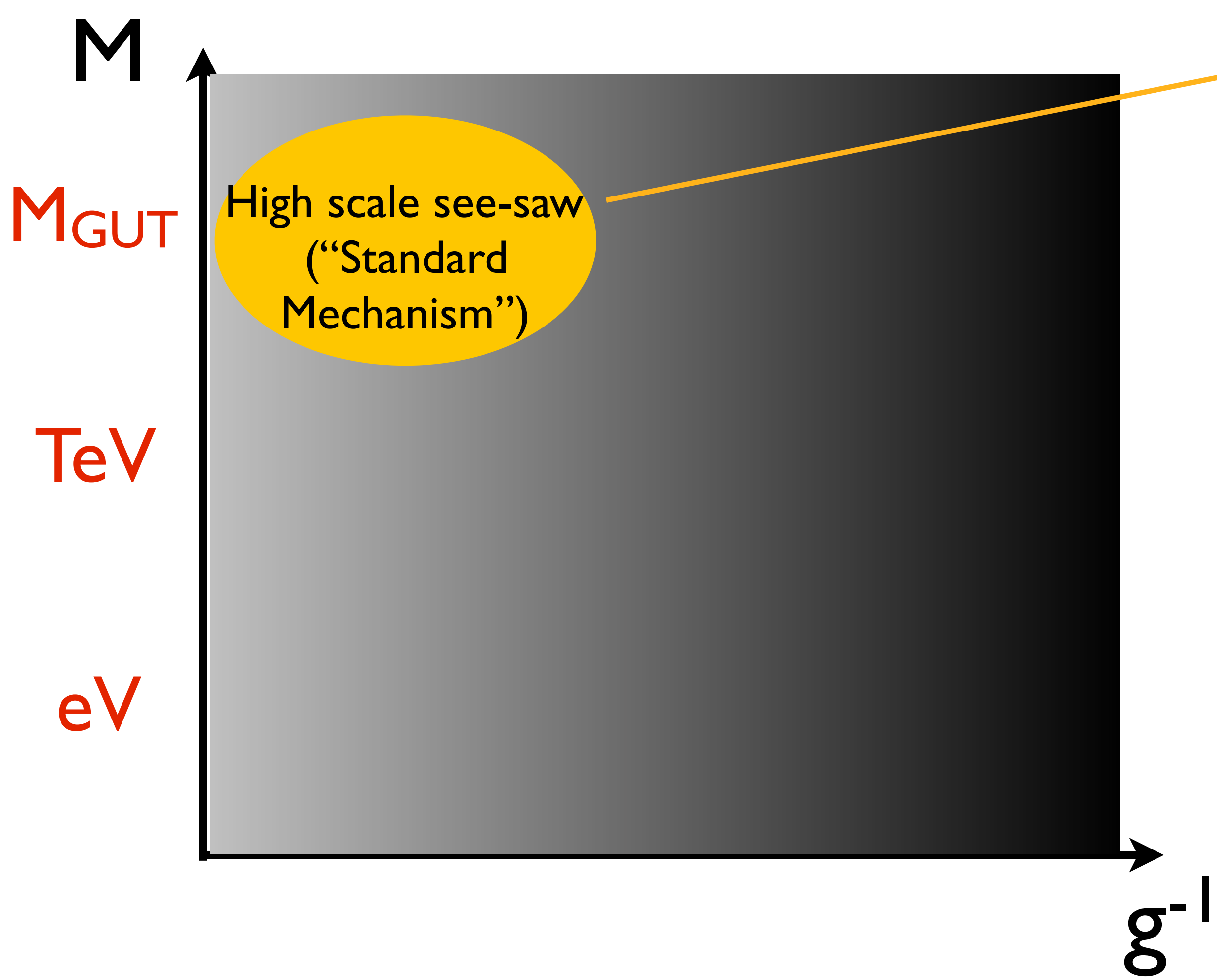
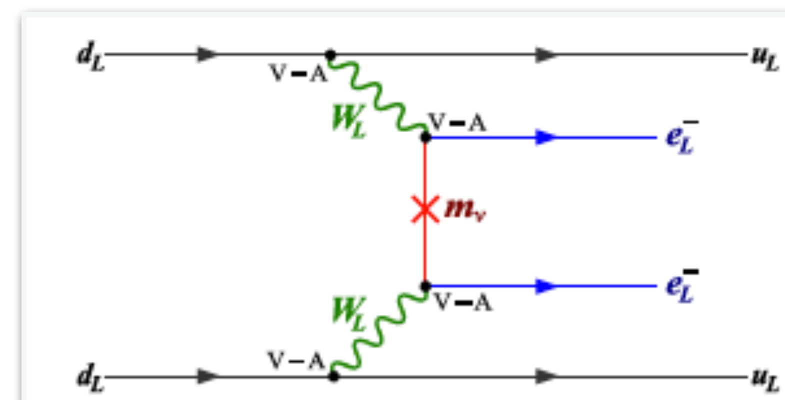


LNV dynamics at M >> TeV:
leaves as the only low-energy footprint
light Majorana neutrino



$$A \propto m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i$$

0νββ and Lepton Number Violation

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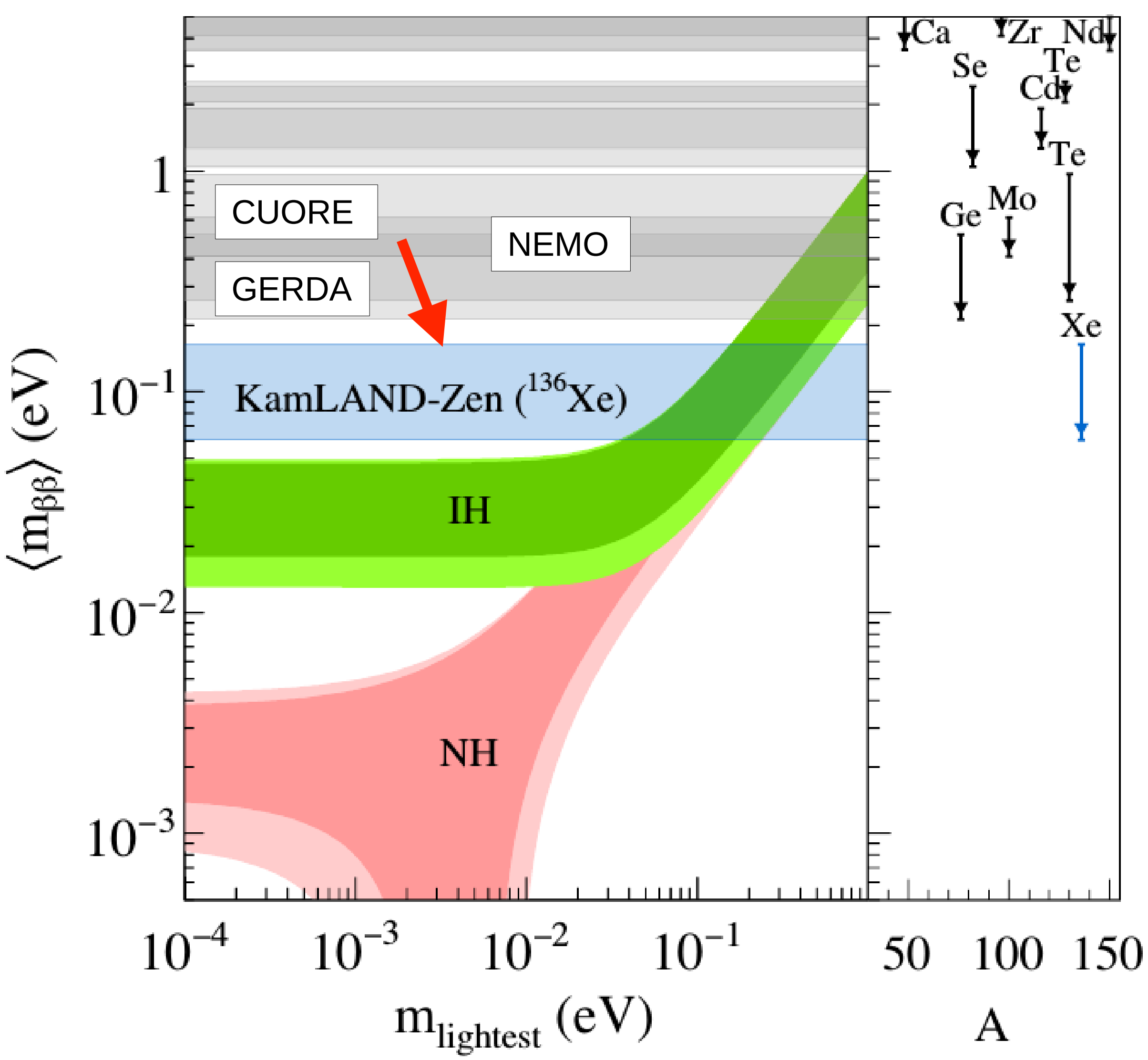

KamLAND-Zen coll., '16

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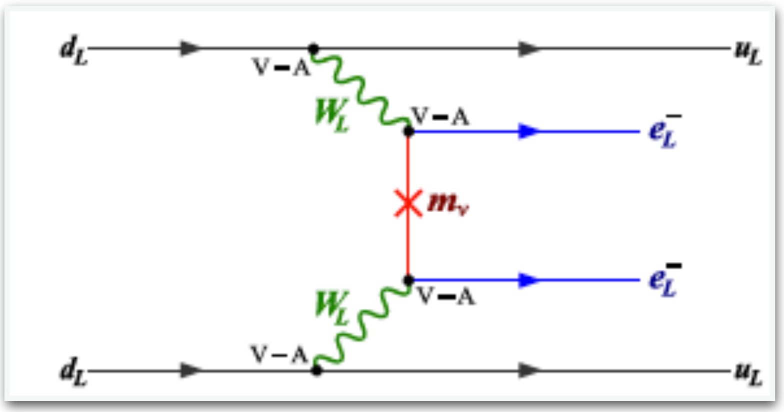


$$A \propto m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i$$

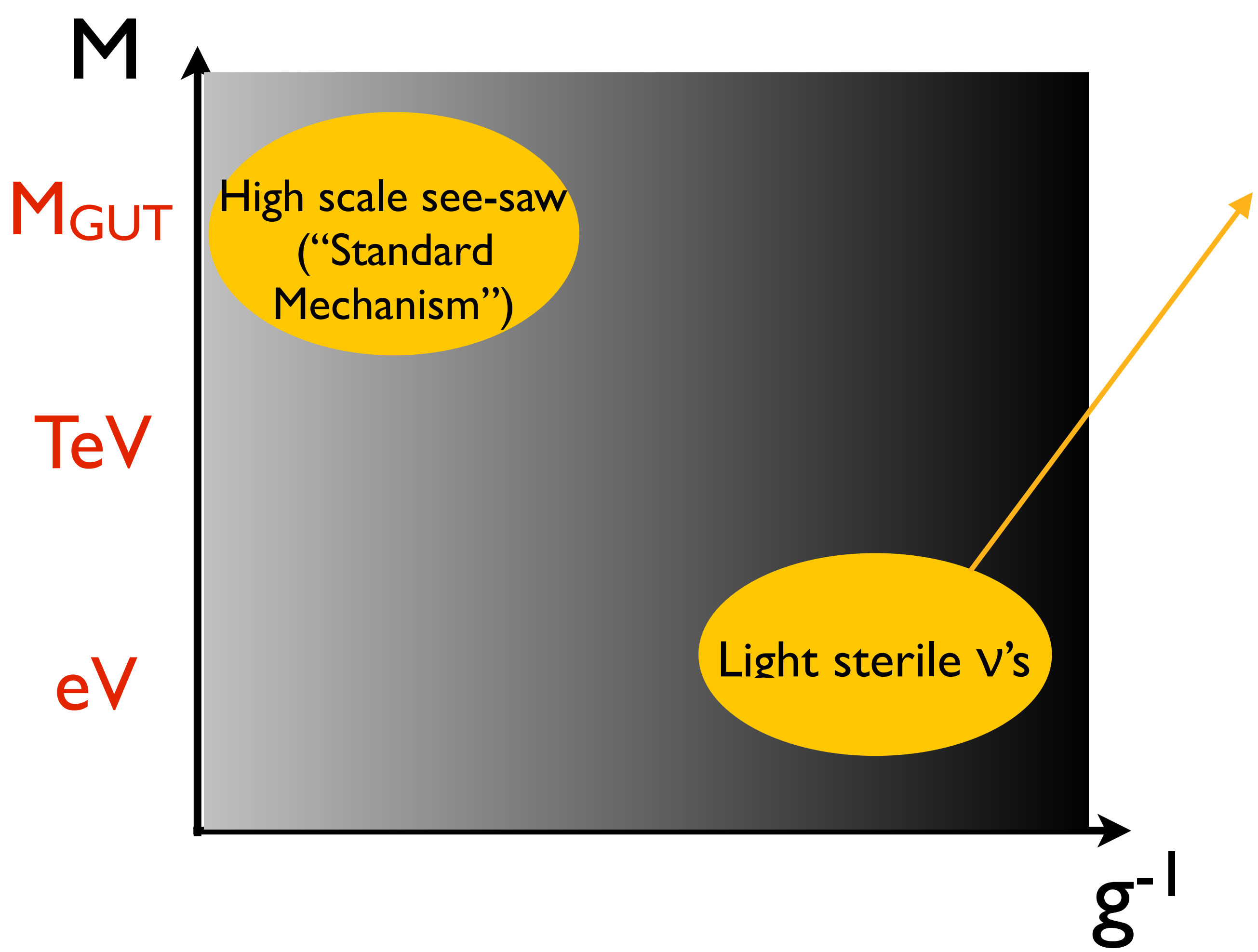
Clear interpretation framework and sensitivity goals ("inverted hierarchy").

Requires difficult nuclear matrix elements: O(50%) uncertainty (spread)

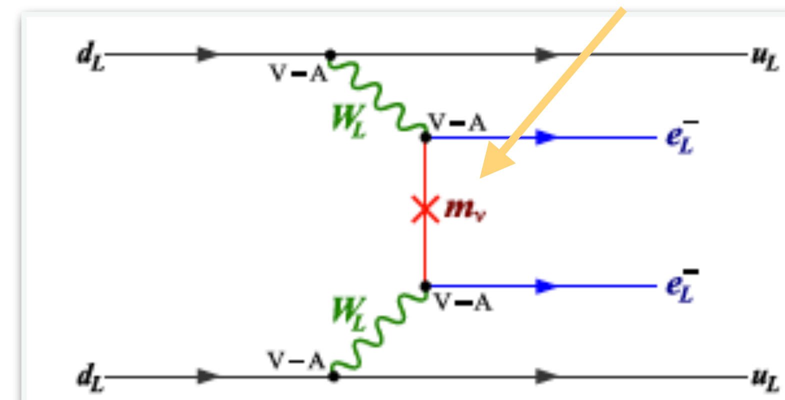
Only limited class of models!

