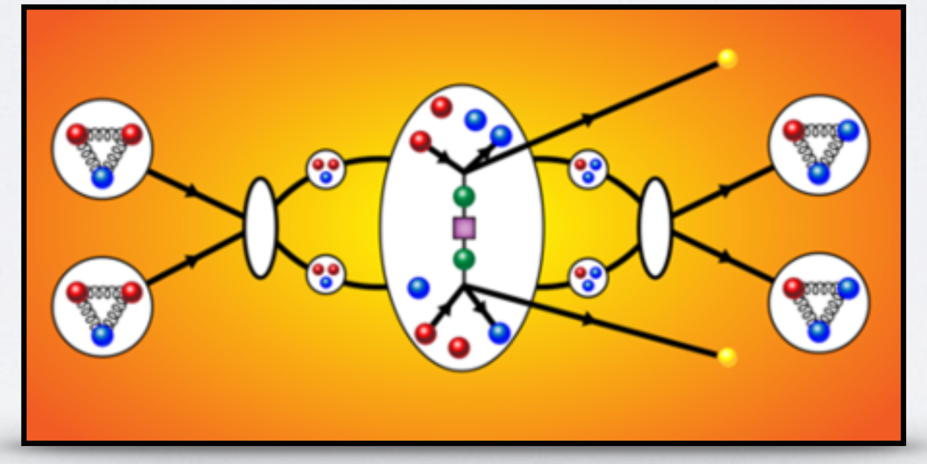
CHIRAL EFFECTIVE FIELD THEORY FOR NEUTRINOLESS DOUBLE BETA DECAY

Jordy de Vries
University of Amsterdam & Nikhef



Work with: V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, M. Hoferichter, U. van Kolck, V. Plakkot, S. Pastore, M. Piarulli, ….

The plan of attack

1. **Introduction to Majorana neutrinos and 0vbb**

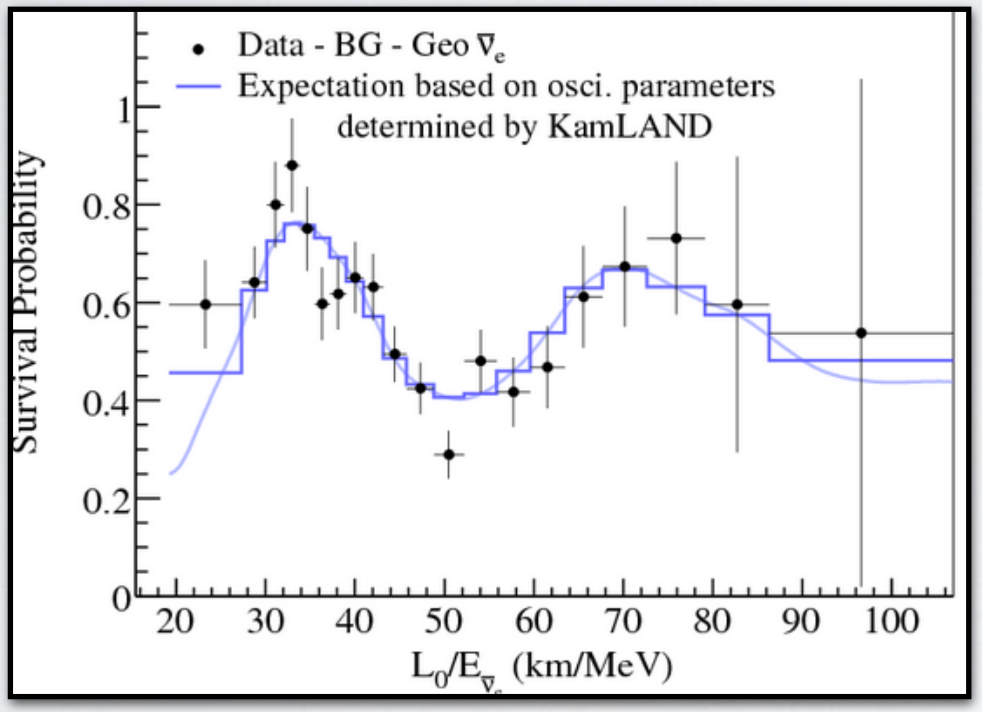
2. Neutrinoless double beta decay from light Majorana neutrino exchange
   - *Controlling nuclear matrix elements !*

3. Flash: Other lepton-number-violating mechanisms in effective field theory

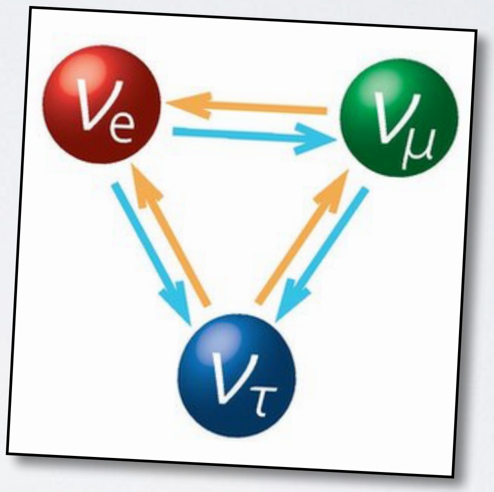
Neutrino masses

- In the original formulation of the Standard Model (Weinberg 1967) neutrinos were considered to be massless particles

- **But neutrinos do have mass !**



$$P(\nu_\mu \to \nu_e) \sim \sin \frac{\Delta m^2 L}{2E}$$



- Biggest mass splitting: $|\Delta m| \simeq 0.05\, eV$ Smallest: $|\delta m| \simeq 0.008\, eV$

- Direct limits: $m_{\nu_e} \leq 0.8\, eV$ **KATRIN experiment**

- Cosmology (DESI 2024) $\sum m_{\nu_i} \leq 0.15\, eV(IH)$ $\sum m_{\nu_i} \leq 0.11\, eV(NH)$

EFTs and neutrino mass: an old story

- Easy fix: Insert gauge-singlet right-handed neutrino υ_R

$$\mathscr{L} = -\, y_\nu \bar{L}\tilde{H}\nu_R \qquad\qquad y_\nu \sim 10^{-12} \rightarrow m_\nu \sim 0.1\,\mathrm{eV}$$

- Nothing really wrong with this….

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$$\mathscr{L} = -\, y_\nu \bar{L}\tilde{H}\nu_R - M_R \nu_R^T C \nu_R$$

'Everything that is not forbidden is compulsary'

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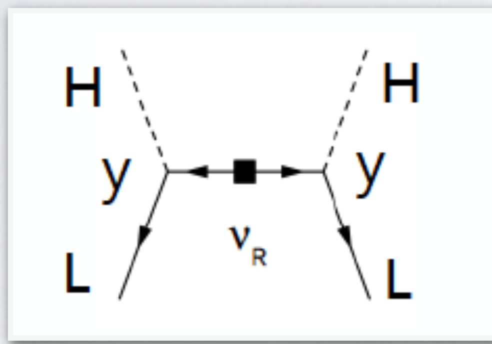
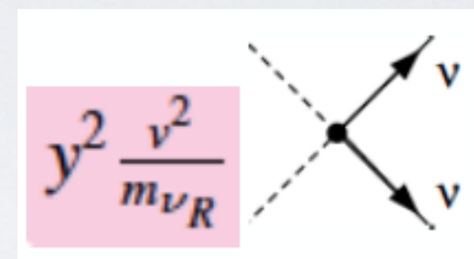
- If M_R is significantly larger than active neutrino masses (< eV) : **see-saw mechanism**
- In case of 1 left and 1 right-handed neutrino: $m_1 \simeq \left| \frac{y_\nu^2 v^2}{m_R} \right| \qquad m_2 \simeq m_R$
- The mass eigenstates are Majorana states $\nu_i^c = \nu_i$

EFT point of view

- Integrating out heavy states leads to local operator
- For light right-handed neutrinos see **V. Plakkot's** talk this afternoon





Weinberg '79

- Obtain the single dimension-5 SMEFT operator

Neutrino Majorana mass

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C \tilde{H}\right)(\tilde{H}^T L) \longrightarrow \mathscr{L}_5 = c_5 \frac{v^2}{\Lambda} \nu^T C \nu \qquad c_5 = y_\nu^2$$

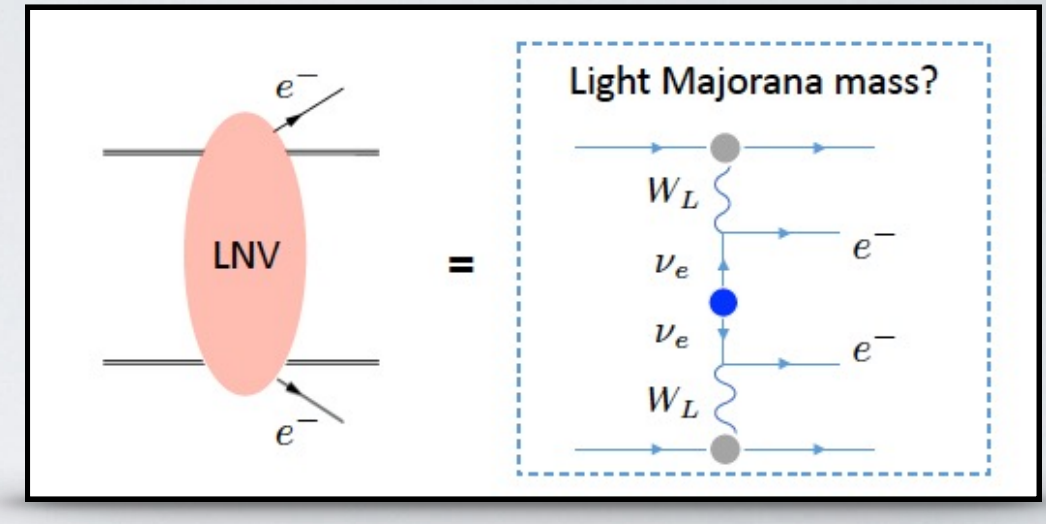
- This term describes neutrino oscillations but implies **Lepton-Number Violation**

Probes of lepton number violation

- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+ + \text{jets}$$

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



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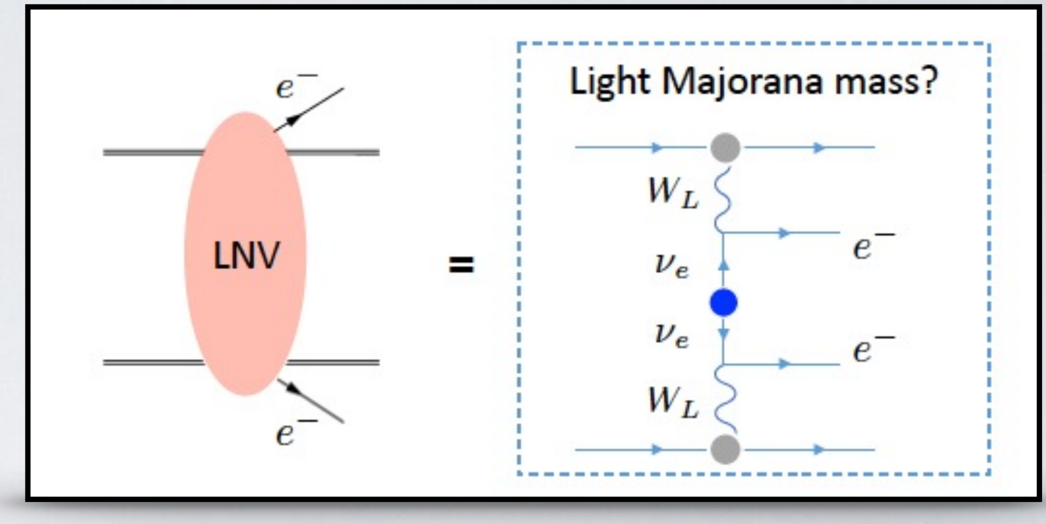

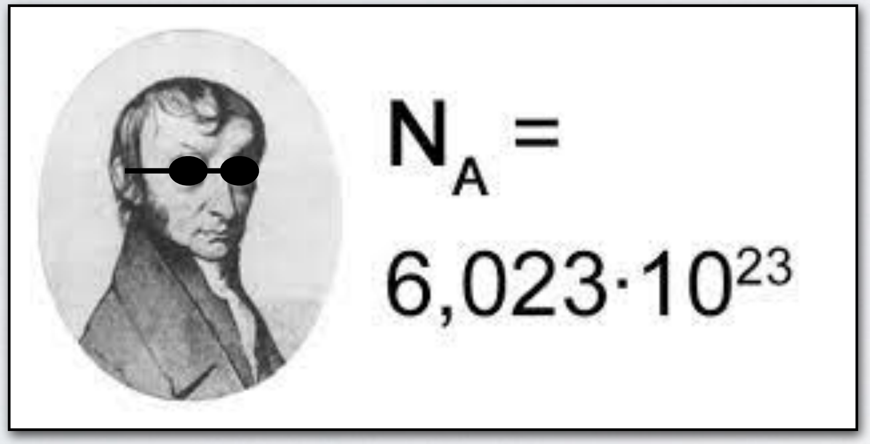

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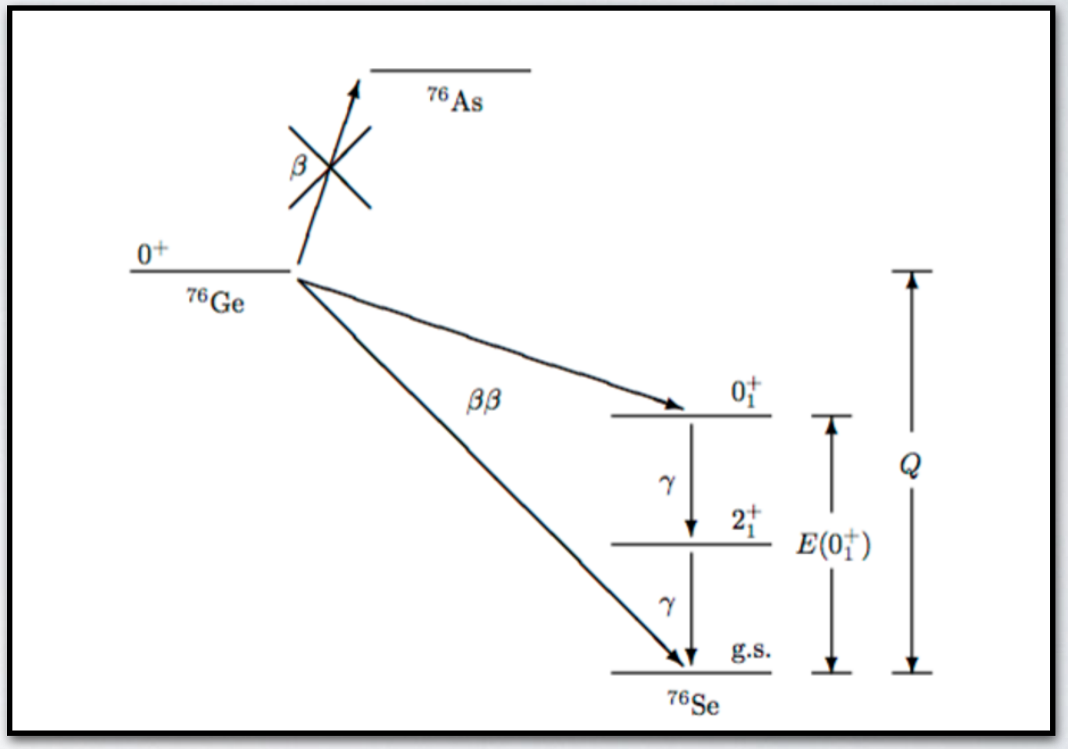
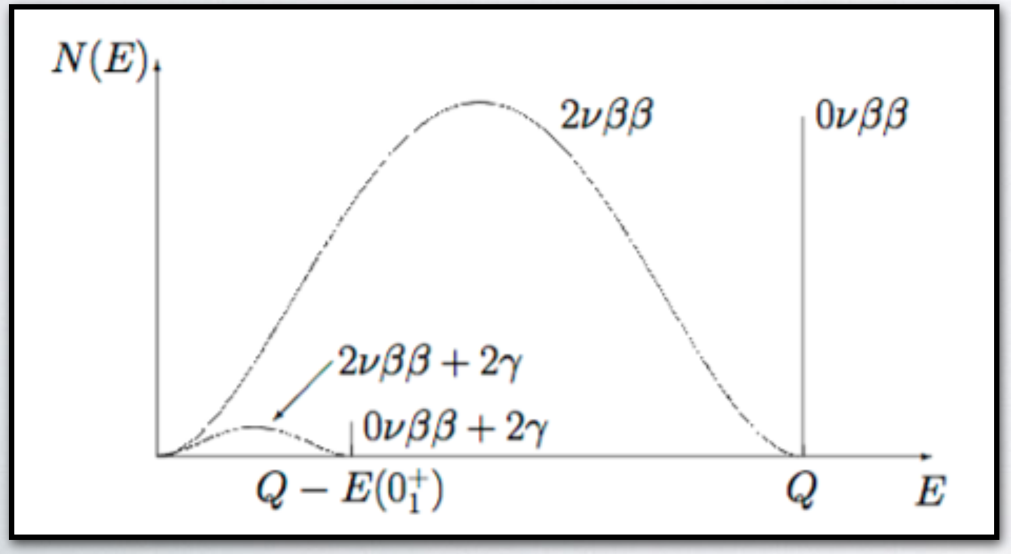


