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Palm Springs, May 29 - June 3 2018

Neutrino-less double beta decay in chiral Effective Field Theory

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Outline

- Effective Field Theory (EFT) framework for $0\nu\beta\beta$
- $0\nu\beta\beta$ from light Majorana ν exchange
  - *A new leading short-range contribution to the neutrino potential*
  - Quick tour of higher order corrections

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, Phys.Rev.Lett. 120 (2018) no.20, 202001

EFT framework for 0νββ

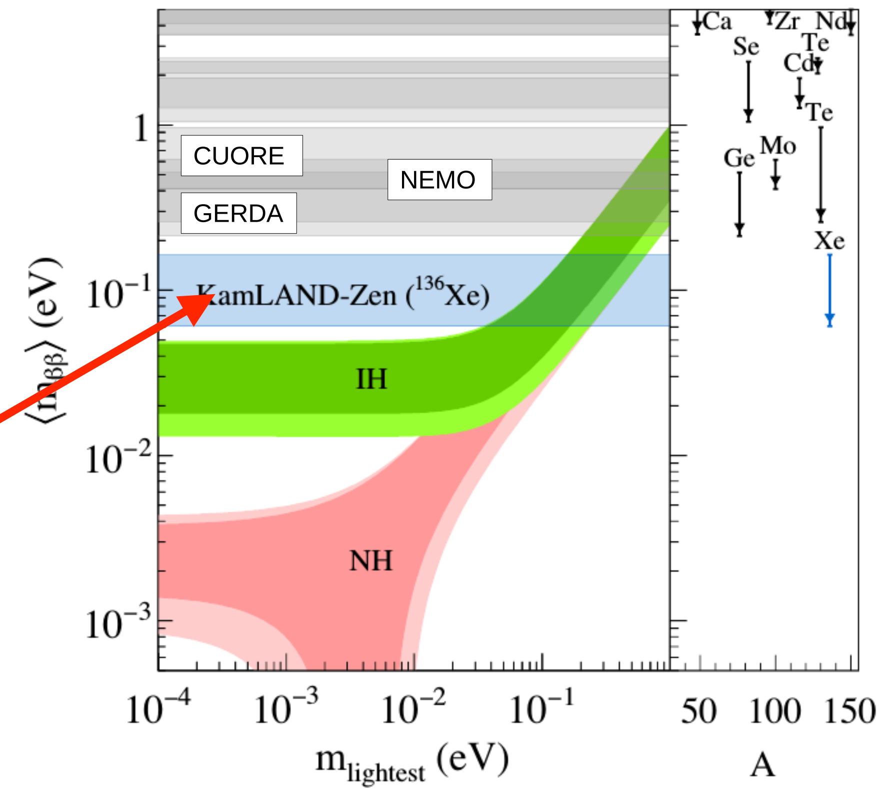
$$(N,Z) \to (N-2, Z+2) + e^- + e^-$$

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

- Impact of 0νββ results most efficiently analyzed in EFT framework:

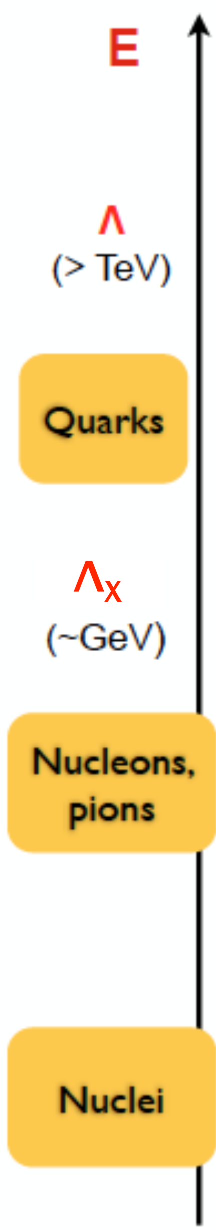
1. Classify sources of Lepton Number Violation and relate 0νββ to other LNV processes (such as pp → eejj at the LHC)

2. Organize contributions to hadronic and nuclear matrix elements in systematic expansion ⇒ controllable uncertainties



KamLAND-Zen coll., '16

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

EFT framework for 0νββ

E

Λ
(> TeV)

Quarks

Λ_χ
(~GeV)

Nucleons, pions

Nuclei

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

Integrate out heavy particles

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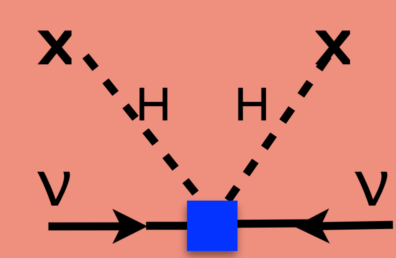
Hadronic matrix elements

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

Nuclear matrix elements

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

Focus on dim-5 operator
$O^{(5)} \sim LLHH$
(Majorana mass for ν)



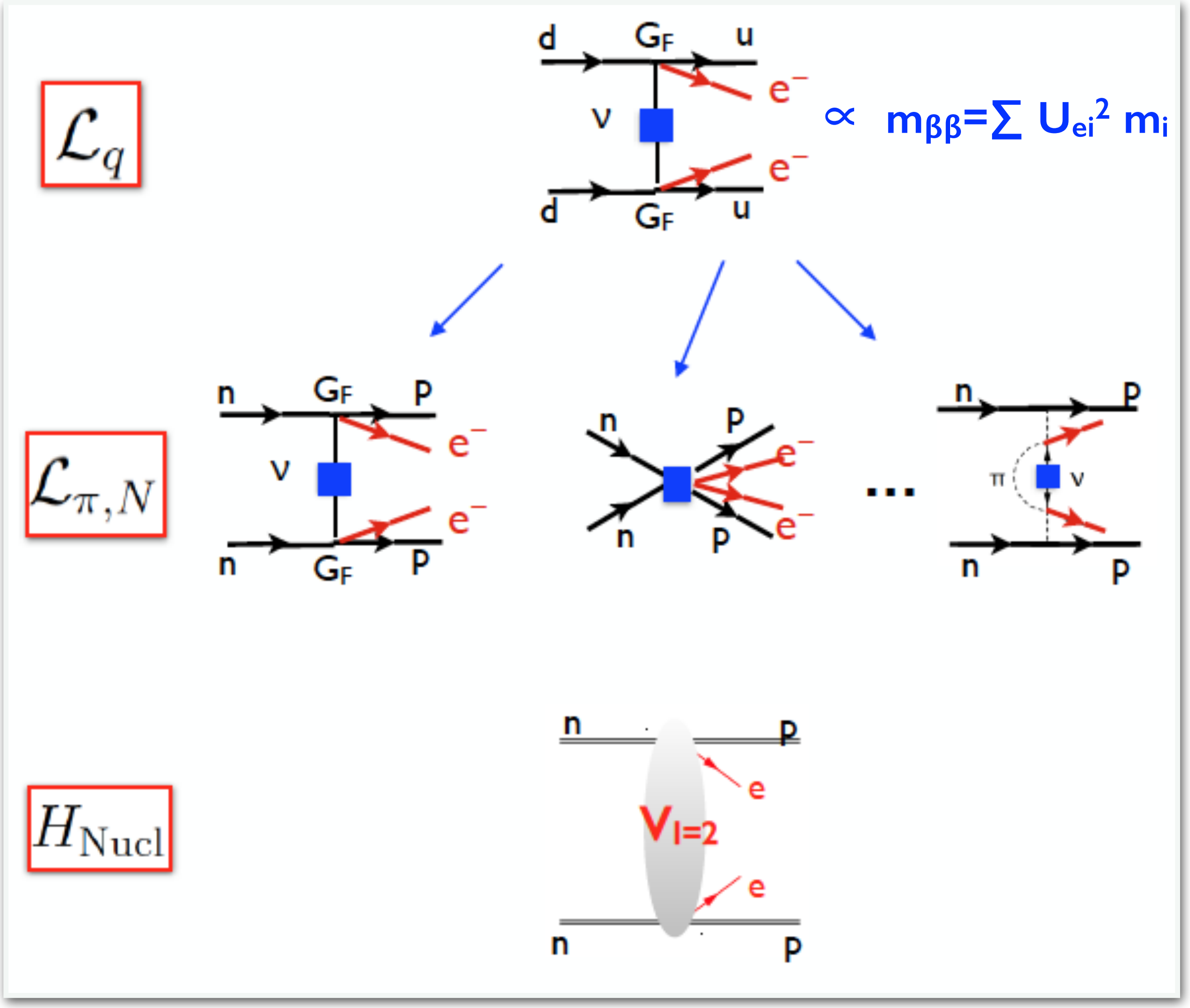
For dim-7,9 and general analysis see
VC, W. Dekens, M. Graesser, E. Mereghetti, J. de Vries
1708.09390 and 1806.xxxxx

Chain of EFT +
lattice QCD & many-body methods

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

From quarks to nuclei

- At $E \sim \Lambda_\chi \sim m_N \sim$ 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 ($Q \sim k_F \sim m_\pi$)
- Integrate out soft and potential ν's and π's with $(E,|\mathbf{p}|)\sim Q$ and $(E,|\mathbf{p}|)\sim(Q^2/m_N, Q)$ → obtain nuclear hamiltonian