0νββ and Lepton Number Violation

- Ton-scale 0νββ searches will probe LNV from a variety of mechanisms

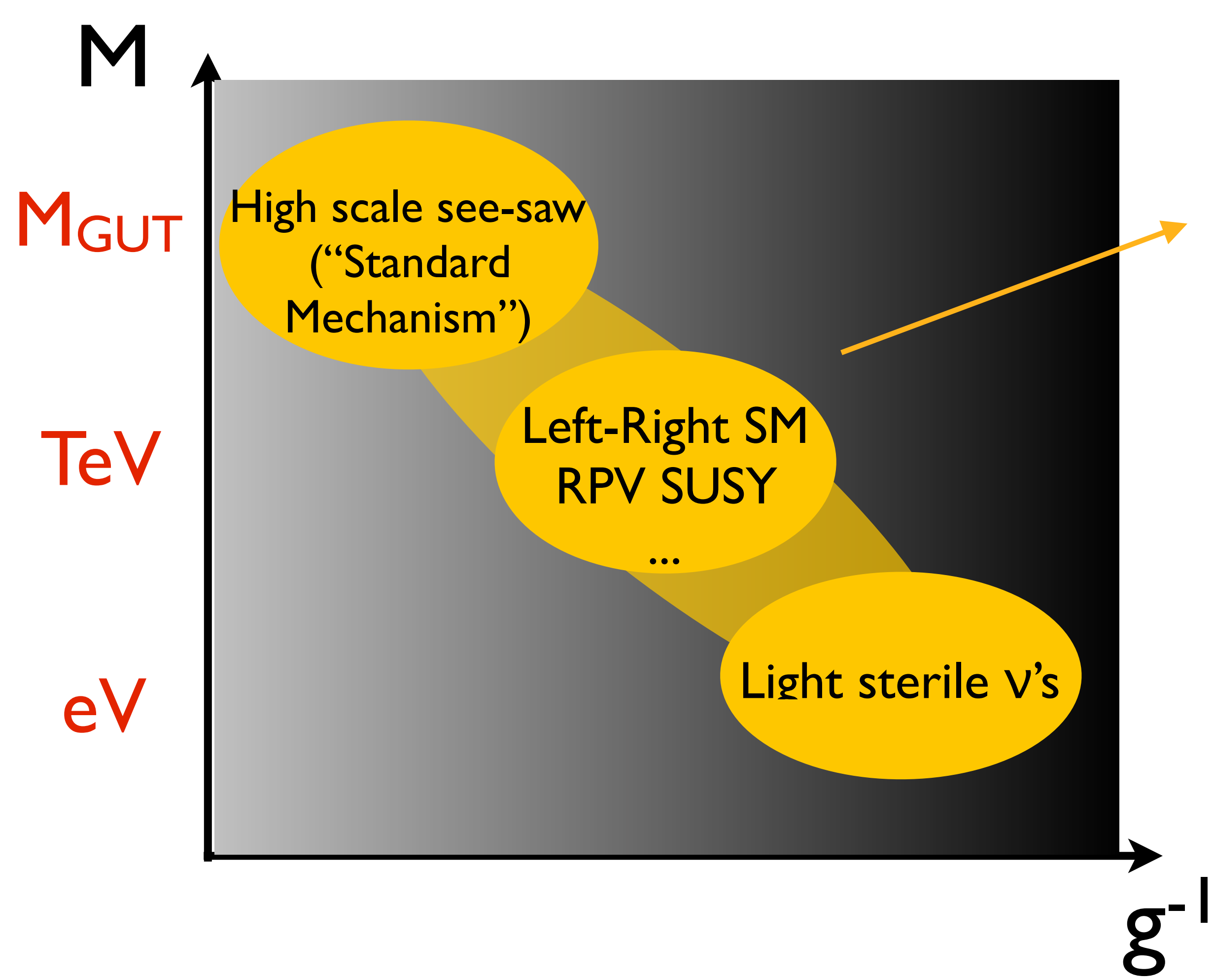


LNV dynamics at M_R ~ eV → GeV: additional light Majorana states



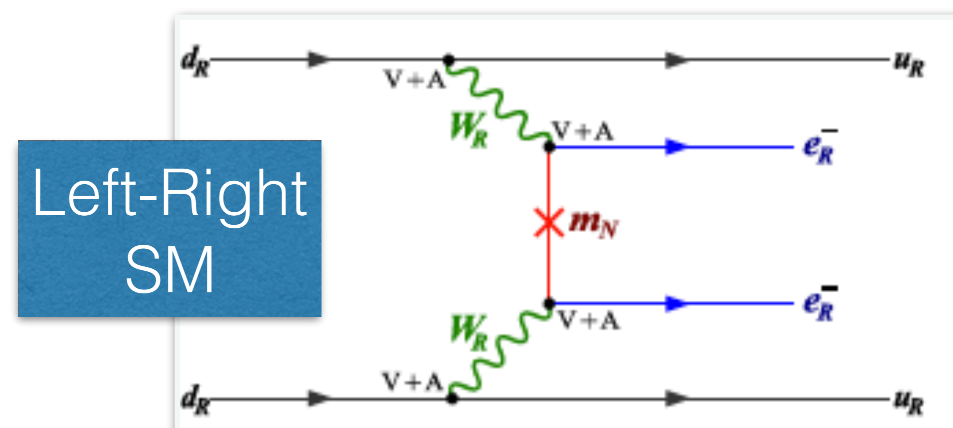
0νββ and Lepton Number Violation

- Ton-scale 0νββ searches will probe LNV from a variety of mechanisms



LNV dynamics could be at any scale > eV.
For M ~ 1-100 TeV one expects

(i) New contributions to 0νββ not directly related to light neutrino mass;
(ii) Collider signatures, such as pp → eejj



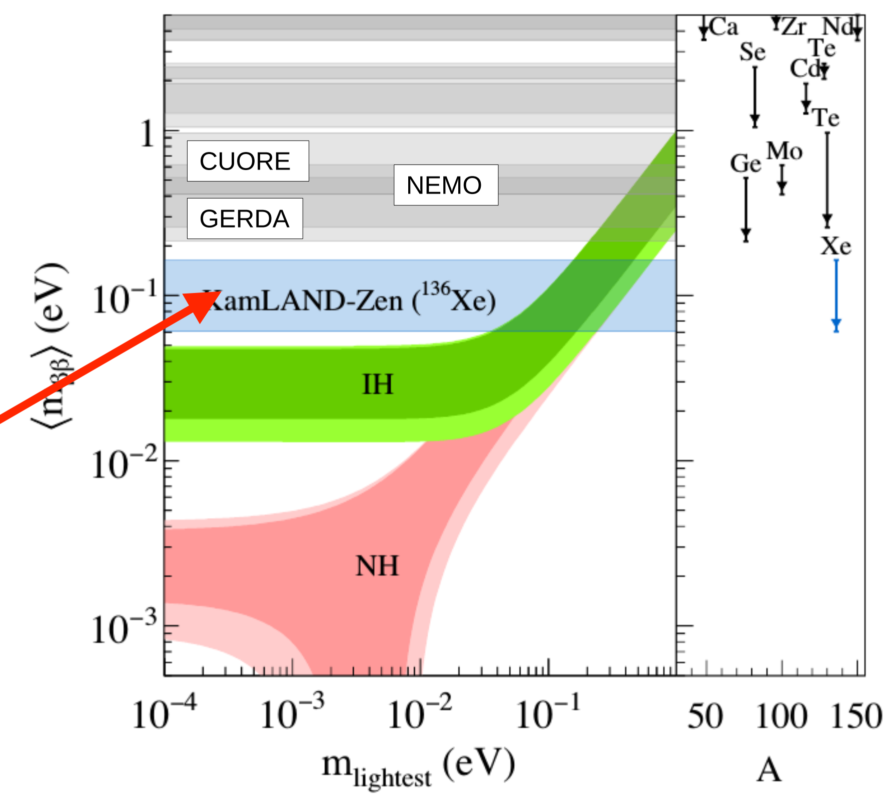
Discovery potential and interpretation of null results depend on a different set of (equally uncertain) hadronic and nuclear matrix elements

Effective theory framework

- Impact of $0\nu\beta\beta$ searches most efficiently analyzed in EFT framework:

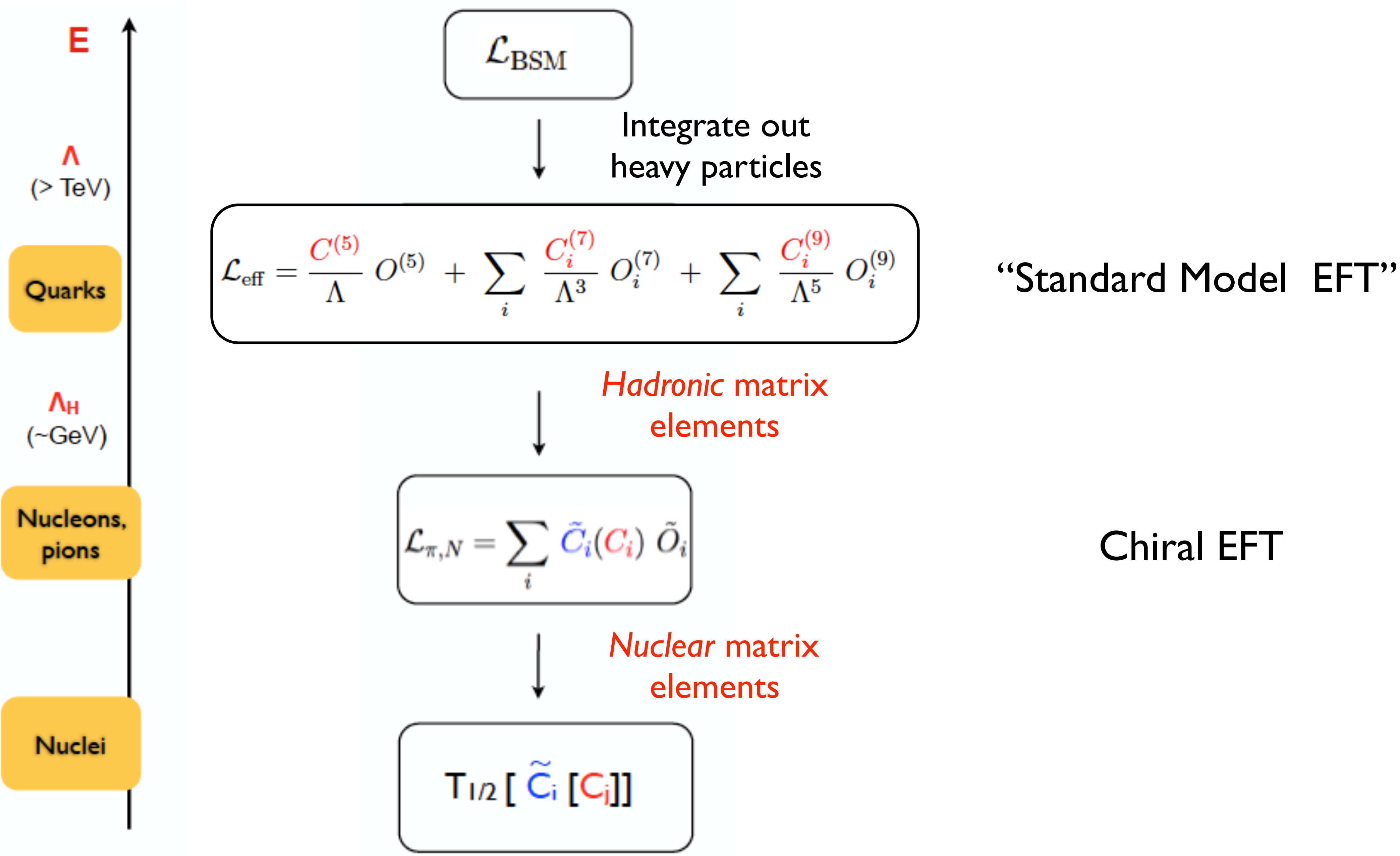
1. Systematically classify sources of Lepton Number Violation and relate $0\nu\beta\beta$ to other LNV processes (such as $pp \to eejj$ at the LHC)

2. Organize contributions to hadronic and nuclear matrix elements
   $\Rightarrow$ controllable uncertainties



KamLAND-Zen coll., '16

EFT framework for 0νββ

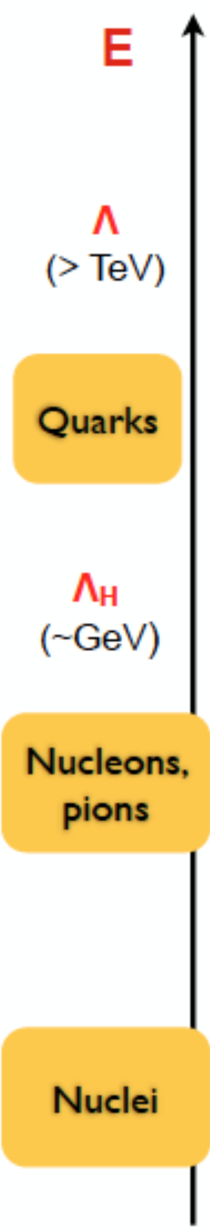


Chain of EFT +

lattice QCD & many-body methods

$\Rightarrow$ $T_{1/2}[\,\tilde{C}_i\,[C_j]\,]$

EFT framework for 0νββ



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

↓ Integrate out heavy particles

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

"Standard Model EFT"

↓ *Hadronic* matrix elements

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

Chiral EFT

↓ *Nuclear* matrix elements

$T_{1/2}[\, \tilde{C}_i\, [C_j]]$

Chain of EFT + lattice QCD & many-body methods → $T_{1/2}[\, \tilde{C}_i\, [C_j]\,]$

$0\nu\beta\beta$ from light Majorana neutrino exchange

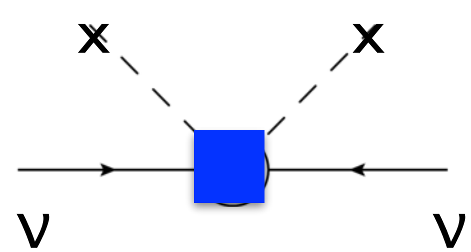
V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729, to appear in Physical Review C

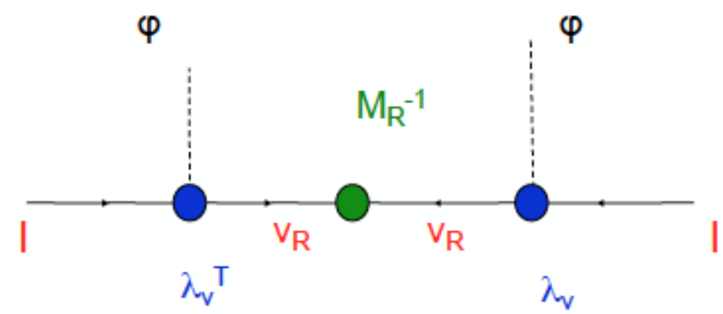
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck
1802.10097, to appear in Physical Review Letters

GeV-scale effective Lagrangian

- Weinberg dim-5 operator induces ΔL=2 operators at dim 3 & 9

Weinberg operator





$$m_{\beta\beta} \sim \frac{v^2}{\Lambda}$$

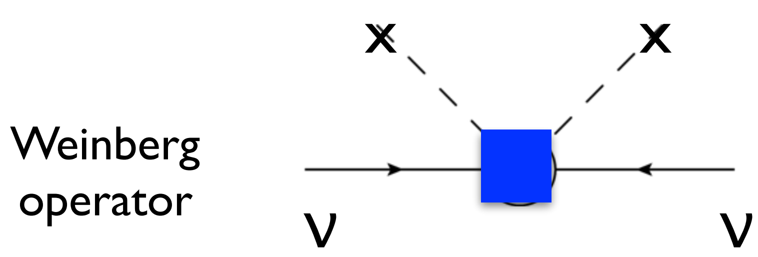
$$m_\nu \sim v_{ew}^2 \lambda_\nu^T M_R^{-1} \lambda_\nu$$