- Isotopes protected from single beta decay

- Neutrinofull double beta decay from Standard Model

$$X(Z,N) \to Y(Z+2,N-2) + 2e^- + 2\bar{\nu}_e$$

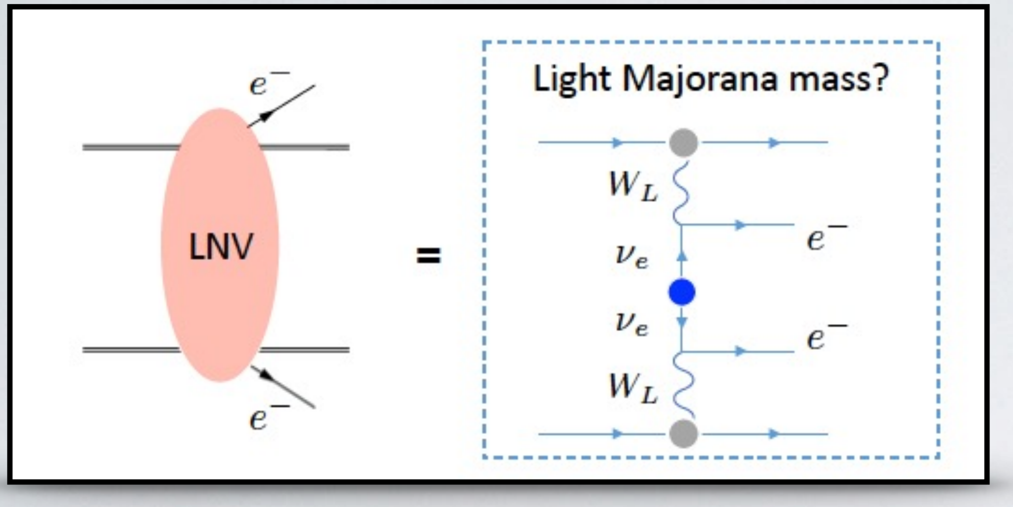
$$T_{1/2}^{2\nu}\left({}^{76}Ge \to {}^{76}Se\right) = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\ yr$$



	Lifetime	Experiment	Year
76Ge	$8.0 \cdot 10^{25}\, y$	GERDA	2018
130Te	$3.2 \cdot 10^{25}\, y$	CUORE	2019
136Xe	$3.8 \cdot 10^{26}\, y$	KamLAND-Zen	2024

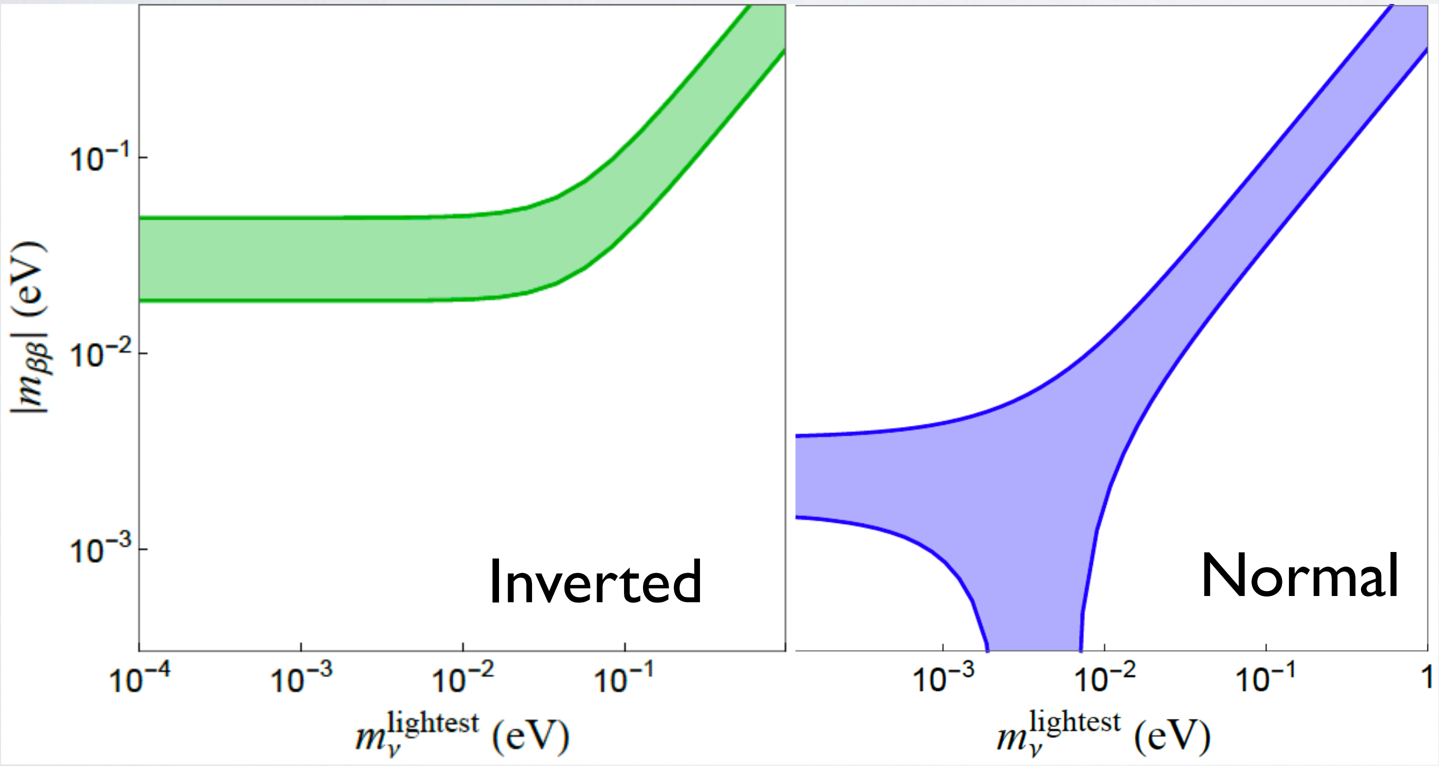
Note: age of universe ~ 10^{10} year

Interpreting 10^{26} years....



$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2 \qquad m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

$$m_{\beta\beta} = m_1\, c_{12}^2 c_{13}^2 + m_2\, s_{12}^2 c_{13}^2 e^{2i\lambda_1} + m_3\, s_{13}^2 e^{2i(\lambda_2 - \delta_{13})}$$ = Effective neutrino mass

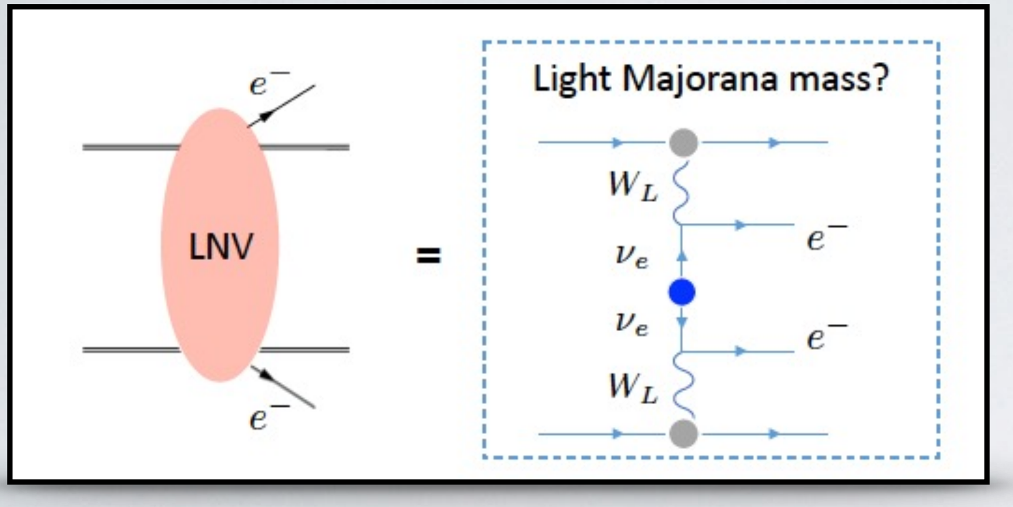


Vary the lightest mass and the ordering

Band from varying unknown phases

How close are experiments ?

Interpreting 10^{26} years....



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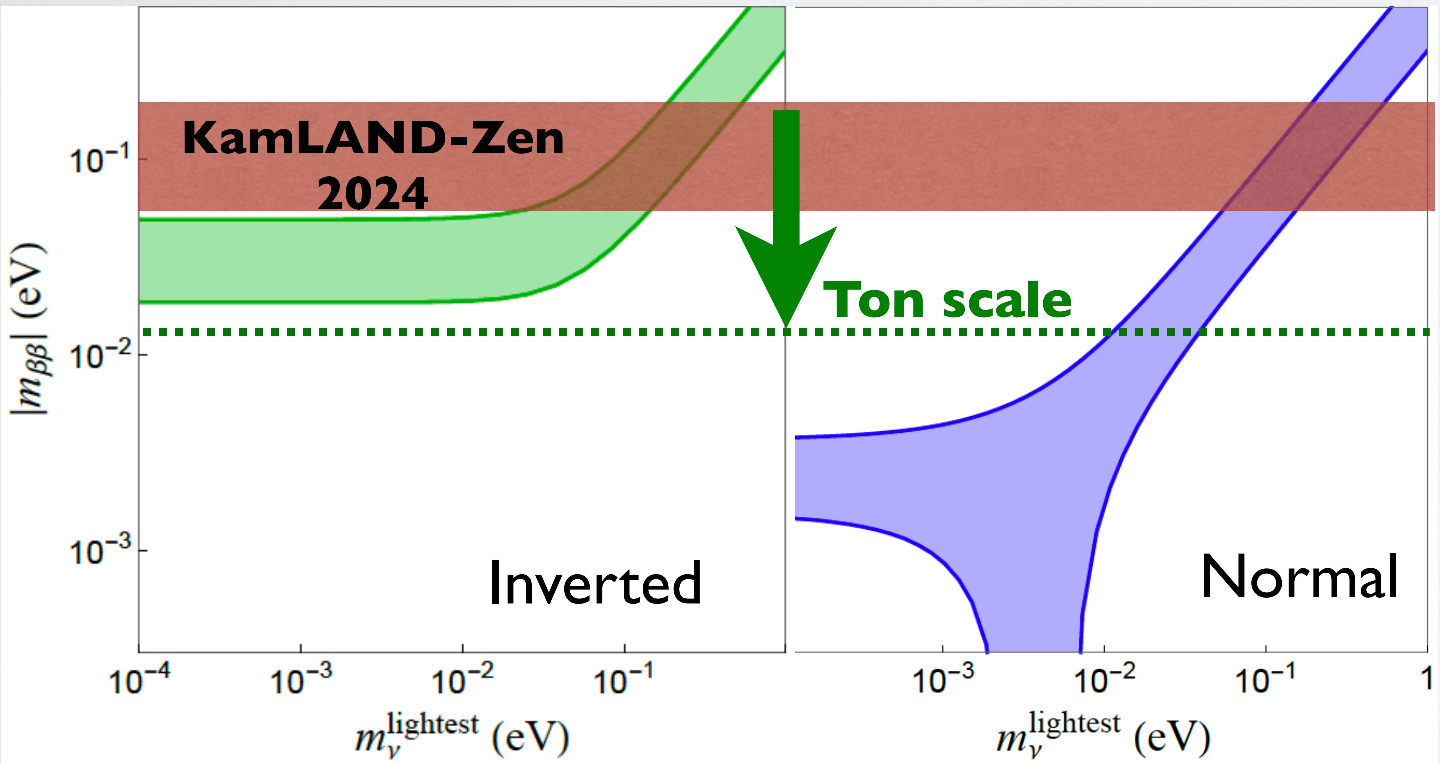


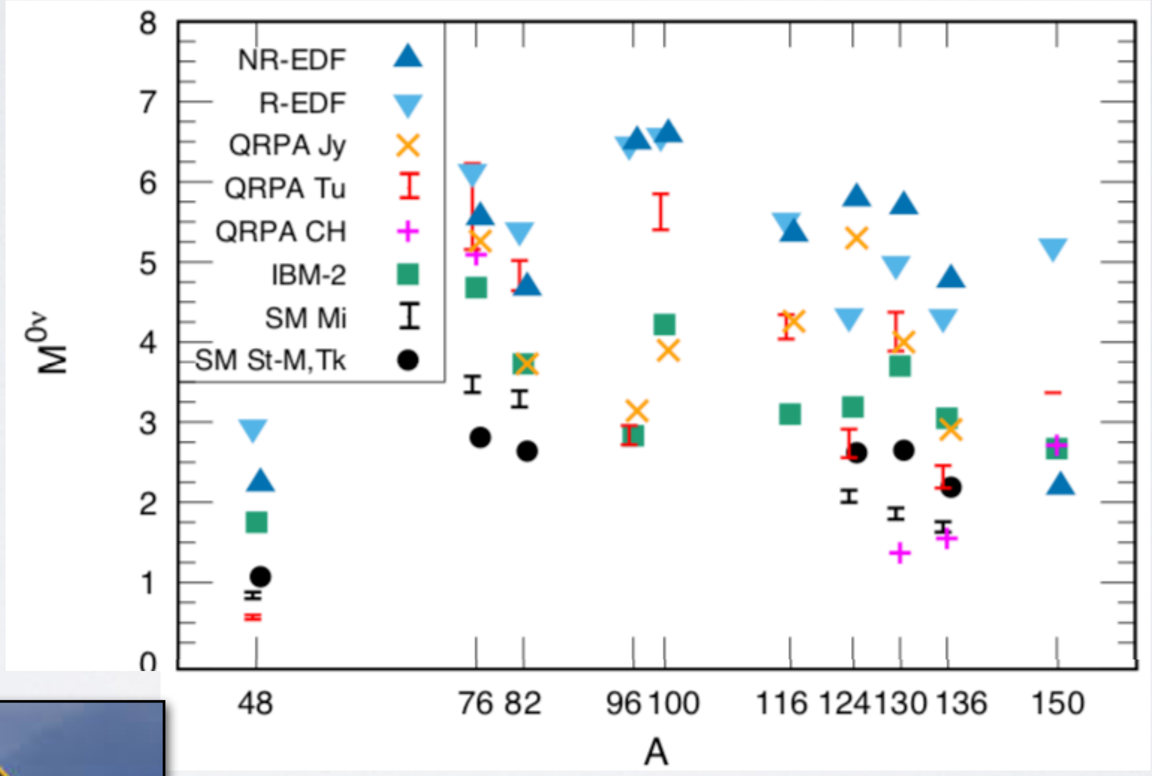
Quite close !!

