Lepton Number Violation in Effective Field Theory

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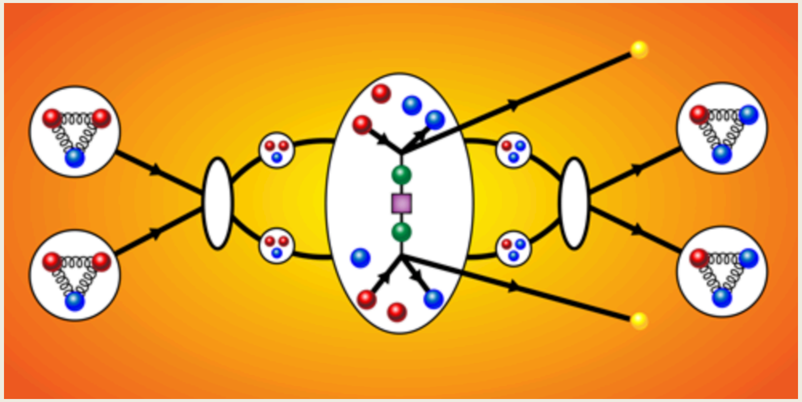

Lepton Number Violation in Effective Field Theory

- **Part I: LNV and neutrinoless double beta decay**

- Part II: An effective field theory approach

    1. Light Majorana mass (the Weinberg operator)

    2. Non-standard mechanisms in EFT

The puzzle of the neutrino mass

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

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

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

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

- Nothing wrong with this!

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

$$L_\upsilon = -M_R \nu_R^T C \nu_R$$

New mass scale not linked to EW scale

- *'Everything that is not forbidden is compulsary'*
- Does such a Majorana mass term exist in nature ?

See-saw type I + Leptogenesis

- Imagine we have both Dirac and Majorana mass term
- See-saw type I: pick

$$M_R >> y_\nu v$$

- The neutrinos then split into a light (active) and heavy (sterile) sector

$$M_{diag} \approx \begin{pmatrix} (y_\nu v)^2 / M_R & 0 \\ 0 & M_R \end{pmatrix} \qquad \begin{array}{l} \nu = \nu_L + \nu_L^c \\ N = \nu_R + \nu_R^c \end{array}$$

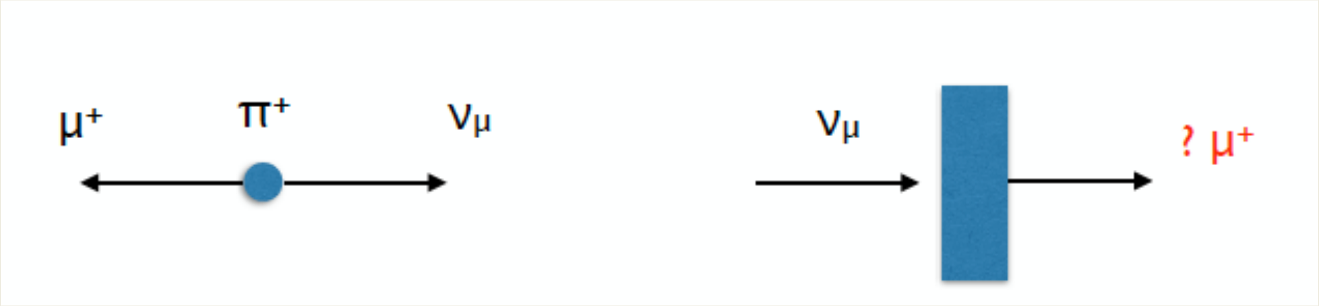
- If $y_\nu \sim 1$, then $M_R \sim 10^{15}$ GeV to get neutrinos masses

- **But M_R could be much lower as well (essentially any mass scale)**

- Heavy right-handed neutrinos (from GeV to > 10^6 TeV) appear in leptogenesis scenarios.

Experimental tests

- **Can we measure if neutrinos are Majorana ?**
- Easy thought experiment (B. Kayser): generate υ beam from pion decays



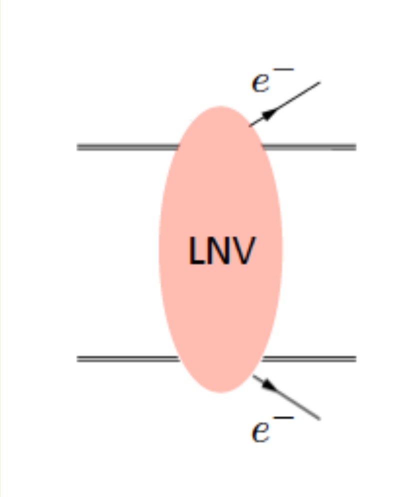
1. A Dirac neutrino will not produce anti-muons at target
2. A Majorana neutrino with right-handed helicity will do that

- **But it is hopeless experimentally !** Fraction of R-helicity neutrinos

$$\left(\frac{m_\nu}{E_\nu}\right)^2 \sim 10^{-18}$$

Cut out the middle man

- More promising: look at **'neutrinoless'** processes
- Produce 2 charged leptons (violate L by two units)



- Many probes imaginable: $K^- \to \pi^+ + 2e^-$

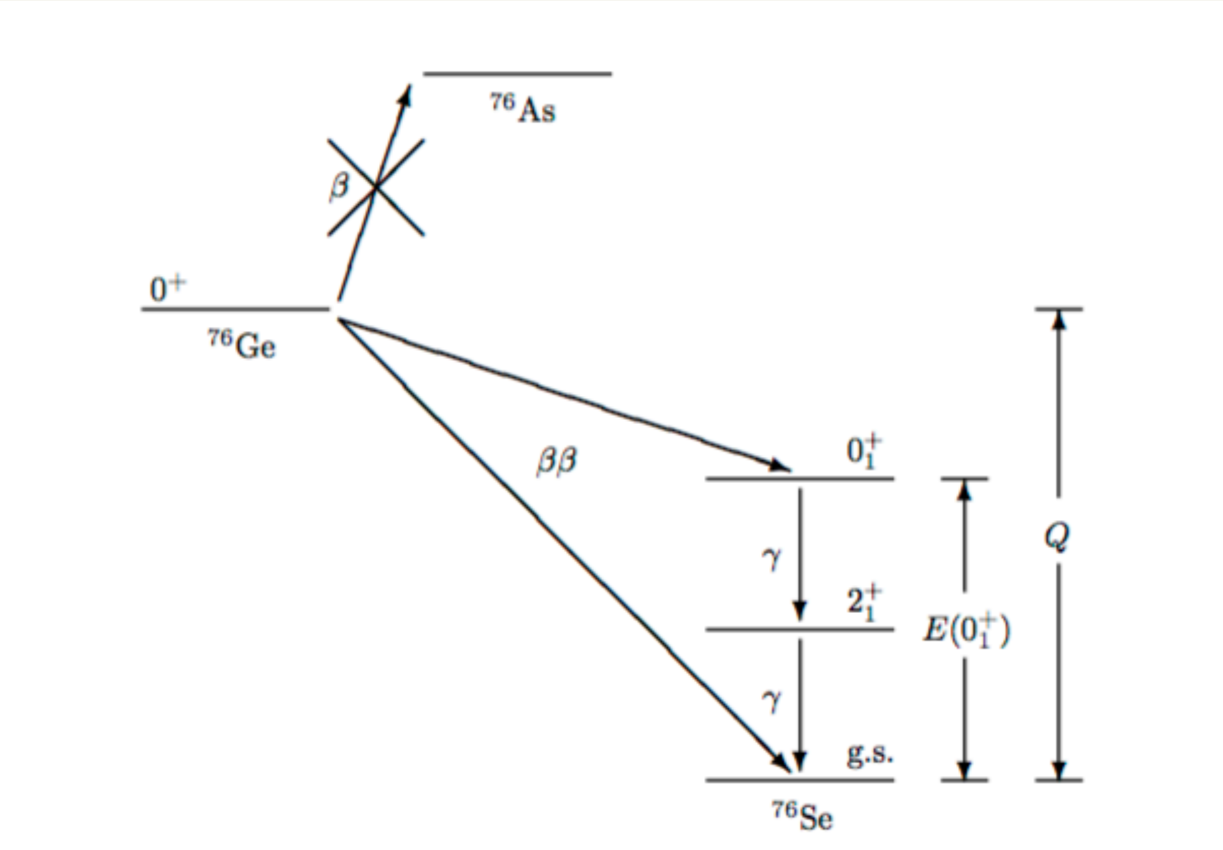
  $pp \to 2e^+ + jets$

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

- **Last process the strongest probe because of Avogadro's number !**

Double beta decay with and without ν's

- Double beta decay is a double-weak process $nn \rightarrow pp + ee + \bar{\nu}_e \bar{\nu}_e$
- Normally **swamped** by single beta decay (additional factor G_F^2)



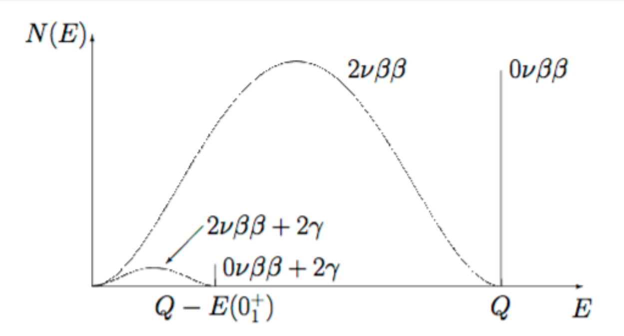
$Q \sim 2\ MeV$

Double beta decay with and without ν's

- Normal double beta decay (2νββ) has been observed

$$\left(A,Z\right)\rightarrow\left(A,Z+2\right)+2\,e^{-}+2\,\bar{\nu}_e$$

$$T_{1/2}^{2\nu}\left({}^{76}Ge\rightarrow{}^{76}Se\right)=\left(1.84^{+0.14}_{-0.10}\right)\times10^{21}\ yr$$



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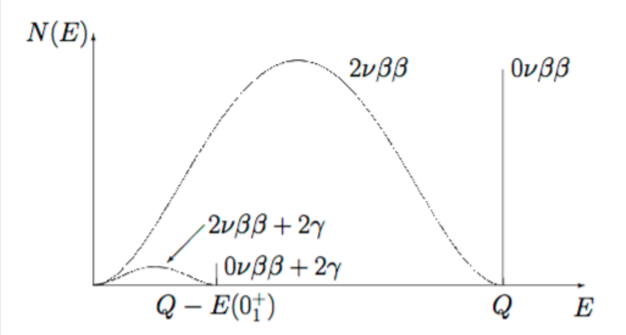


- **Neutrinoless double beta decay (0νββ) looks similar**

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

Furry '39

$$\Delta L = 2$$

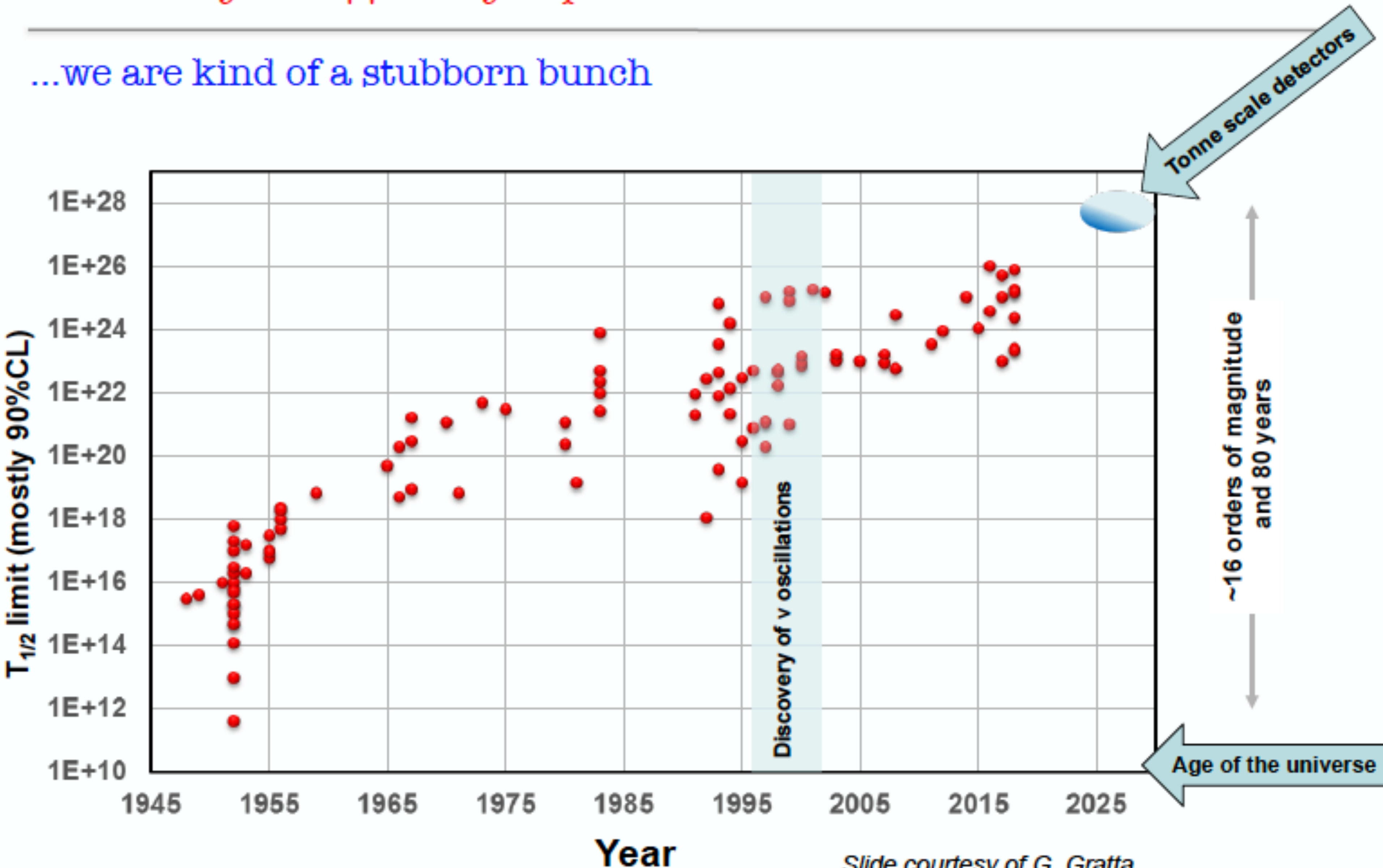
- Violates Lepton Number by two units and **never been observed (yet) …**

	Life time	Collaboration	year
^{76}Ge	8.0 x 10^{25} yr	GERDA	2018
^{130}Te	3.2 x 10^{25} yr	CUORE	2019
^{136}Xe	**1.1 x 10^{26} yr**	**KamLAND-Zen**	**2016**