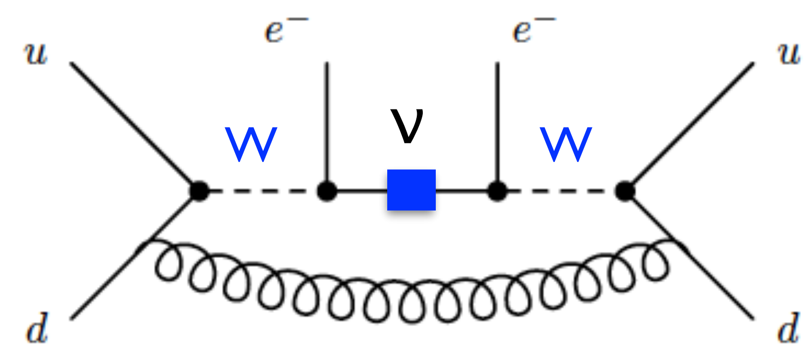
$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL}$$

- $m_{\beta\beta}$ + CC weak interaction → usual "neutrino potential"

GeV-scale effective Lagrangian

- Weinberg dim-5 operator induces ΔL=2 operators at dim 3 & 9





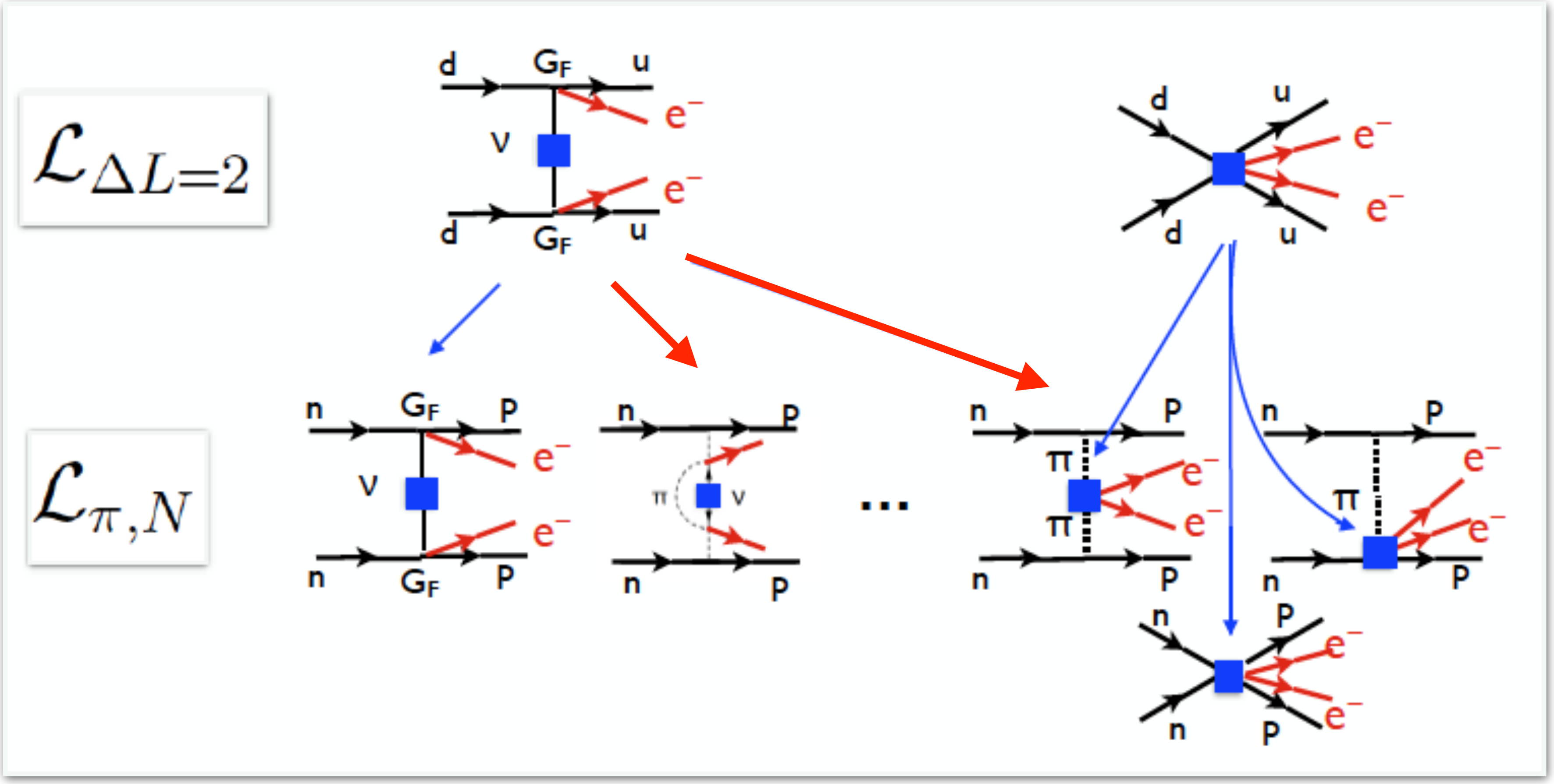
$$m_{\beta\beta} \sim \frac{v^2}{\Lambda}$$

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL} \;+\; \frac{\alpha_s(\mu)}{4\pi}\,\frac{8 G_F^2 V_{ud}^2 m_{\beta\beta}}{\mu^2}\;\bar{e}_L e_L^c\; \bar{u}_L \gamma_\mu d_L\; \bar{u}_L \gamma_\mu d_L$$

- $m_{\beta\beta}$ + CC weak interaction → usual "neutrino potential"
- Arises from integrating out hard ν's and gluons ($q_E^2 > \mu^2$): first hint that there is "short distance" physics even in the light ν_M mechanism

From quarks to hadrons

- At $E \sim \Lambda_\chi \sim$ GeV, "integrate out" hard ν's and gluons ($E, |\mathbf{p}| > \Lambda_\chi$)
- Map ΔL=2 Lagrangian onto π, N operators, organized according to power-counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$)

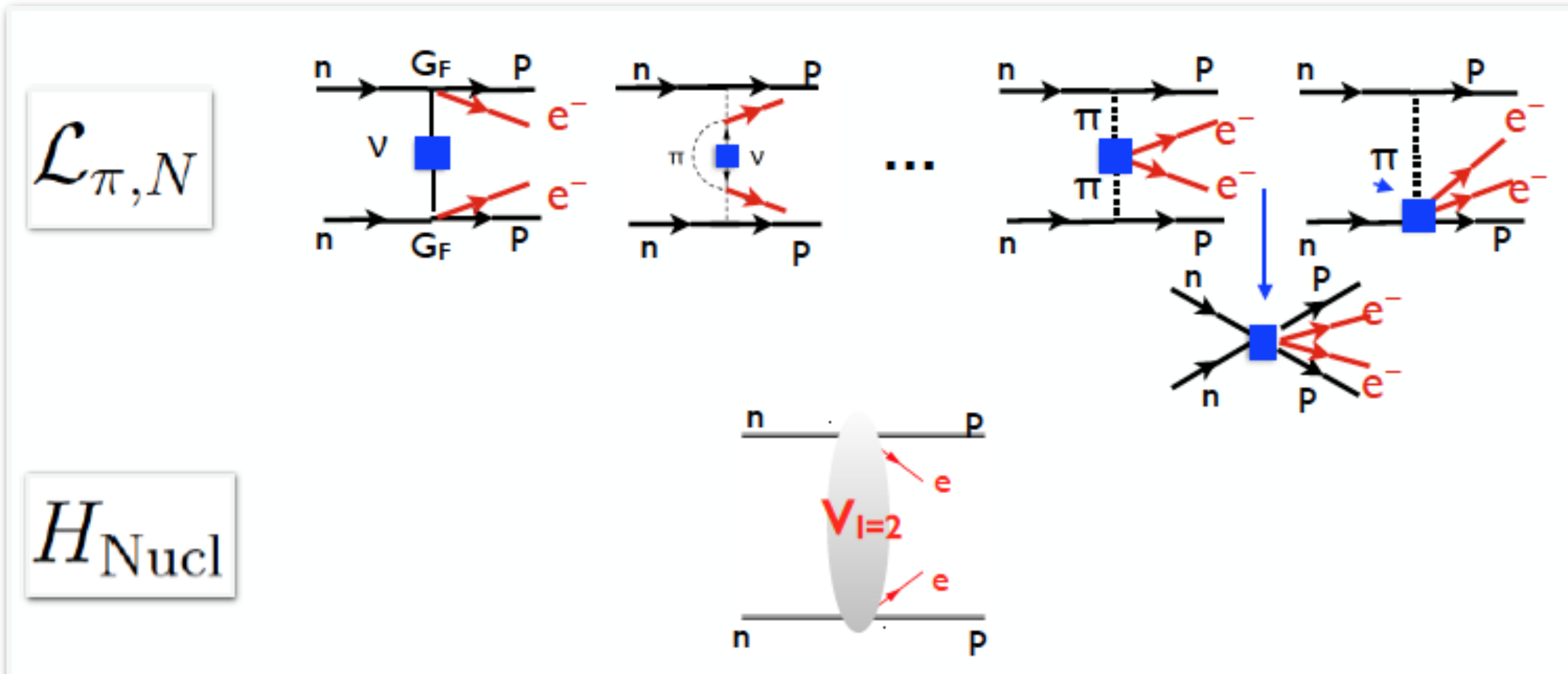


V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729, to appear in Physical Review C

V. Cirigliano, W. Dekens, J. de Vries M. Graesser, E. Mereghetti 1708.09390, published in JHEP

From hadrons to nuclei

- Integrate out ν's and π's with (E,|**p**|)~Q and (E,|**p**|)~(Q^2/m_N, Q)

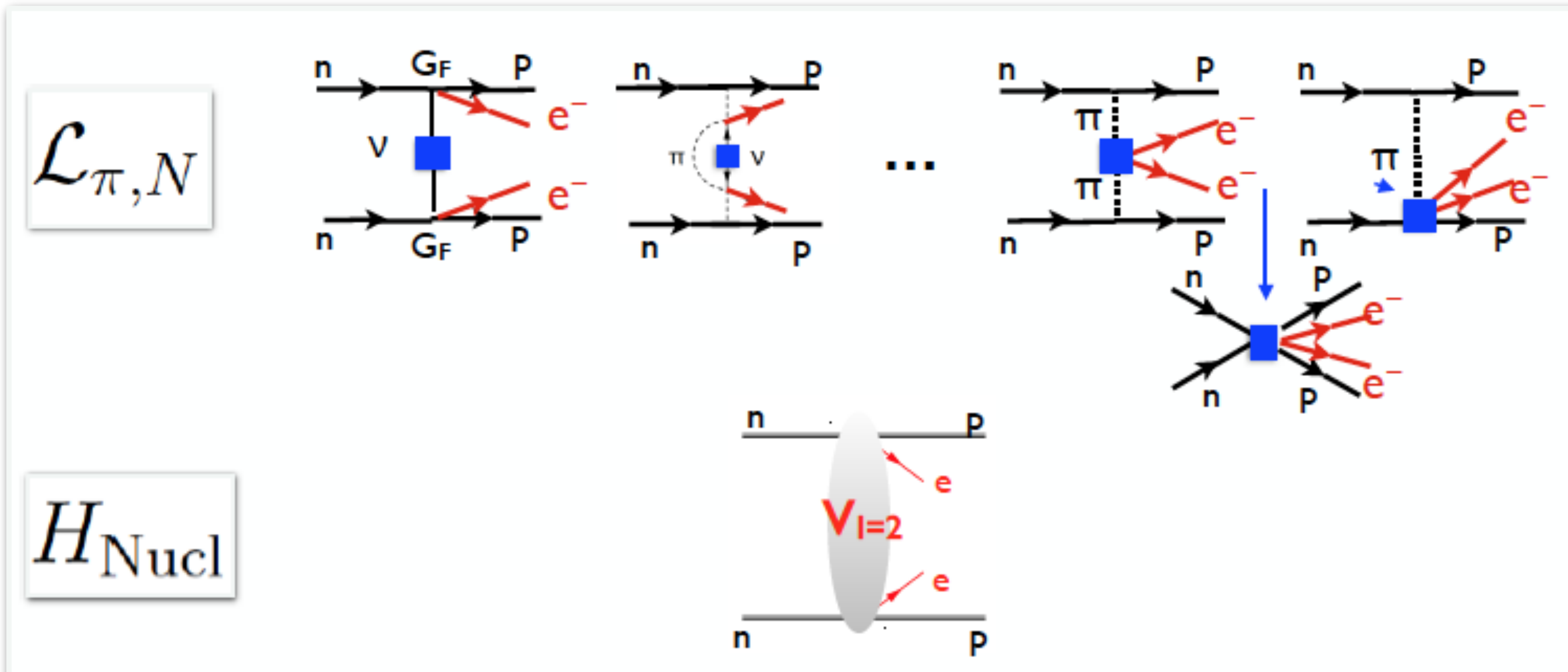


Strong interactions

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

From hadrons to nuclei

- Integrate out ν's and π's with (E,|**p**|)~Q and (E,|**p**|)~(Q^2/m_N, Q)



Strong interactions

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

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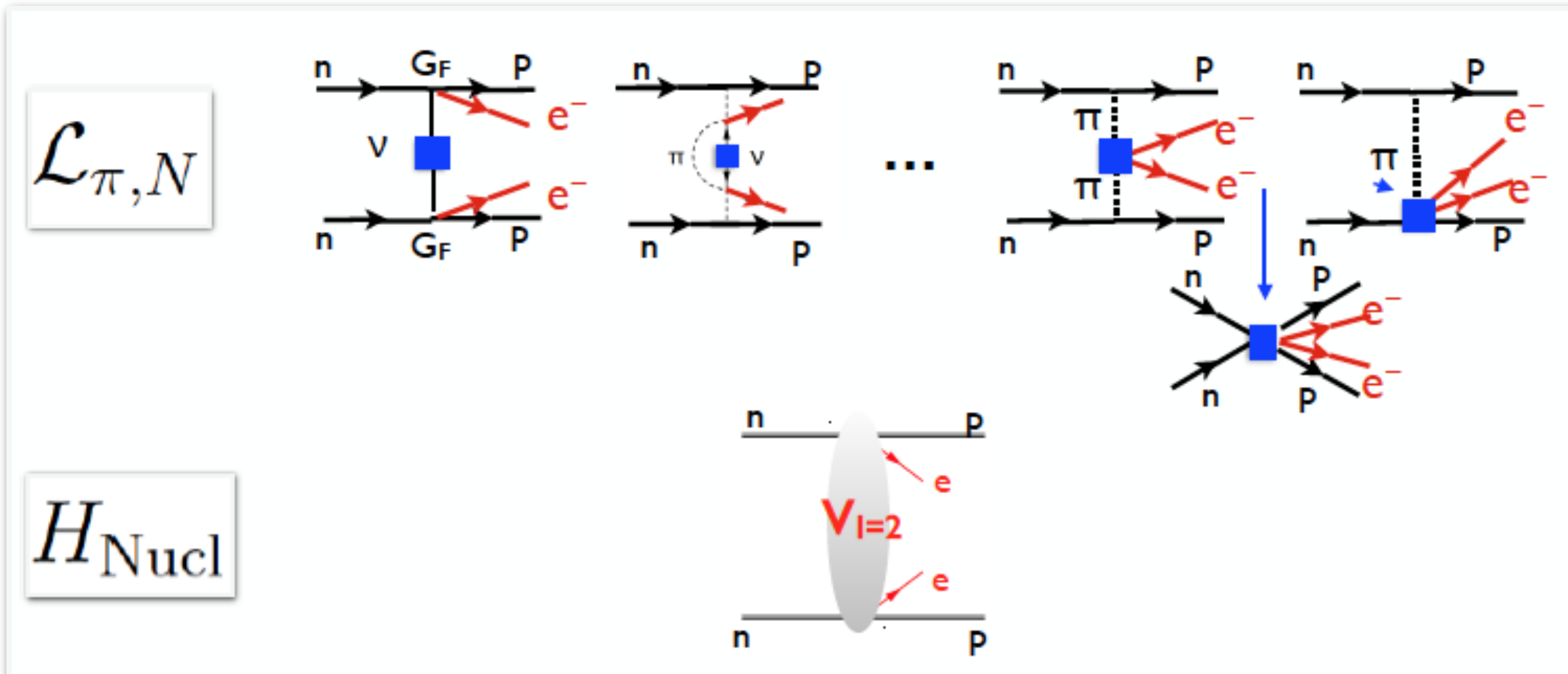
From hadrons to nuclei