Next-generation discovery possible if inverted hierarchy or m_{lightest} >0.01 eV

Towards improved theoretical predictions

- Assuming 'standard' mechanism: uncertainties from **hadronic & nuclear theory**

$\Gamma \sim |M_{0\nu}|^2 (m_{\beta\beta})^2$



Engel-Menendez '16

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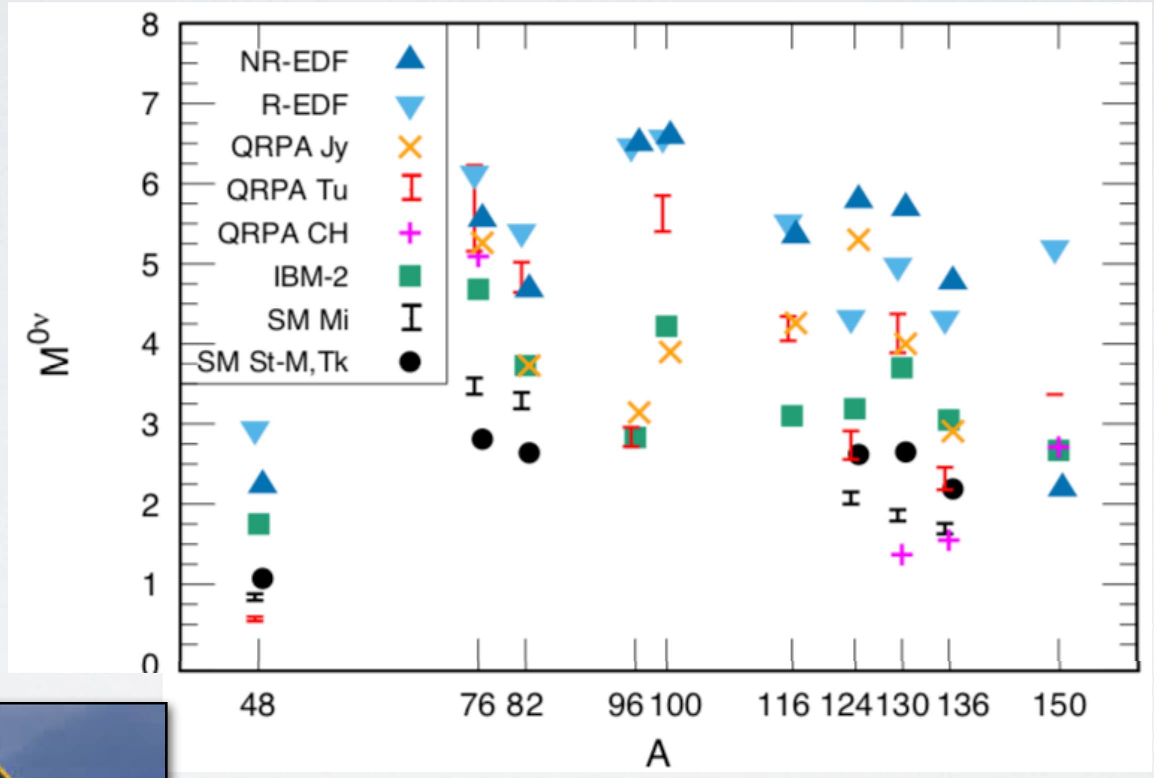


Engel-Menendez '16

Can we (chiral dynamics participants) help ?

The plan of attack

1. Introduction to Majorana neutrinos and 0vbb

2. **0vbb from light Majorana neutrino exchange**
    - *Controlling nuclear matrix elements !*

3. Flash: Other lepton-number-violating mechanisms in effective field theory

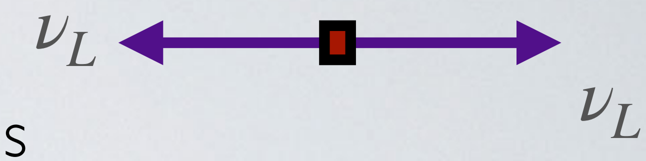
Anatomy of a decay

$$\Gamma^{0\nu} \sim m_{\beta\beta}^2 \cdot g_A^4 \cdot |M_{0\nu}|^2 \cdot G$$

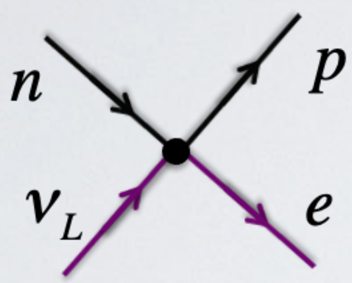
Energy

?	$m_{\beta\beta}^2$	Lepton-number-violating source (*not necessarily neutrino mass*) ***(Particle Physics)***
GeV	g_A^4	From quarks to hadrons ***(Hadronic Physics)***
100 MeV	$|M_{0\nu}|^2 = |\langle 0^+ | V_\nu | 0^+ \rangle|^2$	Nuclear transition matrix element ***(Nuclear Physics)***
MeV	G	Phase space factor ***(Atomic Physics)***

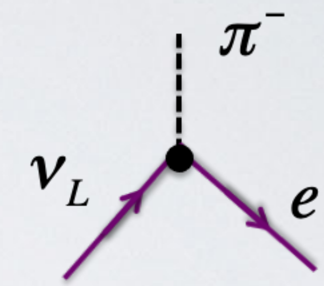
Light Majorana neutrinos (standard mechanism)



- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Basically just use low-energy chiral Lagrangian with weak interactions



$$L_{\chi,Fermi} = G_F f_\pi \left(\partial_\mu \pi^- \, \bar{e}_L \gamma^\mu \nu_L \right)$$
$$+ G_F \, \bar{p} \left(\gamma^\mu - g_A \gamma^\mu \gamma^5 \right) n \, \bar{e}_L \gamma^\mu \nu_L + \cdots$$



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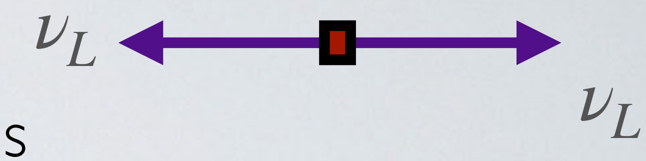

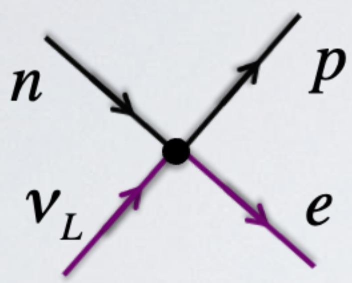

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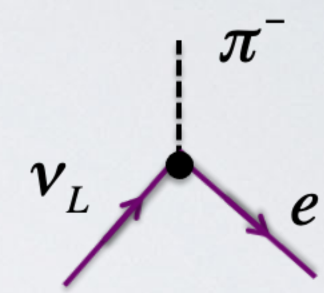
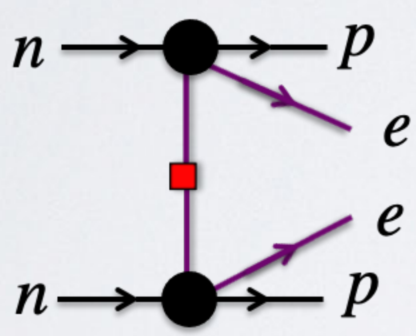


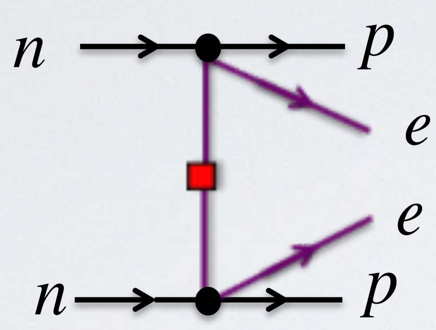


$$V_\nu({}^1S_0) = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

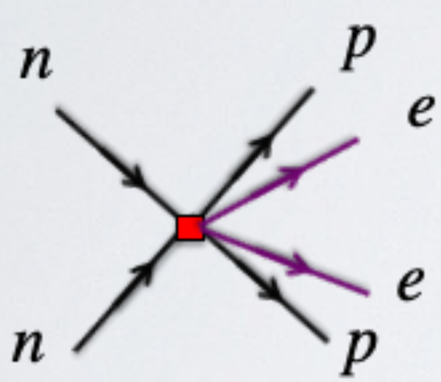
- This is the leading-order 'neutrino potential'

Light Majorana neutrinos (standard mechanism)

- Leads to 'long-range' nn → pp + ee



$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad \mathbf{q} \sim k_F \sim m_\pi$$



- Contributions from virtual hard neutrinos $\mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Naive-dimensional analysis tells us this is NNLO

$$V_\nu^{short} \sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$$

Light Majorana neutrinos (standard mechanism)

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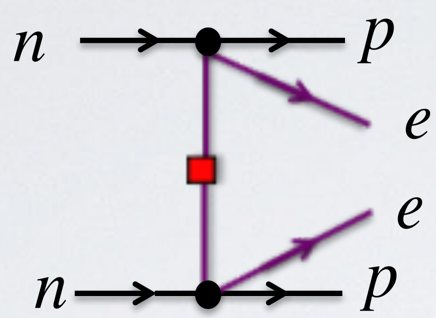

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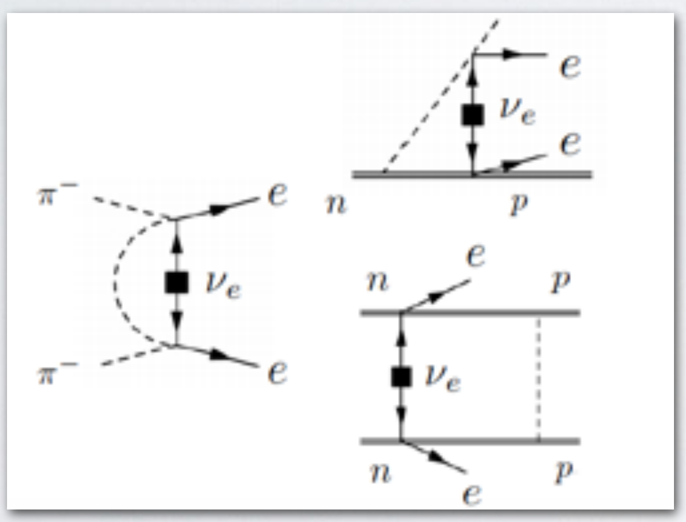
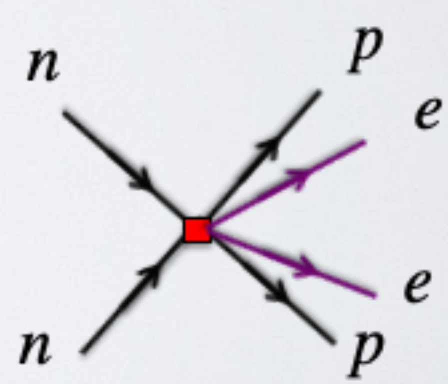
- More contributions at higher orders in chiral perturbation theory



- Loops at N²LO are divergent: come with counter terms

$$V_\nu^{\mathrm{N^2LO}} \sim \left(V_{\mathrm{finite}} + V_{UV} \log \frac{m_\pi^2}{\mu^2} + V_{\mathrm{CT}} \right) \otimes \bar{e}_L e_L^c$$

- Divergences absorbed by counter terms

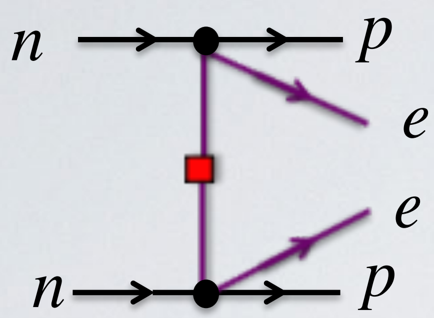


Cirigliano, Dekens, Mereghetti, Walker-Loud '17

- At higher orders also 'closure corrections' and three-body effects

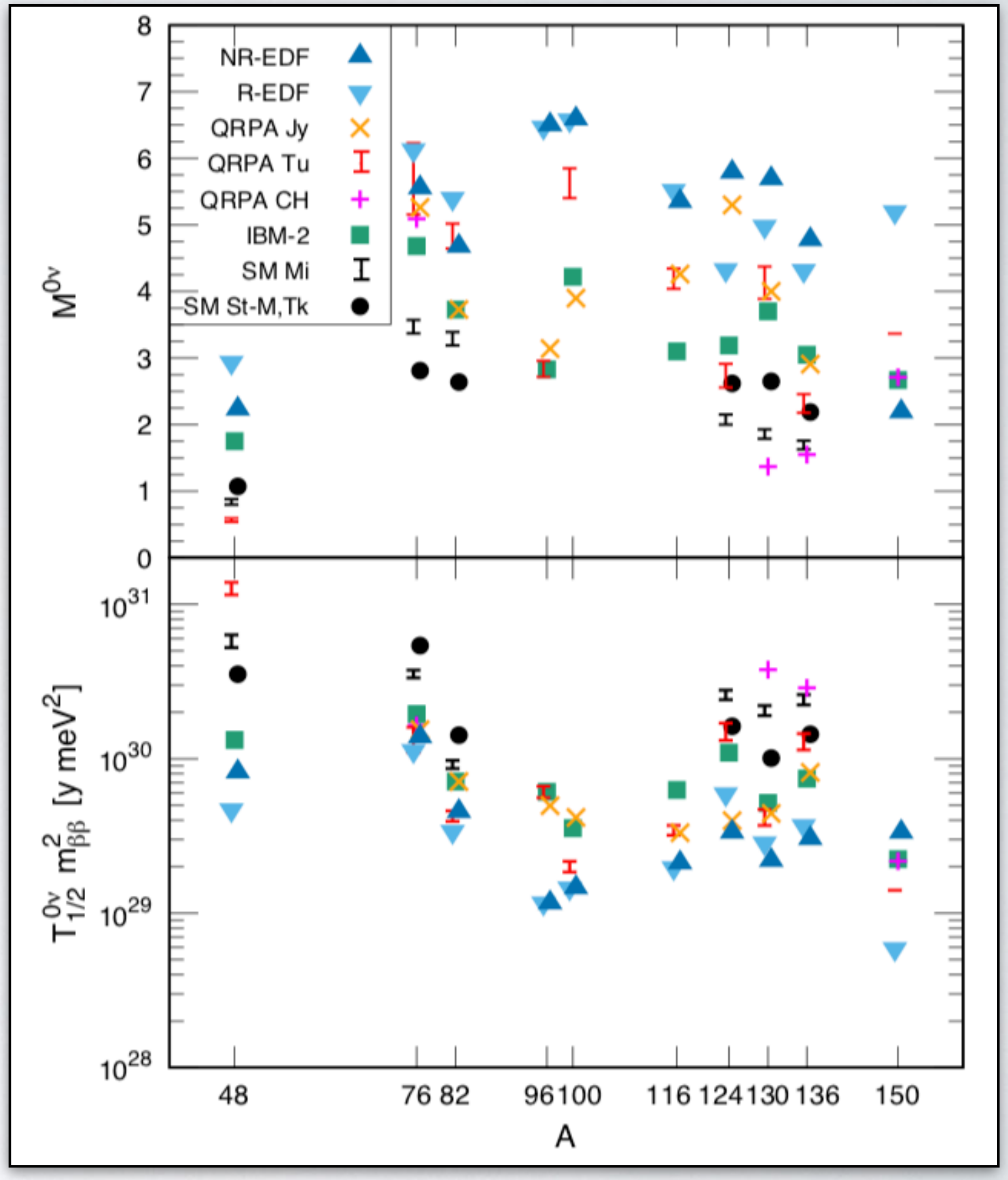
e.g. Engel et al '18

Leading-order transition currents



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

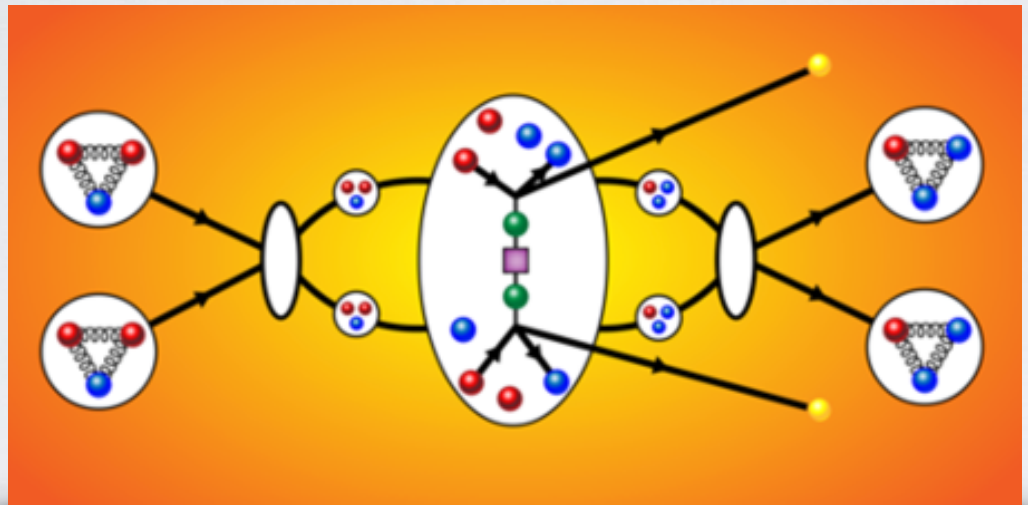
- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown is $m_{\beta\beta}$
- Many-body methods disagree significantly
- Original idea: study simpler nuclear systems
- **Not relevant for experiments but as a theoretical laboratory**