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

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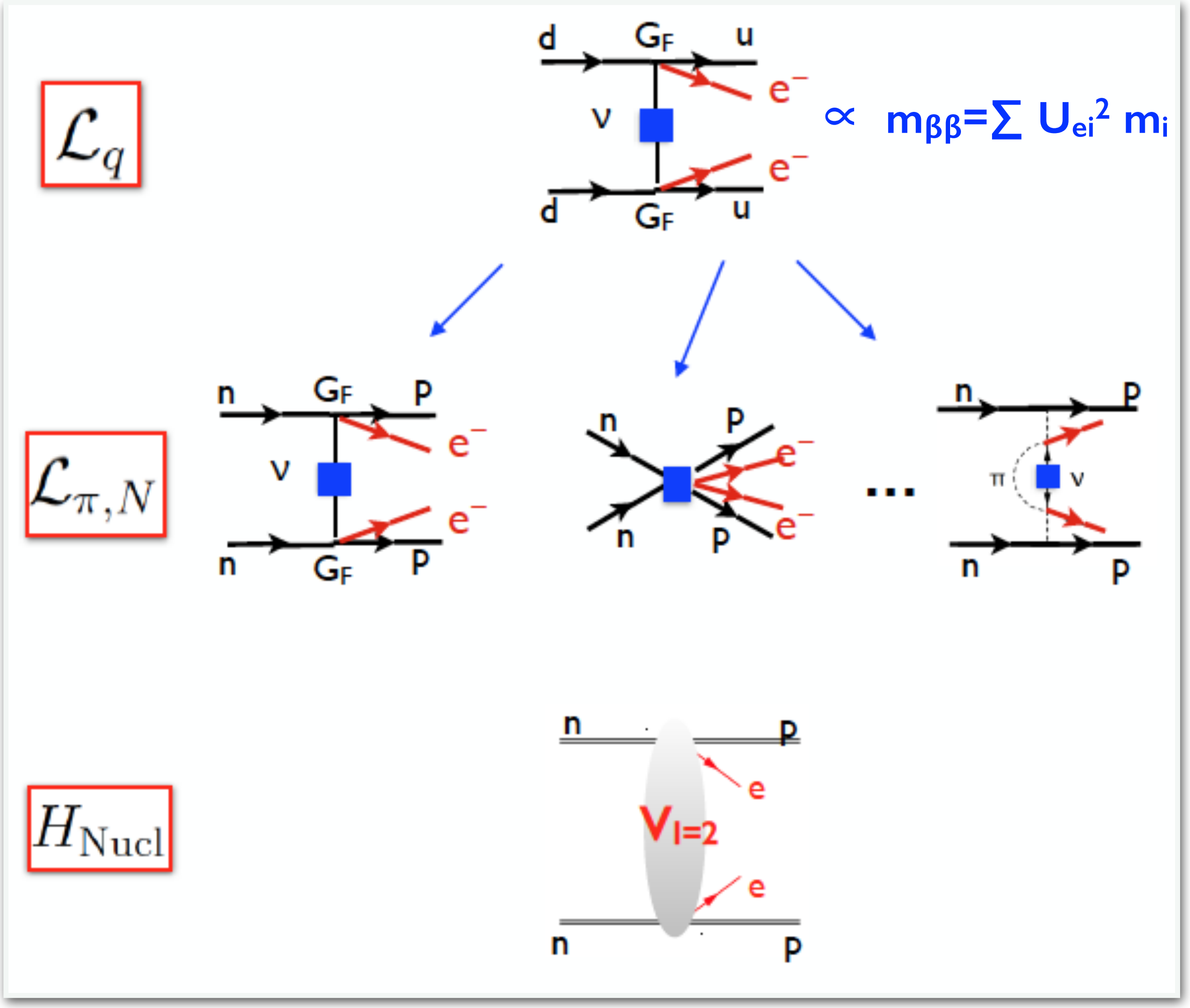

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"Ultra-soft" (e, ν) with $|\mathbf{p}|$, $E \ll k_F$ cannot be integrated out

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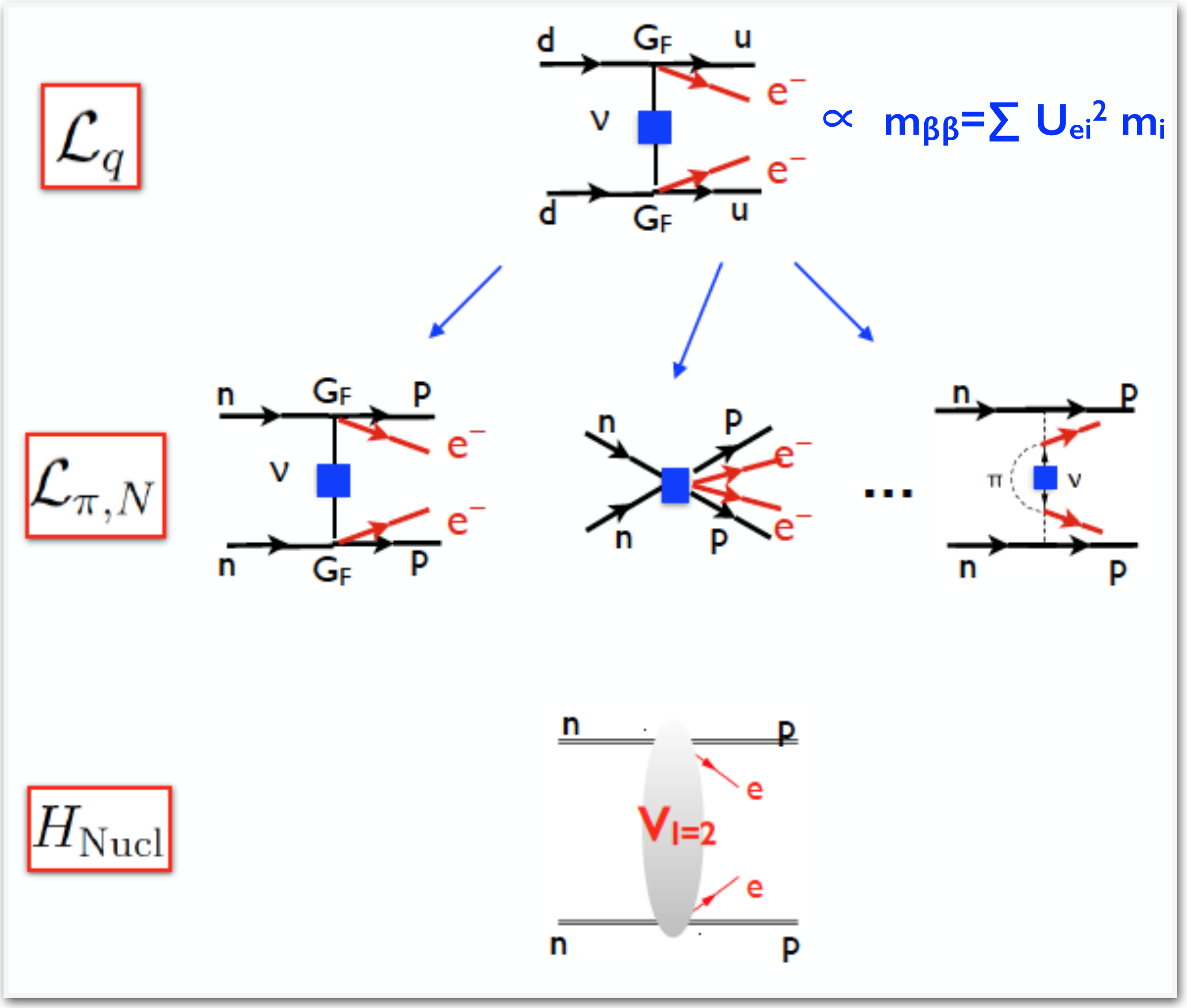

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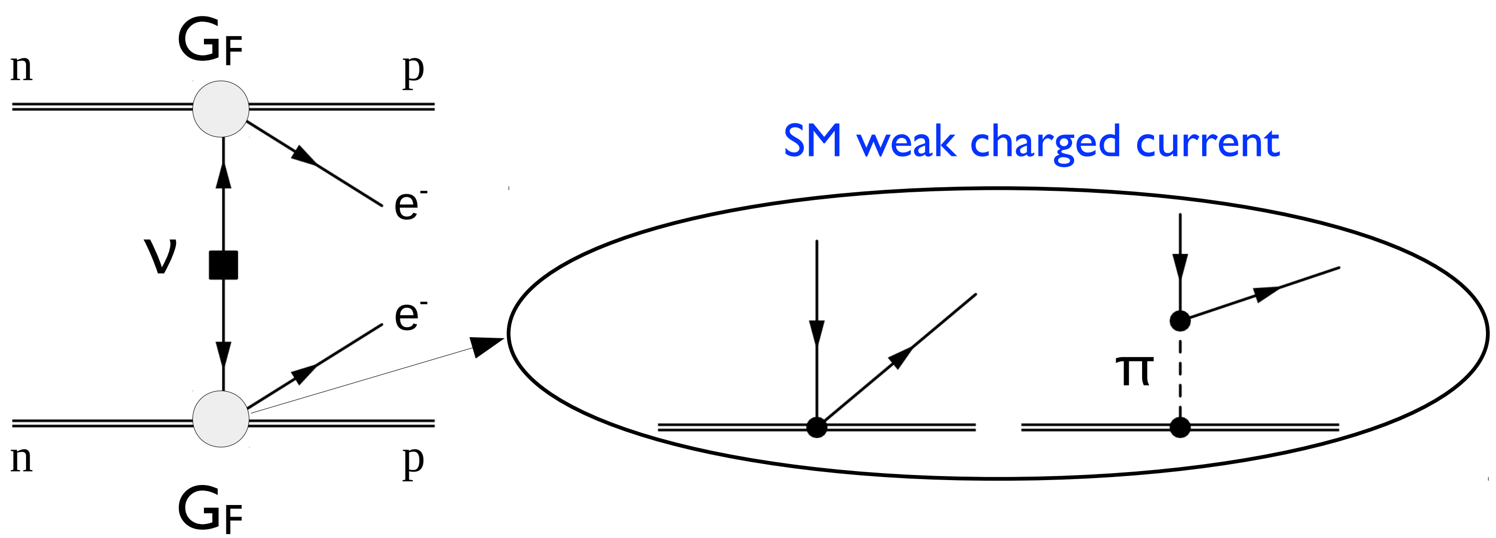
"Ultra-soft" (e, ν) with $|\mathbf{p}|$, $E \ll k_F$ cannot be integrated out