- Integrate out ν's and π's with (E,|**p**|)~Q and (E,|**p**|)~(Q^2/m_N, Q)



Strong interactions

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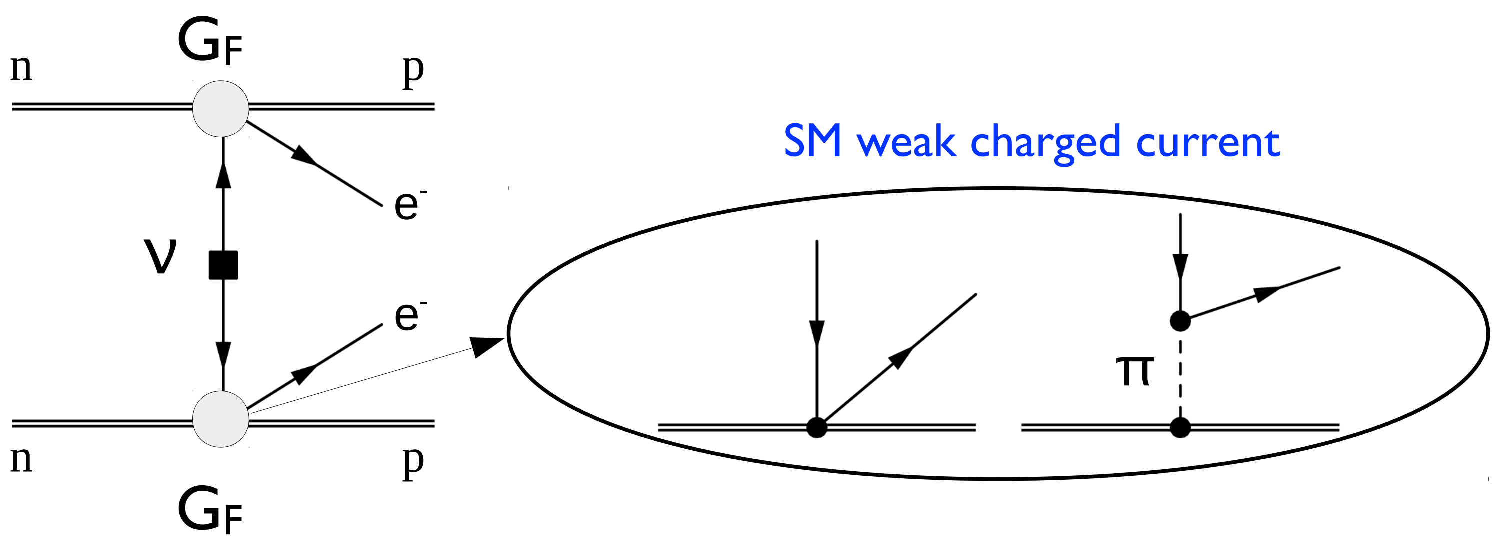
"Isotensor" 0νββ potential mediates nn→pp.

It can be identified to a given order in Q/Λ_χ by computing 2-nucleon amplitudes

$0\nu\beta\beta$ potential from light ν_M

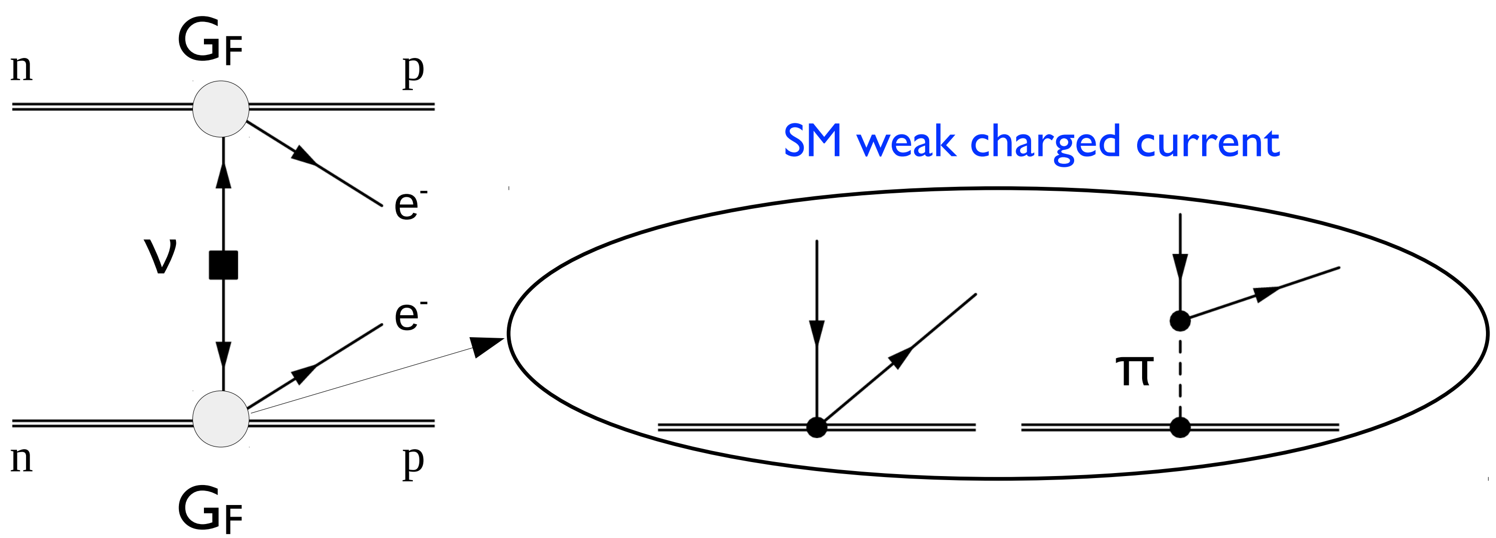


- Leading Order:

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

Hadronic input is g_A

$0\nu\beta\beta$ potential from light ν_M



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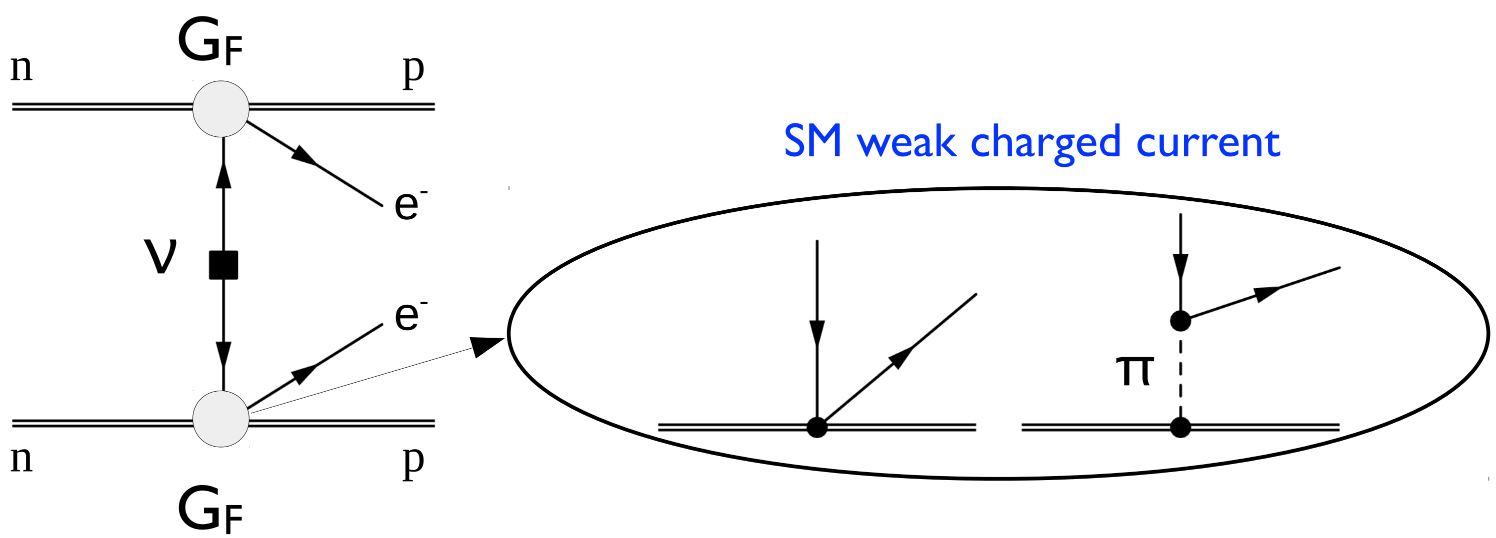
Hadronic input is g_A

Assume for the moment Weinberg counting
for contact 4N interactions ($1/\Lambda_\chi^2$)

0νββ potential from light ν_M

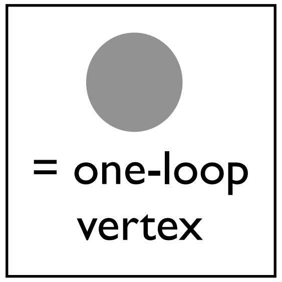


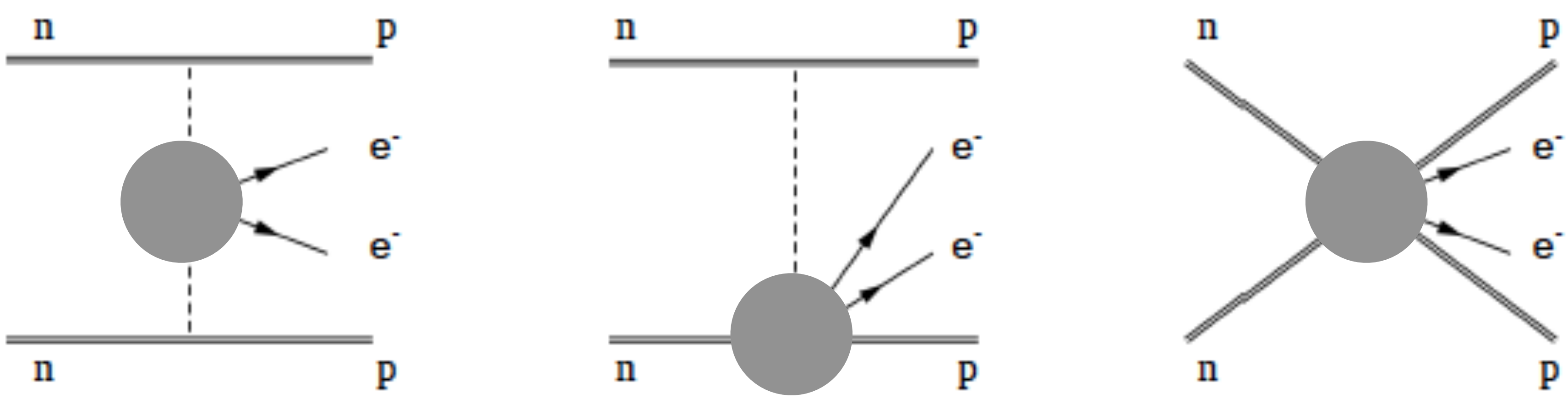
- N^{2}LO:

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

1. Corrections to 1-body currents (radii, magnetic moments, …) usually taken into account via nucleon form factors

$0\nu\beta\beta$ potential from light ν_M





- N^{2}LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)}\log\frac{m_\pi^2}{\mu_{\rm us}^2} + \mathcal{V}_{CT}^{(a,b)}\right)$$

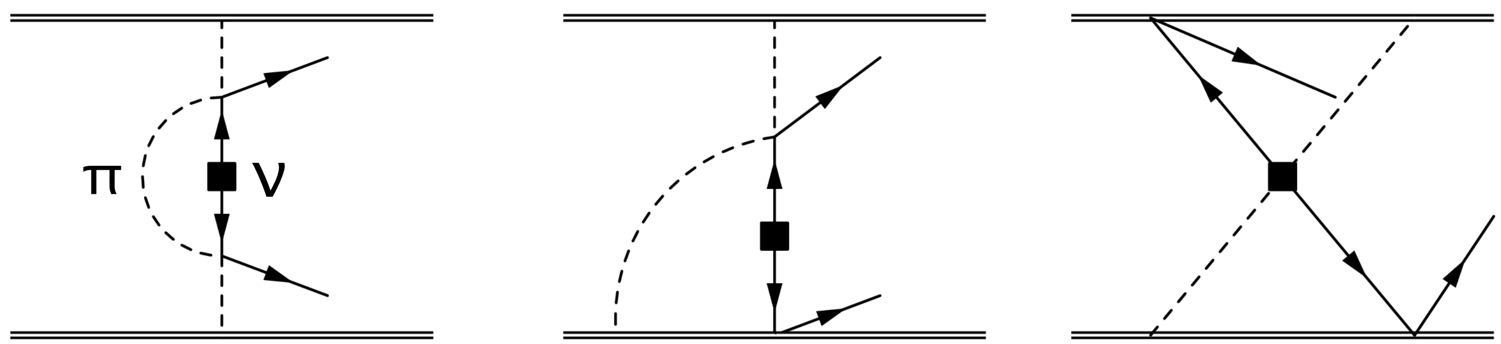
1. Corrections to 1-body currents (radii, magnetic moments, …) usually taken into account via nucleon form factors

2. Pion loops & local interactions: new, non-factorizable piece

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

$0\nu\beta\beta$ potential from light ν_M

Representative loop diagrams



- N^2LO:

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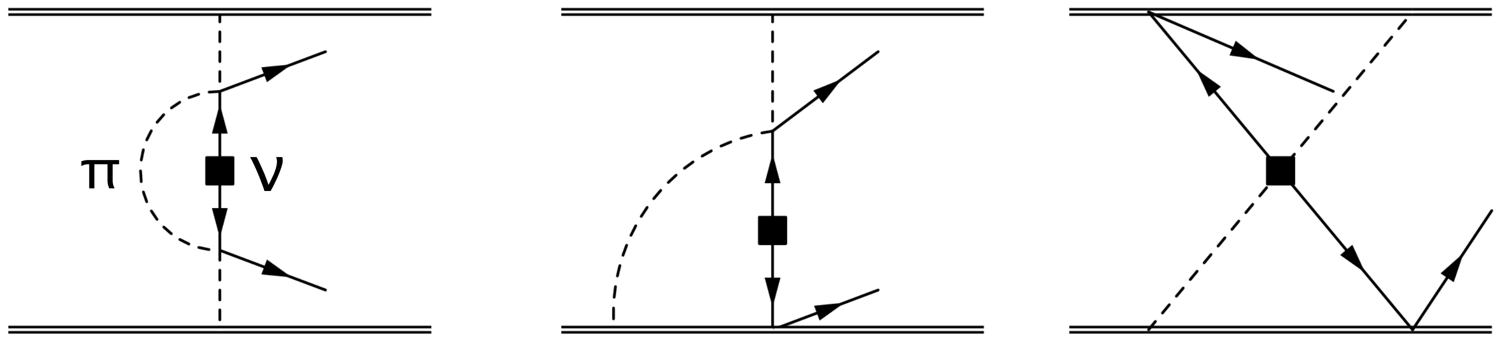
$$\mathcal{V}_{VV}^{(a,b)} = -\frac{g_A^2}{(4\pi F_\pi)^2} \frac{\boldsymbol{\sigma}^{(a)} \cdot \mathbf{q}\, \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q}}{m_\pi^2} \times \left\{ \frac{2(1-\hat{q})^2}{\hat{q}^2(1+\hat{q})} \log(1+\hat{q}) - \frac{2}{\hat{q}} + \frac{7-3\hat{q}L_\pi}{(1+\hat{q})^2} + \frac{L_\pi}{1+\hat{q}} \right\}$$

$$\hat{q} = -q^2/m_\pi^2 \qquad L_\pi = \log \frac{\mu^2}{m_\pi^2}.$$

$0\nu\beta\beta$ potential from light ν_M

Representative loop diagrams

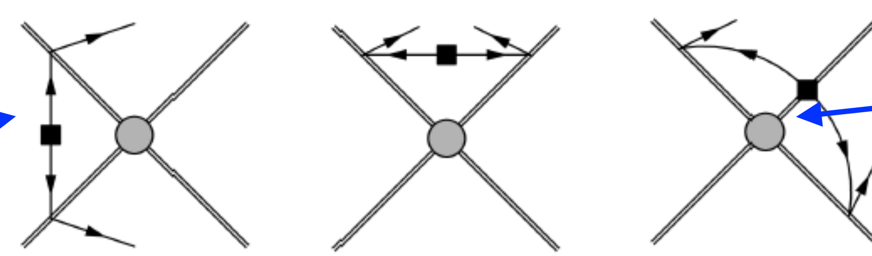


- N^2LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log \frac{m_\pi^2}{\mu_{\rm us}^2} + \mathcal{V}_{CT}^{(a,b)} \right)$$

- To define V_ν, need to subtract contribution from ultrasoft ν's

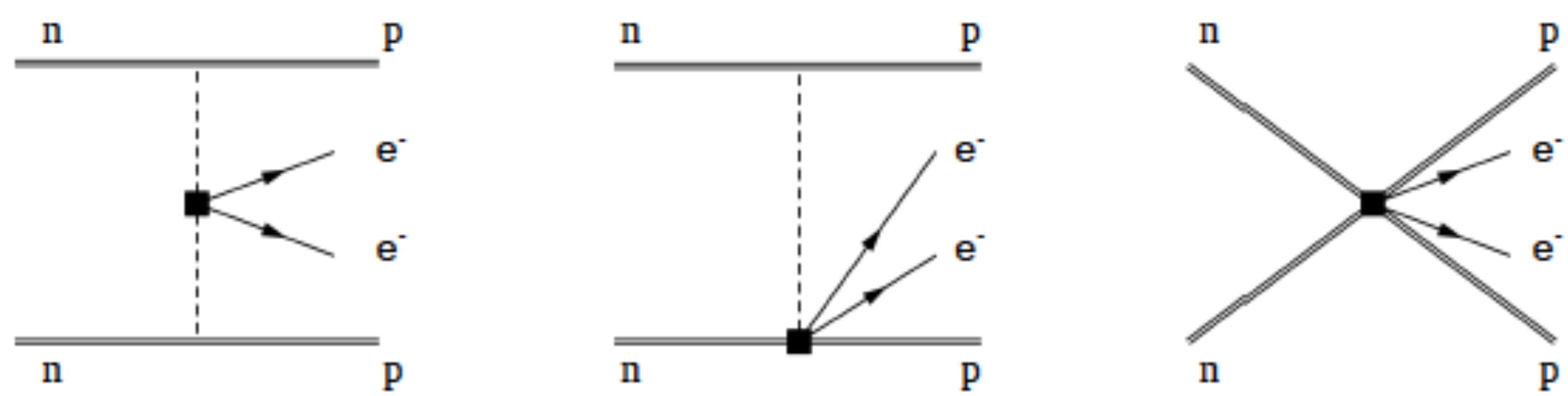
Ultrasoft ν's still present in low-energy theory



Leading order NN potential

$0\nu\beta\beta$ potential from light ν_M

Counterterm diagrams



- N^2LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log\frac{m_\pi^2}{\mu_{us}^2} + \mathcal{V}_{CT}^{(a,b)}\right)$$

- Loops are UV divergent: need LECs encoding physics at E ≳ GeV

$$\mathcal{V}_{CT}^{(a,b)} = \frac{g_A^2}{(4\pi F_\pi)^2}\frac{\boldsymbol{\sigma}^{(a)}\cdot\vec{q}\,\boldsymbol{\sigma}^{(b)}\cdot\vec{q}}{m_\pi^2}\left[\frac{5}{6}g_\nu^{\pi\pi}\frac{\hat{q}}{(1+\hat{q})^2} - g_\nu^{\pi N}\frac{1}{1+\hat{q}}\right] - g_\nu\,\mathbf{1}^{(a)}\times\mathbf{1}^{(b)}$$

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

Scaling of contact 4N operators

- We know that Weinberg counting is not consistent for NN scattering
- m_π dependence of short-range nuclear force should be N^{2}LO

$$\mathcal{L} = -C\,\bar{N}N\bar{N}N - \frac{m_\pi^2}{(4\pi F_\pi)^2} D_2\,\bar{N}N\bar{N}N \qquad C, D_2 \sim 1/F_\pi^2$$

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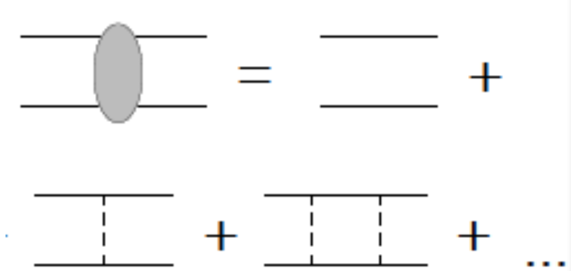
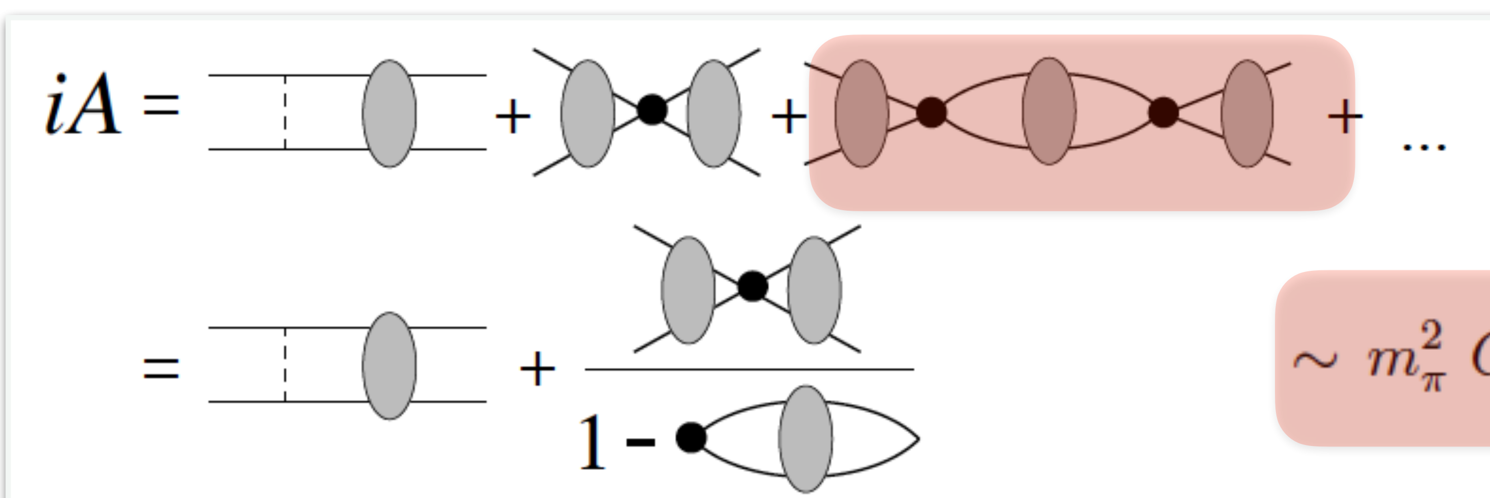
$$\mathcal{L} = -C\ \bar{N}N\bar{N}N - \frac{m_\pi^2}{(4\pi F_\pi)^2} D_2\ \bar{N}N\bar{N}N \qquad C, D_2 \sim 1/F_\pi^2$$

- But UV divergence of the LO amplitude requires promoting it to LO!

Kaplan-Savage-Wise nucl-th/9605002





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

What about contact term in 0νββ?

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Editors' Suggestion | Featured in Physics

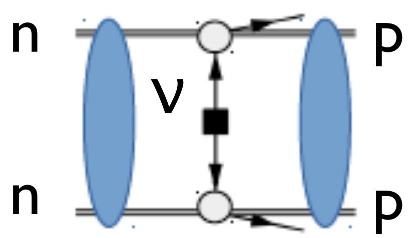
New Leading Contribution to Neutrinoless Double-β Decay

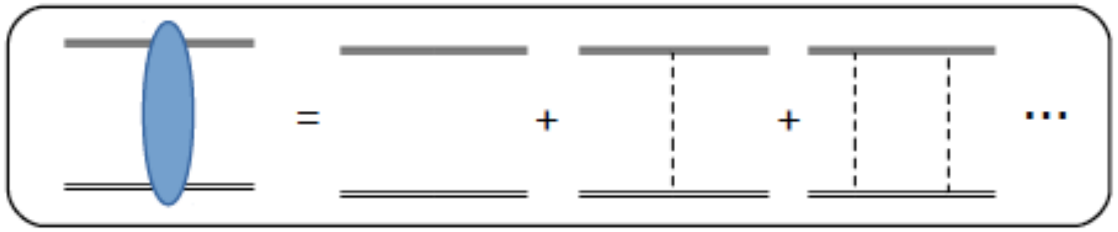
Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1]
Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]

What about contact term in 0νββ?

- Study UV divergences in nn→ppee amplitude, with LO strong potential

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





finite

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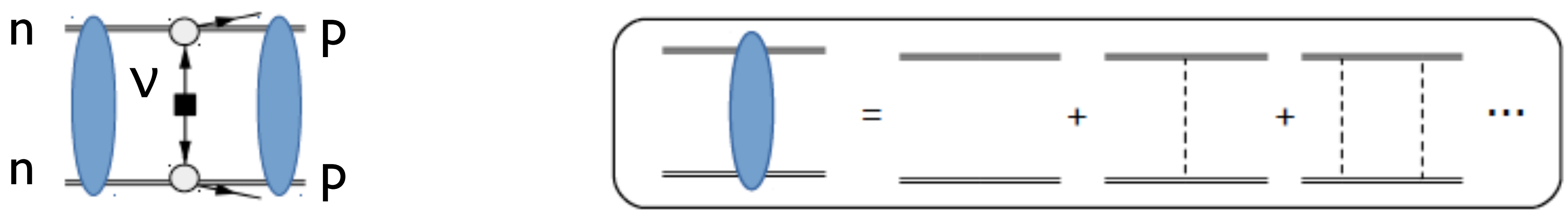

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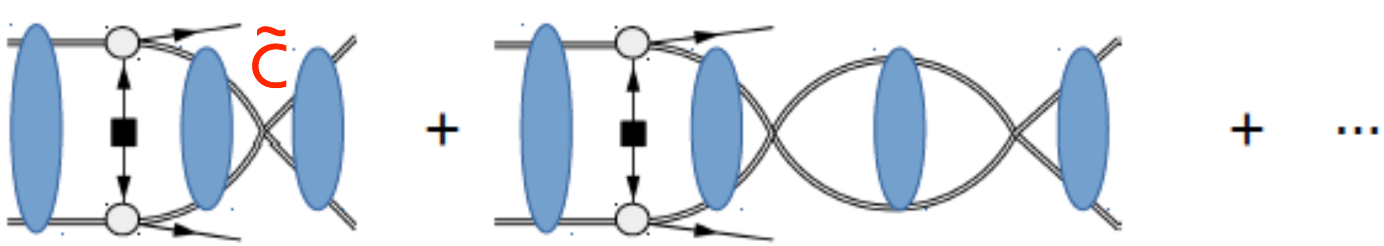

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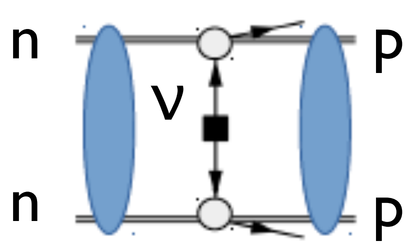

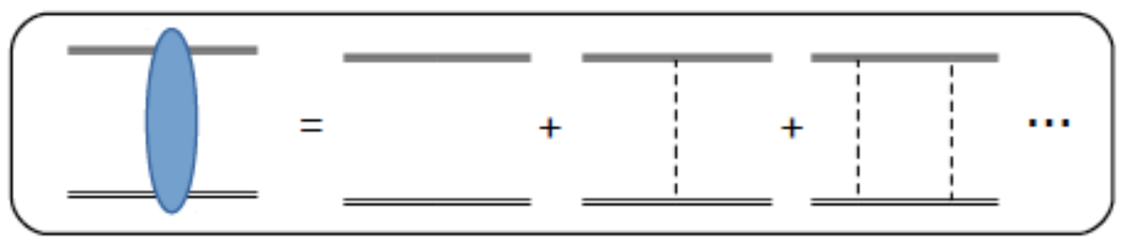

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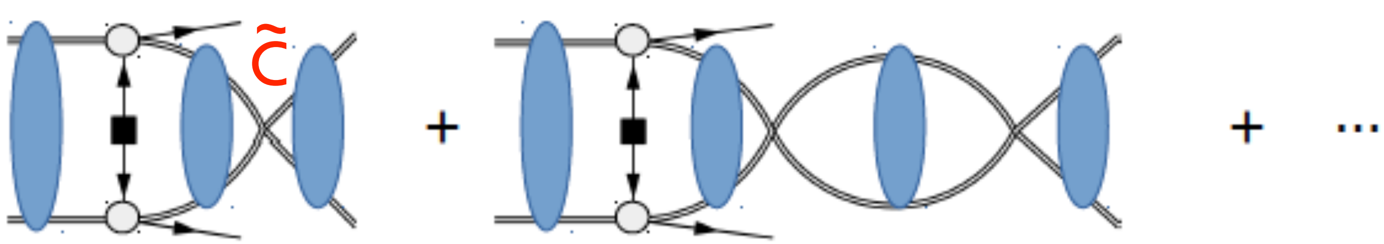