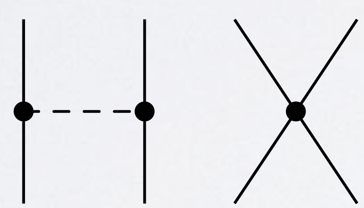
Engel-Menendez '16

Neutron-Neutron → Proton-Proton

- Study simplest nuclear process: nn → pp + ee



- Derive wave functions from chiral effective field theory $T = V + V G_0 T$

LO 

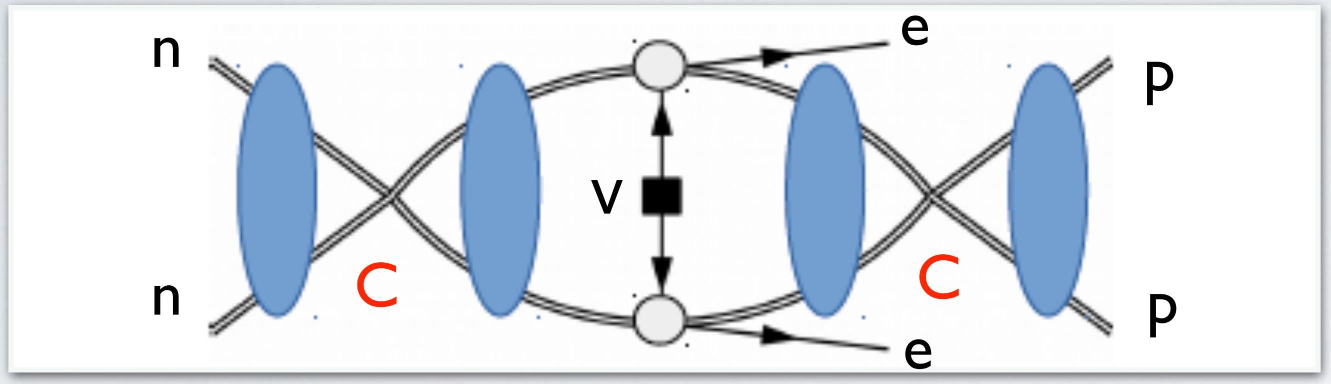
$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

Weinberg 90' 91'

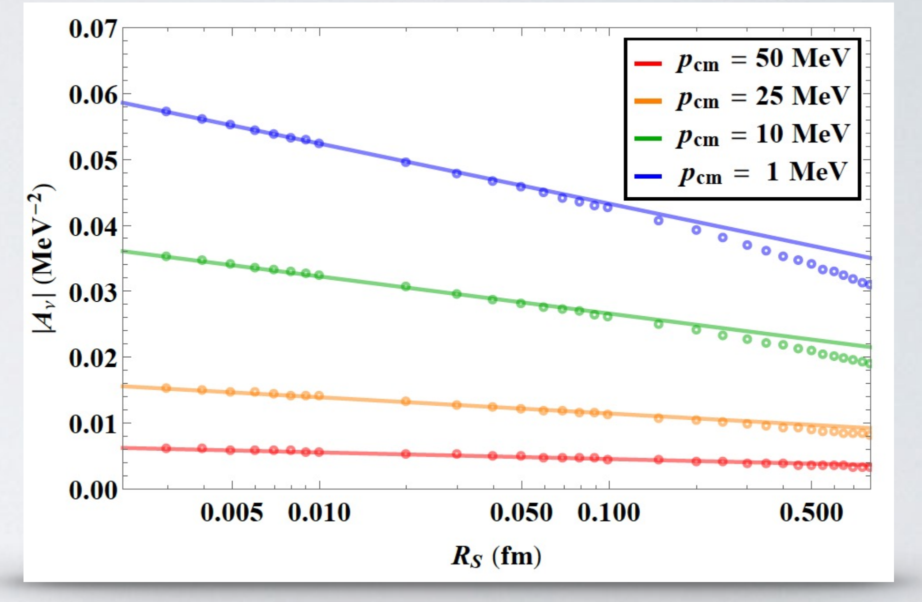
- Contact term low-energy constant fitted to $^1S_0$ scattering length

Leading-order transition currents

- Insert long-distance neutrino exchange into scattering states



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



New divergences

Similar to pion-mass dependence of C_0 in Kaplan/Savage/Wise '98

Phillips/Valderrama PRL '14

Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL '18

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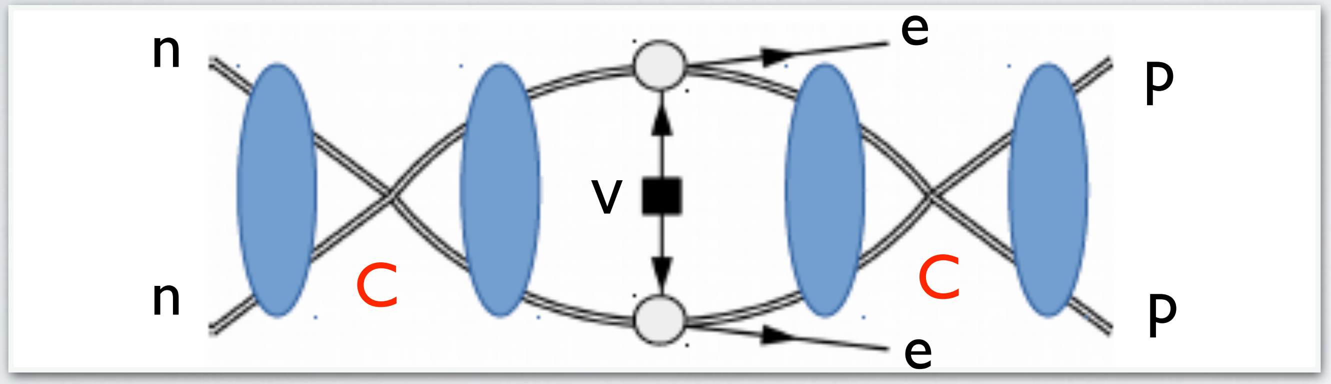

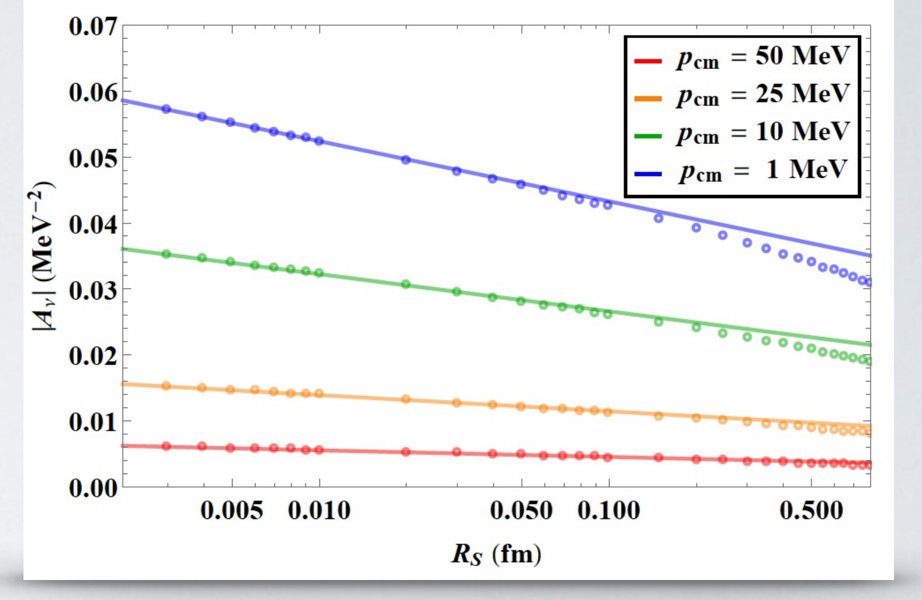

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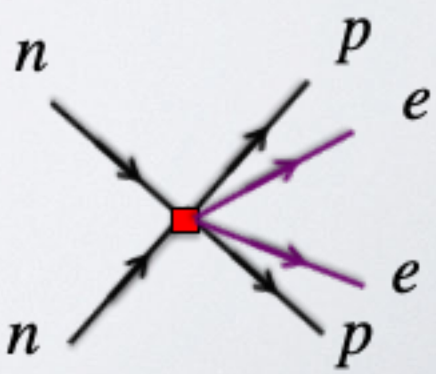
Phillips/Valderrama PRL '14

- **Logarithmic regulator dependence**

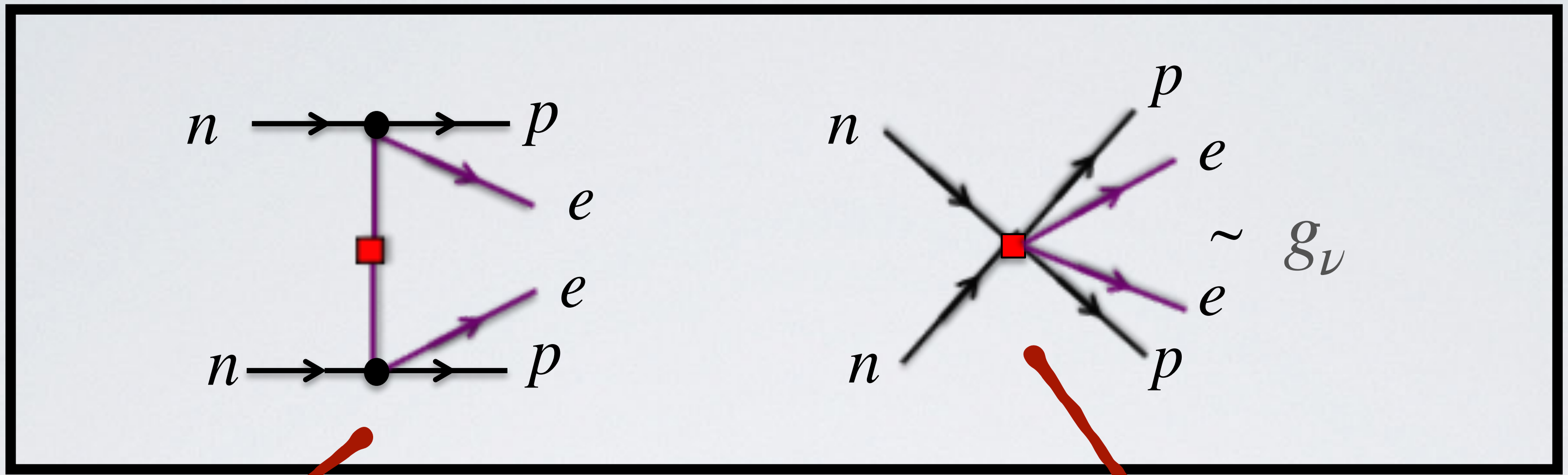
- Divergence indicates sensitivity to short-distance physics (hard-neutrino exchange)

- Suggest to add a counter term: a short-range nn → pp + ee operator



Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL '18

But how big is it ?



'Long-range' neutrino-exchange

'Short-distance' neutrino exchange
required by renormalization of amplitude

- **Short-distance piece depends on unknown QCD matrix element** $\mathbf{g}_\nu$

- How to determine the value of this matrix element ? Obviously no data!

- **Lattice QCD can do this in the future. But not yet....**

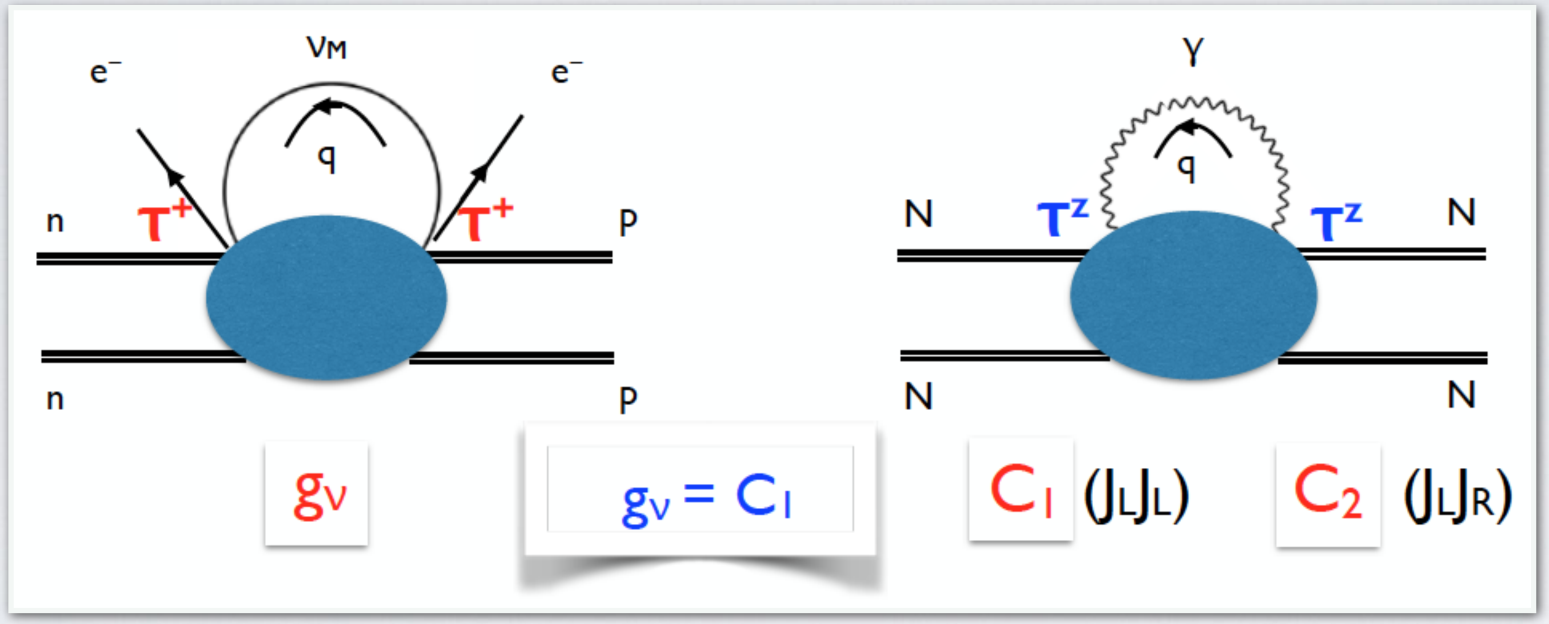
Davoudi, Kadam PRL '21 Briceno et al '19 '20
NPLQCD '24

- But solved already for the 'toy-problem' $\pi^- + \pi^- \to e^- + e^-$

Tuo et al. '19; Detmold, Murphy '20 '22

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions
- Isospin-breaking nucleon-nucleon scattering data determines $\mathbf{C_1+C_2}$
- Electromagnetism conserves **parity** coupling and $\mathbf{g_\nu \sim C_1}$ only