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

Leading order 0νββ potential

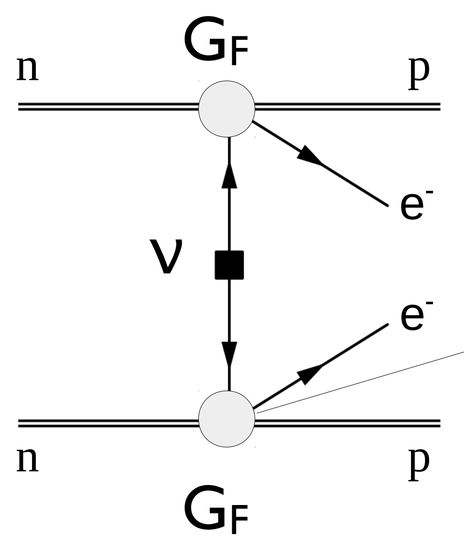


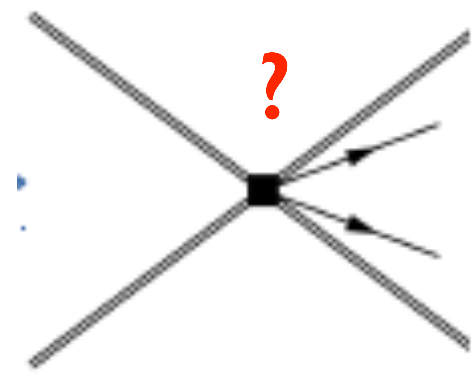
- Tree-level exchange of Majorana neutrinos

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

Hadronic input: g_A

Leading order 0νββ potential





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Hadronic input: g_A

- Symmetries allow non-derivative contact term

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

$g_\nu \sim 1/(4\pi F_\pi)^2$ in NDA / Weinberg counting (and hence sub-leading)
But is it?

Scaling of contact term in 0νββ

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

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

$\tilde{C} \sim 1/F_\pi^2$

from fit to a_{NN}

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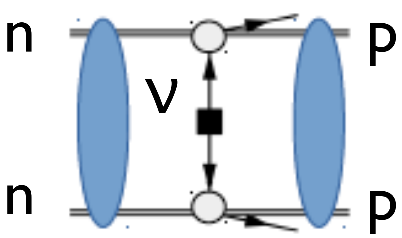

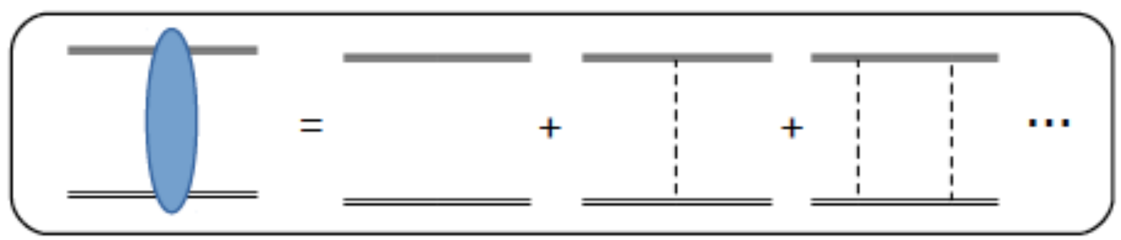

finite

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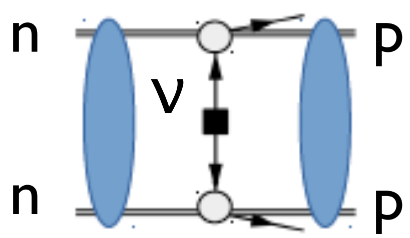
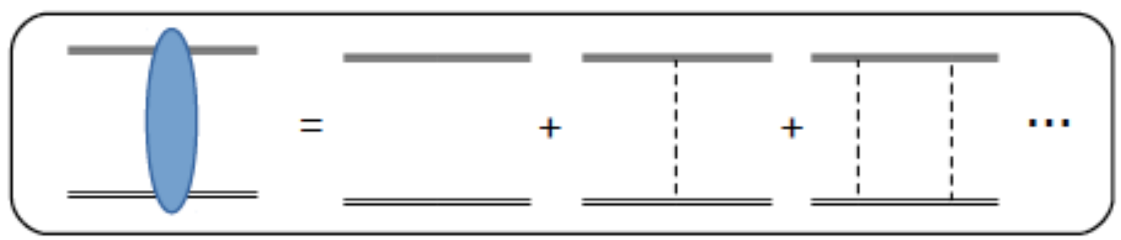
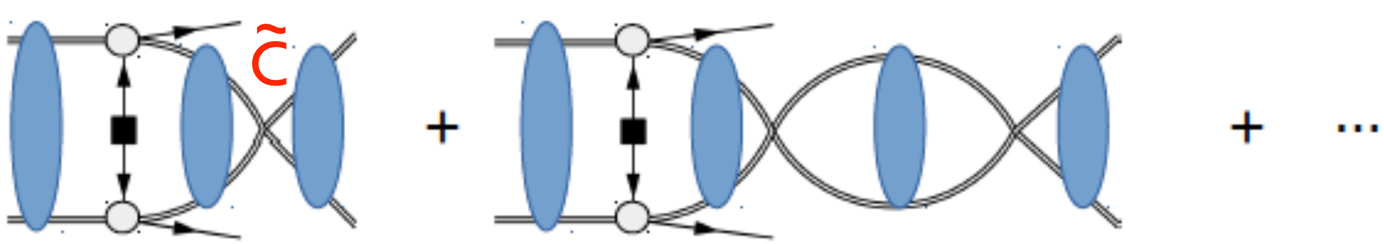




finite



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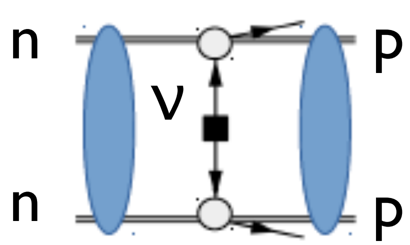

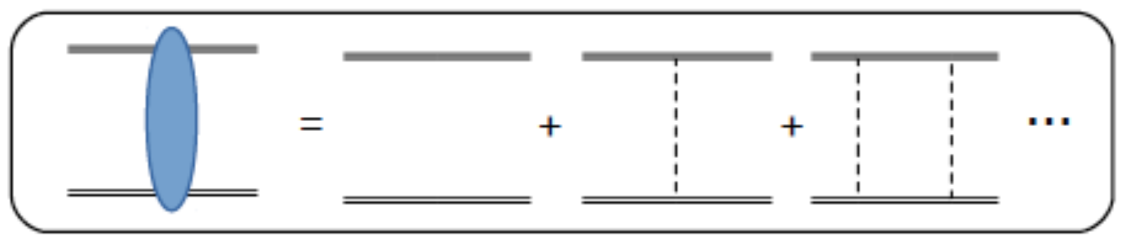

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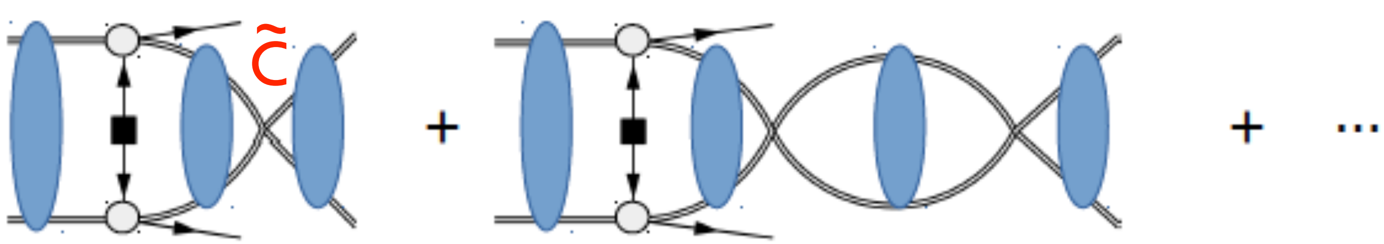

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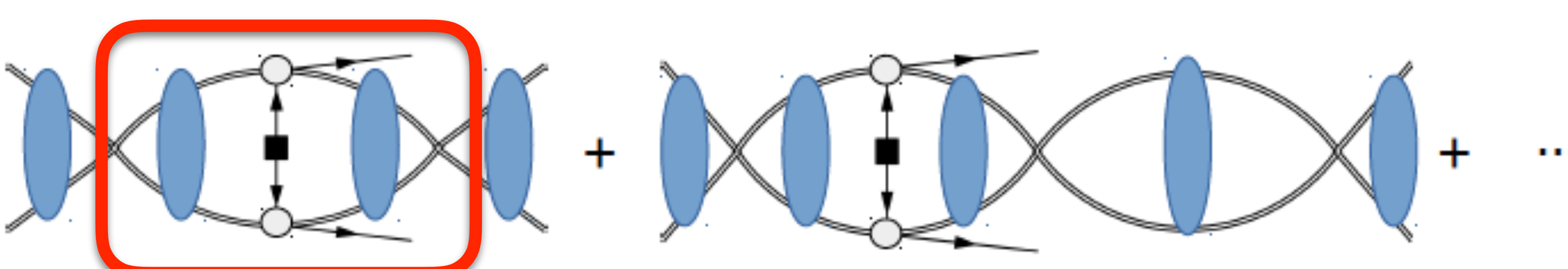

2-loop diagram is UV divergent!