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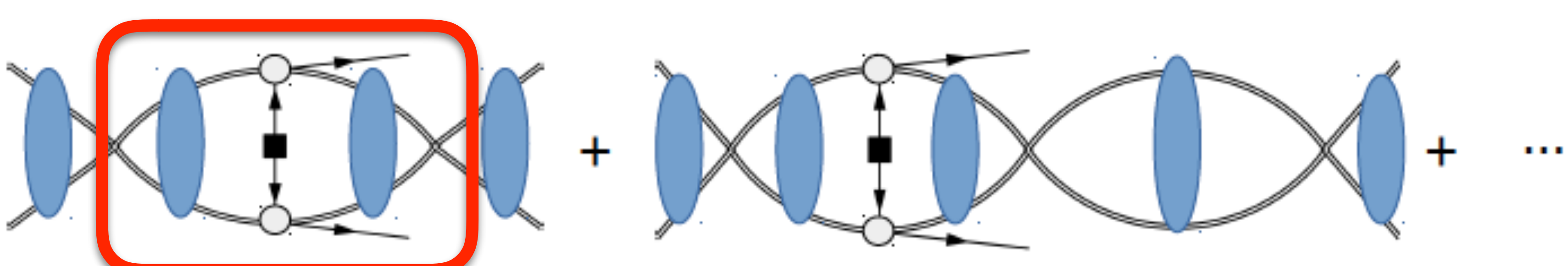


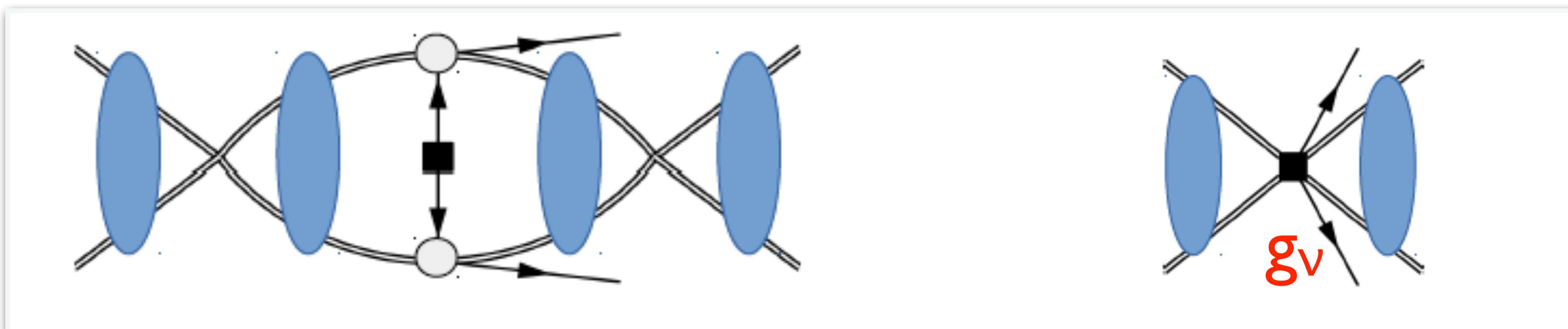
2-loop diagram is UV divergent!

What about contact term in 0νββ?

- Study UV divergences in nn→ppee amplitude, with LO strong potential

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

- Renormalization requires contact LNV operator at LO!



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

- The coupling scales as $g_\nu \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$, same order as $1/q^2$ from tree-level neutrino exchange

If you don’t like Feynman diagrams…

- Same conclusion obtained by solving the Schroedinger equation
  - Use smeared delta function to regulate short range strong potential

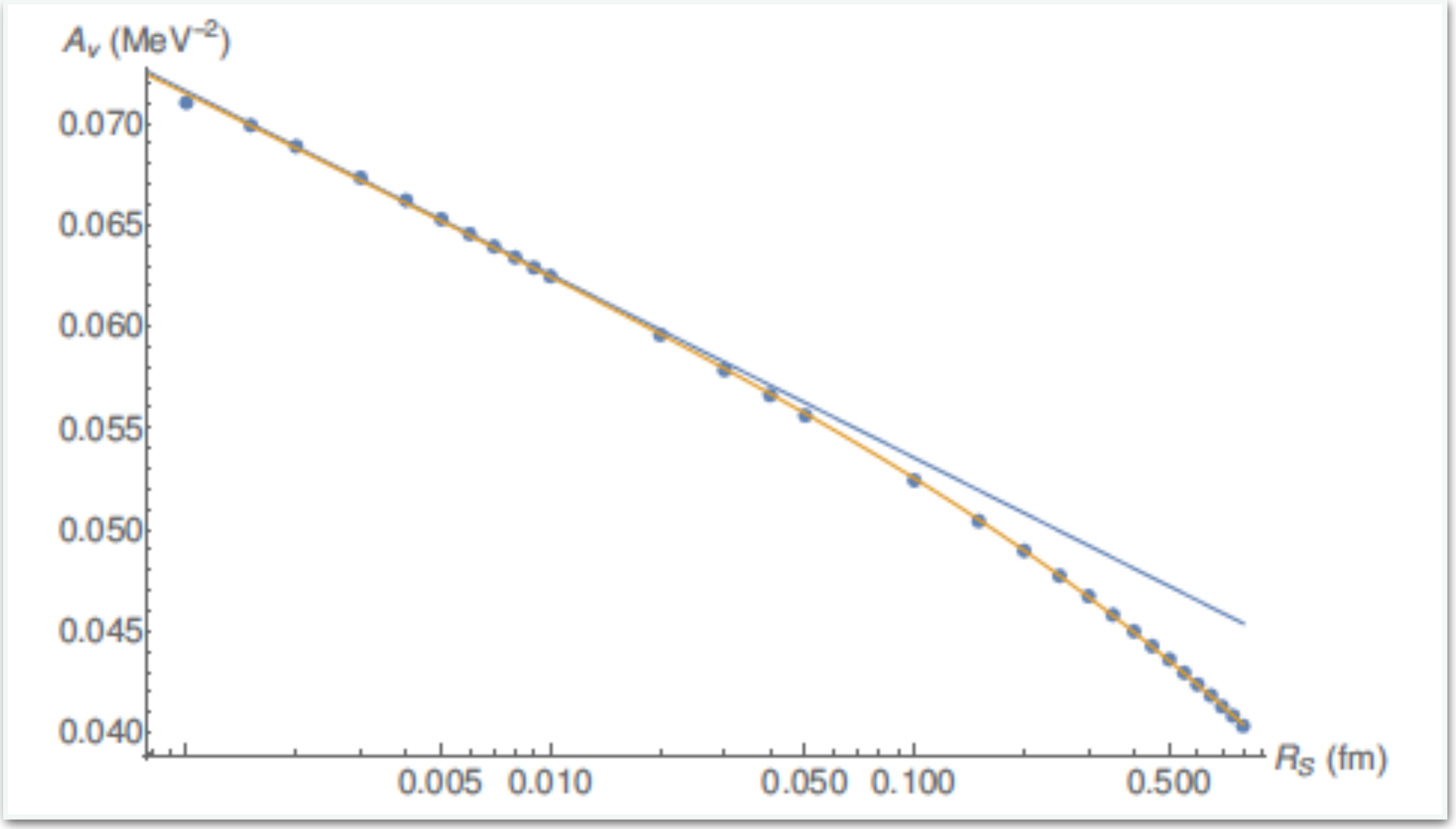
$$\delta^{(3)}(\mathbf{r}) \to \frac{1}{\pi^{3/2} R_S^3} e^{-\frac{r^2}{R_S^2}}$$

  - Compute amplitude

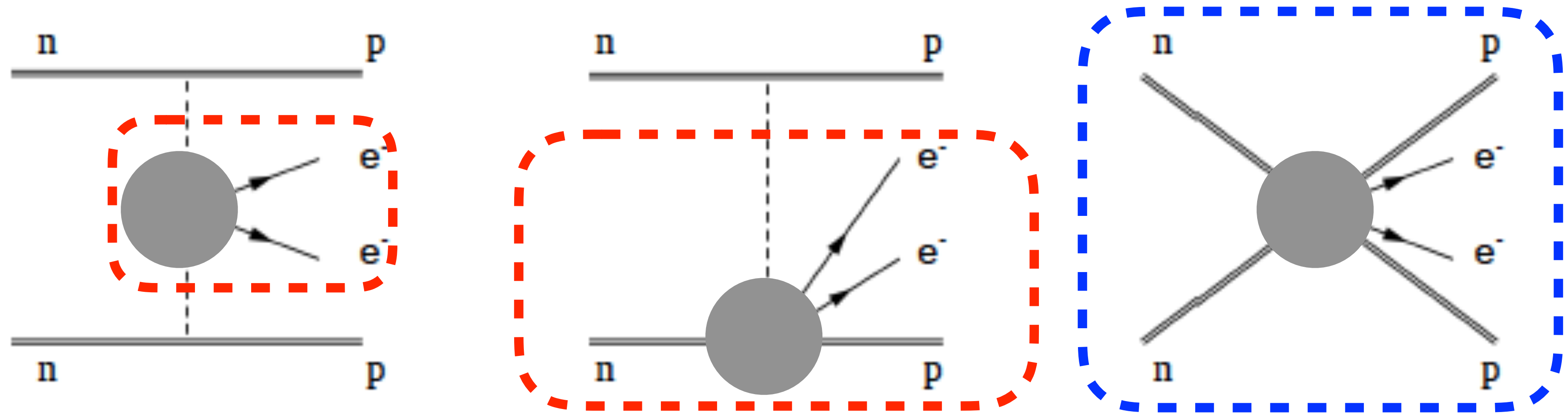
$$\mathcal{A}_\nu = \int d^3\mathbf{r}\, \psi_{\mathbf{p}'}^{-}(\mathbf{r}) V_\nu(\mathbf{r}) \psi_{\mathbf{p}}^{+}(\mathbf{r})$$

- Logarithmic dependence on R_S ⇒

  need LO counterterm $g_\nu \sim 1/F_\pi^2 \log R_S$ to obtain physical, regulator-independent result



Estimating the LECs (I)



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

- LECs can be fixed by matching χEFT to lattice QCD calculation
- Need to calculate matrix elements of a non-local effective action

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

Scalar massless propagator

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

Estimating the LECs (2)

- LECs can be fixed by relating them to EM LECs (hard γ exchange)

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

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

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

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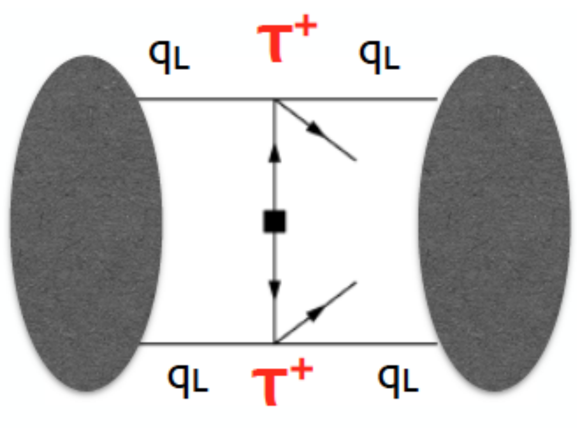
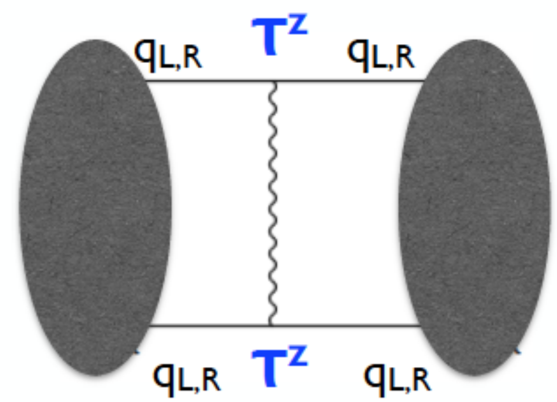
- Neutrino propagator ⇔ γ propagator in Feynman gauge

- ΔL=2 amplitude related by chiral symmetry to I=2 component of electromagnetic amplitude (J_{EM} x J_{EM})

0νββ vs EM isospin breaking





- Two I=2 operators involving four nucleons

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

EM case

$\mathcal{Q}_L = \frac{\tau^z}{2}, \mathcal{Q}_R = \frac{\tau^z}{2}$

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

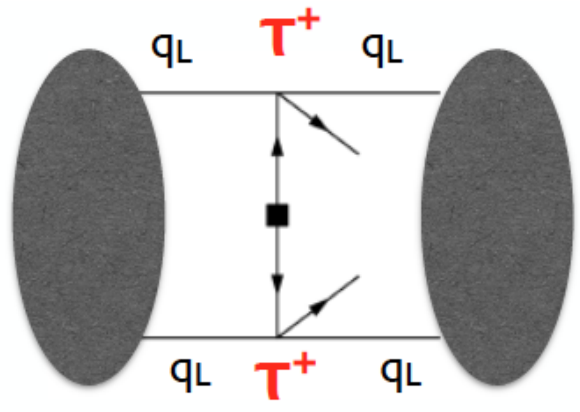
$$e^2 C_2 \left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L \mathcal{Q}_R]}{6} \bar{N}\boldsymbol{\tau}N \cdot \bar{N}\boldsymbol{\tau}N + L \to R \right)$$