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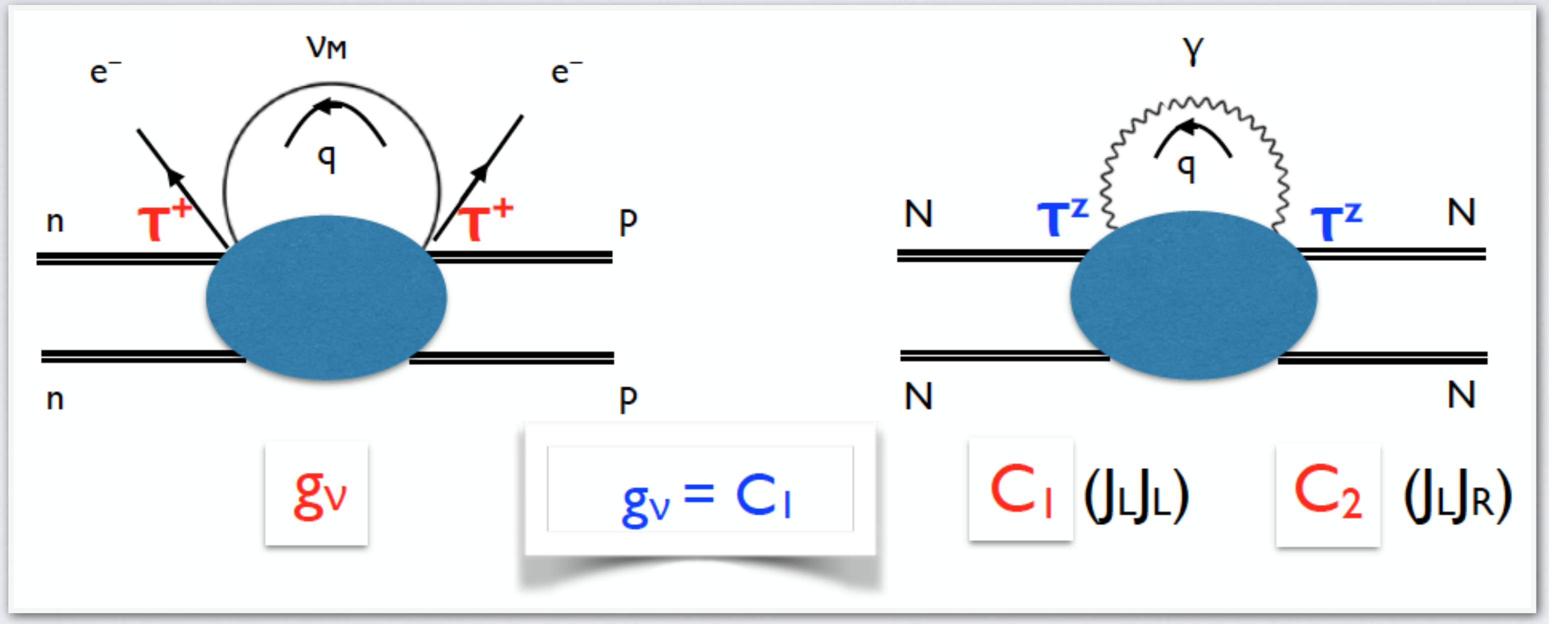

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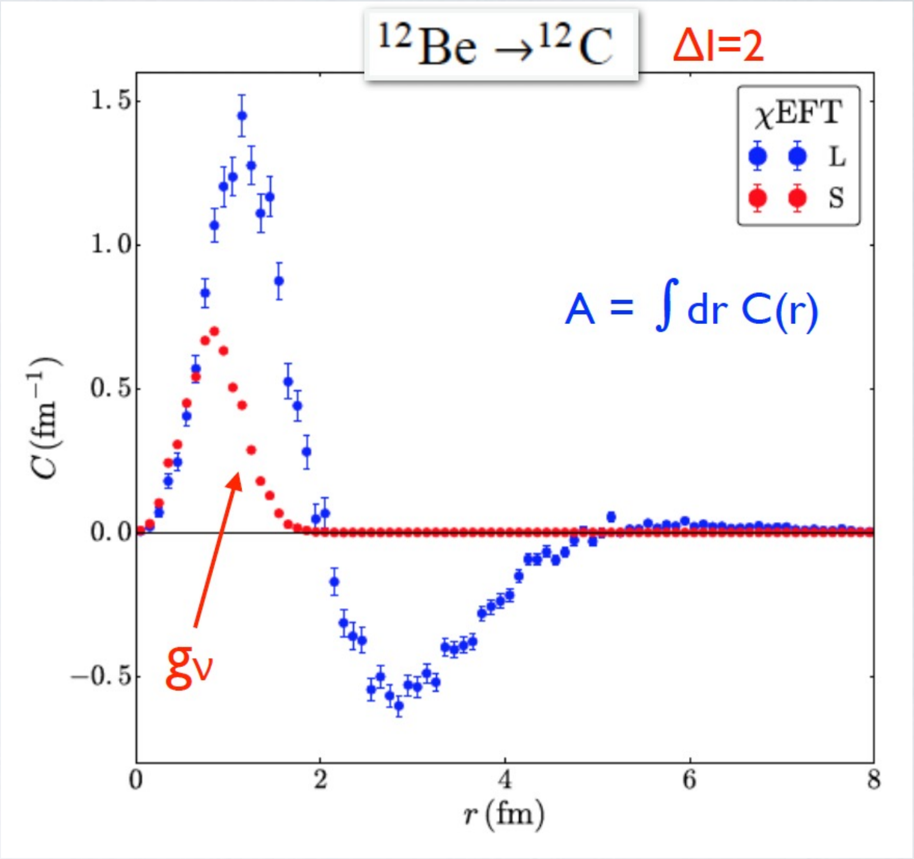
- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **g_ν~C_1** only
- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer '21
- **We originally assumed g_ν~(C_1+C_2)/2, what happens to neutrinoless double beta decay ?**

Impact on nuclear matrix elements

Pastore, Piarulli et al '19



- Use VMC + Norfolk chiral potentials for wave functions
- Extract $g_V \sim (C_1+C_2)/2$ from **same potential**

Nuclear matrix elements	Long Range	Short Range
$^{12}\mathrm{Be} \to {}^{12}\mathrm{C} + e^- + e^-$	0.7	0.5

- Short-distance effects are sizable and change matrix elements by O(1)

- **Caveat-1** Based on $g_V \sim (C_1+C_2)/2$ relation (not so clear)
- **Caveat-2** These are not nuclei of experimental interest

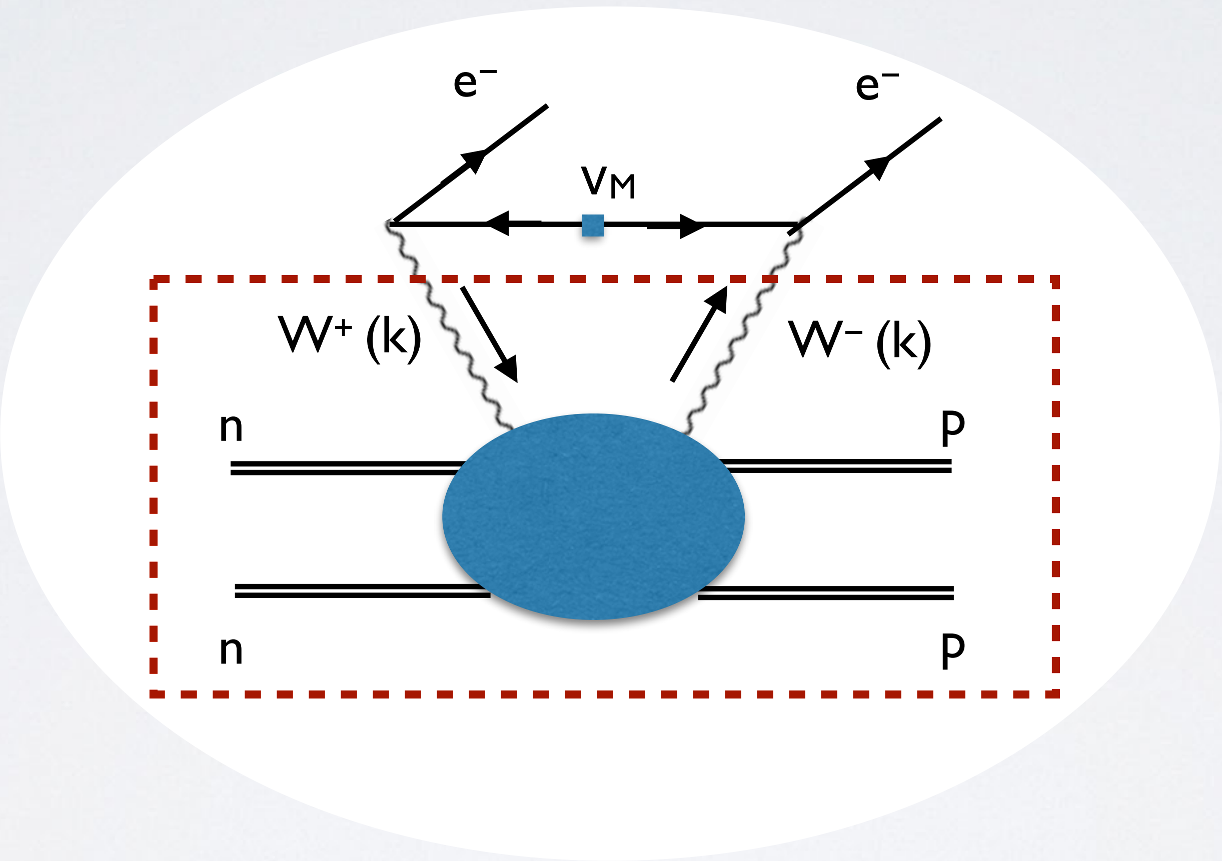
- **Can we do better ?**

An analytic approach

- The nn → pp + ee amplitude can be represented as an integral expression

$$A_\nu \sim G_F^2 \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2} \boxed{\int d^4x e^{ik\cdot x}\langle pp\,|\,T\{J_W^\mu(x)J_W^\nu(0)\}\,|\,nn\rangle}$$

J_W^μ = weak current (V-A)



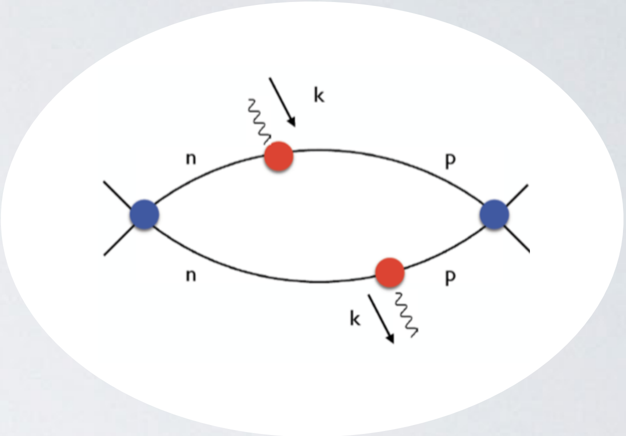
- Can represent the `red box' in regions of the virtual neutrino momentum k

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti JHEP '22 PRL '21

An analytic approach

- The nn → pp + ee amplitude can be represented as an integral expression

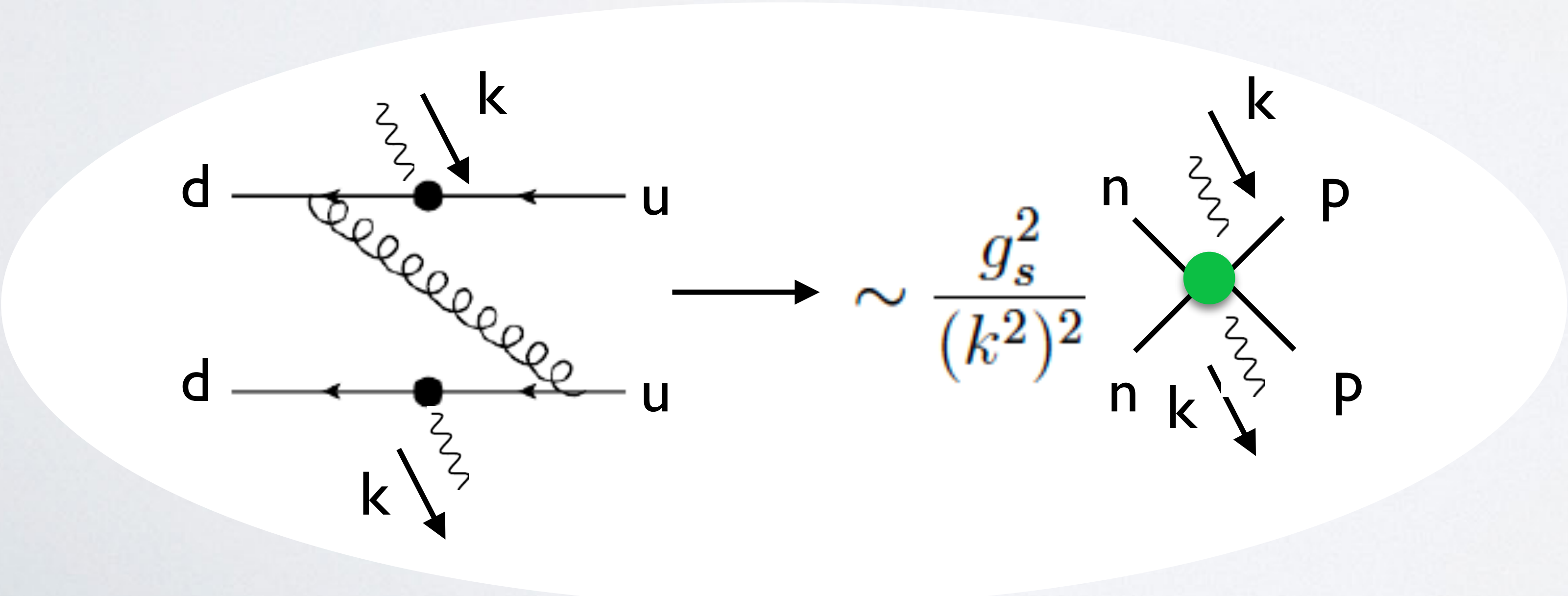
$$A_\nu \sim G_F^2 \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2} \boxed{\int d^4x e^{ik\cdot x}\langle pp\,|\,T\{J_W^\mu(x)J_W^\nu(0)\}\,|\,nn\rangle}$$



- At small virtual momentum: NLO chiral EFT

- Intermediate momentum: (**model-dependent**) resonance contributions to nucleon form factors and to NN scattering

- Large momentum: Perturbative QCD + Operator Product Expansion



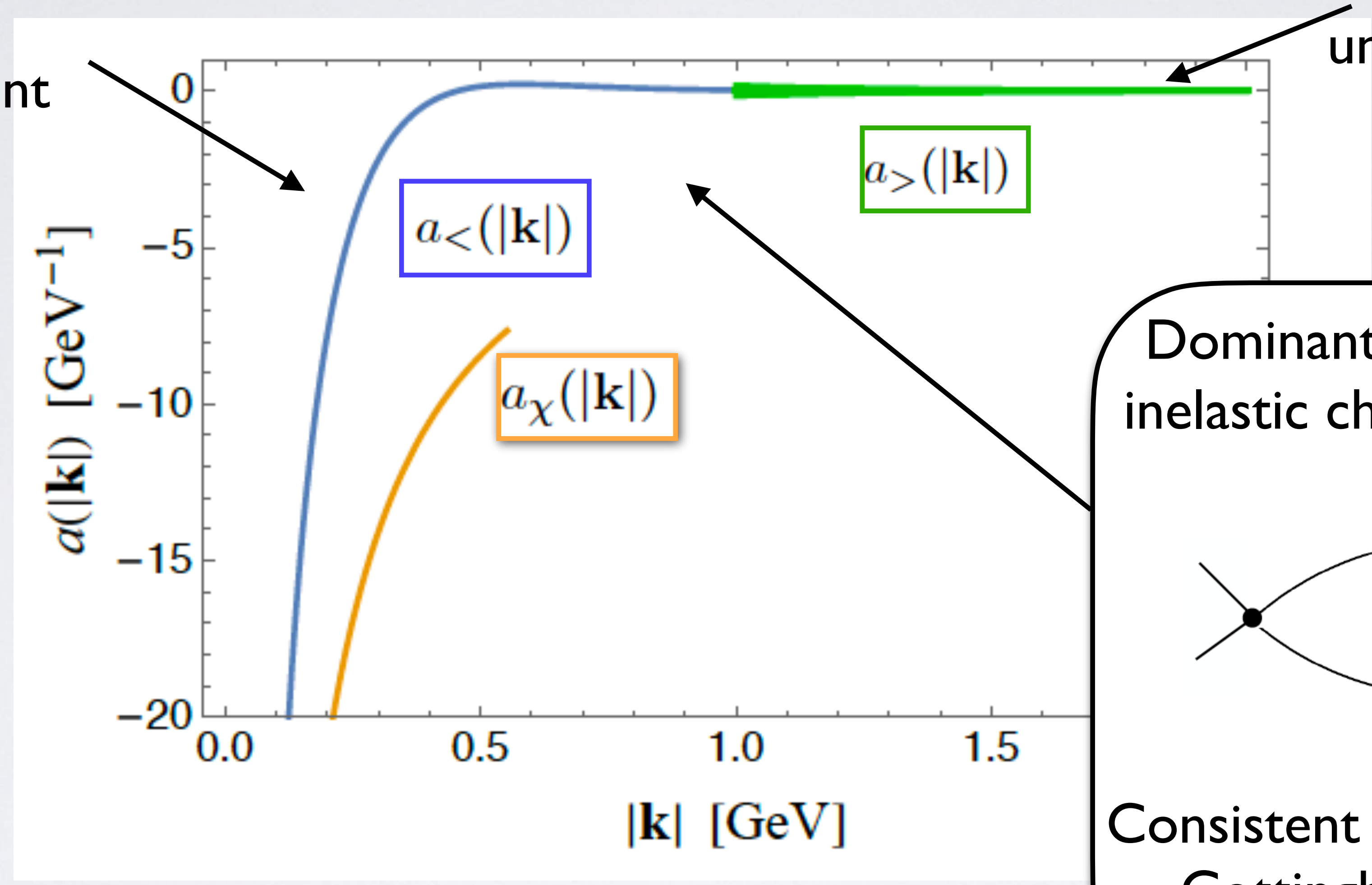
Small dependence on local 4-quark matrix elements