Scaling of contact term in 0νββ

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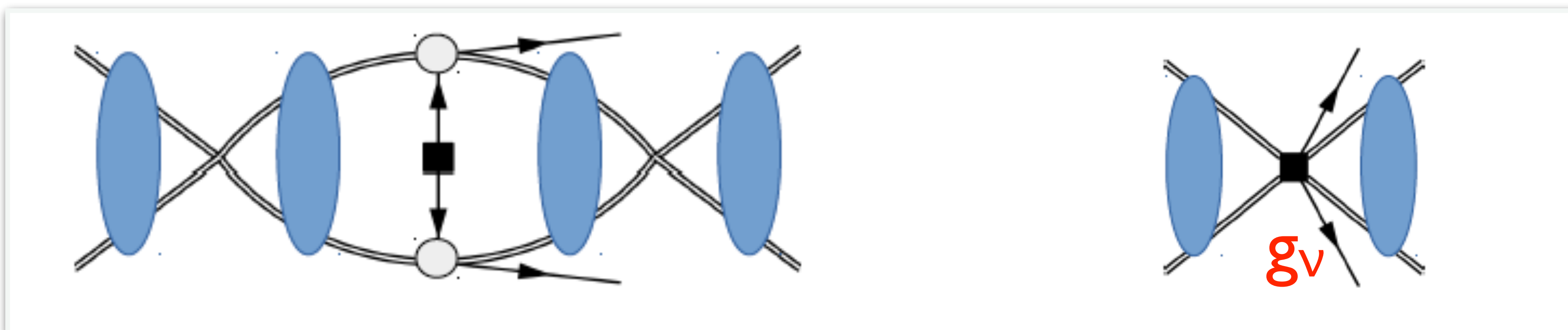
$\tilde{C} \sim 1/F_\pi^2$ from fit to a_{NN}

- 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 $g_\nu \sim 1/F_\pi^2 >> 1/(4\pi F_\pi)^2$, 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: $\tilde{C} \to \tilde{C}\,(R_S) \sim 1/F_\pi^2$

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

  - Compute amplitude

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

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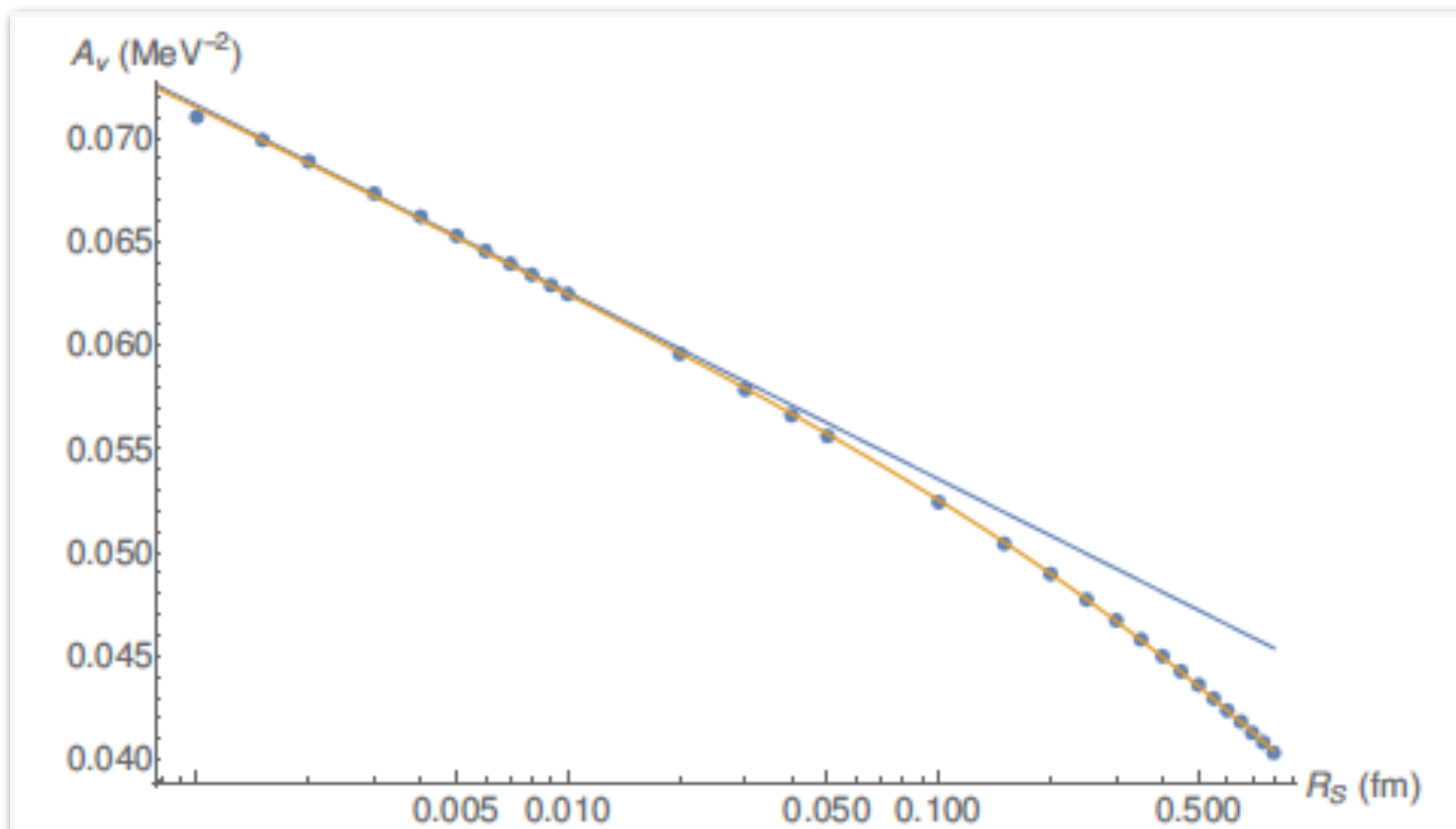
$$\mathcal{A}_\nu = \int d^3\mathbf{r}\, \psi^-_{\mathbf{p}'}(\mathbf{r}) V_\nu(\mathbf{r}) \psi^+_{\mathbf{p}}(\mathbf{r})$$

- Logarithmic dependence on R_S $\Rightarrow$

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



Estimating finite part of g_ν

1) Match χEFT & lattice QCD calculation of hadronic amplitude nn→pp

$$S_{\text{eff}}^{\Delta L=2} = \frac{i8G_F^2V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, T\Big(\bar{u}_L\gamma_\mu d_L(x)\, \bar{u}_L\gamma_\mu d_L(y)\Big) g^{\mu\nu}$$

Scalar massless propagator

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Scalar massless propagator

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

2) Chiral symmetry relates g_ν to I=2 electromagnetic LECs (hard ν vs γ)