Improvements upcoming

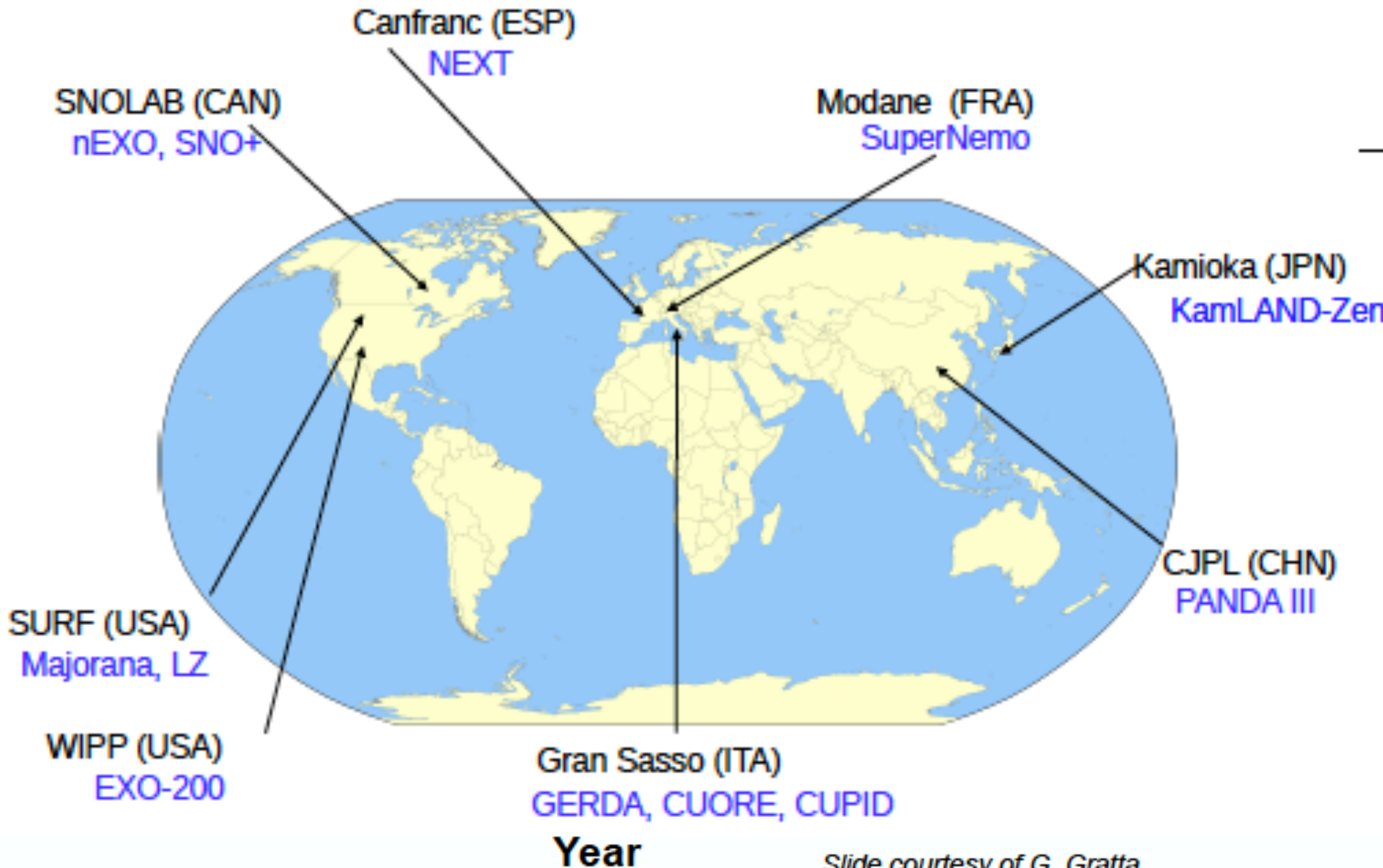
The history of 0νββ decay experiments in one slide

...we are kind of a stubborn bunch



Slide courtesy of G. Gratta
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

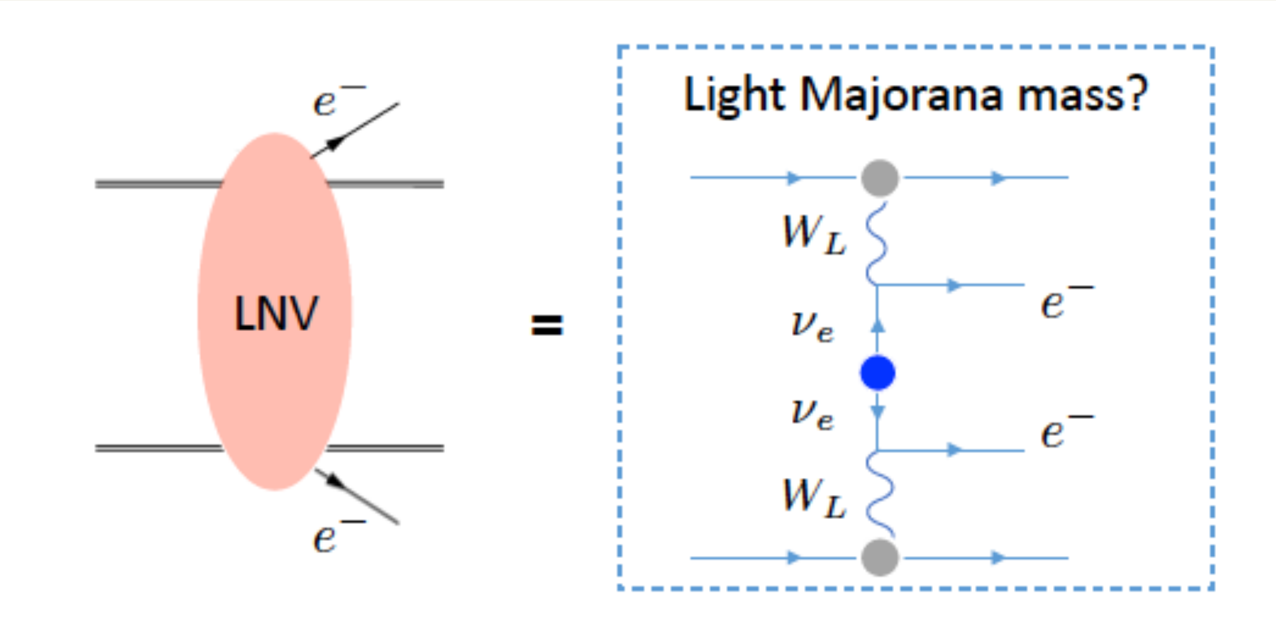
The history of $0\nu\beta\beta$ decay experiments in one slide



Slide courtesy of G. Gratta
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

Standard interpretation

- **0νββ** induced by exchange of 3 light Majorana neutrinos



- **Proportional to neutrino mass (source of LNV)**

$$\frac{1}{T_{1/2}^{0\upsilon}} \sim \Gamma \sim m_{\beta\beta}^2$$

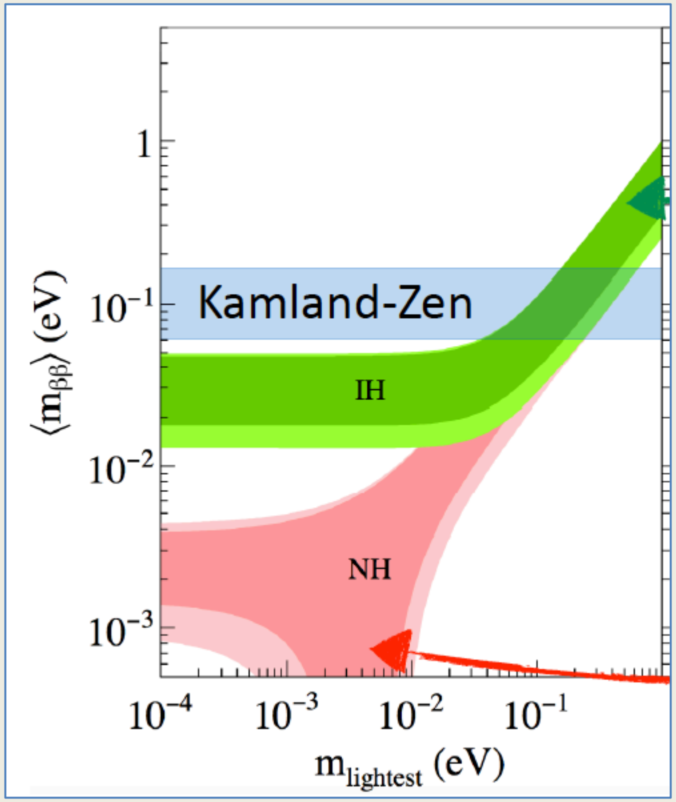
'Effective Neutrino Mass'

$$m_{\beta\beta} = \sum U_{e\,i}^2 m_i$$

Probing the neutrino Majorana mass

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

- **Unknowns: lightest mass, hierarchy, and Majorana phases**



Probing the neutrino Majorana mass

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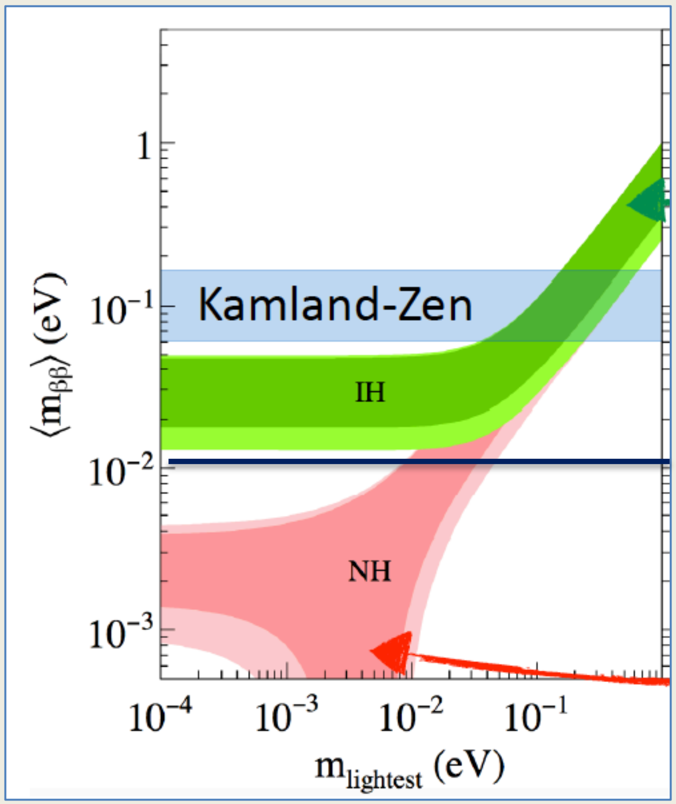


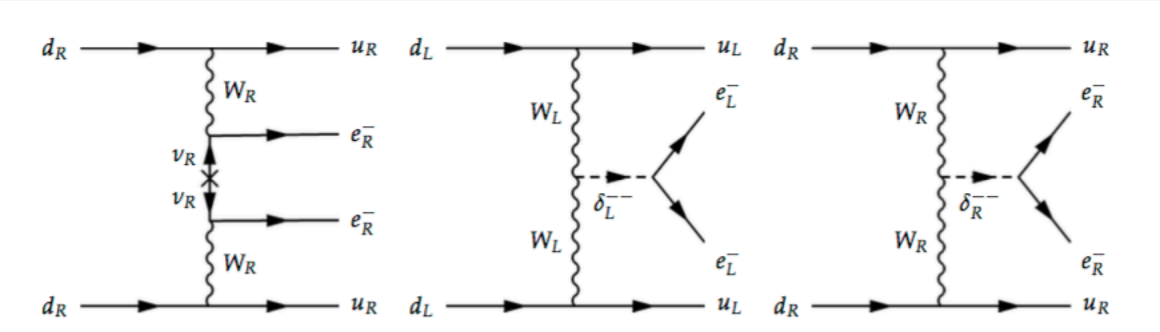
- Interpretation of experiments requires particle/hadronic/nuclear theory
- **Large theoretical uncertainties**

Tonne-scale goal 10^{28} y

- **Tremendous theoretical/experimental effort**
- Cosmology and beta-decay experiments provide complementary input

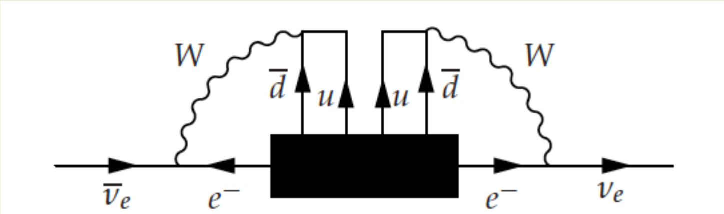
Non-Standard interpretation

- Many models induce lepton-number violation in different ways
- Example: LR symmetry, supersymmetry, leptoquarks…



Thesis Duerr '10

- No direct link to neutrino mass. But **Schechter-Valle** theorem '82



- **Observation of 0vbb implies neutrinos are Majorana states**

The anatomy of the decay

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

Energy

$>?$	$m_{\beta\beta}^2$	Lepton-number-violating (LNV) source *(not necessarily neutrino mass)*. ***(Particle Physics)***
$\sim GeV$	g_A^4	quarks → hadrons ***(Hadronic Physics)***
$\sim 100\,MeV$	$\|M\|^2 = \|\langle 0^+ \| V_\nu \| 0^+ \rangle\|^2$	Nuclear transition matrix element ***(Nuclear Physics… oh no)***
$\sim 10\,MeV$	G	Phase space factor ***(Atomic Physics)***

Neutrinoless double beta decay in EFT

- Part I: What is neutrinoless double beta decay and why bother?

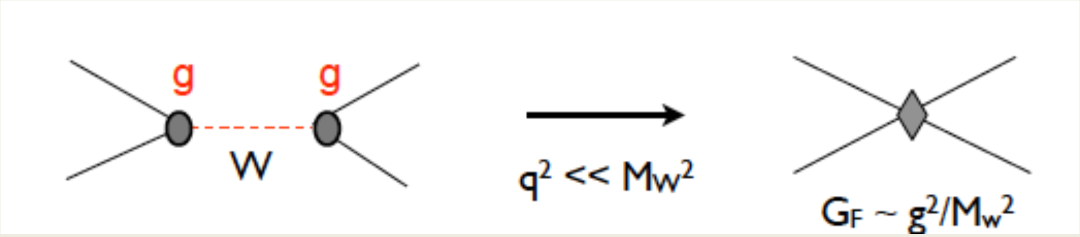
- **Part II: An effective field theory approach**

  1. Light Majorana mass (the Weinberg operator)
  2. Non-standard mechanisms in EFT
  3. Light sterile neutrinos

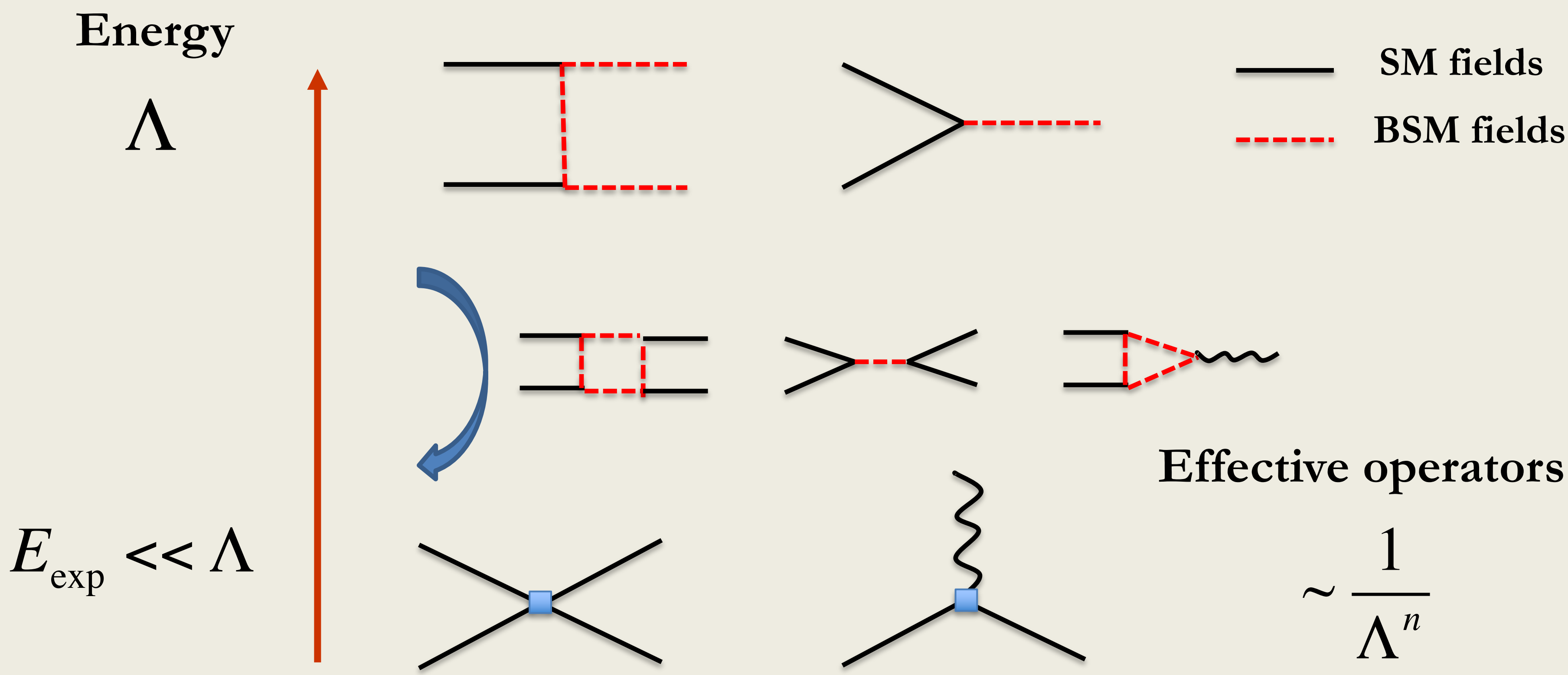
Heavy BSM physics: SM-EFT framework

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

Fermi's theory:



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



Effective lepton number violation

- Lepton number = **accidental** symmetry in Standard Model (at zero T)
- But no longer once we allow for operators of dim>4
- SM as an EFT $$L_{new} = L_{SM} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots$$
- Contain SM fields and obey SM gauge and Lorentz symmetry
- At energy E, operators of dim (4+n) $\sim (E/\Lambda)^n$

Effective lepton number violation

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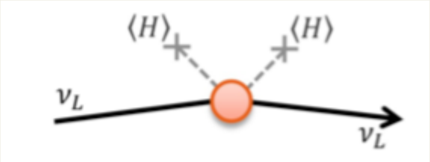
- At energy E, operators of dim (4+n) $\sim (E/\Lambda)^n$
- **Gauge symmetry is restrictive: only 1 dim-5 operator**

$$L_5 = \frac{c_5}{\Lambda}(L^T C \tilde{H})(\tilde{H}^T L) \qquad L^T = \left(\upsilon_L \; e_L\right)$$



- Contains **two** lepton fields and **no** anti-lepton fields →

Weinberg '79

$$L_5 \rightarrow c_5 \frac{v^2}{\Lambda} \nu_L^T C \nu_L$$ → **Majorana neutrino mass term**

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

Higher-order in the SM-EFT

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

Dimension-five

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

- One operator
- Induces Majorana mass

Dimension-seven

Lehman '14

$1: \psi^2 H^4 + \text{h.c.}$

$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^i C L^m) H^j H^n (H^\dagger H)$

$2: \psi^2 H^2 D^2 + \text{h.c.}$

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

$3: \psi^2 H^3 D + \text{h.c.}$

$\mathcal{O}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn} (L^i C \gamma_\mu e) H^j H^m D^\mu H^n$

$4: \psi^2 H^2 X + \text{h.c.}$

$\mathcal{O}_{LHB}$	$\epsilon_{ij}\epsilon_{mn} (L^i C \sigma_{\mu\nu} L^m) H^j H^n B^{\mu\nu}$
$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\tau^I \epsilon)_{mn} (L^i C \sigma_{\mu\nu} L^m) H^j H^n W^{I\mu\nu}$

$5: \psi^4 D + \text{h.c.}$

$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C D^\mu L^j)$
$\mathcal{O}^{(2)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C \sigma^{\mu\nu} D_\nu L^j)$
$\mathcal{O}^{(1)}_{\bar{L}QddD}$	$(Q C \gamma_\mu d)(\bar{L} D^\mu d)$
$\mathcal{O}^{(2)}_{\bar{L}QddD}$	$(\bar{L}\gamma_\mu Q)(d C D^\mu d)$
$\mathcal{O}_{ddd\bar{e}D}$	$(\bar{e}\gamma_\mu d)(d C D^\mu d)$

$6: \psi^4 H + \text{h.c.}$

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

- 12 ΔL=2 operators

Dimension-nine

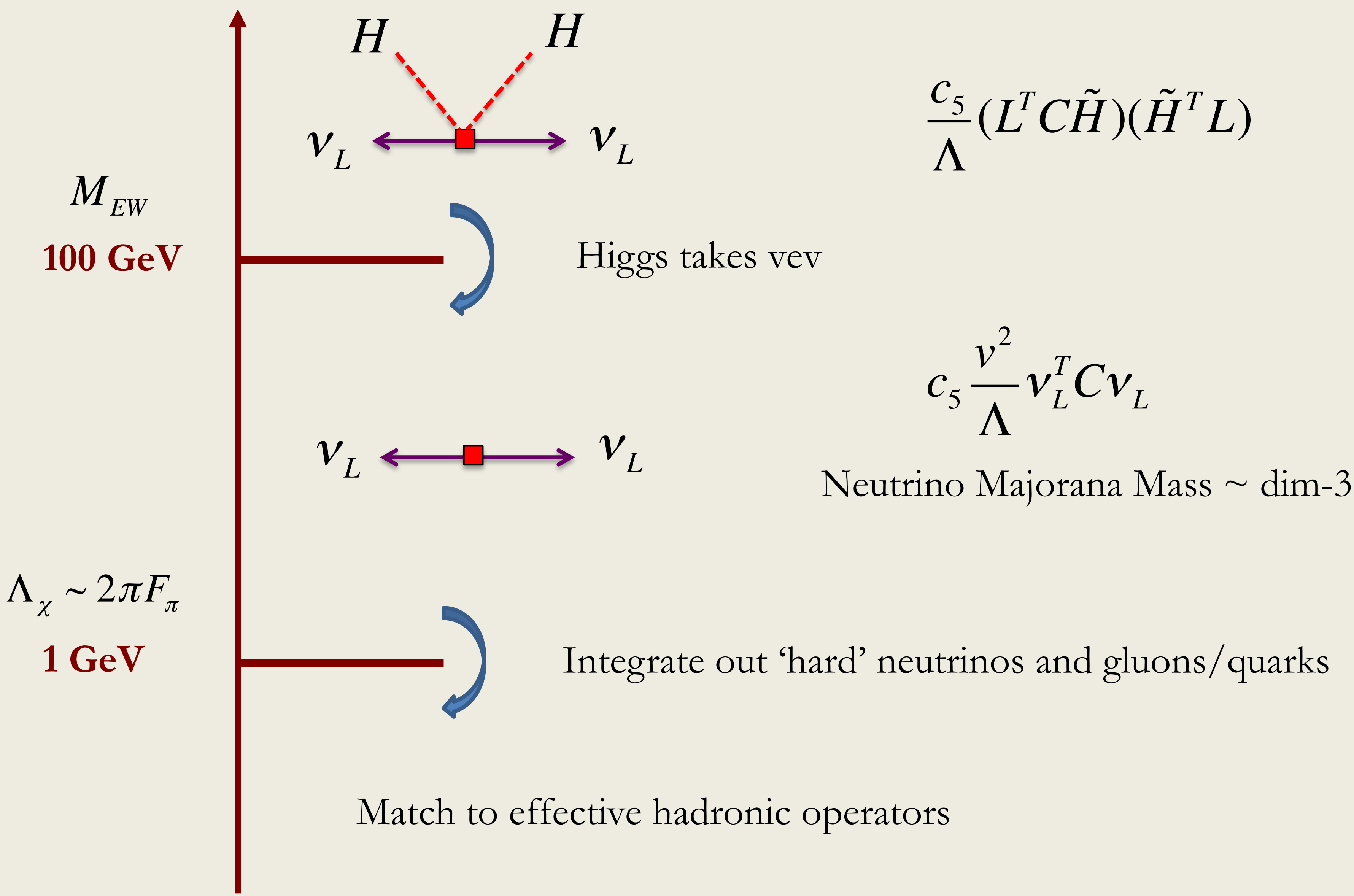
Prezeau et al '03
Graesser et al '17 '18

Full basis not known

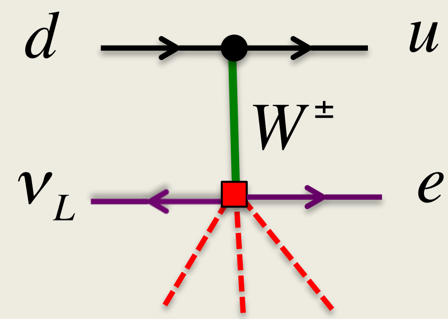
19 4-quark 2-lepton operators after EWSB

- Seems crazy to go to dim-7 if expansion parameter is $\left(\frac{v}{\Lambda}\right)^2 \sim 10^{-24}$
- Example: in LR symmetry $c_5 \sim y_e^2 \sim 10^{-10}$ $c_7 \sim y_e \sim 10^{-5}$ $c_9 \sim y_e^0 \sim 1$
- Then if scale is low ~ $\Lambda \sim (10-100)\,TeV$ dim5 ~ dim7~ dim 9

Crossing the electroweak scale

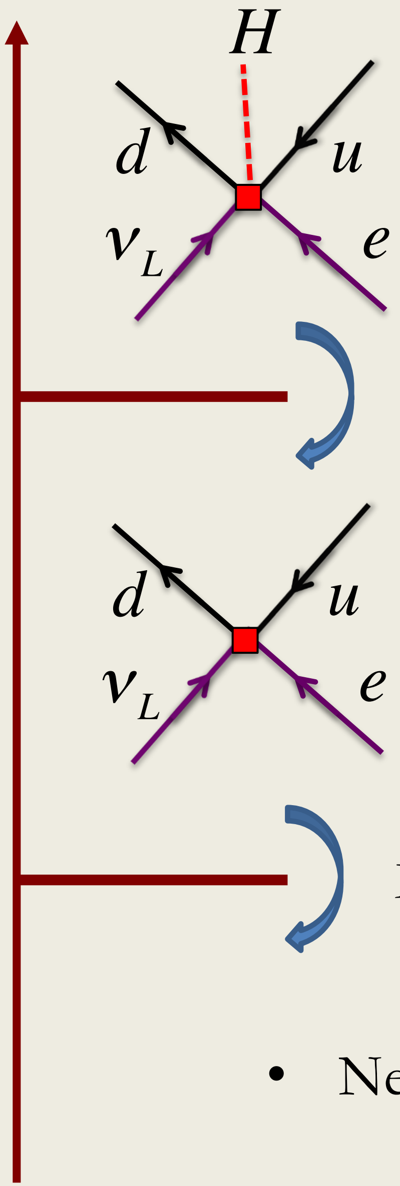


Dimension-7, -9 operators



M_{EW}

100 GeV



Higgs takes vev + integrate out W bosons

$$\sim c_7 \frac{v}{\Lambda^3}$$

- Beta-decay a la Fermi ~ dim-6
- But 'wrong' neutrino
- Hard to probe in single beta decay

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

1 GeV

Hadronization

- Neutron and pion 'beta' decay operators + ….

How do we hadronize ?

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

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

- Quark masses = 0 → QCD has $SU(2)_L x SU(2)_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions are Goldstone)
  - Explicit breaking (quark mass) → pion mass

- ChPT gives systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi \qquad \Lambda_\chi \cong 1\, GeV$
  - **Form of interactions fixed by symmetries**
  - Price to pay: chiral interactions have coupling constants (LECs) not predicted from symmetries alone

Weinberg, Gasser, Leutwyler, and many many others

Chiral effective field theory

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

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

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

Chiral effective field theory

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

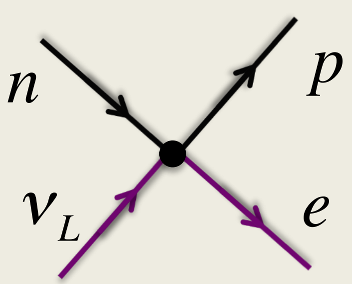
~100 MeV Chiral limit $L_{\chi} = L_{kin} - m_N \bar{N}N + \frac{g_A}{f_\pi} D_\mu \vec{\pi} \cdot \bar{N}\gamma^\mu \gamma^5 \vec{\tau} N + C_0 \, \bar{N}N\bar{N}N$

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

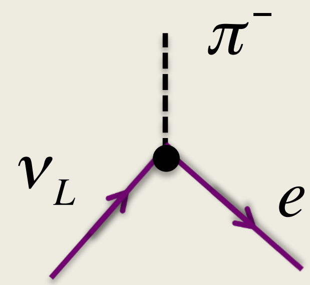
Weak interactions

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

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



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



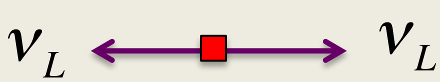
Chiral effective field theory

~ GeV $$L = L_{QCD} + L_{Fermi} - m_{\beta\beta}\nu_L^T C \nu_L \quad + C_{\Gamma}\, \bar{e}\Gamma\bar{\nu}^T\, O_{2q}^{\Gamma} + C_{\Gamma'}\, \bar{e}\Gamma' e^c\, O_{4q}^{\Gamma'}$$

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

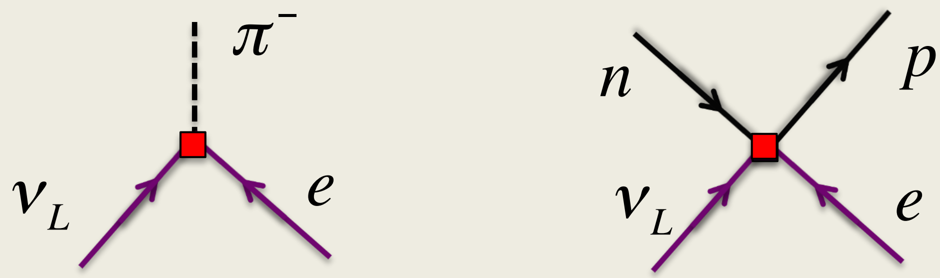
Prezeau et al '03
Cirgliano et al '17 '18

ΔL=2 Majorana mass

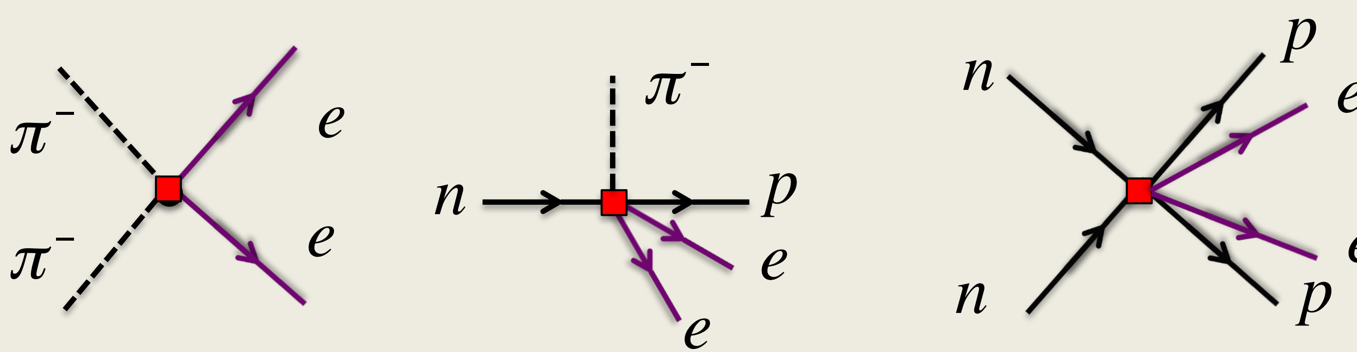


$\sim m_{\beta\beta}$

ΔL=2 beta decay



ΔL=2
'neutrinoless'



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    1. **Light Majorana mass (the Weinberg operator)**
    2. Non-standard mechanisms in EFT
    3. Light sterile neutrinos (very briefly)