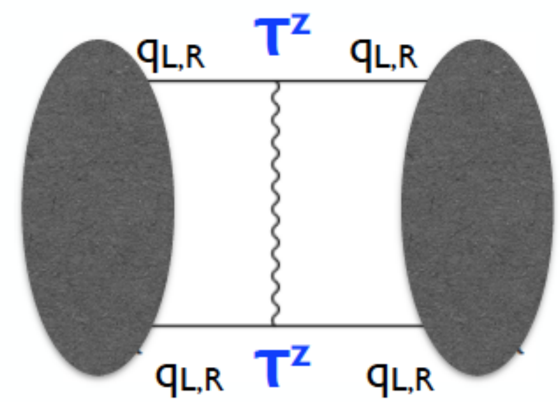
$$\mathcal{Q}_L = u^\dagger Q_L u$$

$$\mathcal{Q}_R = u Q_R u^\dagger$$

$$u = 1 + \frac{i\boldsymbol{\pi} \cdot \boldsymbol{\tau}}{2F_\pi} + \ldots$$

0νββ vs EM isospin breaking





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

ΔL=2 case

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

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

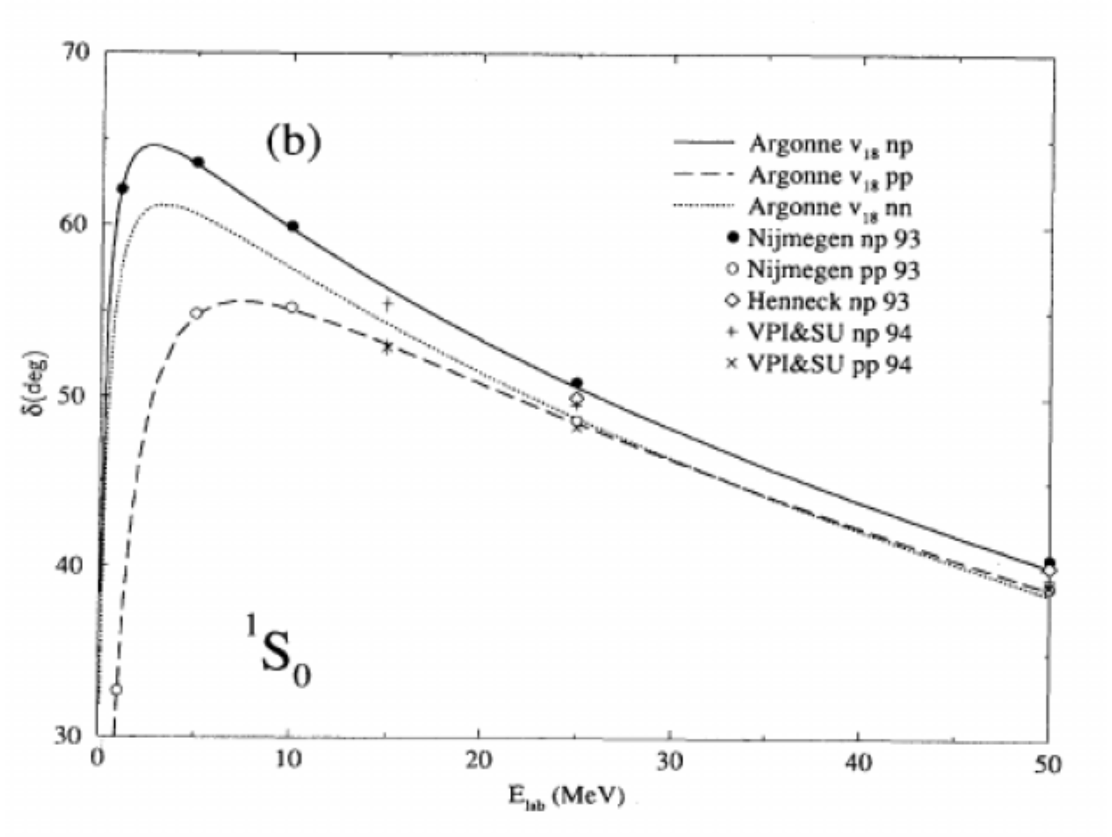
- Chiral symmetry ⇒ $g_\nu = C_1$

$0\nu\beta\beta$ vs EM isospin breaking

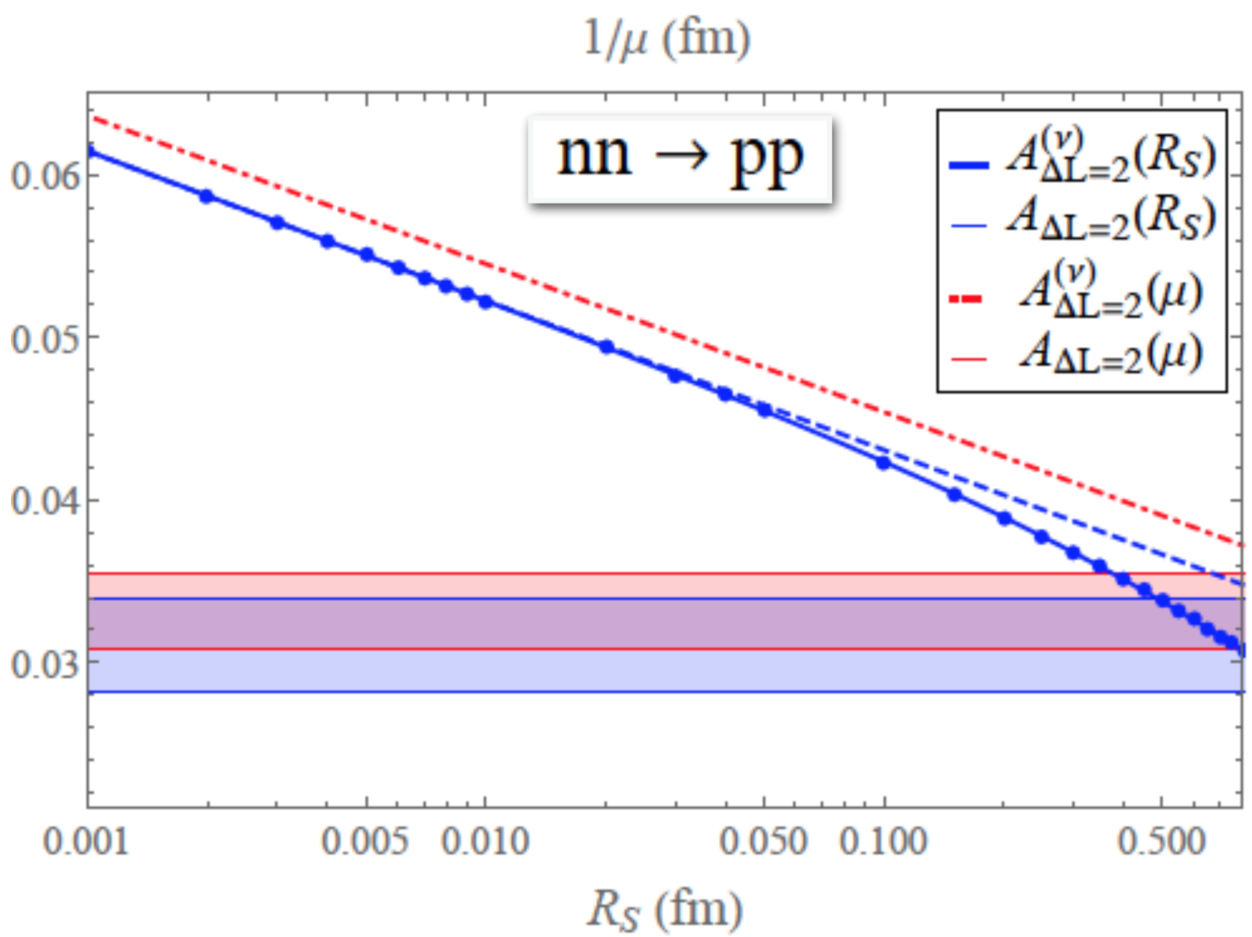
- NN observables cannot disentangle C_1 from C_2 (need pions), but provide data-based estimate of C_1+C_2

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

- Fit to data, including Coulomb potential, pion EM mass splitting, and contact terms confirms that $C_1 + C_2 \sim 1/F_\pi^2 >> 1/(4\pi F_\pi)^2$



Estimating numerical impact



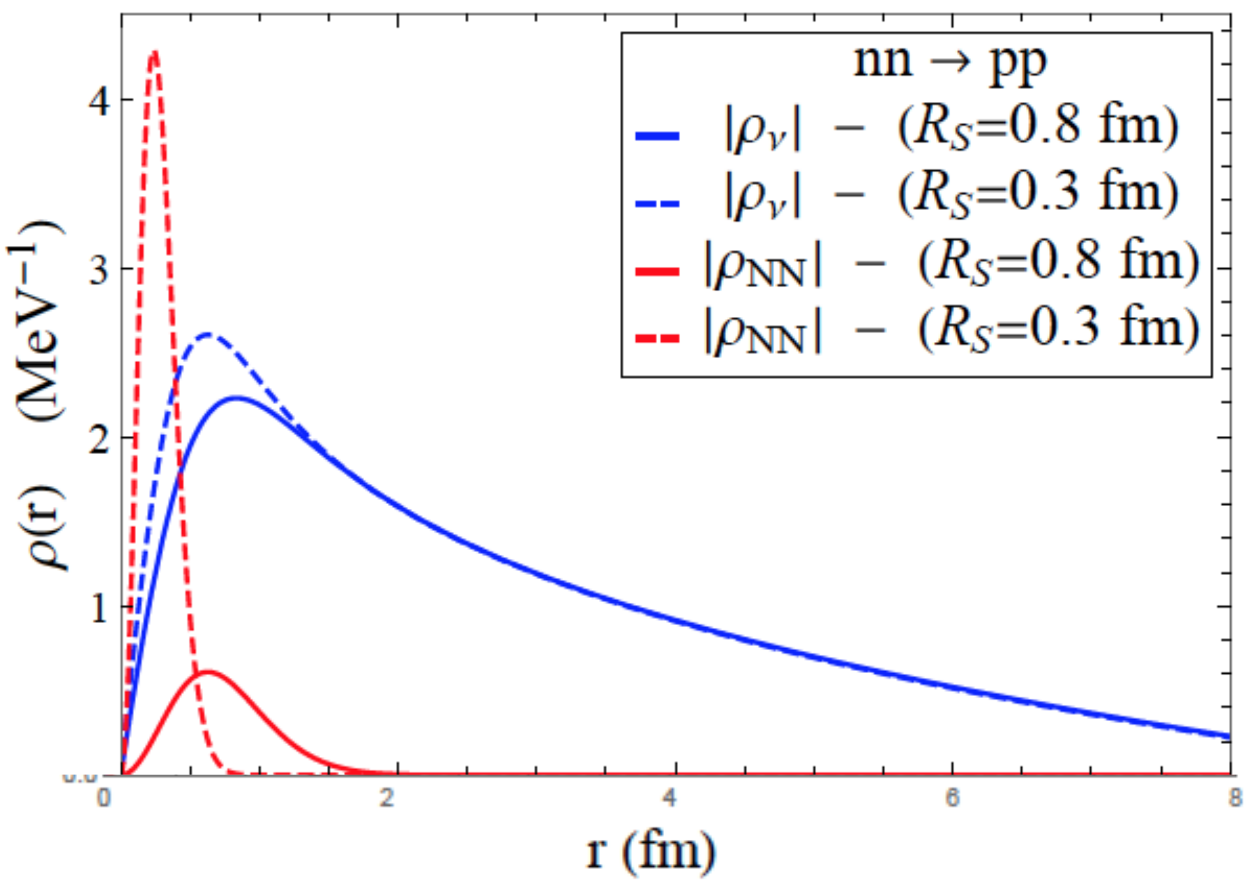
- Assume $C_1=C_2$ and hence $g_V=(C_1+C_2)/2$ at some scale R_S between 0.02 and 0.8 fm, with C_1+C_2 fit to NN data
- $A_{NN}+A_\nu$ is R_S (or μ) independent
- A_{NN}/A_ν ~ 10% (30%) at R_S~0.8 fm (0.3 fm) **
- ** Actual correction will be different because in general $C_1 \neq C_2$

Estimating numerical impact

$$A = \int dr \;\; \rho(r)$$

nn → pp

ΔI=0

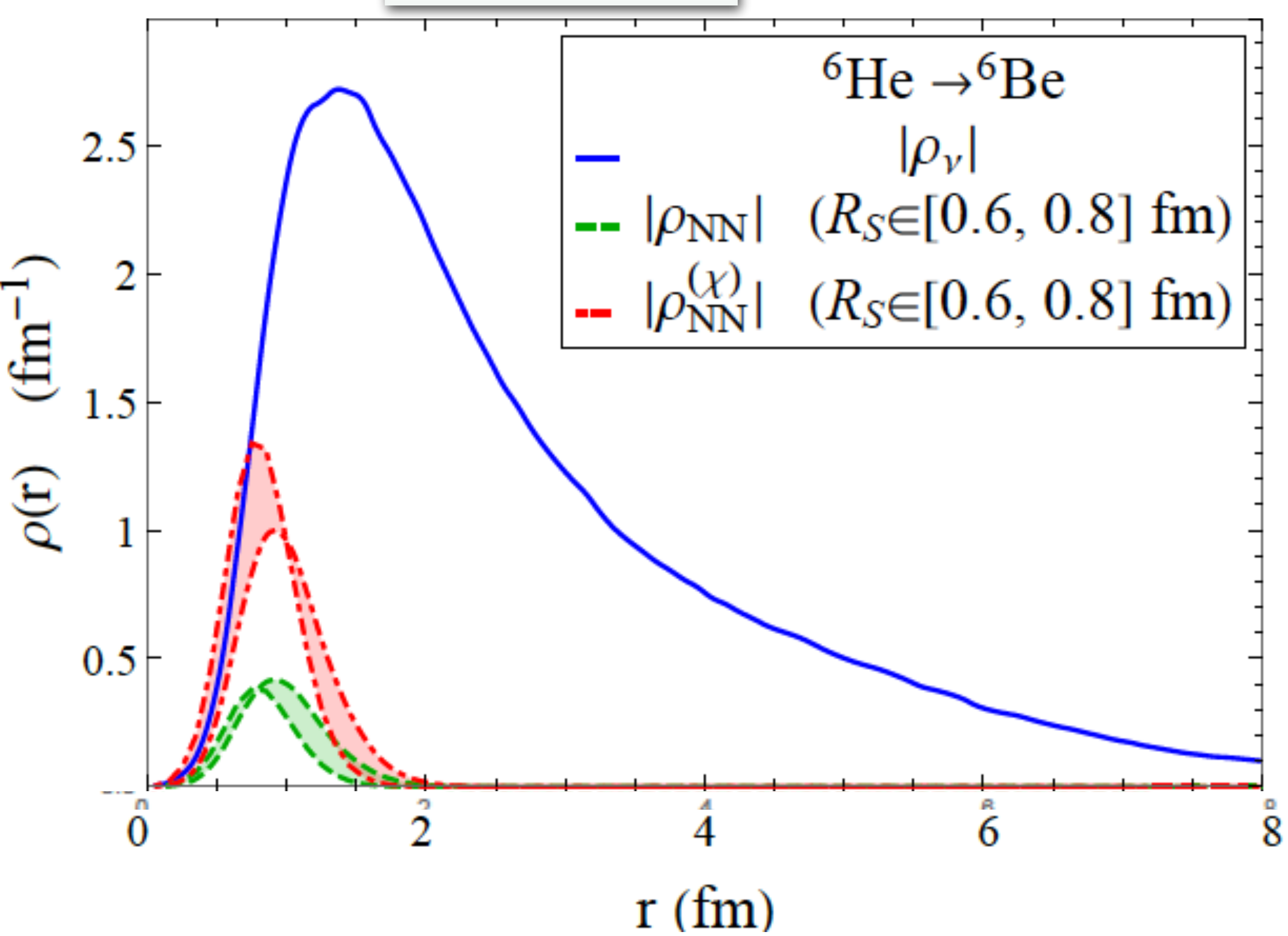


- Anatomy of this result: look at "matrix-element density" as function of inter-nucleon distance
- What about nuclei?
- We explored the impact on light nuclei with wavefunctions obtained via Variational Monte Carlo from AV18 (NN) + U9 (NNN) potentials