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

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

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

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

Two I=2 NN non-derivative operators: chiral symmetry ⇒ $g_\nu = C_1$

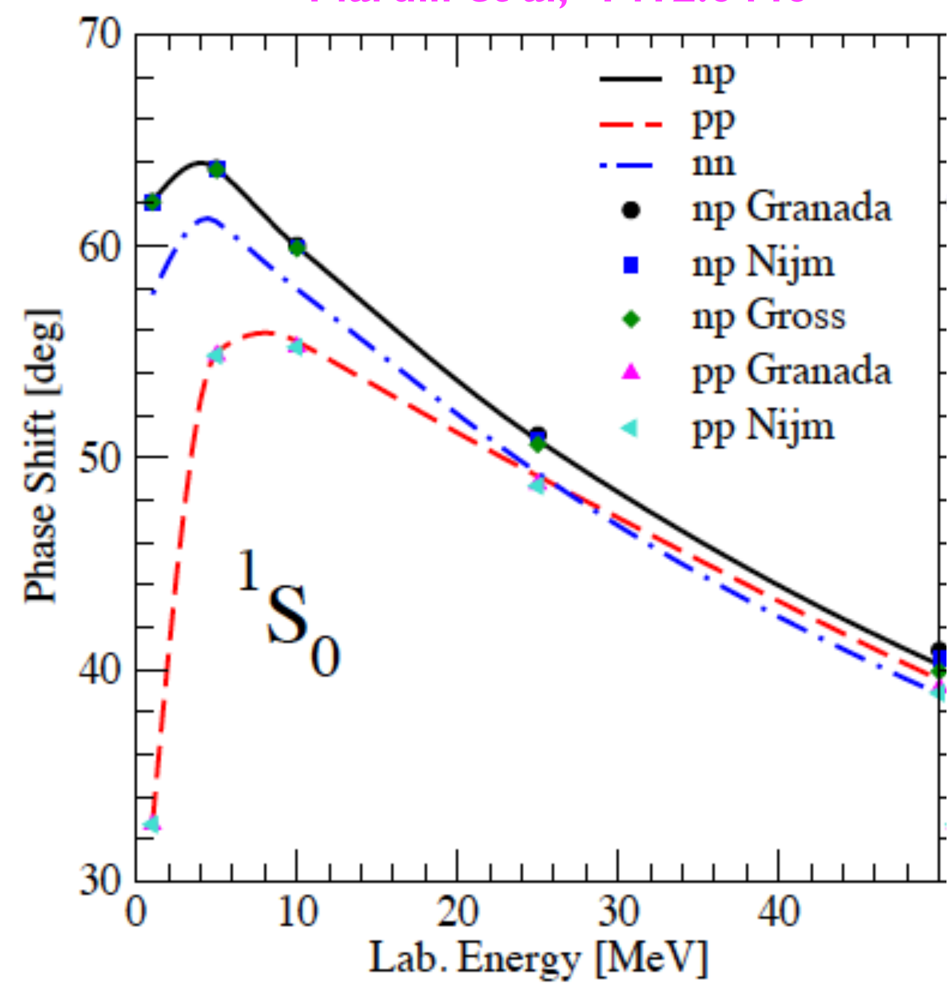
$0\nu\beta\beta$ vs EM isospin breaking

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

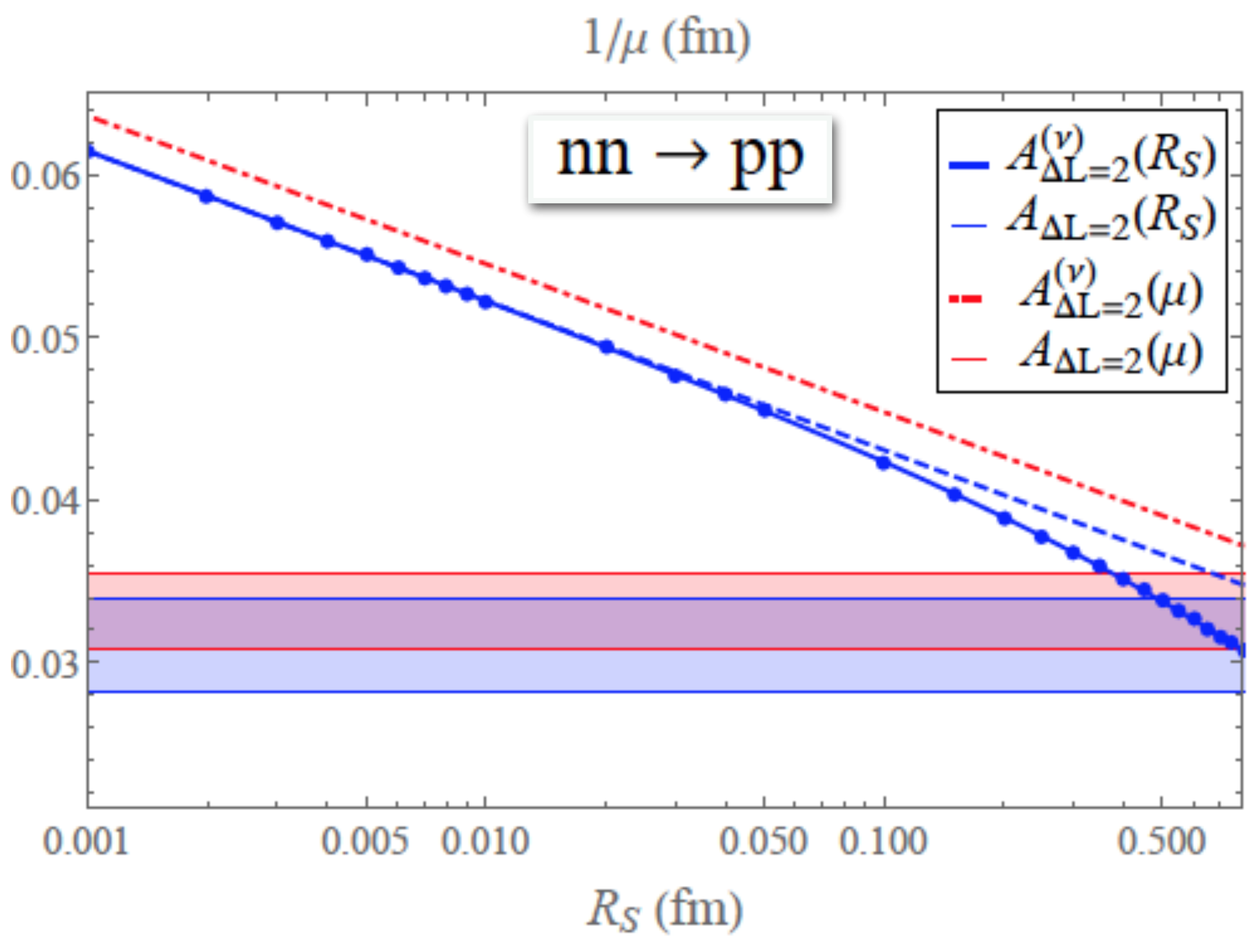
- $C_1 + C_2$ controls IB combination of $^1S_0$ scattering lengths $a_{nn} + a_{pp} - 2\, a_{np}$

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

Piarulli et al, 1412.6446



Estimating numerical impact (1)

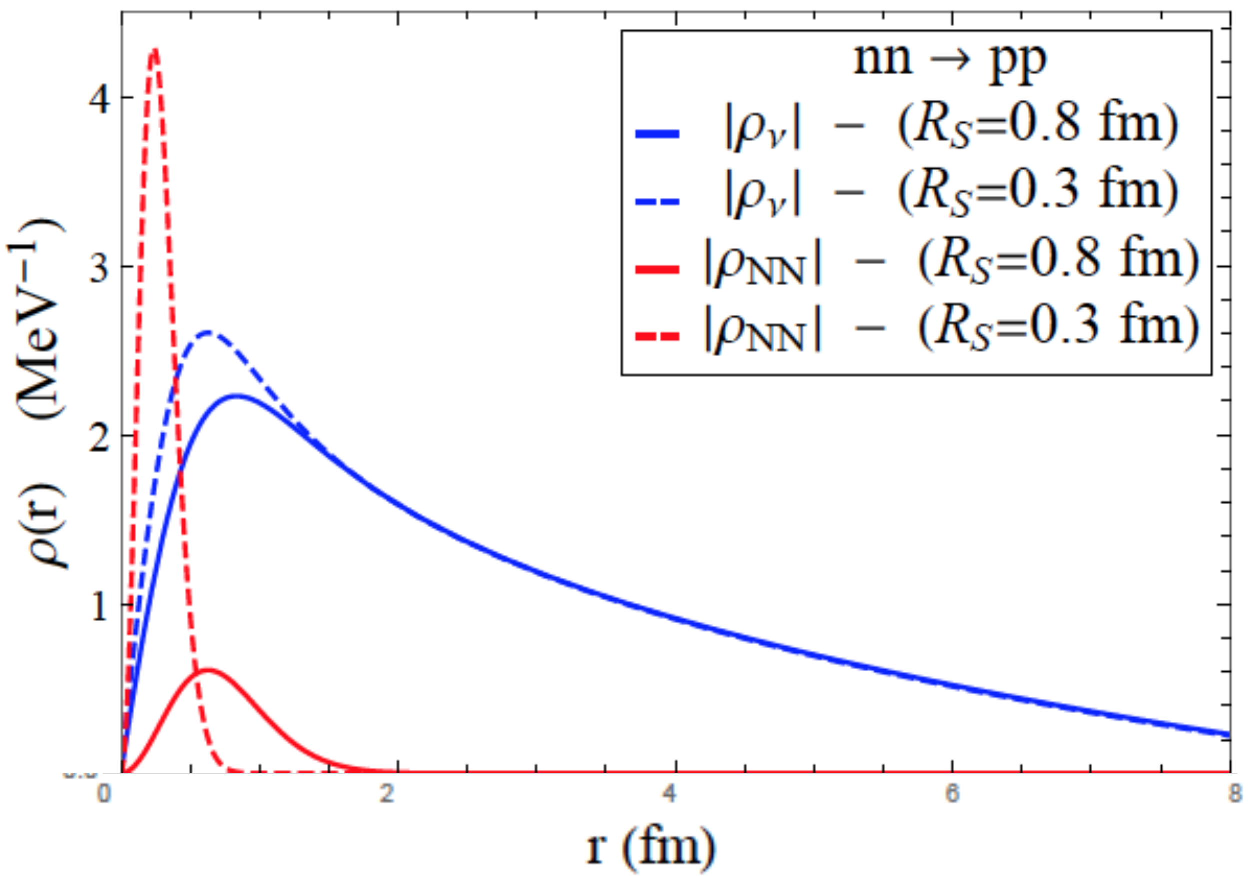


- Assume $C_1=C_2$ and hence $g_\nu=(C_1+C_2)/2$ at some scale R_S
- $A_{NN}+A_\nu$ is R_S (or μ) independent and A_{NN}/A_ν ~ 10% (30%) at R_S~0.8 fm (0.3 fm) **
- ** Actual correction will be different because in general $C_1 \neq C_2$

Estimating numerical impact (1)