Chiral effective field theory

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

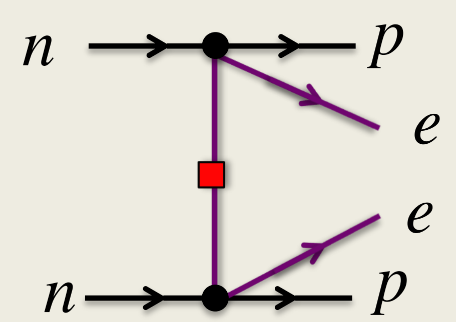
---

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

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

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

$q \sim k_F \sim m_\pi$



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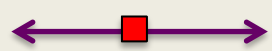
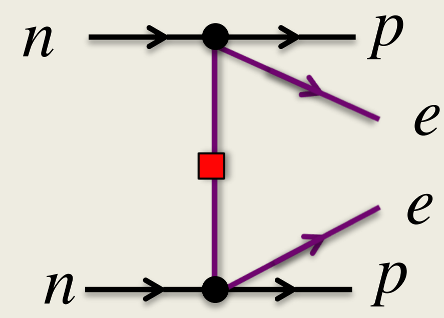
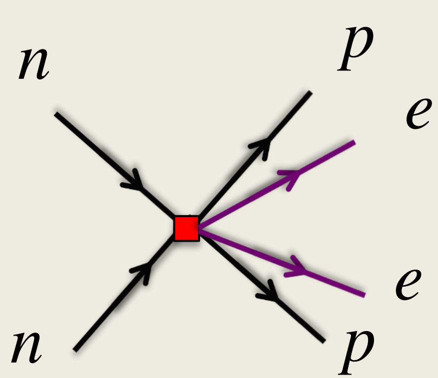
LO interaction : ν_L  ν_L $\sim m_{\beta\beta}$



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

$q \sim k_F \sim m_\pi$

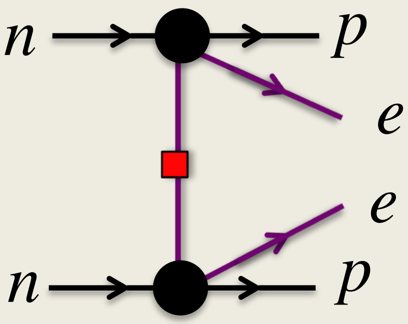
\`Hard' neutrino exchange $(E, |\vec{p}| > \Lambda_\chi)$ → short-range operators

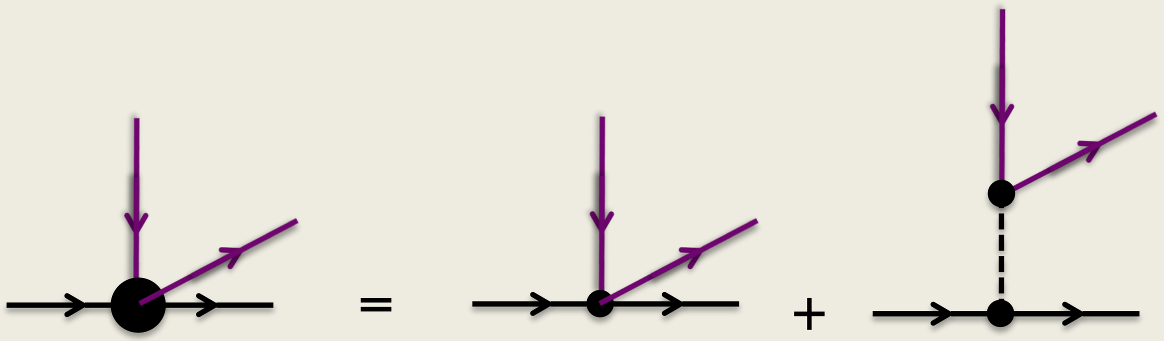


Expected at N²LO
(Weinberg counting/Naive
Dimensional Analysis) $\sim \dfrac{m_{\beta\beta}}{\Lambda_\chi^2}$

Majorana mass contribution

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

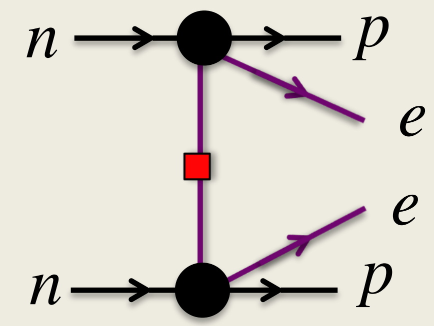




In $^1S_0$ $$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\vec{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{\left(\vec{q}^2 + m_\pi^2\right)^2}\right] \otimes \bar{e}_L e_L^c$$

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

The neutrino amplitude

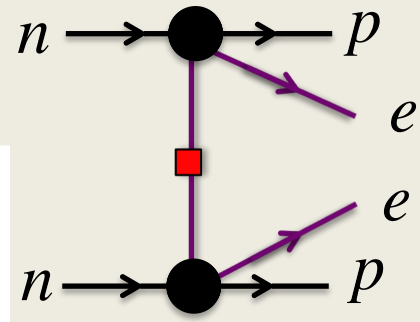


- At LO the 'standard' mechanism is long-range

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

- Insert between initial- and final-state nuclear wave functions
- **Different methods have roughly a factor 3 spread**

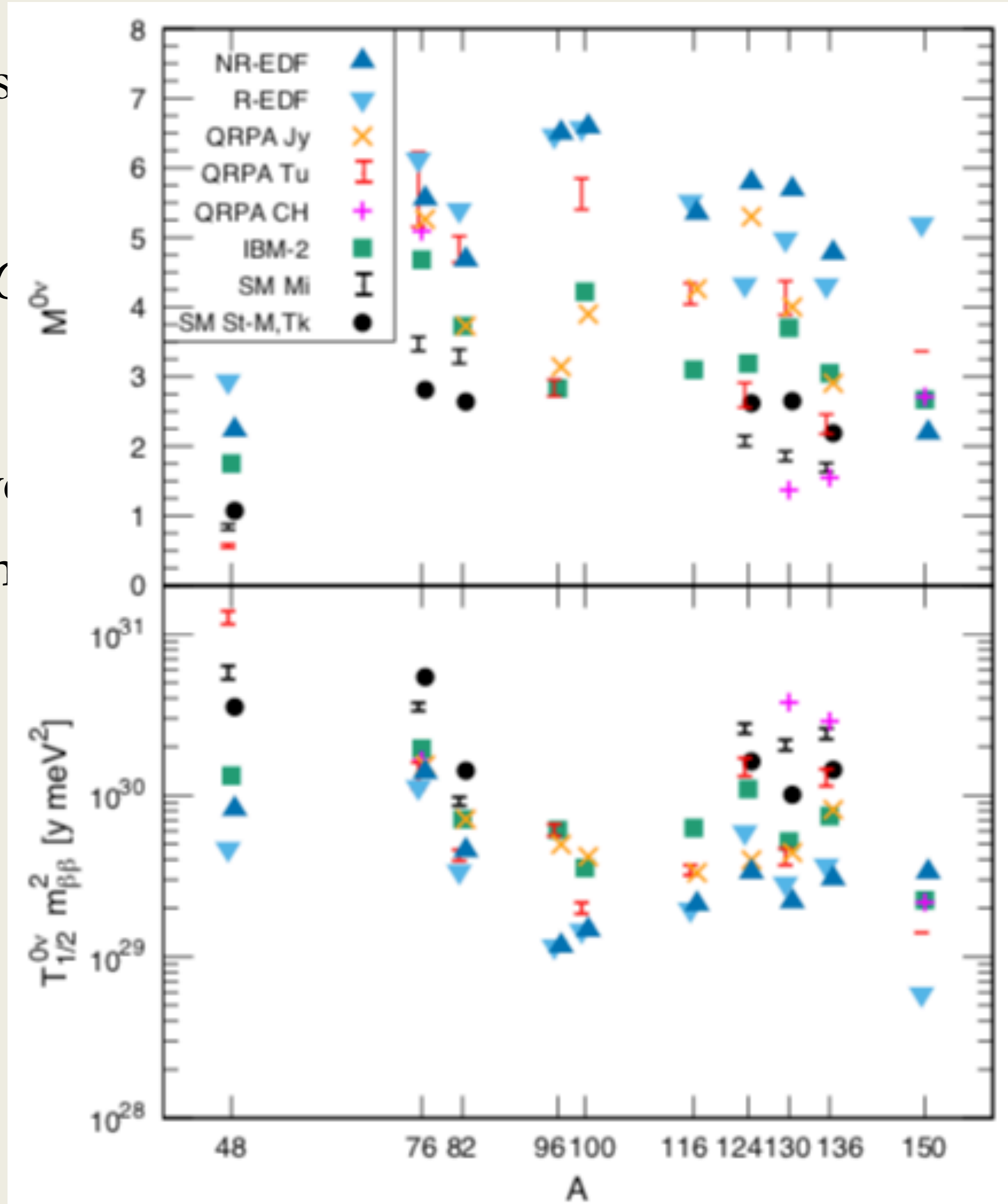
The neutrino amplitude



- At LO the 's

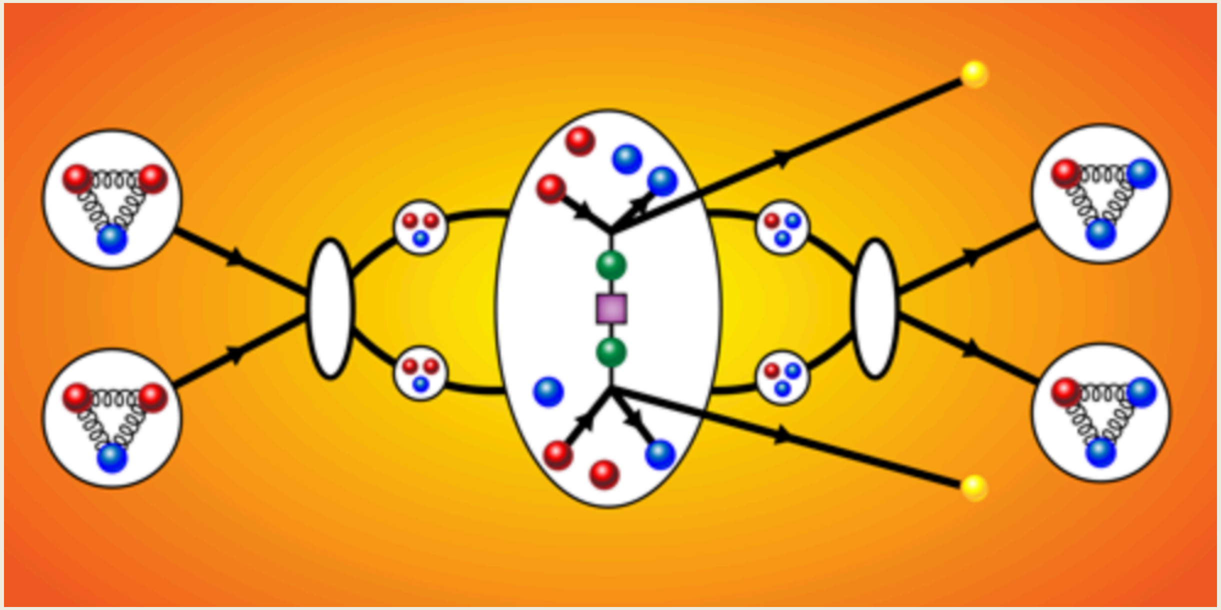
$V_\nu = (2C$ … e_L^c

- Insert betw … ons
- **Different n**



How confident are we about all of this ?

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

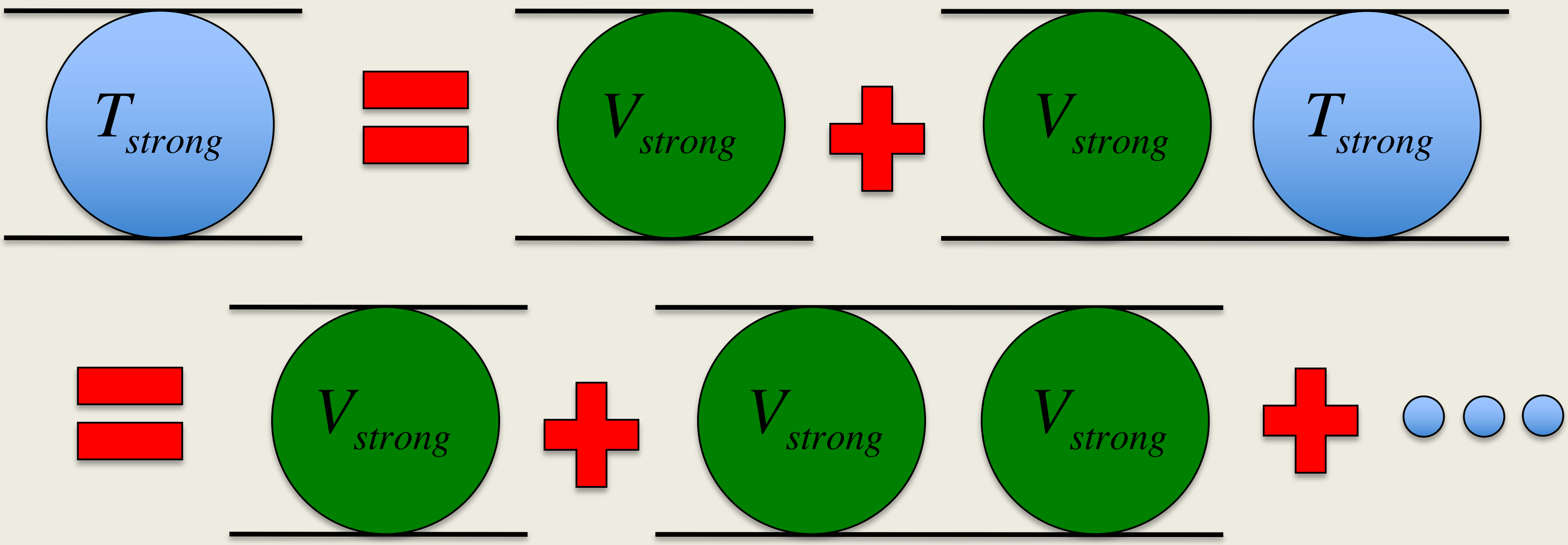


"A new leading contribution to 0νββ", 1802.10097, PRL 120

Nucleon-nucleon scattering

- To describe NN scattering we need to solve a LS equation

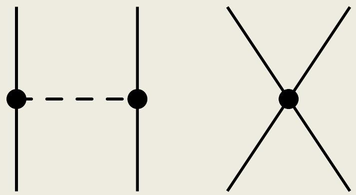
$$T = V + VG_0T$$



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

Nucleon-nucleon scattering

- To describe NN scattering we need to solve a LS equation $T = V + VG_0T$
- The potential itself calculated in **perturbation theory**

LO 

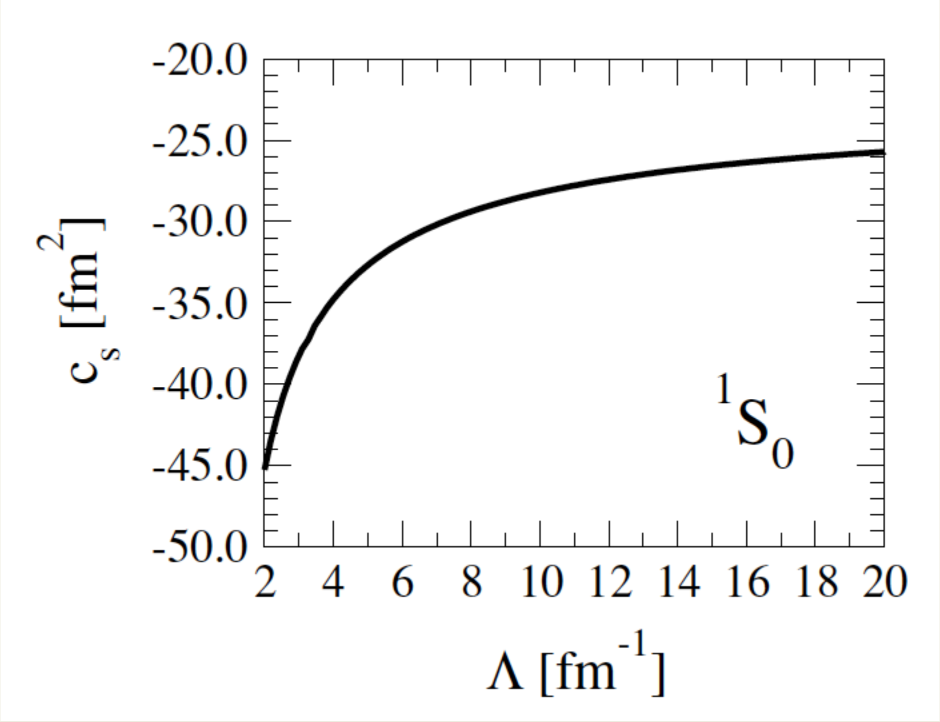
$$V^{^1S_0}_{strong}(LO) = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\vec{q}^2 + m_\pi^2} + \cdots$$

