A NEW LEADING MECHANISM FOR NEUTRINOLESS DOUBLE-BETA DECAY

Bira van Kolck

Institut de Physique Nucléaire d'Orsay

and *University of Arizona*

with

V. Cirigliano (LANL), W. Dekens (LANL),
J. de Vries (Nikhef), M.L. Graesser (LANL),
E. Mereghetti (LANL), S. Pastore (LANL)

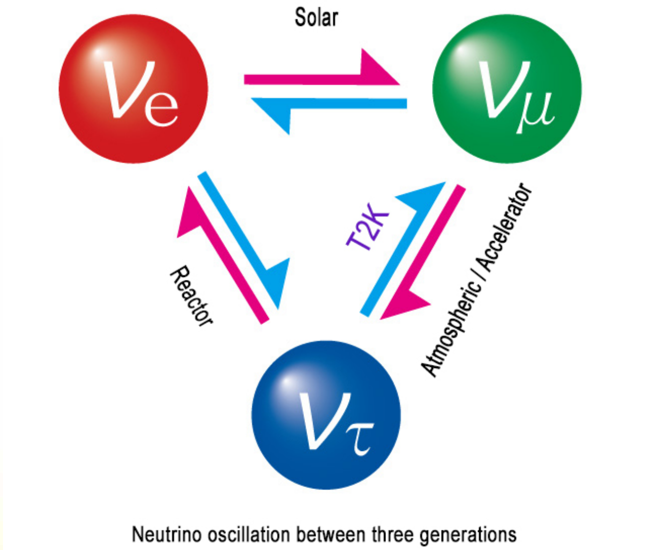
Supported by CNRS and US DOE

Outline

- Introduction
- Neutrinoless Double-Beta Decay
- The Way of Effective Field Theory
- Renormalization
- Estimate of Low-Energy Constant
- *"Ab Initio"* Example
- Discussion
- Conclusion

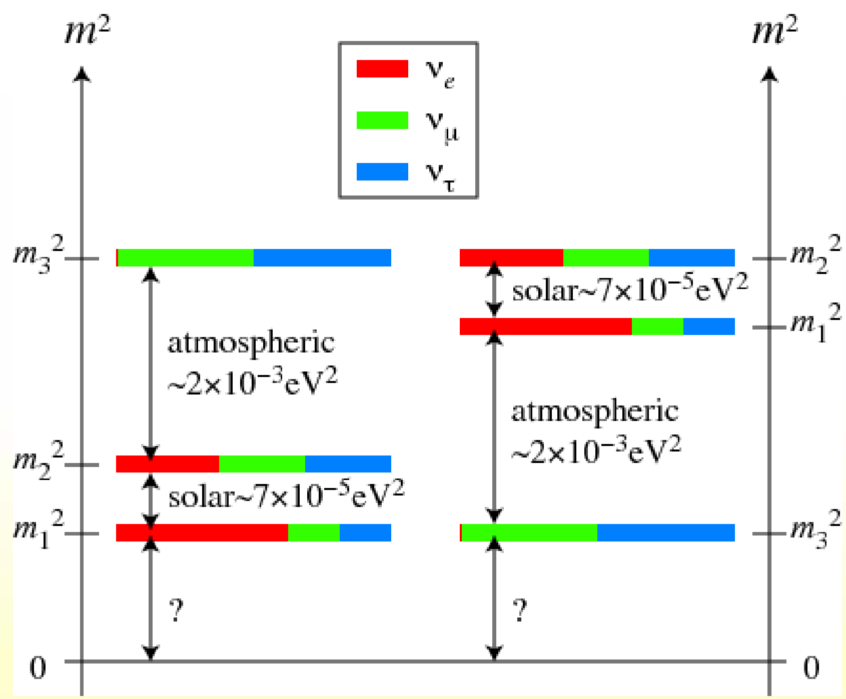
Introduction

one of the
most important discoveries
after Standard Model



$$P_{i \to j} \approx \sin^2(2\theta_{ij}) \sin^2\left(\frac{L}{4E}\Delta m_{ij}^2\right)$$

(two flavors)



King '15

neutrinos mix and have mass

$m_i \lesssim 2$ eV PDG '18

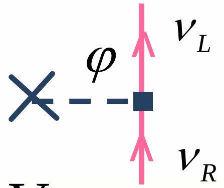
SM not complete

Two mechanisms

1) (light) right-handed neutrinos $\nu_R \neq \nu_R^c \equiv C\gamma^{0T}(\nu_L)^\dagger$ $\qquad C = i\gamma_2\gamma_0$