nn → pp

ΔI=0



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

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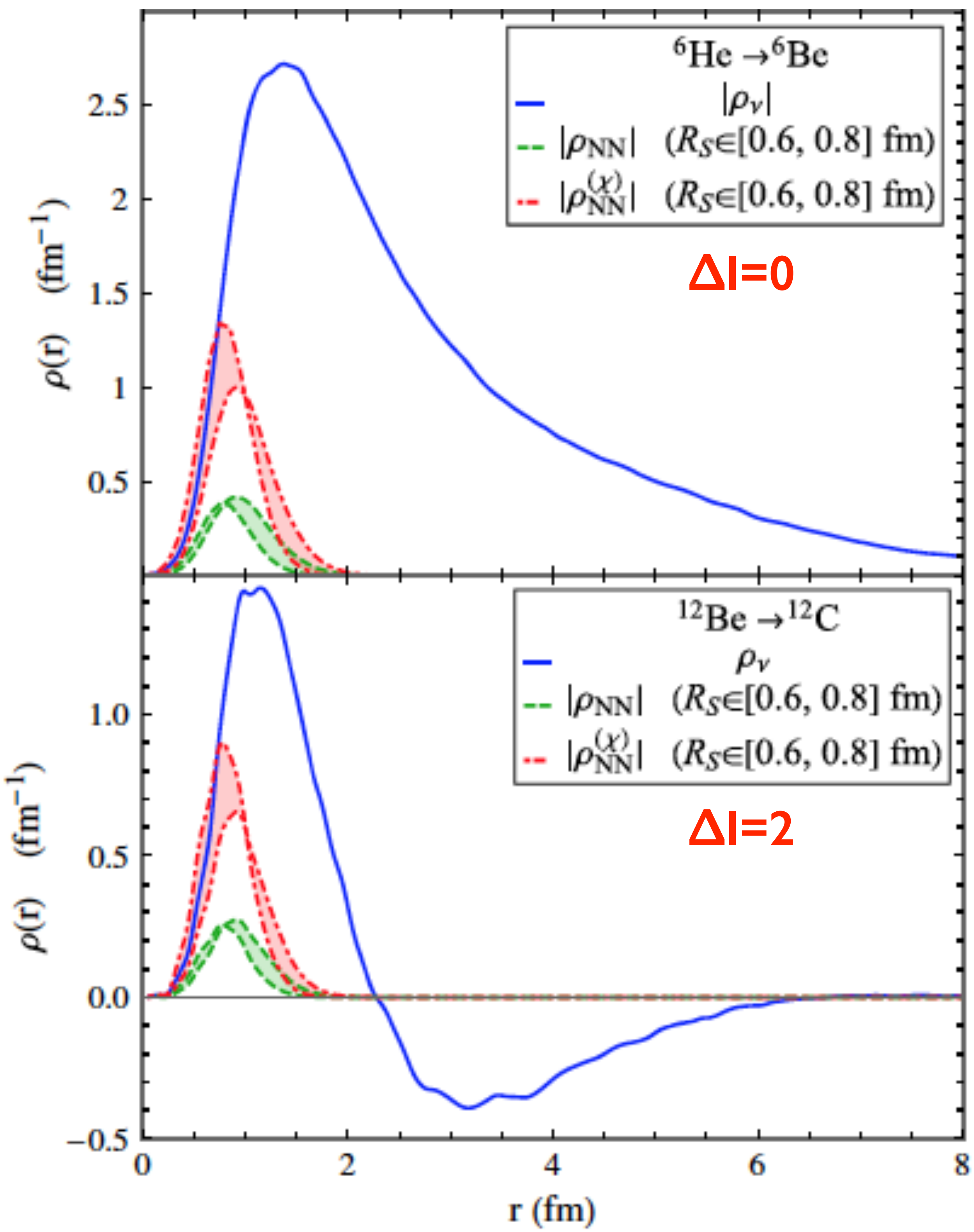
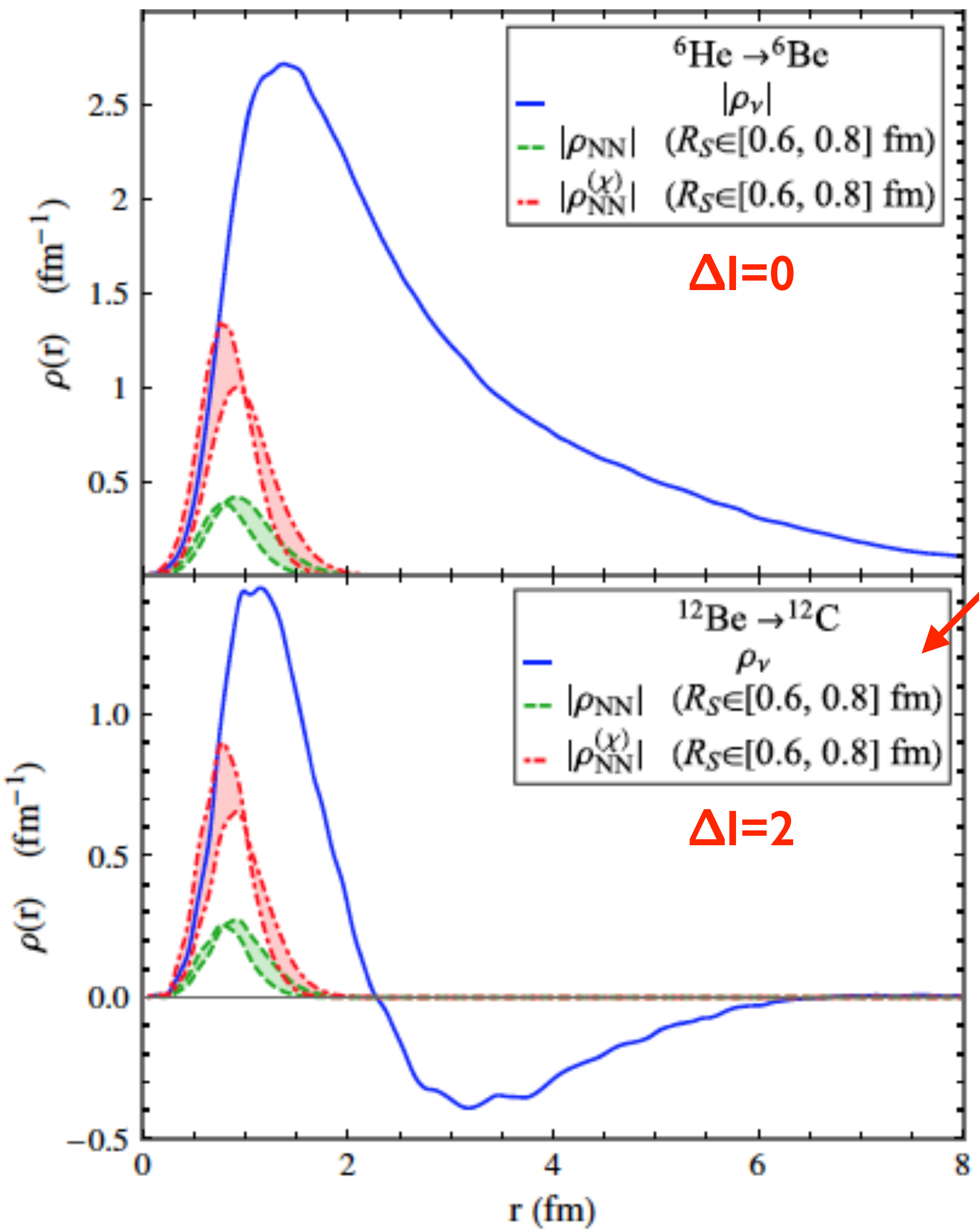
- $A_{NN}+A_\nu$ is R_S (or μ) independent and $A_{NN}/A_\nu \sim$ 10% (30%) at R_S~0.8 fm (0.3 fm) **
- ** Actual correction will be different because in general $C_1 \neq C_2$
- To gain Insight on this result, look at "matrix-element density" as function of inter-nucleon distance

Estimating numerical impact (2)



- What about nuclei?
- For light nuclei: used wavefunctions obtained via Variational Monte Carlo from AV18 (NN) + U9 (NNN) potentials
- Hybrid calculation at this stage: can't expect R_S-independence
- $g_V \sim (C_1+C_2)/2$ taken from fit to NN data (ours vs Piarulli et al. 1606.06335)

Estimating numerical impact (2)



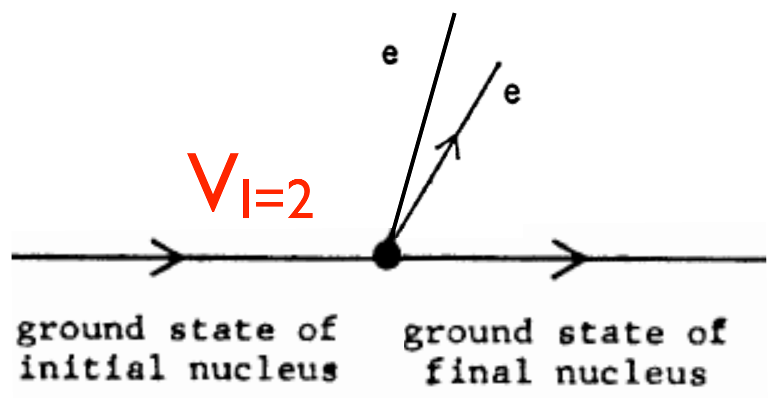
g_ν contribution sizable in ΔI=2 transition (*due to node*): for A=12, A_{NN}/A_ν = 25%-55%

Transitions of interest ($^{76}Ge \to$ ^{76}Se, …) have ΔI=2 and node ⇒

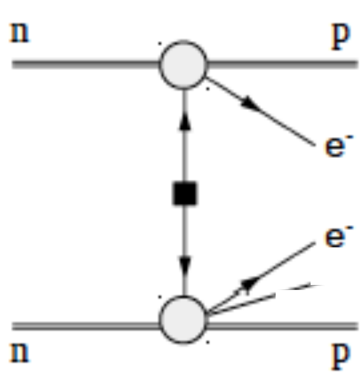
$m_{\beta\beta}$ phenomenology can be significantly affected!

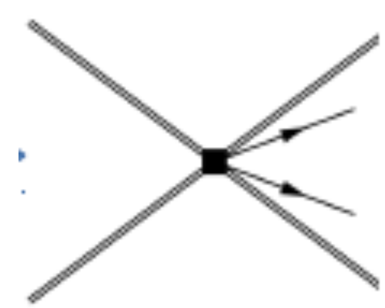
Anatomy of 0νββ amplitude in χEFT

Figure adapted from Primakoff-Rosen 1969



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

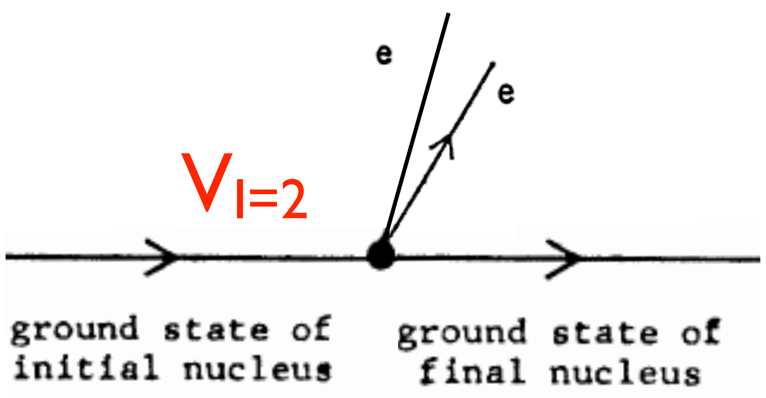




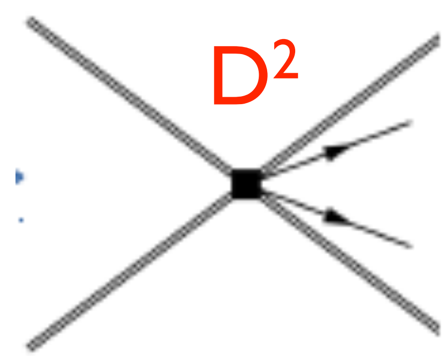
New short range contribution

Anatomy of 0νββ amplitude in χEFT

Figure adapted from Primakoff-Rosen 1969



- NLO: New short range derivative operator $V_{\nu,1} \sim ND^2N\ NN$?