Determining the contact term

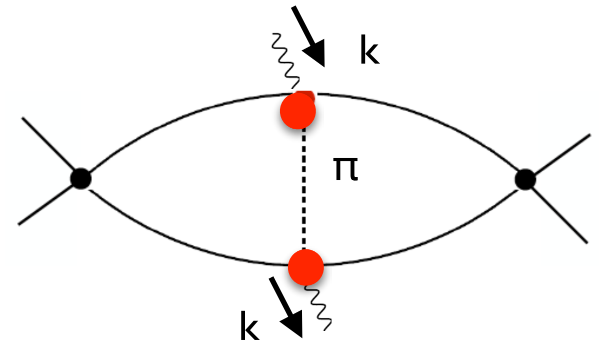
$$A_\nu \sim \int_0^\Lambda dk\, a_<(k) + \int_\Lambda^\infty dk\, a_>(k)$$

Steep falloff controlled by the $^1S_0$ effective range: model-independent

Small uncertainty due to unknown local operator matrix element



Dominant uncertainty from inelastic channels (NNπ , …):



Consistent with <30% effect in Cottingham approach to π,N EM mass splittings

- Matching: $$2\tilde{C}_1(\mu_\chi) = \frac{1+2g_A^2}{2} - \int_0^{\mu_\chi} d|\mathbf{k}|\; a_\chi(|\mathbf{k}|) + \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$
- Inelastic channels studied by Graham van Goffrier (UCL PhD thesis '24) and found to be small

The total amplitude

- The result is an expression for **total nn →pp + ee amplitude**

$$|A_\nu(|\mathbf{p}|,|\mathbf{p}'|)| = -\,0.019(1)\,\mathrm{MeV}^{-2}$$

$$|\mathbf{p}| = 25\,\mathrm{MeV}$$

$$|\mathbf{p}'| = 30\,\mathrm{MeV}$$

- Example: in dimensional regularization in MS-bar scheme

$$g_\nu^{NN}(\mu = m_\pi) = (1.3 \pm 0.1 \pm 0.2 \pm 0.5)$$

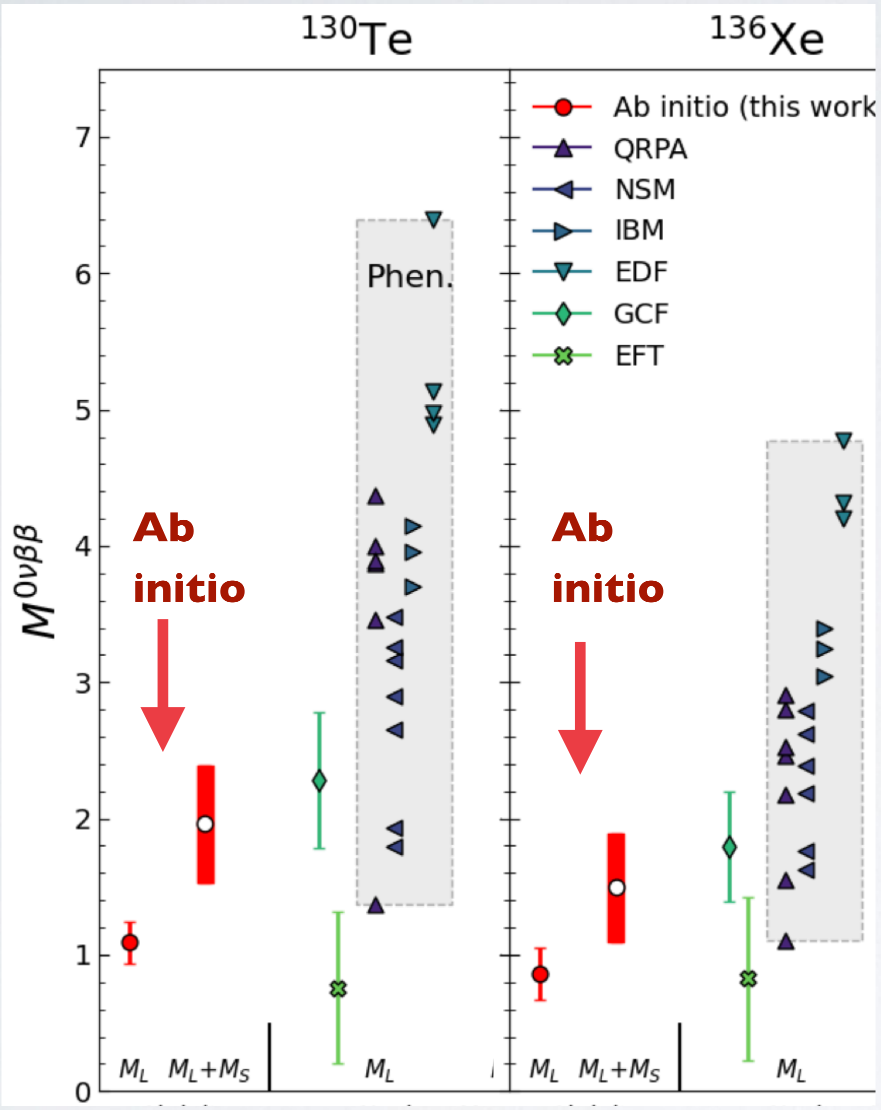
- Matching to 'fake-data' possible for **any scheme** suitable for nuclear calculations
- Now used to include the contact term into ab initio 0vbb calculations
- Same strategy was used to 'predict' EM corrections to nucleon-nucleon scattering

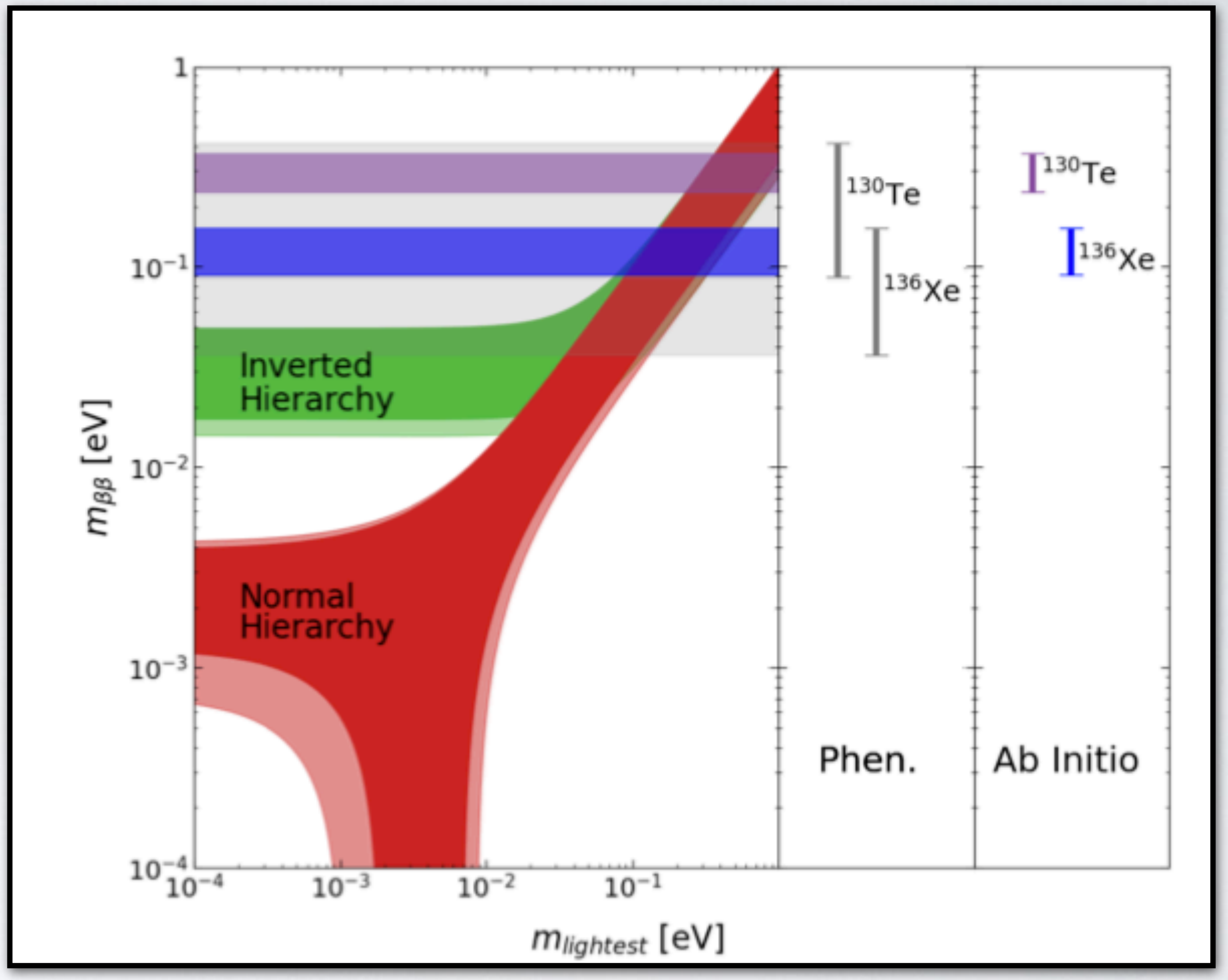
$$a_{CIB} = \frac{a_{nn} + a_{pp} - 2a_{np}}{2} = (14 \pm 5)\,\mathrm{fm} \qquad a_{CIB}^{\mathrm{data}} = (10.4 \pm 0.2)\,\mathrm{fm}$$

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti JHEP '22 PRL '21

Impact on realistic nuclei

- Some results from last year (2307.15156 Belley et al) using **VS-IMSRG**
- See also: Belley et al PRL '24 for detailed 76Ge analysis

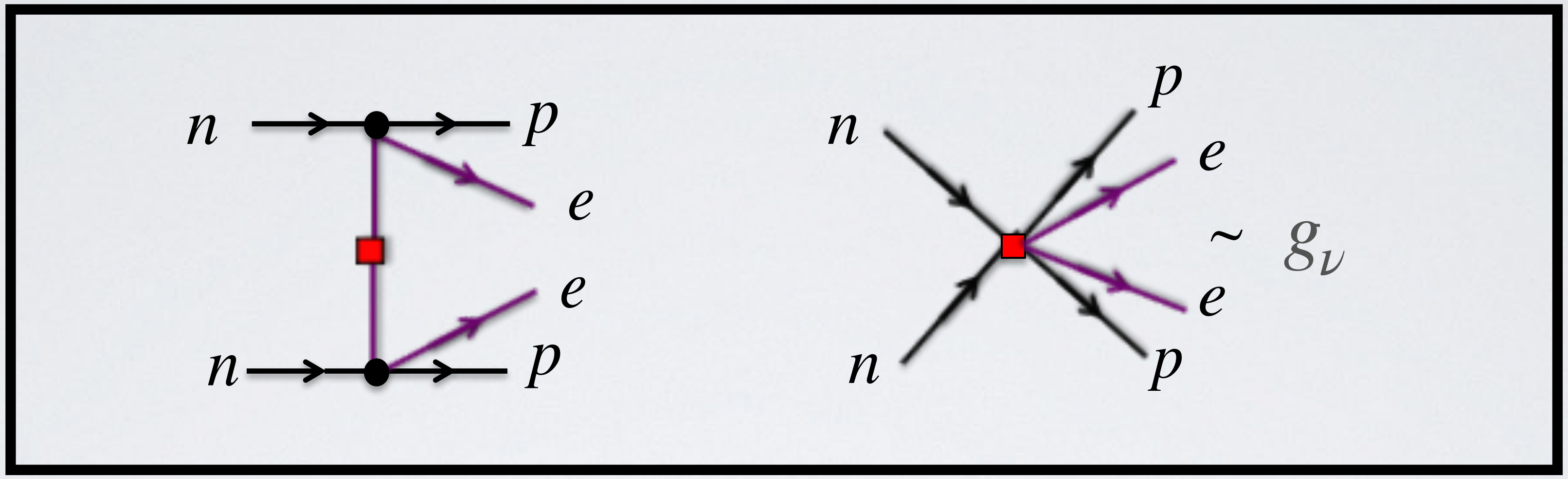




- Ab initio calculations find small long-distance NMEs compared to other methods
- **Partially compensated by new short-distance interaction (50-100% effect)**
- Just using various ab initio methods leads to significantly smaller uncertainty bands
- Question: how to compare ab initio to phenomenological interactions including short-distance ?

Higher-order corrections

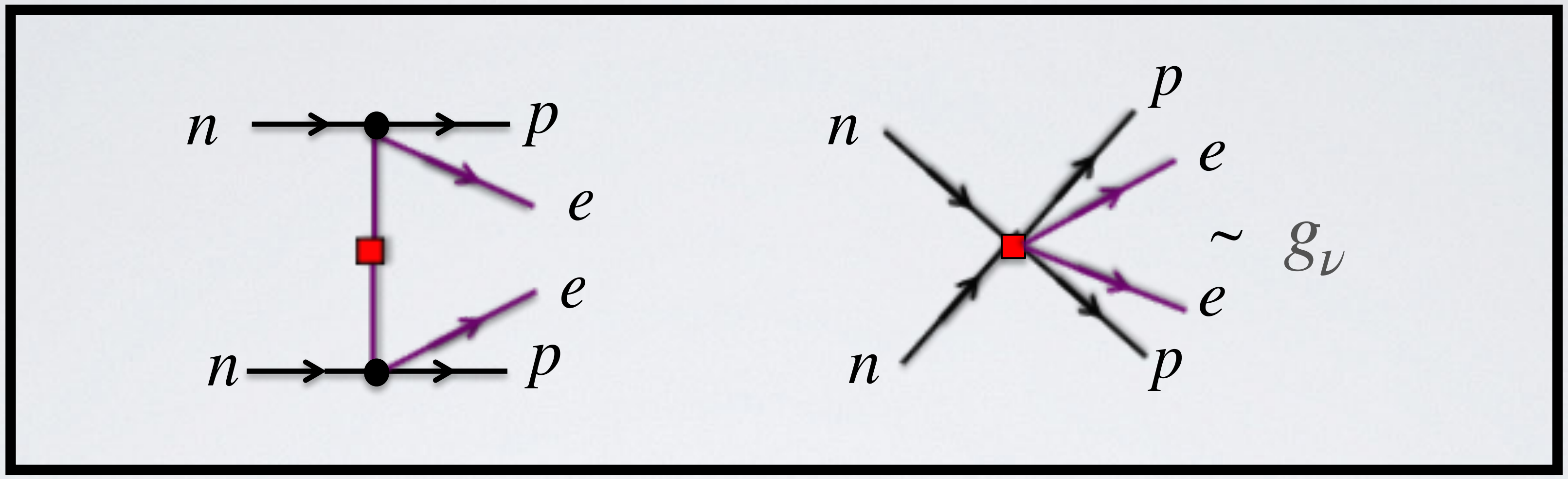
- It seems now that the leading-order 0vbb current contains 2 terms