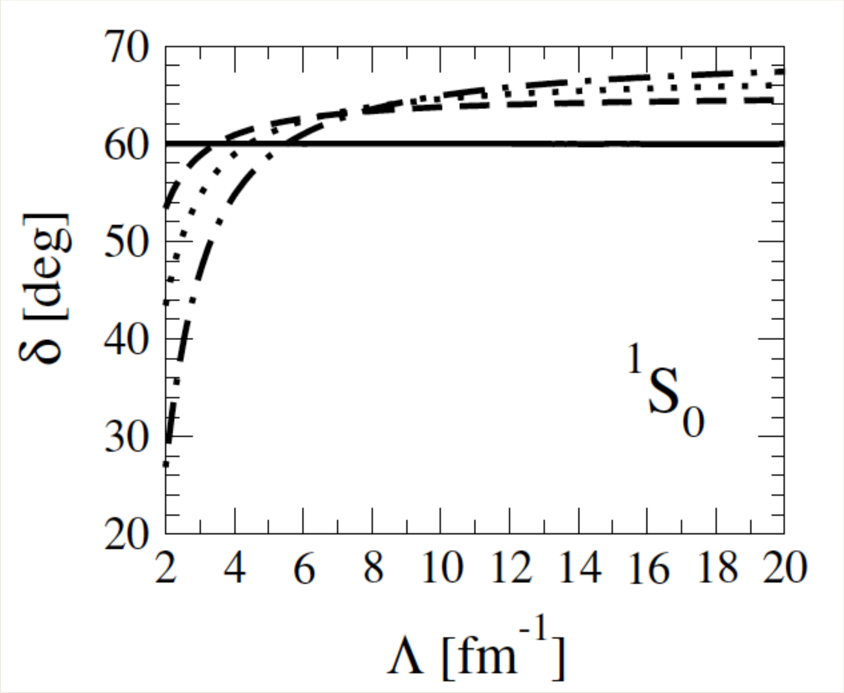
- Numerical solutions require a regulator $V \rightarrow e^{-\frac{p^6}{\Lambda^6}}\, V\, e^{-\frac{p'^6}{\Lambda^6}}$

- **Observables should be regulator independent!**
- The counter term $C_0(\Lambda)$ fitted to low-energy data (**scattering lengths**)
- Predictions are made for nucleon-nucleon **phases shifts** (all energies)

Nucleon-nucleon scattering

- Counter term shows a logarithmic dependence on cut-off
- **Without counter term the calculations makes no physical sense !**





Fit to 10 MeV data

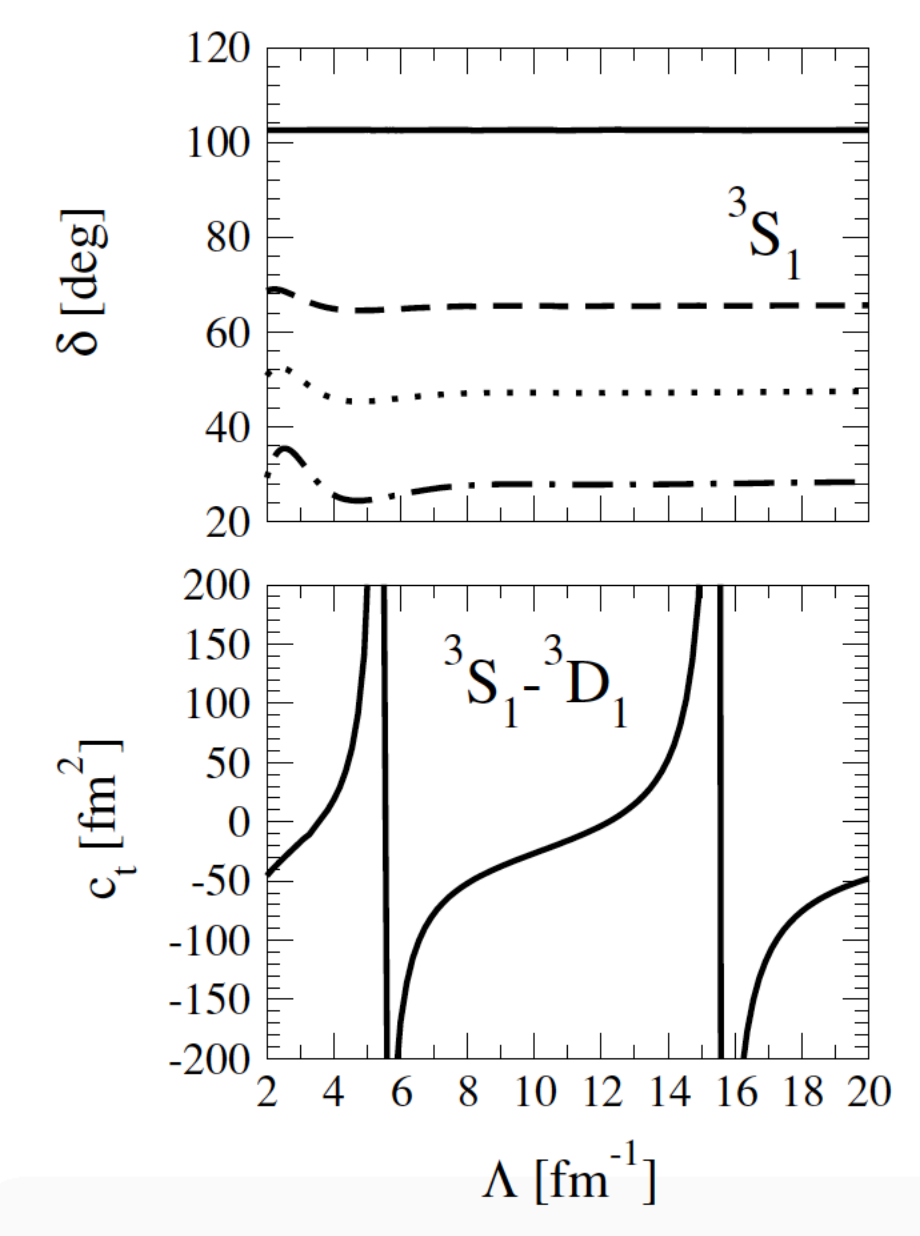
50 MeV

100 MeV

190 MeV

Nogga et al '05

Nucleon-nucleon scattering



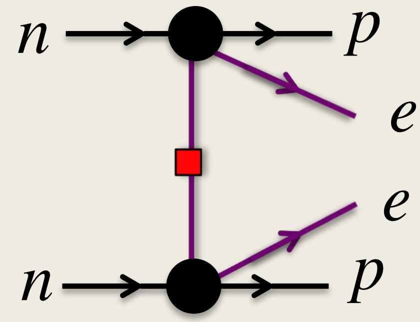
50 MeV

100 MeV

190 MeV

Nogga et al '05

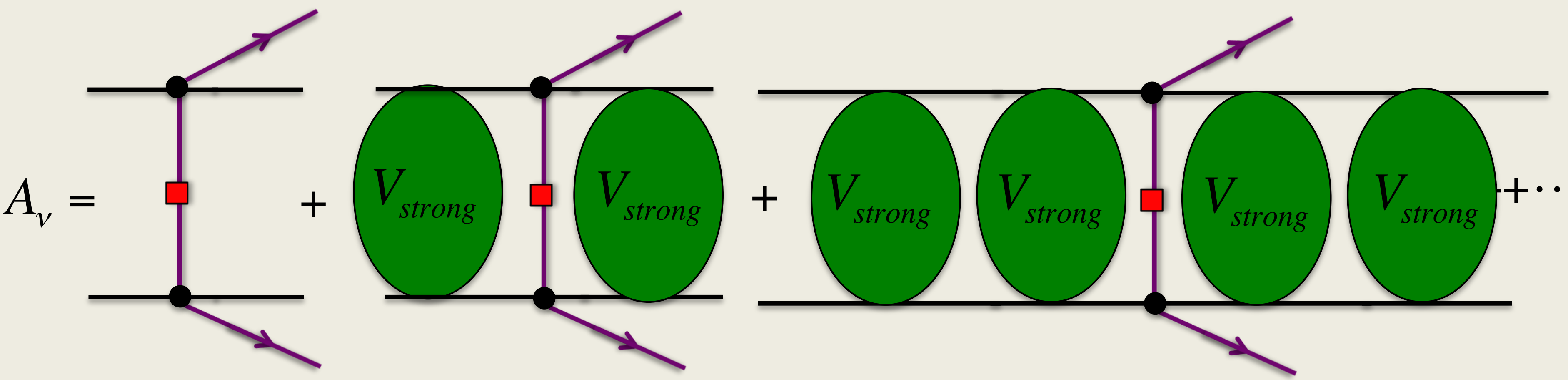
The neutrino amplitude



- Now insert the neutrino potential

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

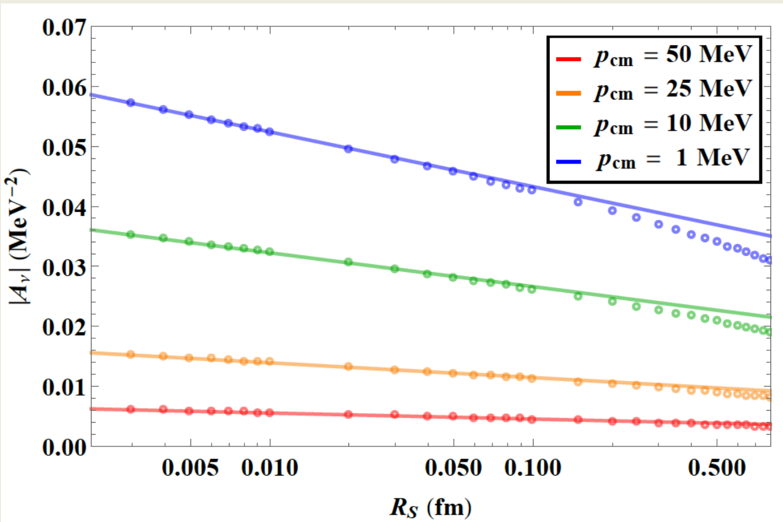
$$A_\nu = V_\nu + V_\nu G_0 T_{LO} + T_{LO} G_0 V_\nu + T_{LO} G_0 V_\nu G_0 T_{LO}$$



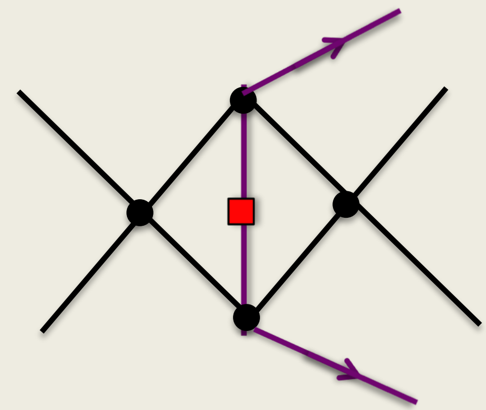
- **Can be measured in principle → should be independent of regulator !!**

The new neutrino amplitude

- Now re-insert the 0vbb current in nuclear wave functions



JdV et al, PRL '18

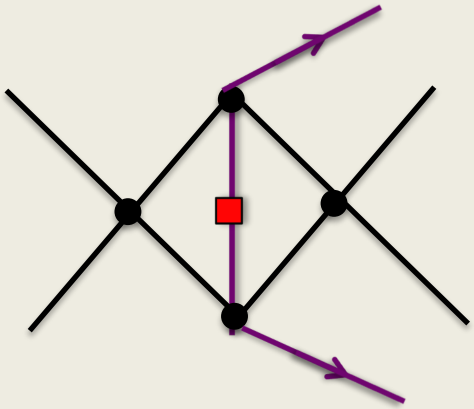


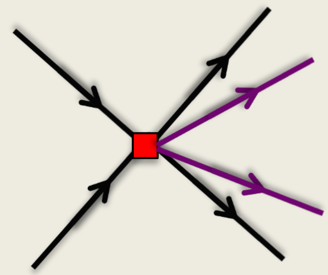
$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\varepsilon} + \log\frac{\mu^2}{p^2}\right)$$

- **The amplitude is logarithmically dependent on the regulator !**
- The nuclear force has a short-distance component → 'amplitude is sensitive to short-range neutrino exchange'

Non-perturbative renormalization

- Divergence is **nothing scary** in an EFT calculation
- It just signals dependence on hard scales → need a counter term





$\sim g_{\nu}^{NN}$

- Contact term comes with new LEC ~ QCD dynamics at $<(\Lambda_{\chi})^{-1}$
- **Neutrino mass** $m_{\beta\beta}$ **not directly connected to decay rate**
- Not expected to be a small correction. **It is leading order !**
- **How to determine the value of the new LEC ?**

Determining the LEC

- Determine the counter term in absence of data ?

Strategies to get g_ν^{NN}

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

   Interesting progress on ππ→ ee

   Nicholson et al '18, Feng et al '18 '19
   Murphy/Detmold '20

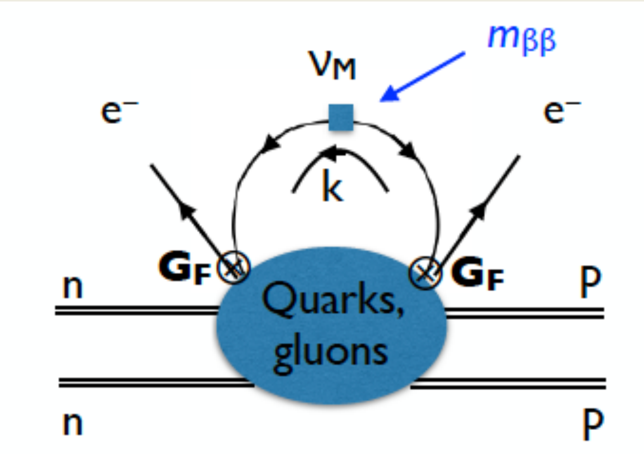
   Can this be done for two-nucleon processes?