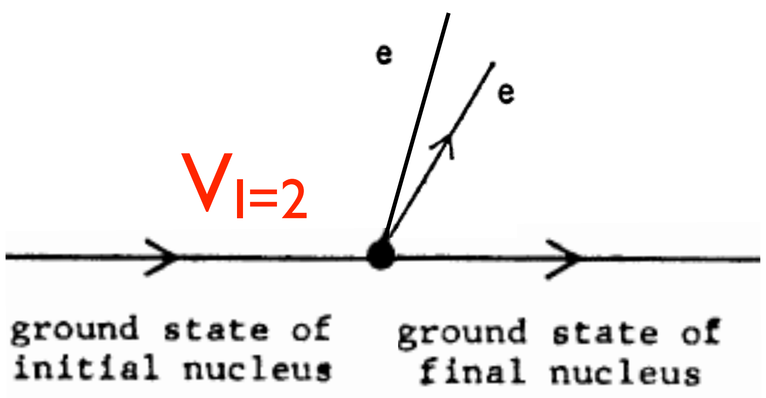


UNDER INVESTIGATION

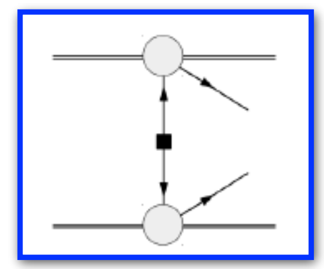
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck

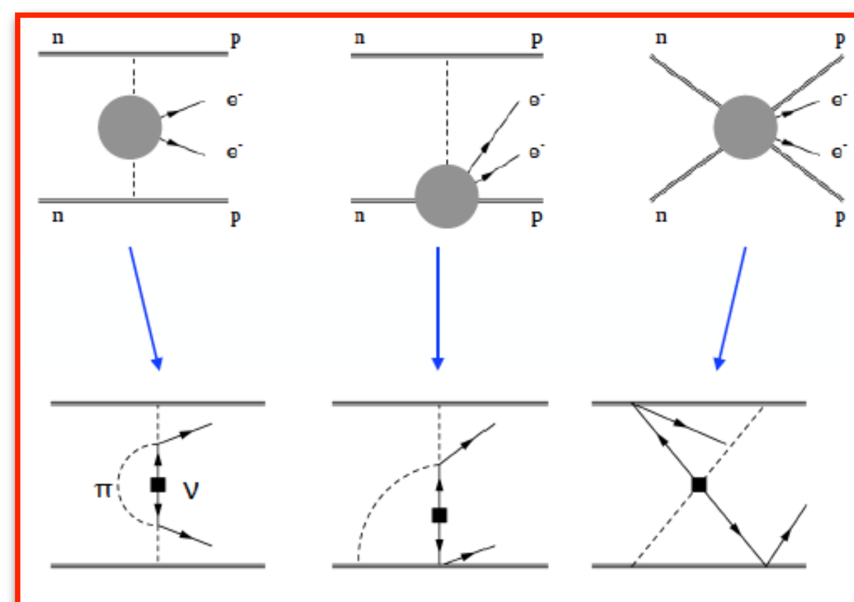
Anatomy of $0\nu\beta\beta$ amplitude in χEFT

Figure adapted from Primakoff-Rosen 1969



- N2LO (1):
  - Factorizable corrections to 1-body currents (radii, …)
  - Ground state matrix element of $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$ [π-N loops and contact terms]
  - New non-factorizable terms as important as form-factors**



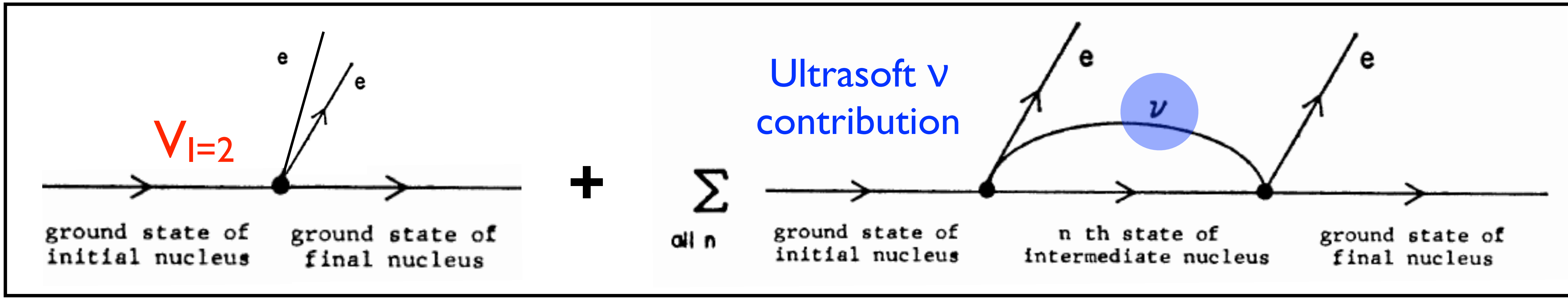


** S. Pastore, J. Carlson, V. Cirigliano, W. Dekens, E. Mereghetti, R. Wiringa 1710.05026

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

Anatomy of 0νββ amplitude in χEFT

Figure adapted from Primakoff-Rosen 1969



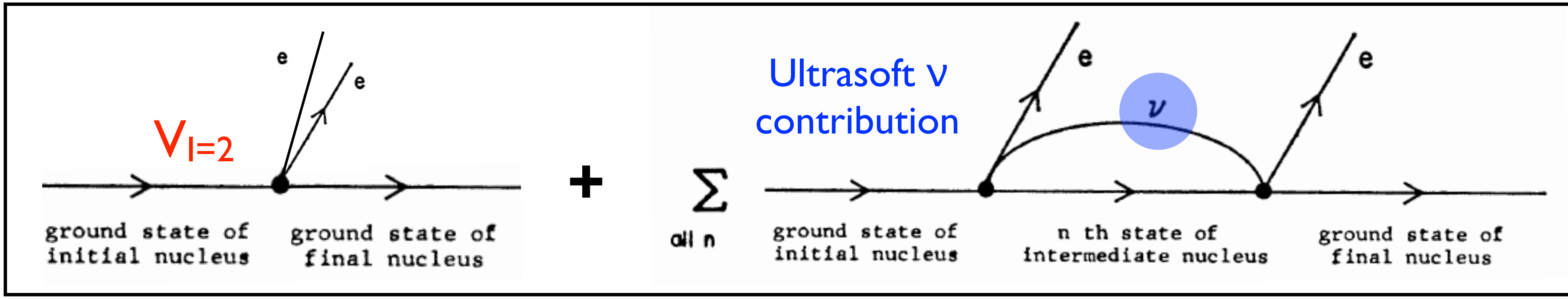
- N2LO (2): ultrasoft ν loop suppressed by $(E_n - E_i)/(4\pi k_F)$

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

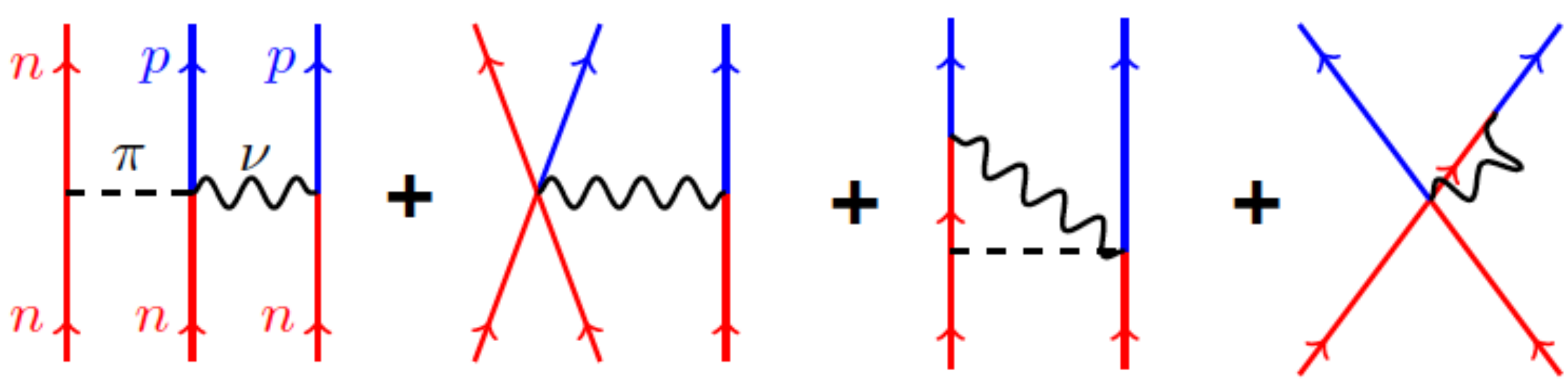
- Ultrasoft neutrinos couple to *nuclear* states: sensitivity to $E_n - E_i$ and $\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle$ that also determine 2νββ amplitude → corrections to closure approximation
- μ_{us} dependence cancels with $V_{\nu,2}$. Non-trivial consistency check!