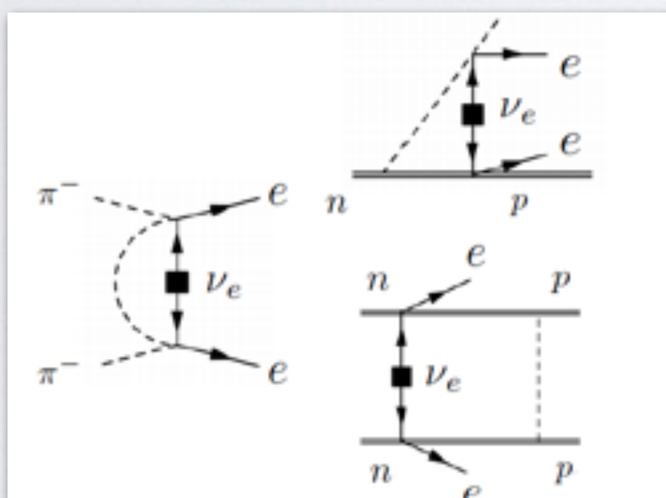
- **Are there more surprises ?**

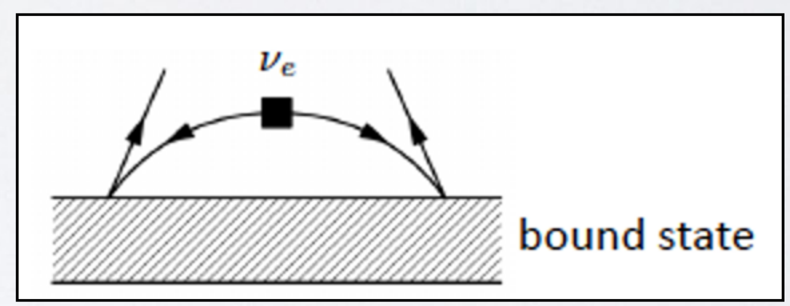
Higher-order corrections

- It seems now that the leading-order 0vbb current contains 2 terms



- At NNLO we get additional contributions from loops





'Soft' neutrinos

'Ultra-soft' neutrinos

- Ultrasoft depends on nuclear structure

$$\sum_n \langle f|J_\mu|n\rangle\langle f|J^\mu|i\rangle \times \int \frac{d^3k}{(2\pi)^3}\frac{1}{E_\nu[E_\nu + (E_n - E_0) - i\epsilon]}$$

Higher-order corrections in the nuclear shell model

- Soft loops (Cirigliano et al '17) and ultrasoft (Dekens et al '24) calculated in chiral EFT
- Implemented by Javier Menendez and collaborators (2408.03374) in Shell Model

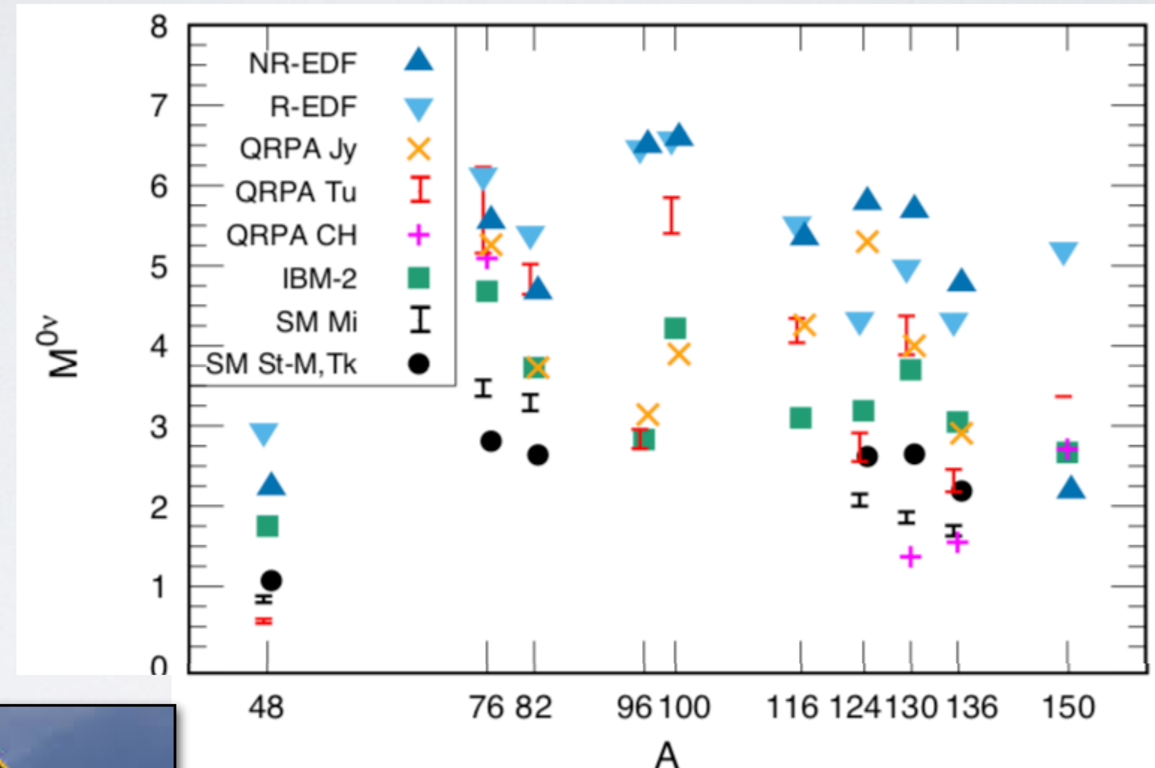
Nucleus	NSM			
	LO		N^2LO	
	L	S	usoft	loops
^{48}Ca	0.92(14)	0.43(20)	0.01(3)	0.05(7)
^{76}Ge	3.57(25)	0.97(48)	-0.26(0)	0.05(16)
^{82}Se	3.38(20)	0.91(43)	-0.24(1)	0.05(15)
^{96}Zr				
^{100}Mo				
^{116}Cd				
^{124}Sn	2.79(63)	1.06(52)	-0.21(5)	0.06(16)
^{130}Te	2.68(79)	1.07(50)	-0.20(7)	0.06(16)
^{136}Xe	2.26(53)	0.86(41)	-0.17(5)	0.05(13)

- Confirms that these effects are relatively small (usoft -10% corrections roughly)
- Comforting that no other supposedly small corrections are found to be large !

Towards improved theoretical predictions

- Assuming 'standard' mechanism: uncertainties from **hadronic & nuclear theory**

$\Gamma \sim |M_{0\nu}|^2 (m_{\beta\beta})^2$



Engel-Menendez '16

Can we (chiral dynamics participants) help ?

Seems so but more work is needed !
We should update the '16 review plot !

The plan of attack

1. Introduction to Majorana neutrinos and 0vbb

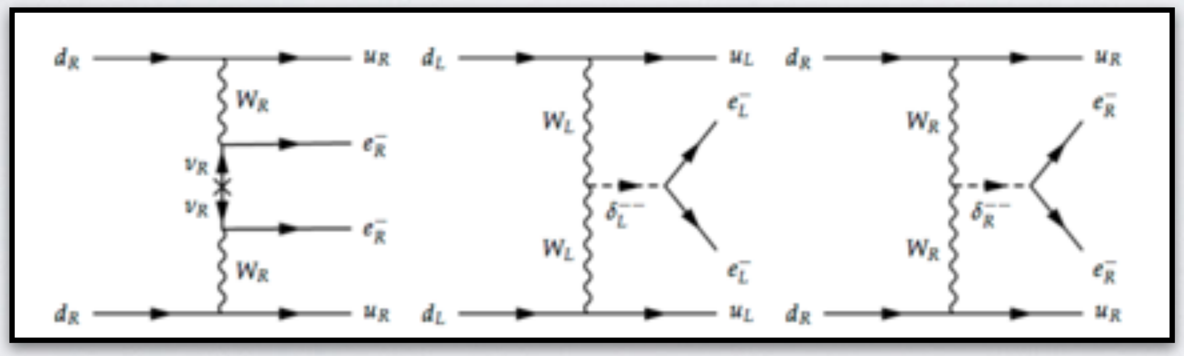
2. 0vbb from light Majorana neutrino exchange

   - *Controlling nuclear matrix elements !*

3. Other Lepton-number-violating mechanisms in EFT

Beyond neutrino masses

- Neutrinoless double beta decay can be caused through other mechanisms !
- For instance in *left-right symmetric models, supersymmetry, leptoquarks* ….

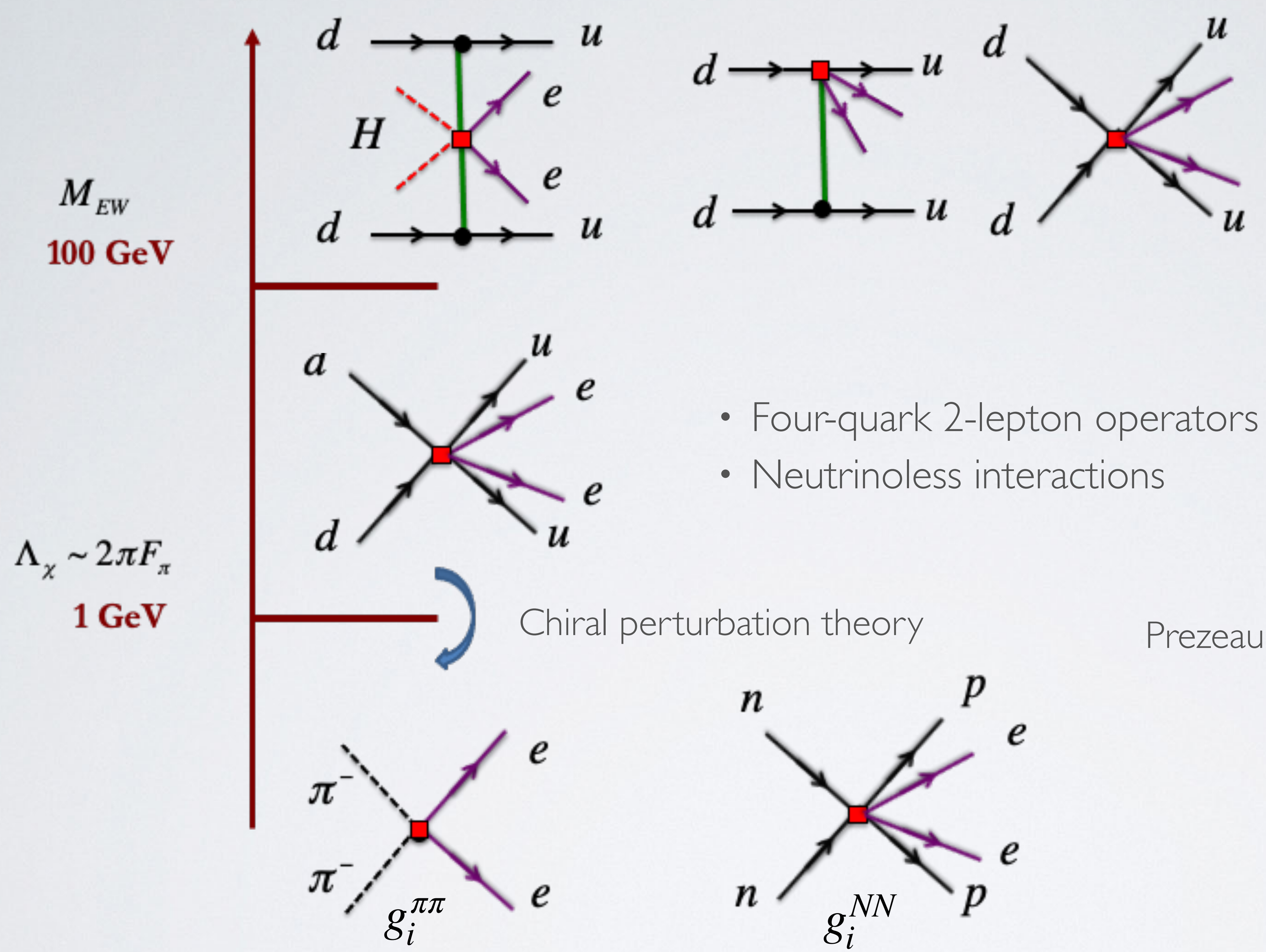


- No light neutrinos appear at all in these processes but **same observable signature**
- If scale of LNV is high they can be captured by effective field theory techniques

$$\mathscr{L}_{LNV} = \frac{c_5}{\Lambda}\left(L^T C\tilde{H}\right)(\tilde{H}^T L) + \sum_i \frac{d_i}{\Lambda^3} O_{7i} + \sum_i \frac{f_i}{\Lambda^5} O_{9i} + \dots$$

- Disentangling the origin from 0vbb measurements will be a **hard (luxury)** problem

Example dim-9 operators



- Four-quark 2-lepton operators
- Neutrinoless interactions

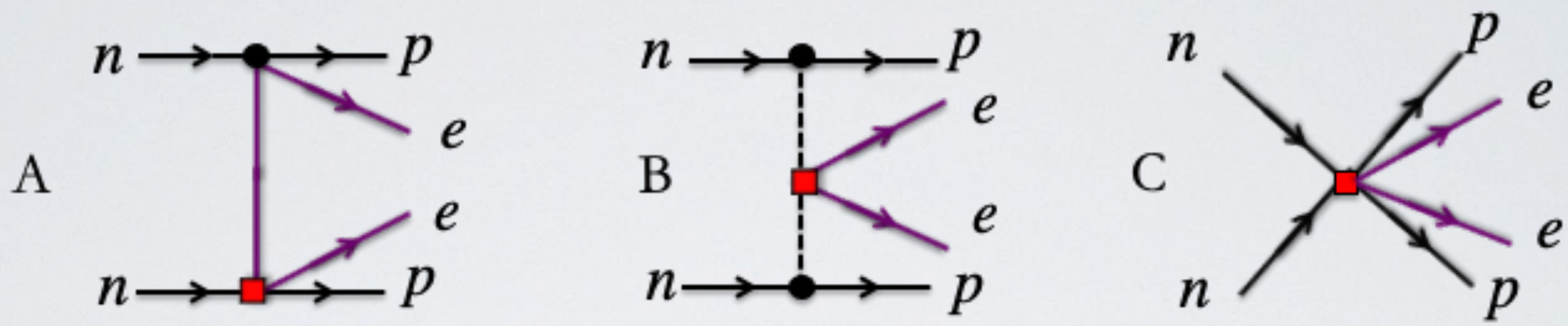
Prezeau et al '03

- Pionic operators lead to leading-order neutrinoless double beta decay contributions !
- **Depend on four-quark matrix elements: great improvements by CalLat**

$$g_4^{\pi\pi} = -(1.9 \pm 0.2)\,\mathrm{GeV}^2 \qquad g_5^{\pi\pi} = -(8.0 \pm 0.6)\,\mathrm{GeV}^2$$

Nicholson et al '18

New 0vbb topologies



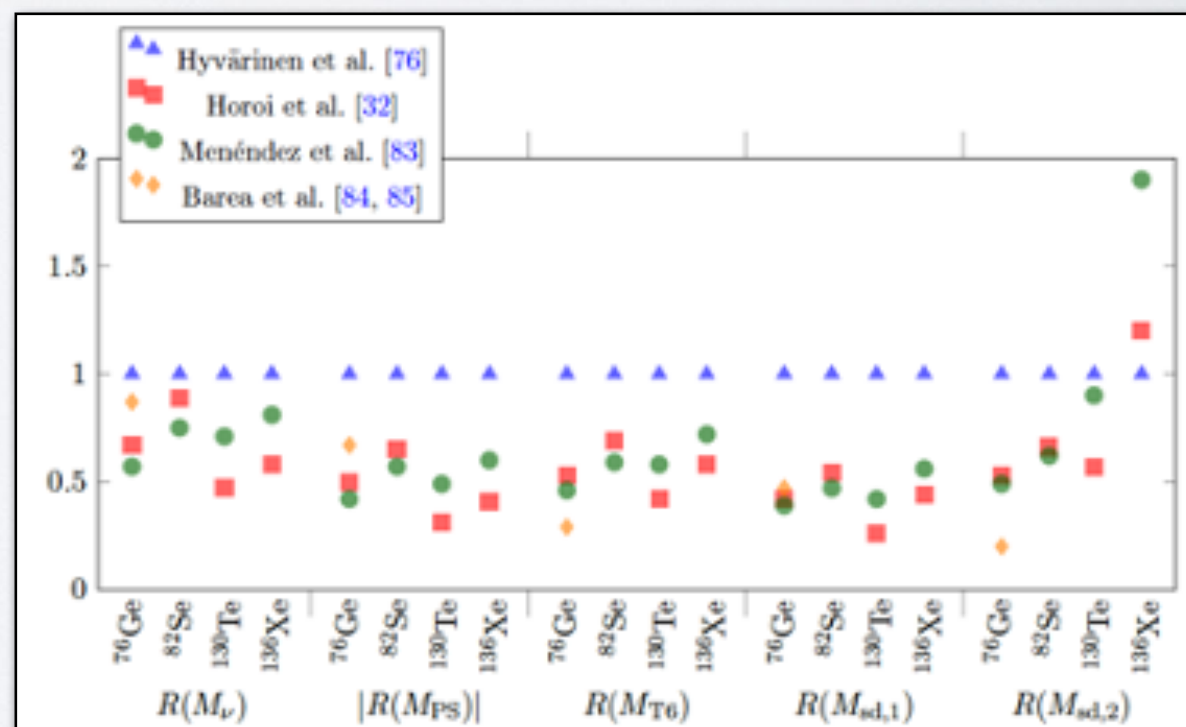
- Straightforward to calculate generalized 0vbb transition current
- Need additional nuclear matrix elements (NMEs)
- **At leading-order in Chiral-EFT: 15 NMEs (all in literature)**
- Similar uncertainties as before