2. Calculate contributions from virtual neutrinos in soft and hard regime + interpolate

   Cirigliano, Dekens, JdV, Hoferichter, Mereghetti '20 '21

A matching strategy

- Hadronic part of LNV amplitude given by



$$\mathcal{M} = 2g^{\mu\nu} \int \frac{d^4k}{(2\pi)^4} \frac{\langle f|\hat{\Pi}^{LL}_{\mu\nu}(k)|i\rangle}{k^2 + i\epsilon}$$

$$\hat{\Pi}^{LL}_{\mu\nu}(k) = \int d^4r\ e^{ik\cdot r}\ T\Big(\bar{u}_L\gamma_\mu d_L(r/2)\ u_L\gamma_\nu d_L(-r/2)\Big)$$

- Idea: do energy integral through Cauchy and split d^3k integral
- Compute with chiral EFT and asymptotic QCD in appropriate regions.
- Glue regions together using resonance interpolation.
- Extension of single nucleon analysis of Cottingham (1963)

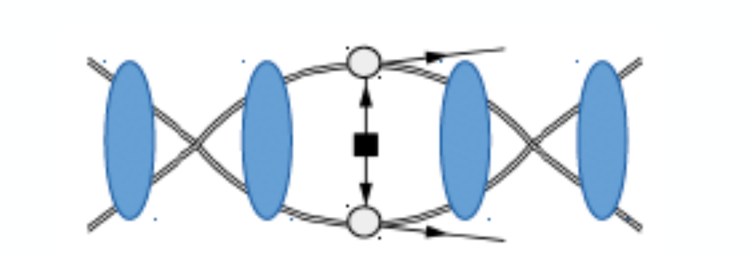
$$\mathcal{M} = \int \frac{d\mathbf{k}}{(2\pi)^3} \langle f_- | \hat{O}^{LL}(\mathbf{k}) | i_+ \rangle$$

- Initial- and final-state wave functions are scattering states

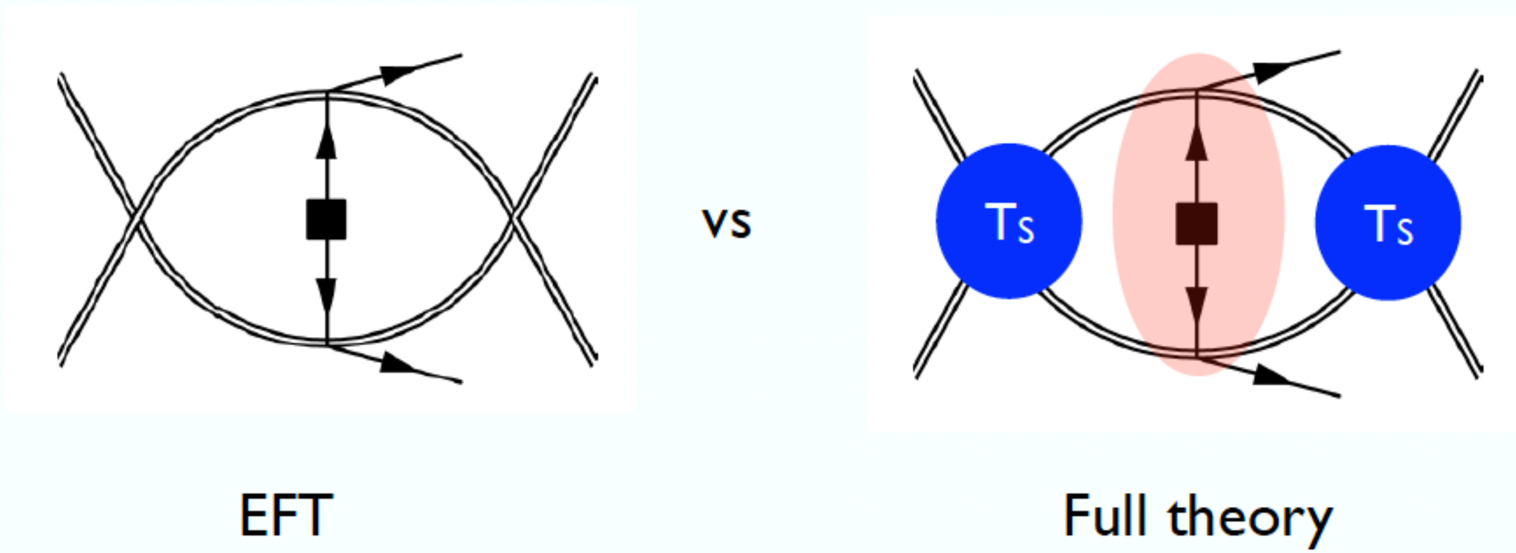
$$\mathcal{M} \;=\; \int \frac{d\mathbf{k}}{(2\pi)^3} \langle f_0 | \left(\hat{T}(E')\hat{G}_+^{(0)}(E') + I\right) \hat{O}^{LL}(\mathbf{k}) \left(I + \hat{G}_+^{(0)}(E)\,\hat{T}(E)\right) | i_0 \rangle$$

- Split M in a "<" and ">" part for $|\boldsymbol{k}| < \boldsymbol{\Lambda}$ and $|\boldsymbol{k}| > \boldsymbol{\Lambda}$ ($\boldsymbol{\Lambda} \sim$ GeV)

- For $|\boldsymbol{k}| \ll \boldsymbol{\Lambda}$, we can use chiral EFT for the integrand reliably.
- At leading order, only NN intermediate states (NNpi at higher orders)



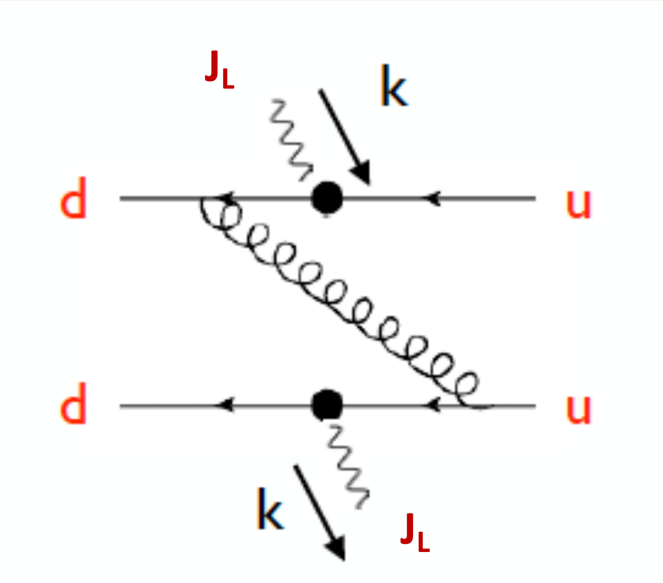
$$\mathcal{M}_C = \int \frac{d\mathbf{k}}{(2\pi)^3} \langle f_0| \left(\hat{T}_S(E')\hat{G}_+^{(0)}(E')\right) \hat{O}^{LL}(\mathbf{k}) \left(\hat{G}_+^{(0)}(E)\,\hat{T}_S(E)\right) |i_0\rangle$$



- In full theory, use single nucleon form factors (e.g. $g_A(q^2)$) to extend integrand to intermediate region: $m_\pi < k < \Lambda$
- Modify strong T-matrix at larger k
- Use high-quality 1S0 NN potentials in intermediate range

Large-k regime

- For $|\boldsymbol{k}| \gg \boldsymbol{\Lambda}$ we use operator-product expansion



$$\hat{O}^{LL}_{>}(\mathbf{k}) = \frac{3g_s^2}{4}\frac{1}{|\mathbf{k}|^5}\, O_1$$

Effective contact operator

$$O_1 = \bar{u}_L\gamma_\mu d_L\, \bar{u}_l\gamma^\mu d_L$$

- Asymptotic behaviour ensures amplitude converges

$$\mathcal{M}^{>} = \frac{3\alpha_s}{2\pi}\int_\Lambda^\infty d|\mathbf{k}|\,\frac{1}{|\mathbf{k}|^3}\,\langle f_-|\, O_1(0)\,|i_+\rangle$$

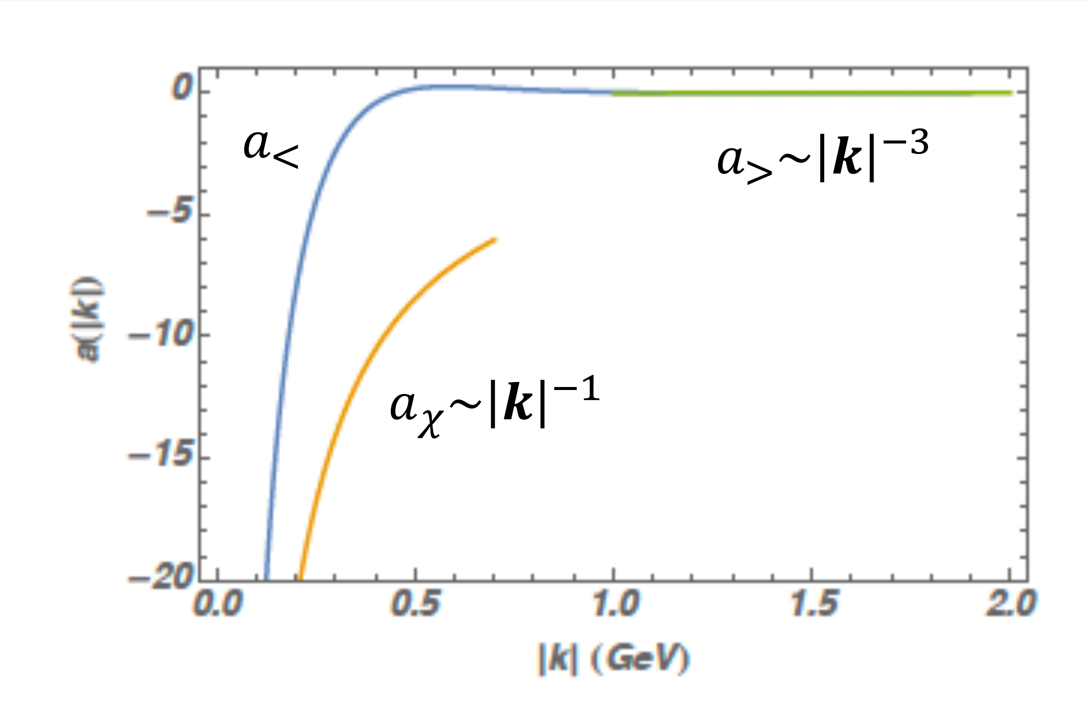
- Dependence on matrix element of O_1 turns out to be small

Let's finally match

- Want to obtain a value for rescaled counter term $g_\nu^{NN} = \left(\frac{m_N}{4\pi} C\right)^2 \tilde{g}_\nu$

$$2\,\tilde{g}_\nu(\mu_\chi) = \frac{1+2g_A^2}{2} - \int_0^{\mu_\chi} d|\mathbf{k}|\; a_\chi(|\mathbf{k}|) + \int_0^{\Lambda} d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^{\infty} d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$

- Here μ_χ is the renormalization scale (dim reg in MS-bar)



Let's finally match

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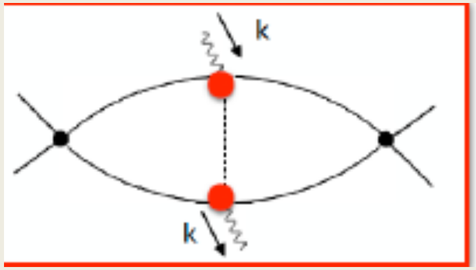
- Here μ_{χ} is the renormalization scale (dim reg in MS-bar)

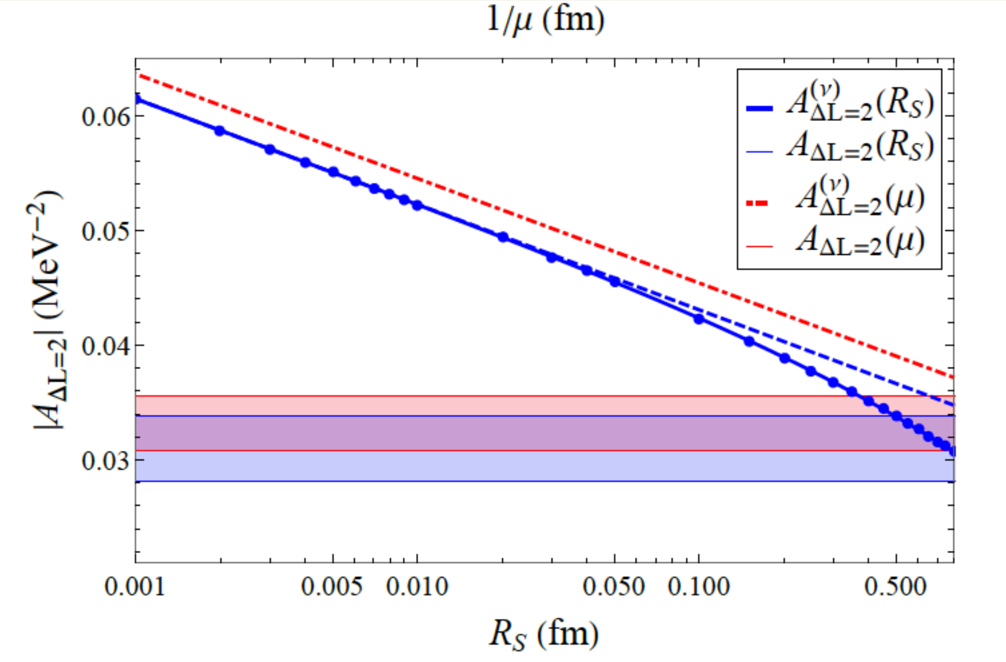
$$\tilde{g}_{\nu}(\mu_{\chi} = m_{\pi}) = (1.3 \pm 0.1 \pm 0.2 \pm 0.5)$$

- Errors from Λ & local matrix elements, form factors, and inelastic intermediate states
- Same strategy used to calculate electromagnetic corrections to NN scattering
- **Agrees with data within (sizeable) errors**



Partial success

- Recalculate amplitude with modified neutrino potential including CT



Cirigliano et al, PRL '18

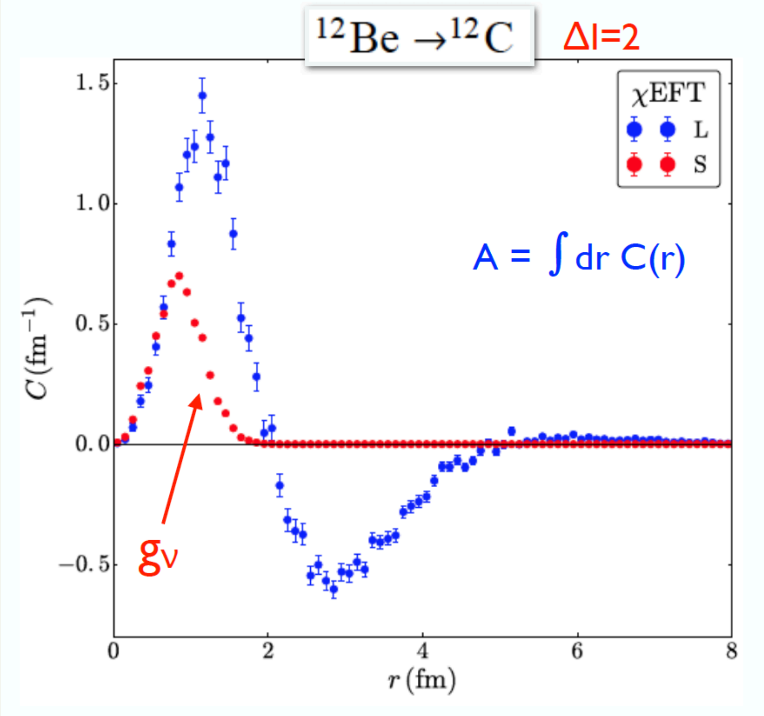
- Total amplitude is regulator independent: **data-driven !**
- For regulators R_S ~ (0.3-0.8) fm about 50% corrections
- Need to do this for nuclei instead of nucleon-nucleon

Ab initio calculations of light nuclei

- Ab initio chiral calculations limited to light nuclei

$$^{12}Be \rightarrow {}^{12}C + e + e$$

- `Quantum Monte Carlo‘ calculations with chiral potential
- The short-distance operator modifies the total amplitude by **(70-100)%**