Anatomy of 0νββ amplitude in χEFT

Figure adapted from Primakoff-Rosen 1969



- Beyond N2LO: "2-body current x 1-body current " starts at N3LO



Wang-Engel-Yao 1805.10276

Conclusions

- Chiral EFT analysis of light ν_M exchange contribution to $0\nu\beta\beta$
  - Key new result: leading order contact nn → pp operator. LEC enhanced by $(4\pi)^2$ compared to naive dimensional analysis. O(1) impact on sensitivity to $m_{\beta\beta}$
  - At N2LO, identified new non-factorizable potential & corrections to closure approximation due to "ultrasoft" ν's
- Important aside: same enhancements affect nn → pp contacts induced by dim-9 LNV operators (= short-distance mechanisms)
- Outlook / future work:
  - Determination of LO coupling g_ν: match to lattice QCD, I=2 EM observables, models…

Backup

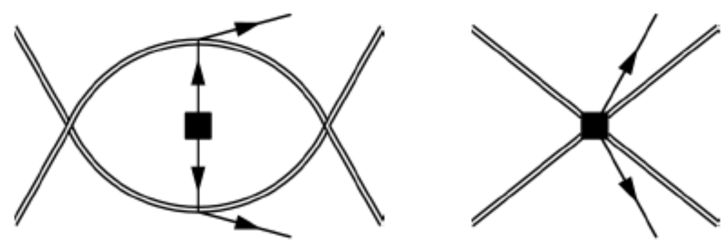
0vββ potential in pionless EFT

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

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \left\{ \frac{1}{\mathbf{q}^2} \left(g_V^2 - g_A^2 \boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} \right) - \frac{2 g_\nu^{NN}}{(4\pi F_0)^2} \mathbf{1}^{(a)} \times \mathbf{1}^{(b)} \right\}$$

$$g_\nu^{NN} = \mathcal{O}\left(\frac{\Lambda_\chi^2}{\aleph^2}\right)$$

- Need leading order counterterm to make the S-matrix element scale-independent



$$\mathcal{A}\left(nn(^1S_0) \to pp(^1S_0)\right) \sim G_F^2 m_{\beta\beta} \left\{ \left(\frac{T}{C_s(\mu)}\right)^2 \left(\left(\frac{m_N C_s(\mu)}{4\pi}\right)^2 (1 + 3g_A^2)\, I_2 - \frac{2 g_\nu^{NN}}{(4\pi F_0)^2} \right) + \dots \right\}$$

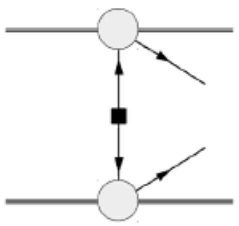
$$g_\nu^{NN}(\mu) = (4\pi F_0)^2 \left(\frac{m_N C_s(\mu)}{4\pi}\right)^2 \tilde{g}_\nu^{NN}(\mu) \qquad C_s = C_S - 3C_T = \frac{4\pi}{m_N(a_s^{-1} - \mu)} \qquad \frac{d}{d\log\mu}\tilde{g}_\nu^{NN} = \frac{1+3g_A^2}{2}$$

Closure approx. and its corrections

- 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 $\bar{E} - E_i$

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

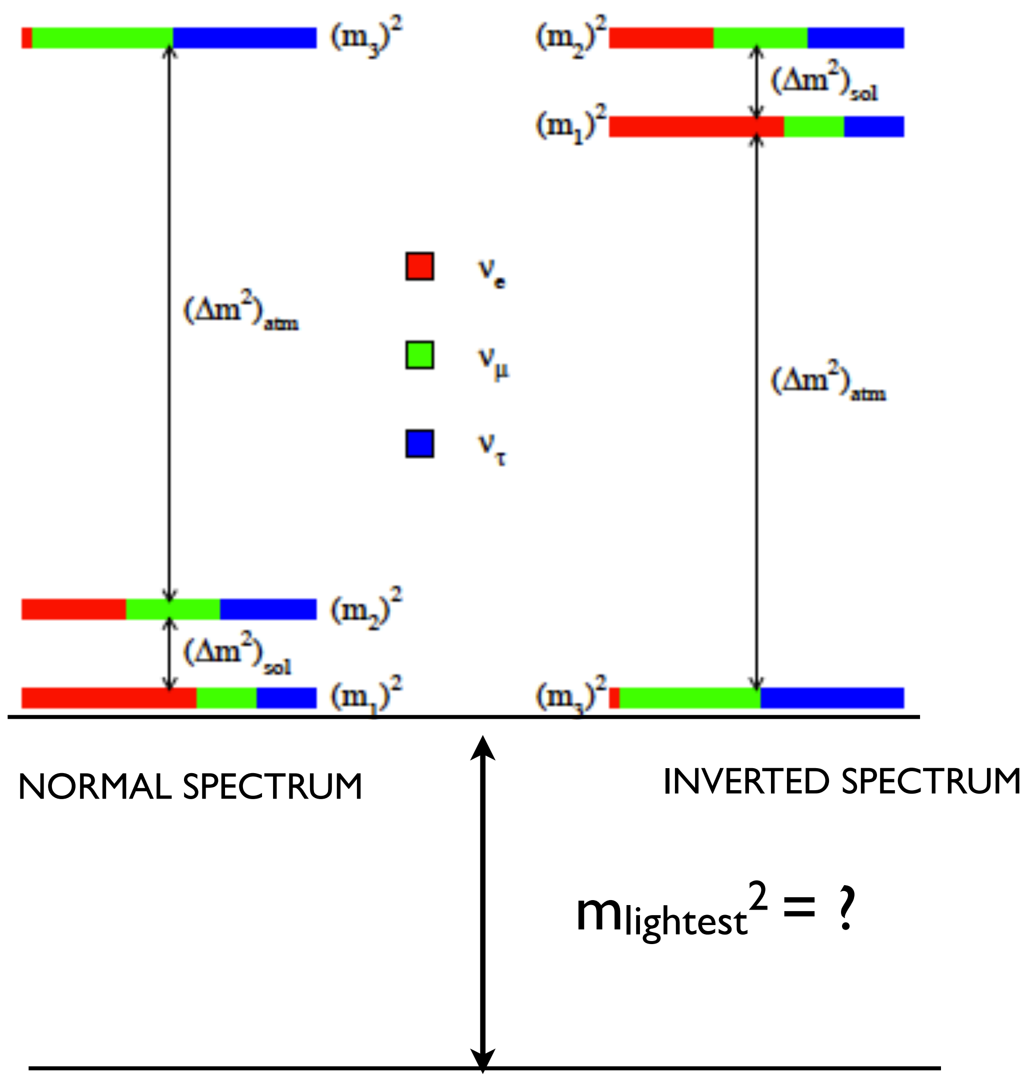
$$|\mathbf{q}| \gg E_n - E_i$$



High-scale seesaw

- Strong correlation of 0νββ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



High-scale seesaw

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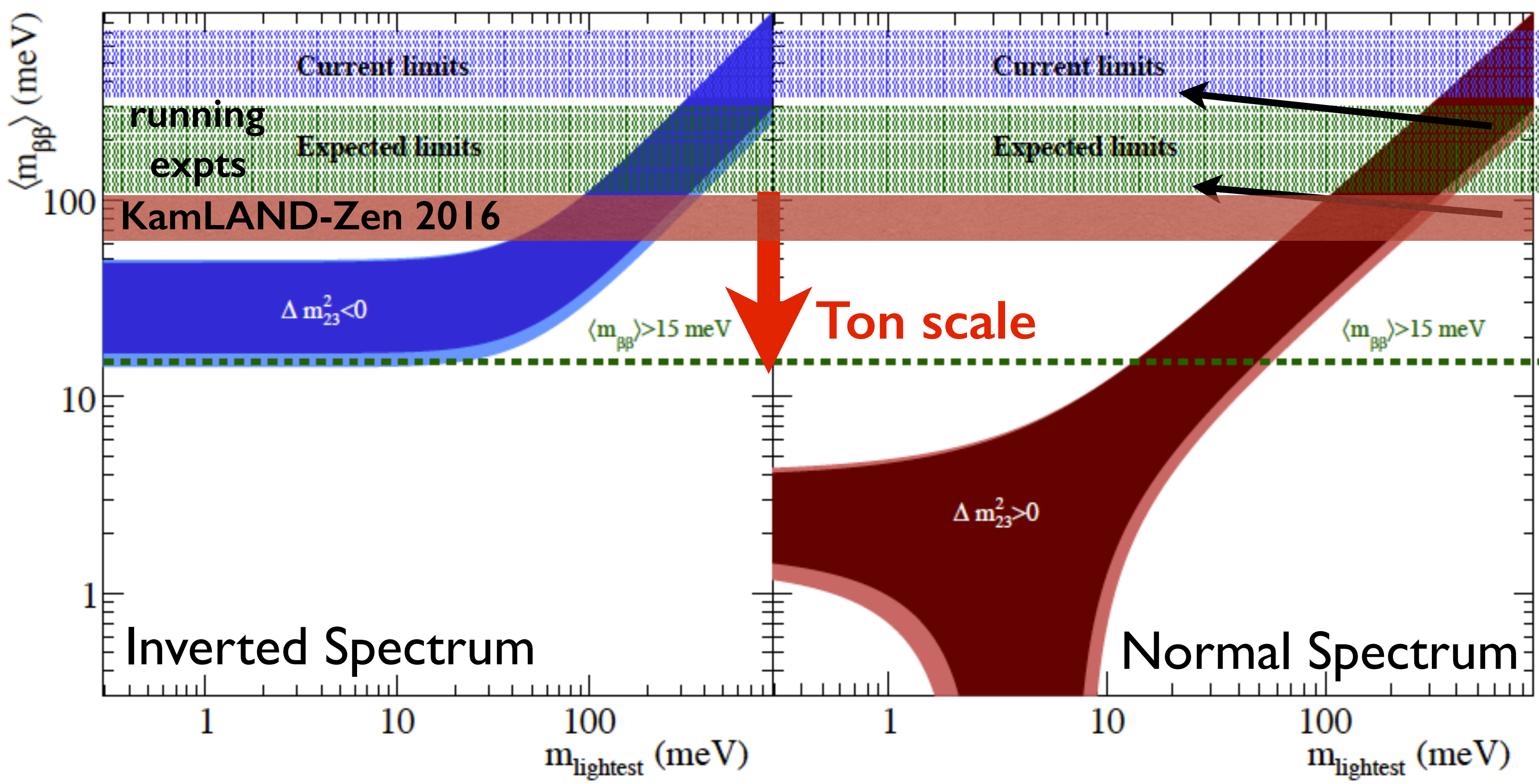
$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$

Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)



Assume most “pessimistic” values for nuclear matrix elements

- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

Status of nuclear matrix elements

Engel-Menendez 1610.06548