Cirigliano et al '17 '18

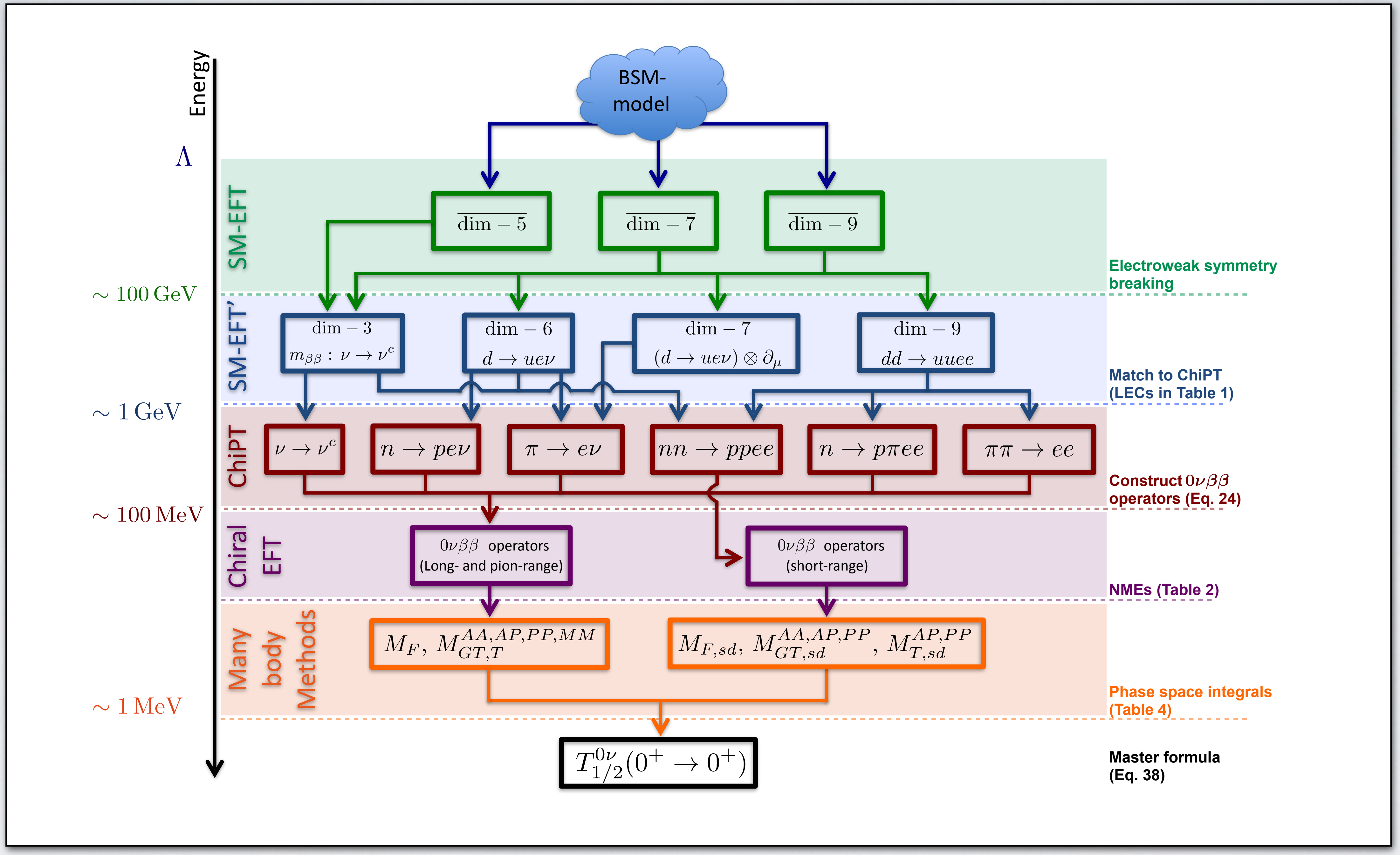
NMEs	^{76}Ge [74]	[31]	[81]	[82, 83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_T^{AA}	–	–	–	
M_T^{AP}	-0.35	0.01	-0.01	
M_T^{PP}	0.10	0.00	0.00	
M_T^{MM}	-0.04	0.00	0.00	

NMEs	^{76}Ge			
$M_{F,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,sd}^{PP}$	0.32	0.00	0.02	0.38

Hyvarinen/Suhonen '15
Menendez et al '17 '18
Barea et al '15 '18
Horoi/Neacsu '17



The 0vbb metro map



- Open-access Phyton tool (***NuDoBe***) that automizes all of this in SM-EFT framework

download: https://github.com/OScholer/nudobe
online tool: https://oscholer-nudobe-streamlit-4foz22.streamlit.app/

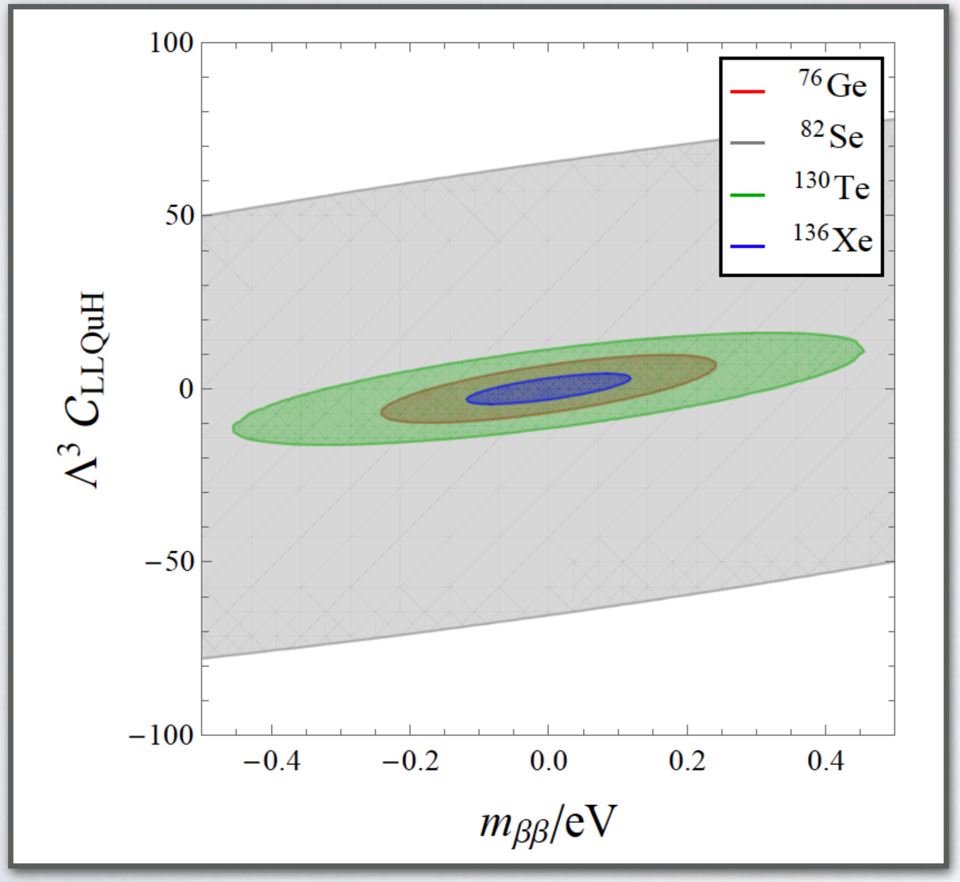
Scholer, Graf, JdV' 23

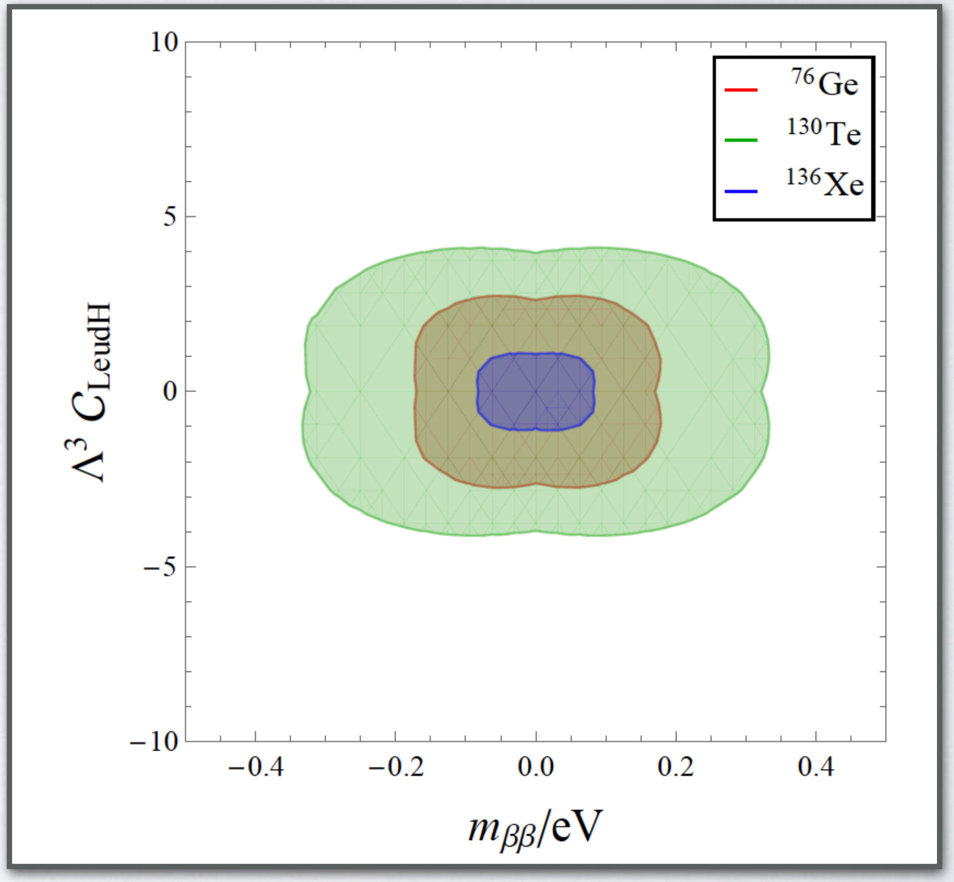
Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?
- Example: ratios of decay rates of various isotopes

Deppisch/Pas '07, Lisi et al '15, Graf/Scholer '22

- **Unfortunately, different isotopes not too discriminating**
- Ratios suffer from nuclear/hadronic uncertainties

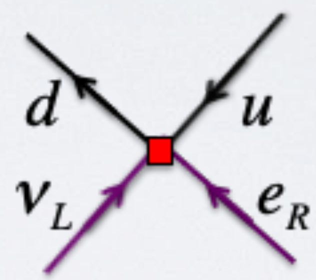




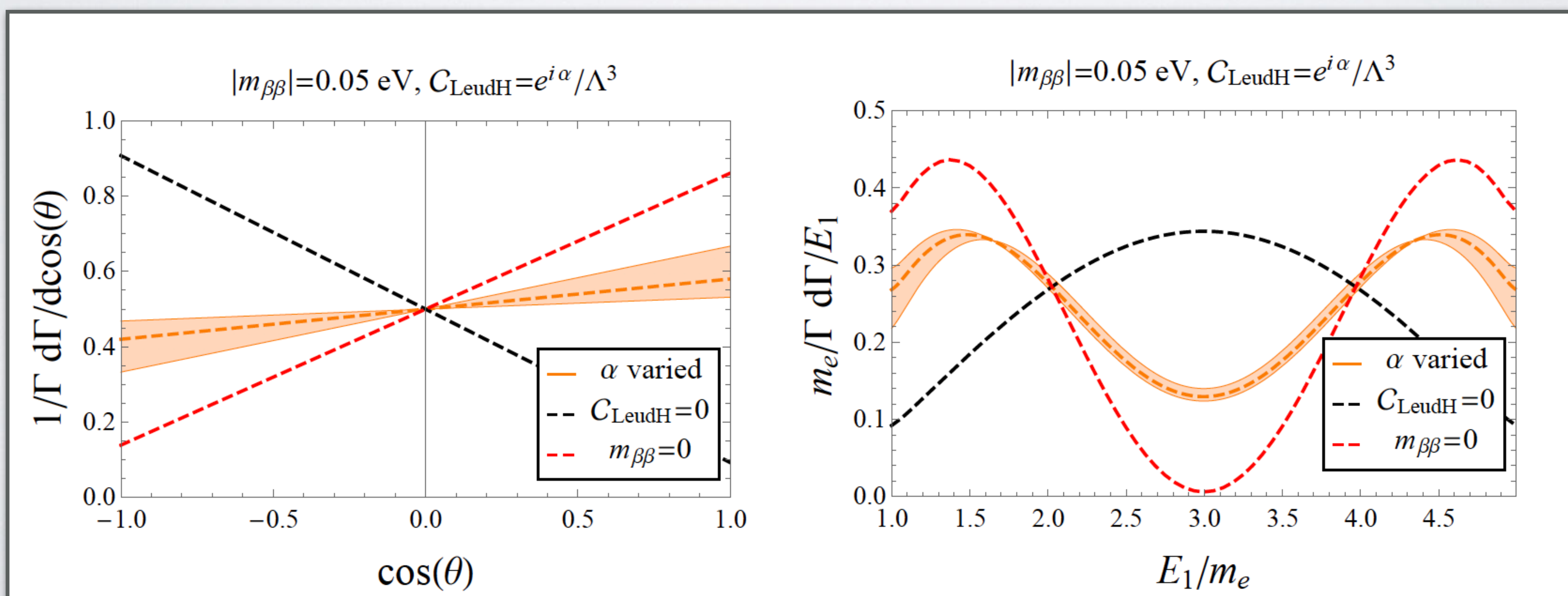
Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?

- **One could in principle measure angular&energy electron distributions**



$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$ $\Lambda \sim 50\,\mathrm{TeV}$

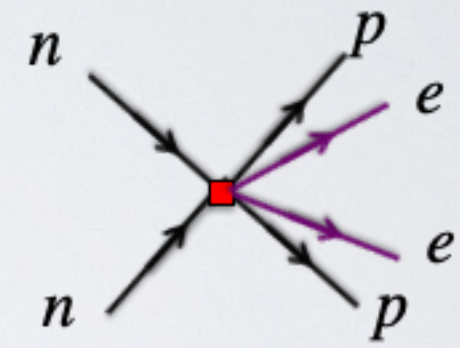


Concluding remarks

- **Neutrinoless double beta decay best way to determine if neutrinos are Majorana states**

- Heroic experimental effort ! Hadronic/Nuclear theory needed to interpret data

- Progress from EFT + lattice + nuclear structure



- New findings: standard mechanism depends on short-distance physics
  Impacts ab initio calculations of heavy nuclear decays

- End-to-End EFT framework for any LNV source (easy to use)

- Not discussed: extension to light sterile neutrinos

See talk by V. Plakkot this afternoon