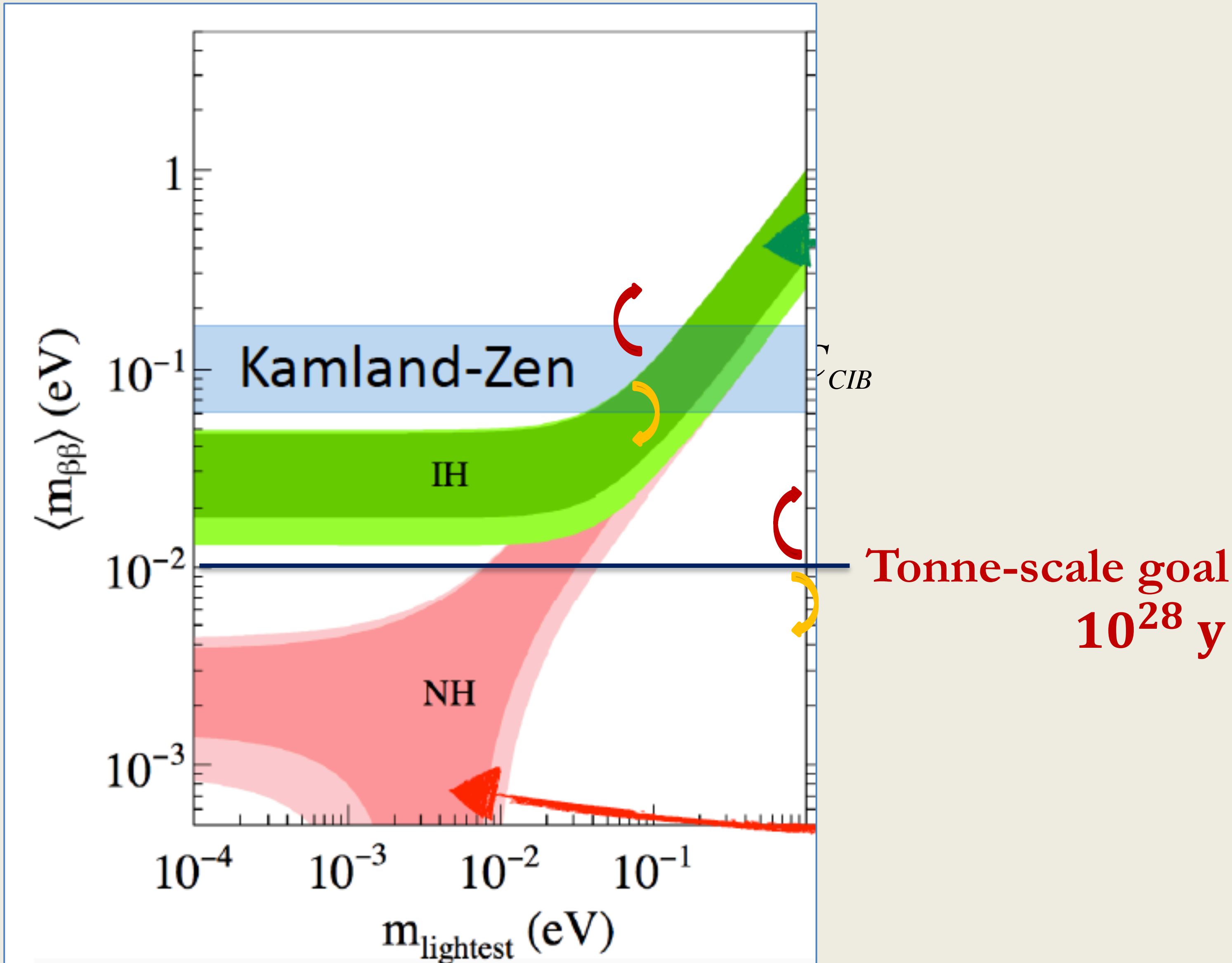
Dimensionless NME	Long range	Short range
$^{12}Be \rightarrow {}^{12}C + e + e$	0.7	0.55

- Next goal: include this for large-scale nuclei used in experiments

Ab Initio Treatment of Collective Correlations and the Neutrinoless Double Beta Decay of ^{48}Ca

J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodríguez, and H. Hergert
Phys. Rev. Lett. **124**, 232501 – Published 11 June 2020

Exciting to see what will happen



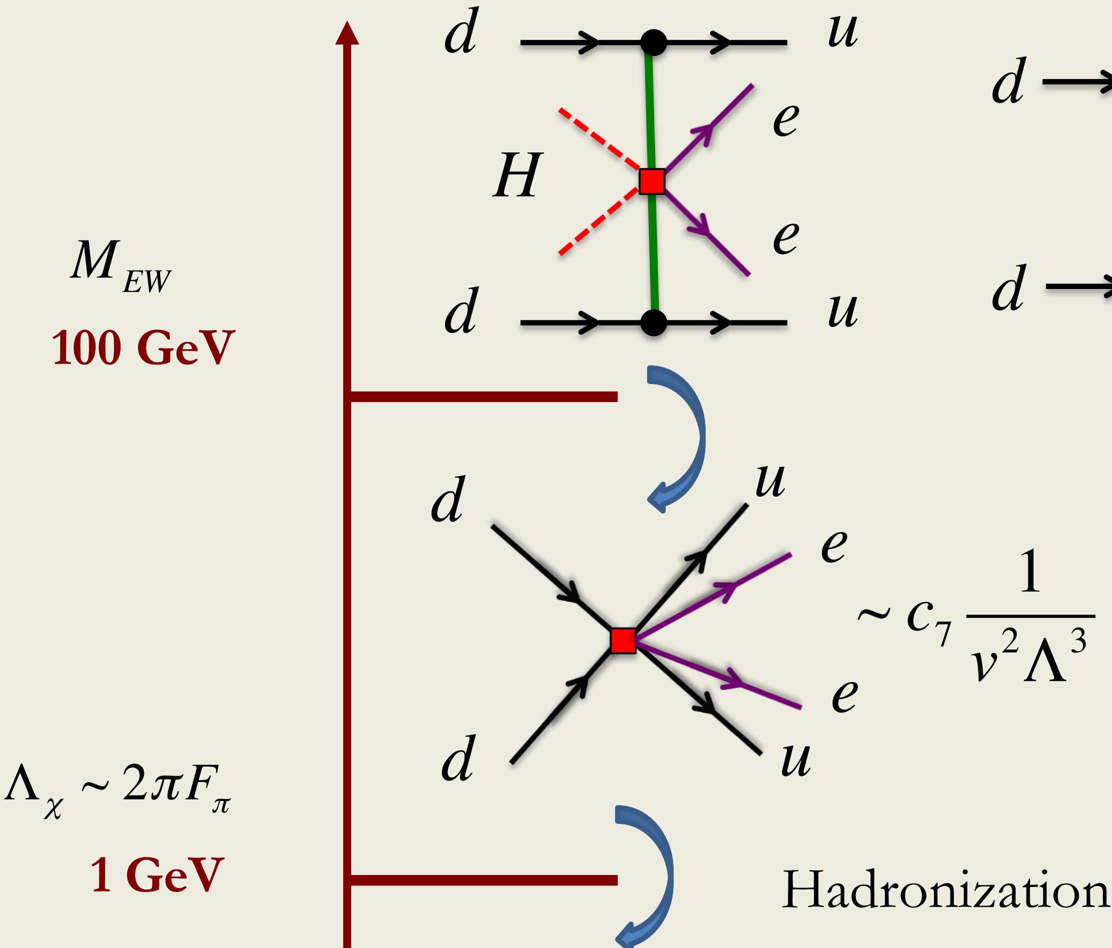
Lepton Number Violation in Effective Field Theory

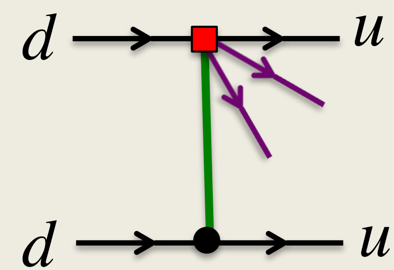
- Part I: LNV and neutrinoless double beta decay

- Part II: An effective field theory approach

  1. Light Majorana mass (the Weinberg operator)
  2. **Non-standard mechanisms in EFT**
  3. Light sterile neutrinos (very briefly)

Crossing the electroweak scale





- $0\nu\beta\beta$ operators ~ ‘dim 9’
- Several operators with left- and/or right-handed quarks

- Difficult as similar operators not in ‘standard’ beta decay

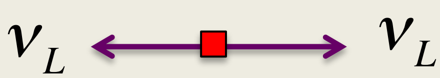
Chiral effective field theory

~ GeV $$L = L_{QCD} + L_{Fermi} - m_{\beta\beta}\nu_L^T C \nu_L \quad + C_\Gamma\, \bar{e}\Gamma\bar{\nu}^T\, O_{2q}^{\Gamma} + C_{\Gamma'}\, \bar{e}\Gamma' e^c\, O_{4q}^{\Gamma'}$$

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

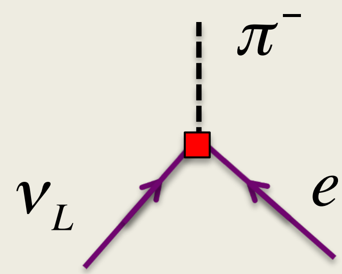
Prezeau et al '03
JdV et al '17 '18

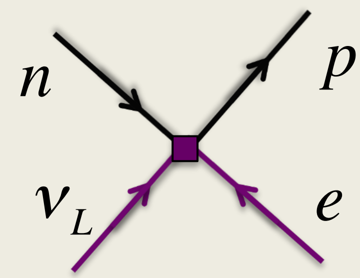
ΔL=2 Majorana mass



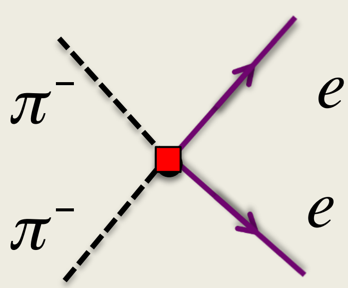
$\sim m_{\beta\beta}$

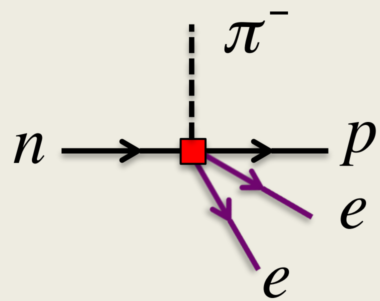
ΔL=2 beta decay

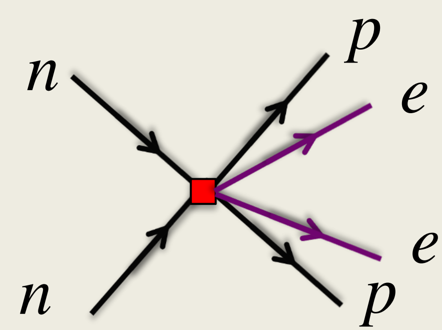




ΔL=2
'neutrinoless'

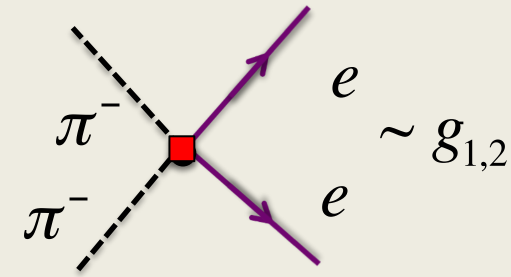






Higher-dimensional LNV sources

- Certain dim-7 and dim-9 LNV operators lead to
- LECs calculated from SU(3) arguments or lattice

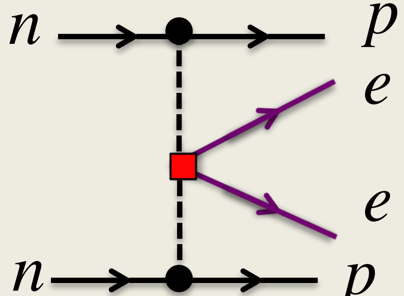


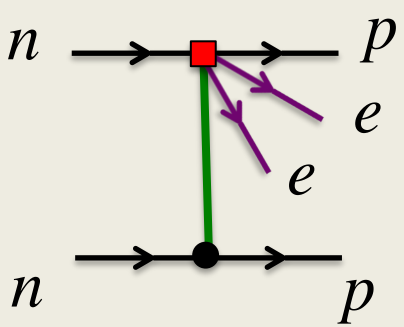
$$L^{(9)}_{\Delta L=2} = \left\{ C_1^{(9)} \bar{u}_L \gamma^\mu d_L \;\; \bar{u}_L \gamma^\mu d_L + C_4^{(9)} \bar{u}_L \gamma^\mu d_L \;\; \bar{u}_R \gamma^\mu d_R \right\} \frac{\bar{e}_L e_L^c}{v^5}$$

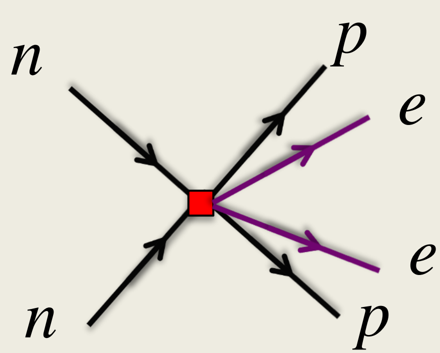
$$g_1 = -(1.9 \pm 0.2)\, GeV^2 \qquad g_2 = -(8 \pm 0.6)\, GeV^2$$

Cirigliano et al '17, Nicholson et al '18

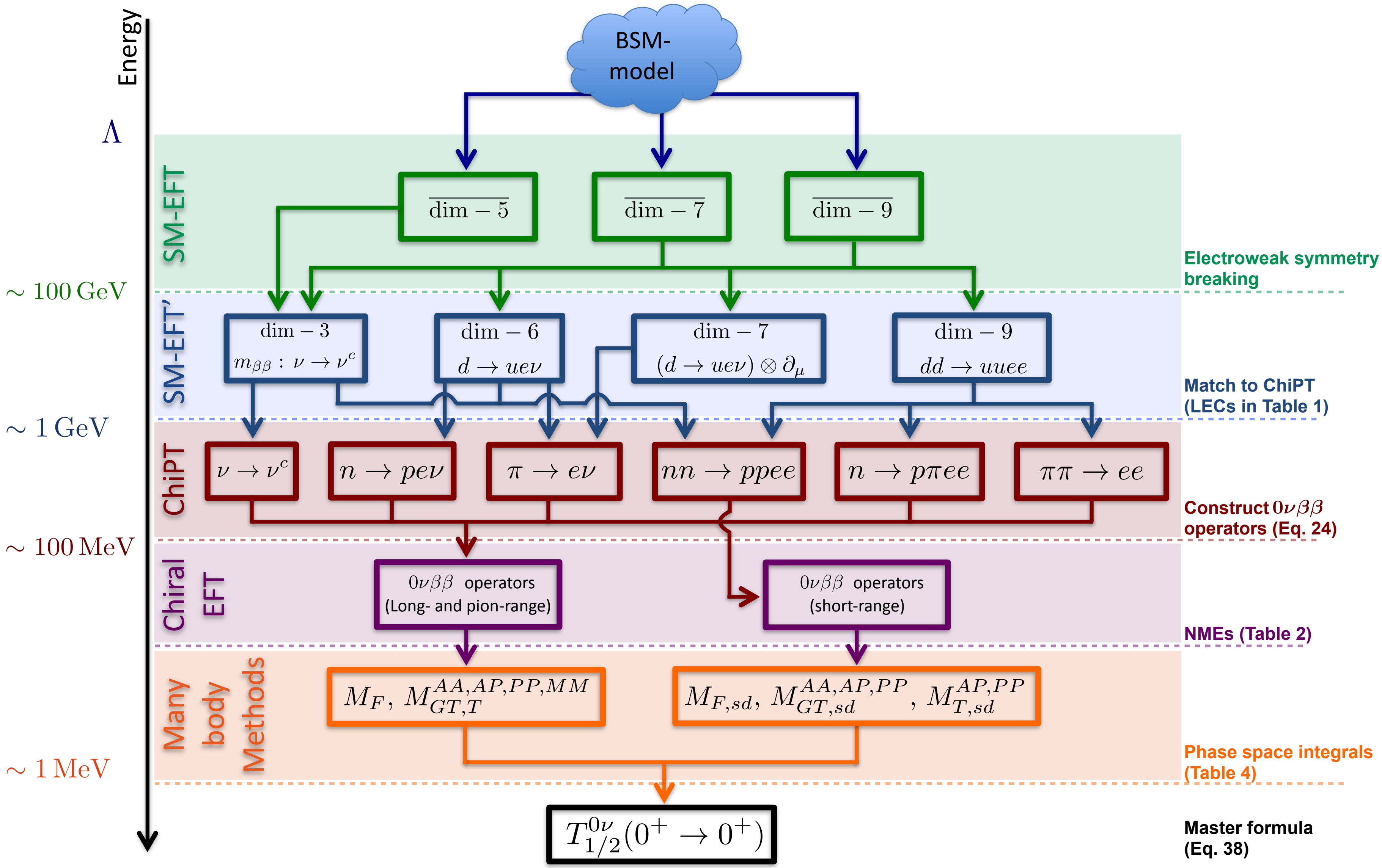
- Quite different from earlier 'vacuum factorization' estimates
- Addtional contributions to the neutrino potential