Estimating numerical impact

$$A = \int dr \ \rho(r)$$

$^6He \rightarrow {}^6Be$ ΔI=0



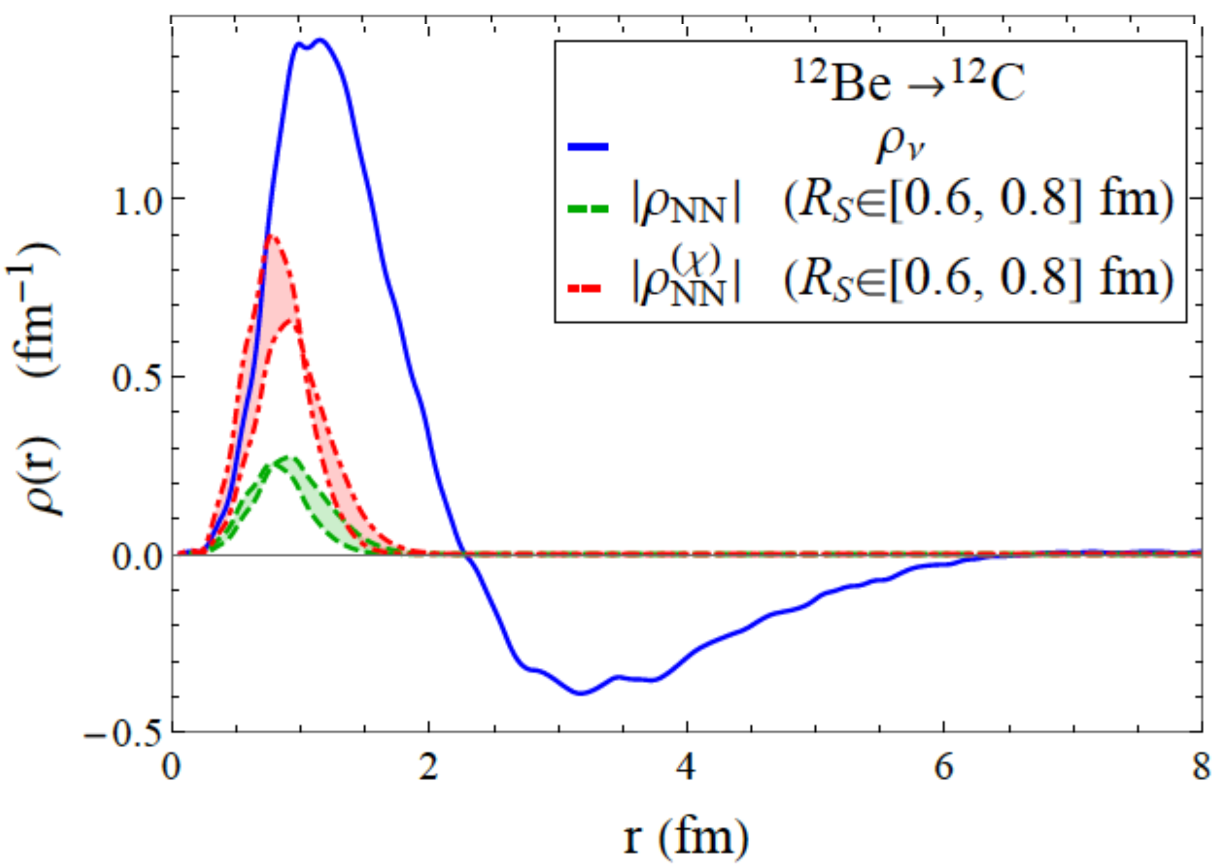
For ΔI=0 transitions situation is similar to nn→pp case

- Hybrid calculation at this stage: can't expect R_S-independence
- $g_\nu \sim (C_1+C_2)/2$ taken from fit to NN data (ours vs Piarulli et al. 1606.06335)

Estimating numerical impact

$$A = \int dr \;\; \rho(r)$$

$^{12}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}$ ΔI=2



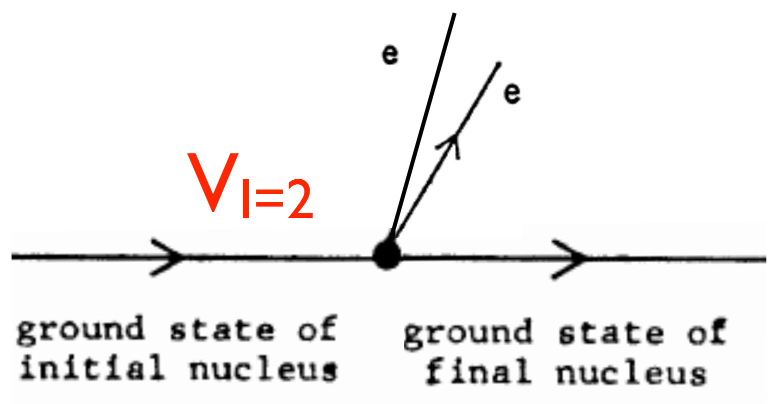
g_ν contribution sizable in
ΔI=2 transition (due to node):
for A=12, A_{NN}/A_ν = 25%-55%

Transitions of experimental interest (^{76}Ge→ ^{76}Se, …) have ΔI=2
⇒ $m_{\beta\beta}$ phenomenology can be significantly affected!

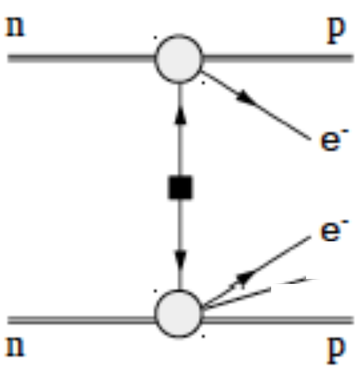
Anatomy of 0νββ amplitude in chiral EFT

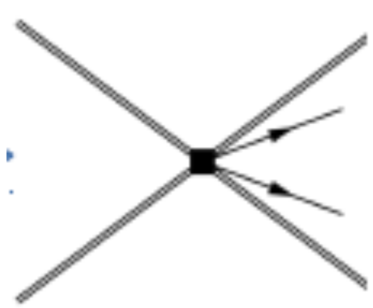
0νββ amplitude summary

Figure adapted from Primakoff-Rosen 1969



- Leading amplitude controlled by *ground state* matrix element of $V_{\nu,0}$

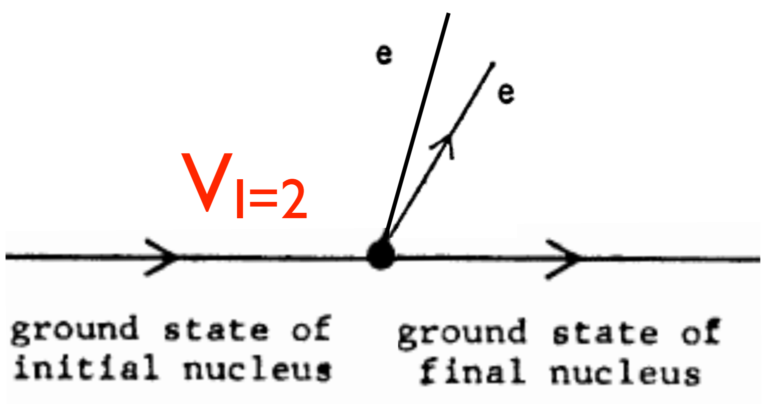




New short range contribution

0vββ amplitude summary

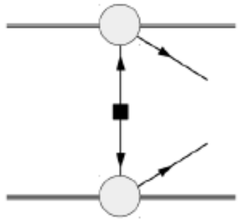
Figure adapted from Primakoff-Rosen 1969



- Leading amplitude controlled by *ground state* matrix element of $V_{\nu,0}$
- Modulo contact term, standard analysis agrees with $V_{\nu,0}$ if use closure and neglect $\bar{E} - E_i$

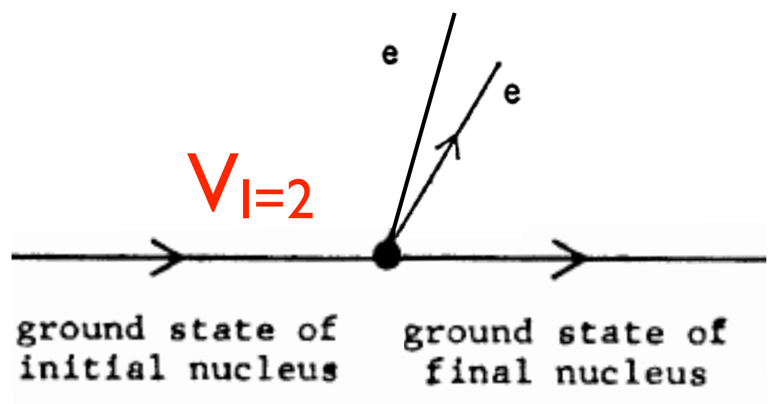
$$\sum_n \frac{\langle f|J^\mu(\mathbf{q})|n\rangle\langle n|J_\mu(-\mathbf{q})|i\rangle}{|\mathbf{q}|(|\mathbf{q}| + E_n - E_i)} \longrightarrow \frac{\langle f|J^\mu(\mathbf{q})J_\mu(-\mathbf{q})|i\rangle}{|\mathbf{q}|(|\mathbf{q}| + \bar{E} - E_i)} \longrightarrow \langle f|\frac{J^\mu(\mathbf{q})J_\mu(-\mathbf{q})}{|\mathbf{q}|^2}|i\rangle$$

$$|\mathbf{q}| \gg E_n - E_i$$



0νββ amplitude summary

Figure adapted from Primakoff-Rosen 1969



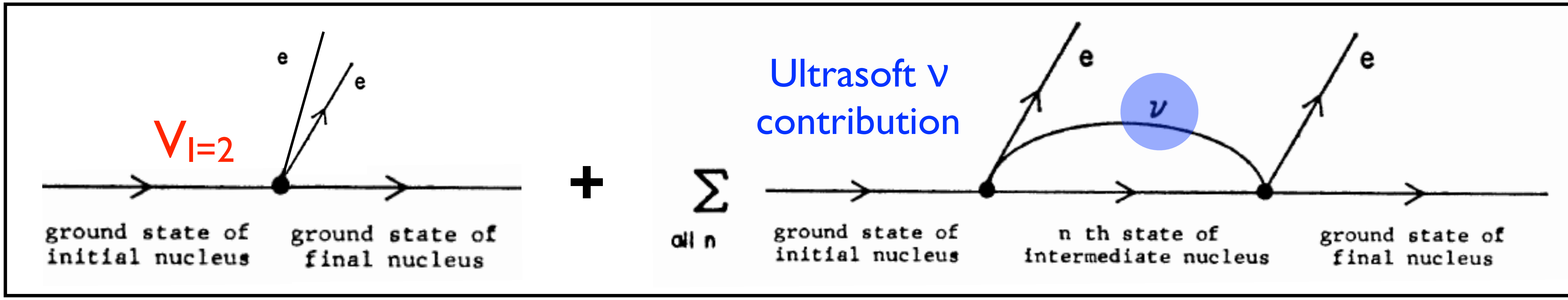
- N2LO amplitude (1):

  - Factorizable corrections to 1-body currents (radii,, …)
  - Ground state matrix element of $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$
    New non-factorizable effects as large as form-factor effects**

** S. Pastore, J. Carlson, V. Cirigliano, W. Dekens, E. Mereghetti, R. Wiringa 1710.05026, published in PRC

0νββ amplitude summary

Figure adapted from Primakoff-Rosen 1969



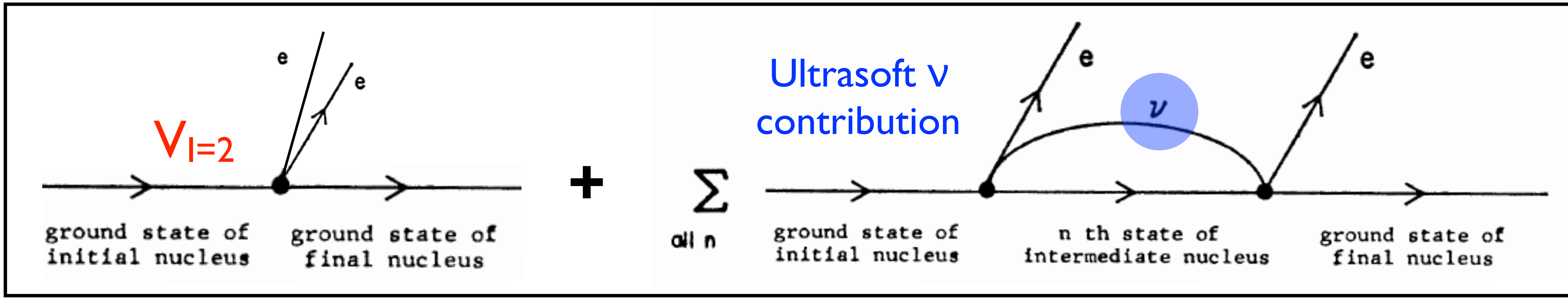
- N2LO amplitude (2): ultrasoft ν loop suppressed by $(E_n - E_i)/(4\pi k_F)$

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

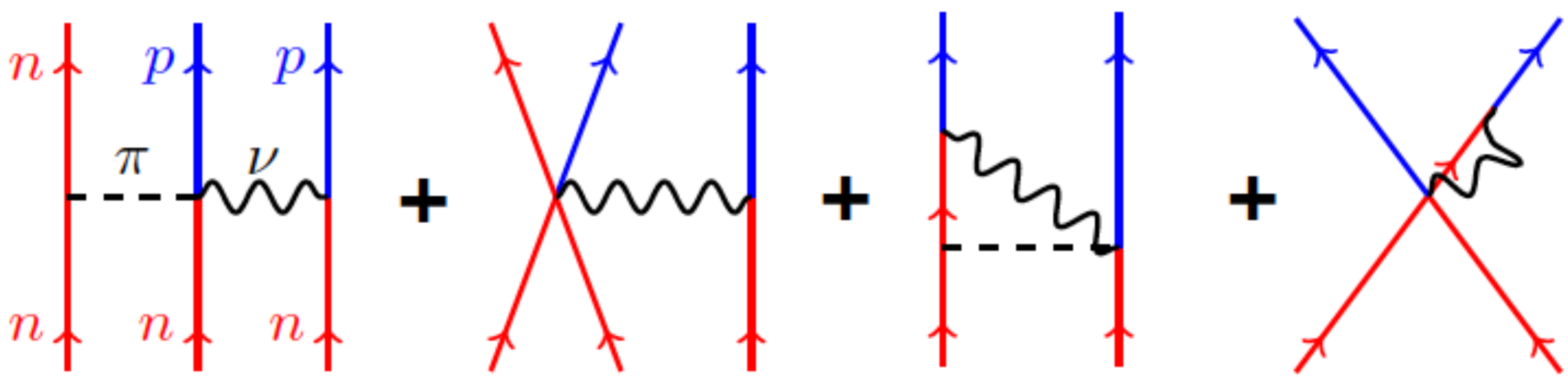
- Ultrasoft neutrinos couple to nuclear states: sensitivity to $E_n - E_i$ and $\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle$ that also determine 2νββ amplitude
- μ_{us} dependence cancels with $V_{\nu,2}$. Non-trivial consistency check!

0νββ amplitude summary

Figure adapted from Primakoff-Rosen 1969



- Note: 2-body x 1-body currents terms start at N3LO



From J. Engel's talk at INT, March 2018

Conclusions

- Chiral EFT analysis of light ν_M exchange contribution to $0\nu\beta\beta$
  - Identified potential to LO and N^2LO
  - Key new result: leading order contact nn → pp operator. LEC enhanced by $(4\pi)^2$ versus naive dimensional analysis. O(1) impact on sensitivity to $m_{\beta\beta}$
  - Corrections to "closure approximation" from "ultrasoft" neutrinos parameterized in terms $E_n - E_i$ and $\langle f |J_\mu| n\rangle\langle n| J^\mu |i\rangle$

- Outlook / future work:
  - Determination of LO coupling: match to lattice QCD, I=2 EM observables, models…
  - Scaling of contact nn → pp operators with derivatives