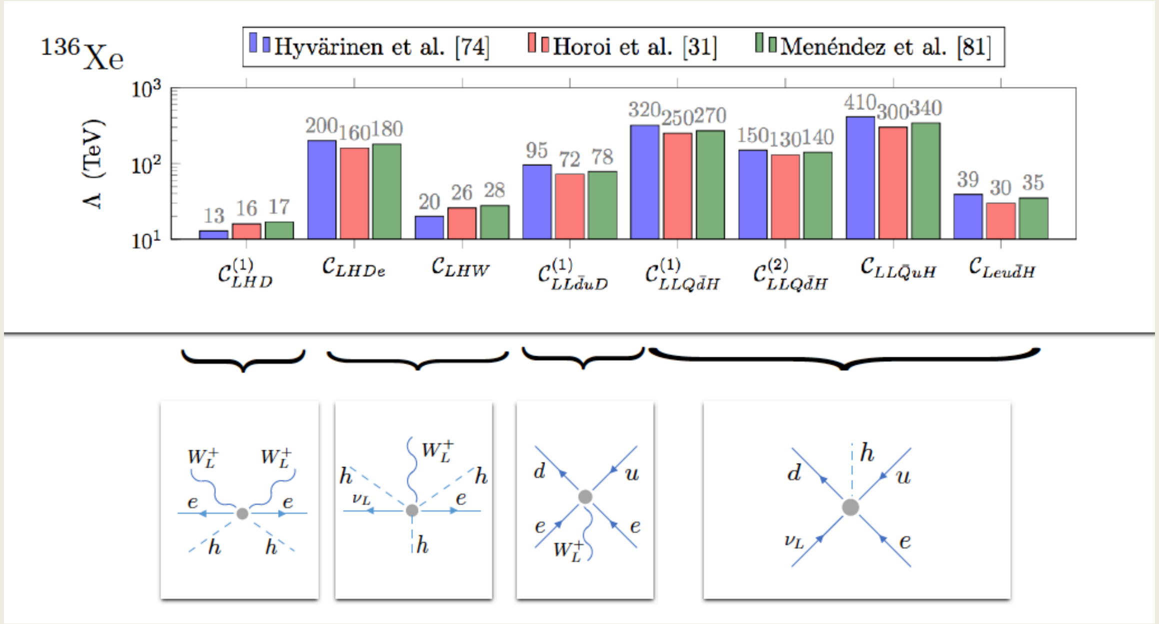
‘The neutrinoless double-beta metro map’



Turn the Crank

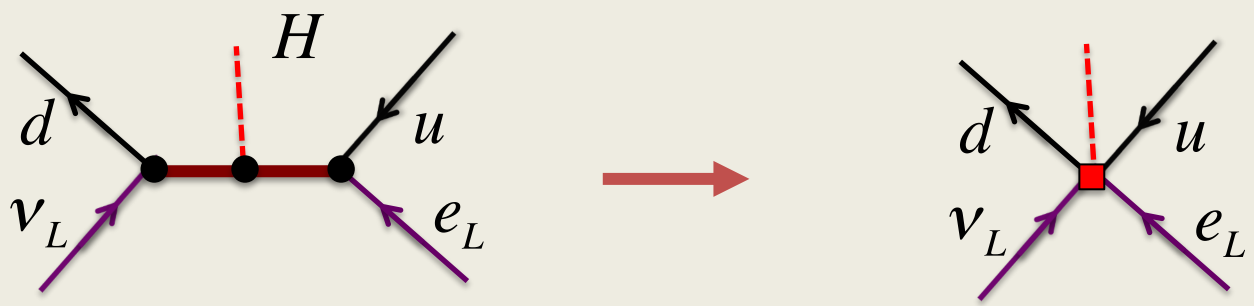
- **KAMLAND experiment** $T_{1/2}^{0\nu}\left({}^{136}Xe \rightarrow {}^{136}Ba\right) > 1.07\times 10^{26}\ yr$

- Limits on dim-7 couplings at O(100) TeV $C_i \sim (v/\Lambda)^3$
- Limits on dim-9 couplings at O(5) TeV $C_i \sim (v/\Lambda)^5$



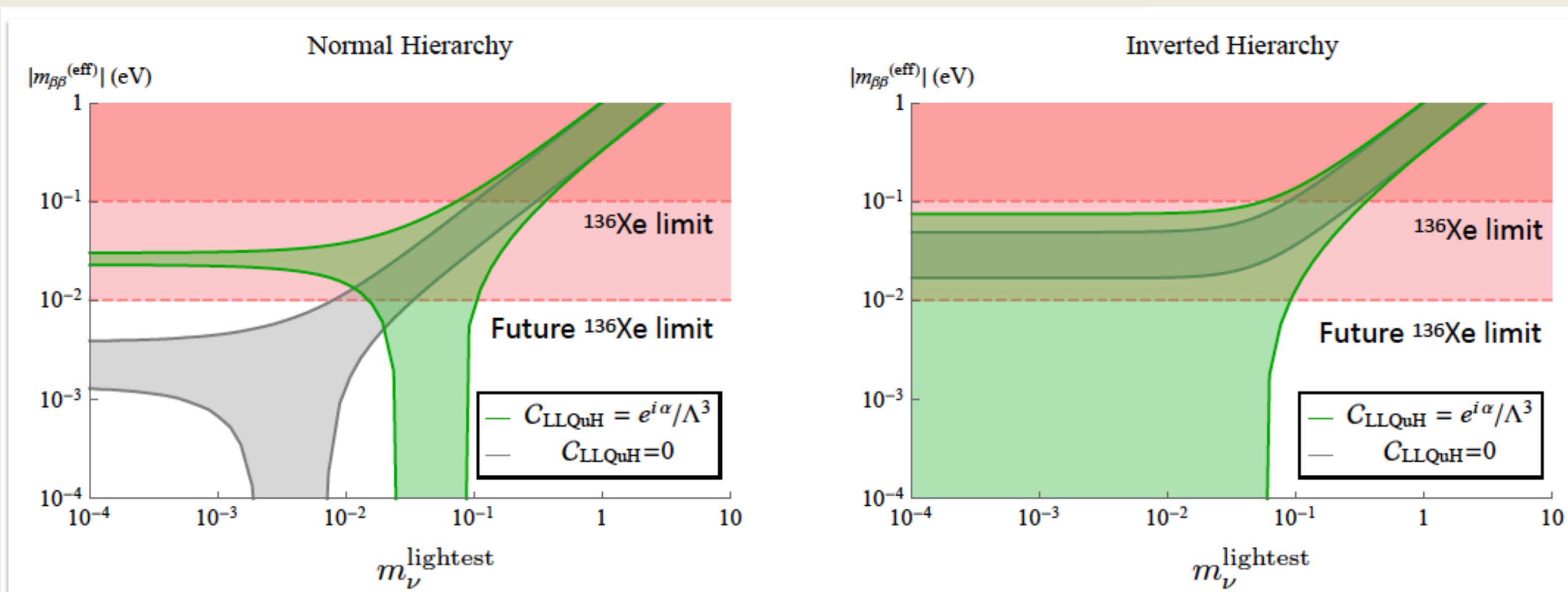
Phenomenology

Example: dim-7 operator e.g. appearing in leptoquark models



$C_7 \sim (v/\Lambda)^3$

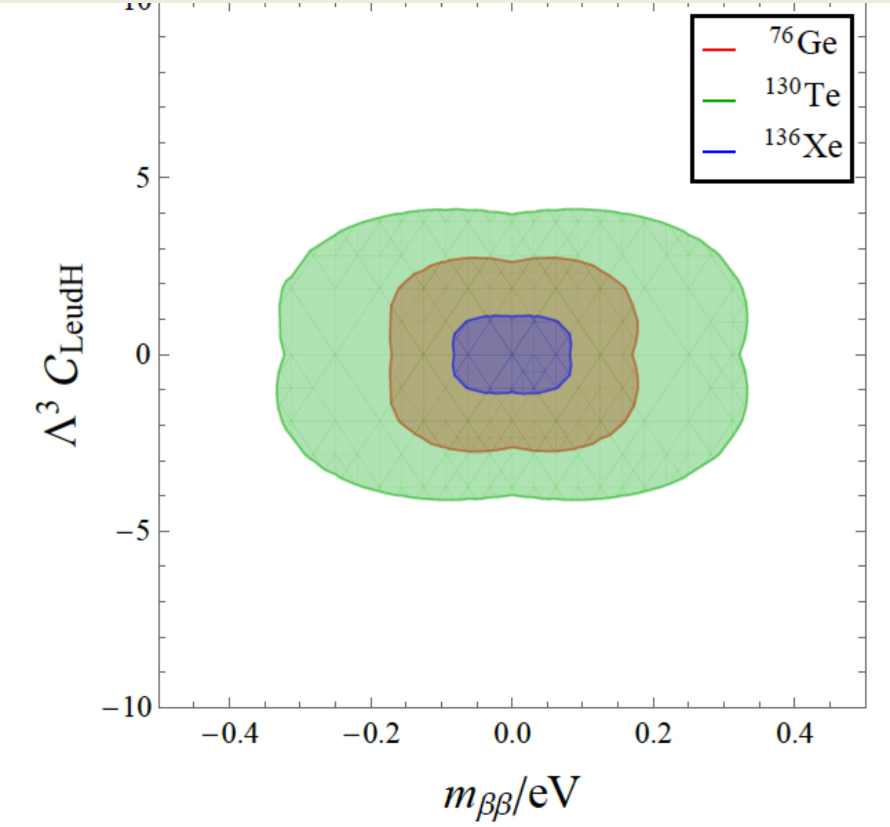
$\Lambda > 400\ TeV$



Disentangling LNV sources

- A single measurement can be from any LNV operator
- Need several measurements to unravel the source

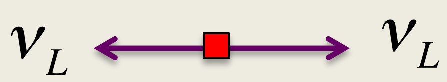
- However, total rates in different isotopes not very helpful….
- Similar Q values and all $0^+ \rightarrow 0^+$

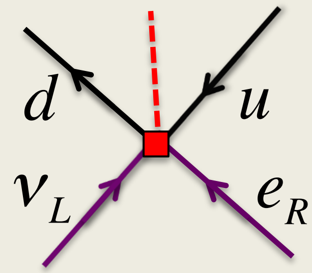


Disentangling LNV sources

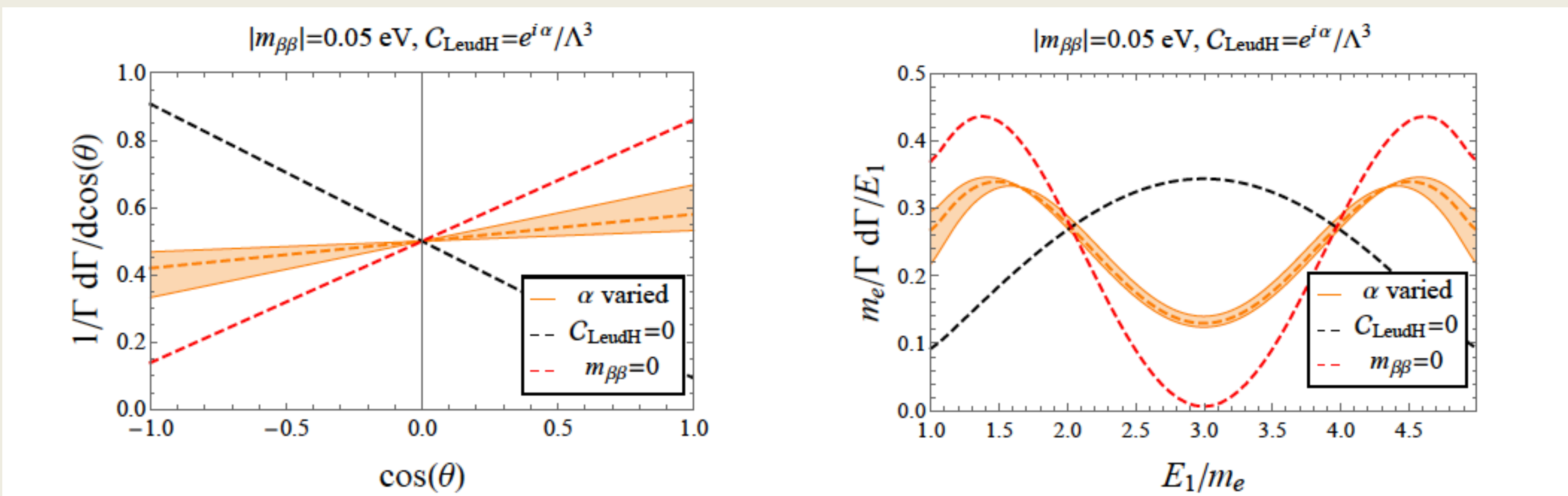
- A single measurement can be from any LNV operator
- Need several measurements to unravel the source

- Instead: **angular & energy** distributions of electrons (science fiction?)

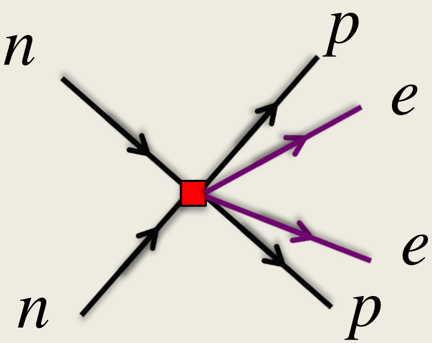




$$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$$



Conclusion/Summary

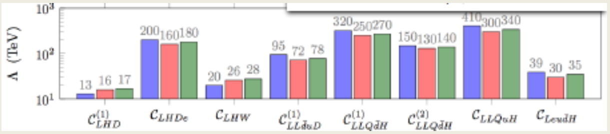


Neutrinoless Double Beta Decay

- ✓ Powerful search for BSM physics (probe high scales)
- ✓ Well motivated in order to probe nature of neutrino masses
- ✓ **However, complicated low-energy observable**

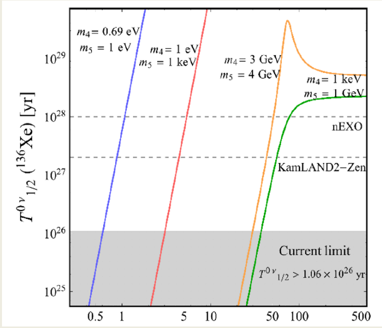
Standard Model EFT and chiral EFT frameworks

- ✓ Keep track of **symmetries** (gauge/lepton#/chiral) from Tev to nuclear scales
- ✓ Standard mechanism: **LO contact nn→ pp + ee operator must be added**



Phenomenology

- ✓ Current experiments set very strong limits (>500 TeV in some cases)
- ✓ **Master formula to include all contributions up to dim-9**
- ✓ **Recent: add effects of light sterile neutrinos**
- ✓ **Connection to other probes: LHC, beamdump, Leptogenesis, in progress**



Some phenomenology

- Consider a simple 'minimal' scenario 3 + 2 sterile neutrinos
- Can account for all neutrino mass splittings and mixing angles
- Leads to 1 massless neutrino
- But 0vbb decay rates too small to measure even with nEXO