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\nu_R} + \ldots \qquad \mathcal{L}_{\nu_R} = -y_\nu\left(\overline{\ell}_L\tilde{\varphi}\nu_R + \text{H.c.}\right)$$

$\langle\varphi\rangle \sim v/\sqrt{2}$



$v \simeq 246\ \text{GeV}$

$$= -\frac{y_\nu v}{\sqrt{2}}\left(\overline{\nu}_L\nu_R + \text{H.c.}\right) + \ldots$$

Dirac mass

$\nu_D \equiv \nu_L + \nu_R$ $\qquad m_\nu \sim 0.1\,\text{eV} \Rightarrow y_\nu \sim 10^{-12}$ $\qquad$ possible but why?

cf.
- $y_e \sim 3\cdot 10^{-6}$
- different from quark mixing pattern

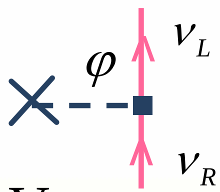
Two mechanisms

1) (light) right-handed neutrinos $\nu_R \neq \nu_R^c \equiv C\gamma^{0T}(\nu_L)^\dagger$

Majorana '37
...

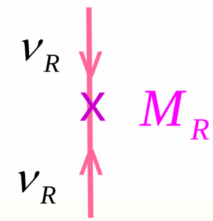
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\nu_R} + \dots \qquad \mathcal{L}_{\nu_R} = -y_\nu\left(\overline{\ell}_L \tilde{\varphi}\nu_R + \text{H.c.}\right) - \frac{M_R}{2}\left(\overline{\nu}_L^c \nu_R + \text{H.c.}\right)$$

$\langle\varphi\rangle \sim v/\sqrt{2}$



$v \simeq 246\ \text{GeV}$

$$= -\frac{y_\nu v}{\sqrt{2}}\left(\overline{\nu}_L \nu_R + \text{H.c.}\right) + \dots$$



new mass scale!

Dirac mass

Majorana mass $|\Delta L| = 2$

$M_R \lesssim y_\nu v$ can explain some of the experimental anomalies

possible but why²?

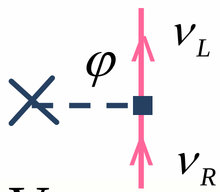
Two mechanisms

1) (light) right-handed neutrinos $\nu_R \neq \nu_R^c \equiv C\gamma^{0T}(\nu_L)^\dagger$

Majorana '37
...

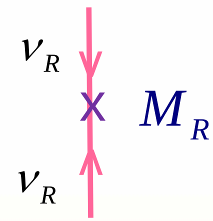
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\nu_R} + \ldots \qquad \mathcal{L}_{\nu_R} = -y_\nu \left(\overline{\ell}_L \tilde{\varphi} \nu_R + \text{H.c.}\right) - \frac{M_R}{2}\left(\overline{\nu}_L^c \nu_R + \text{H.c.}\right)$$

$\langle\varphi\rangle \sim v/\sqrt{2}$



$v \simeq 246$ GeV

$$= -\frac{y_\nu v}{\sqrt{2}}\left(\overline{\nu}_L \nu_R + \text{H.c.}\right) + \ldots$$



new mass scale!

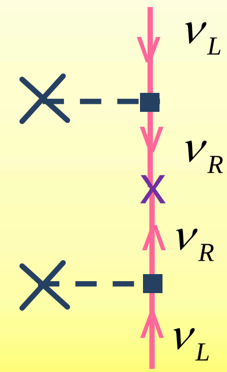
Dirac mass

Majorana mass $|\Delta L| = 2$

$\nu_M = \nu_L + \nu_R^c + \ldots$

$M_R \gtrsim y_\nu v$

$$M \to U^\dagger M U \approx \begin{pmatrix} (y_\nu v)^2/M_R & 0 \\ 0 & M_R \end{pmatrix}$$



$m_\nu \sim 0.1\,\text{eV} \Rightarrow y_\nu \sim y_e\sqrt{M_R/v}$

alleviates fine-tuning

$\text{N} = \nu_R + \nu_L^c + \ldots$

decouples at low energies

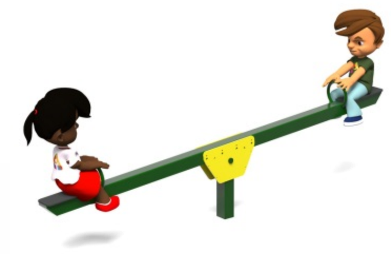
Natural possibility: $M_R \sim M_{\not{L}} \gg v \Rightarrow (y_\nu v)^2 / M_R \ll v$

makes leptogenesis possible

Fukugita + Yanagida '86

Minkowski '77
...

(type I) see-saw mechanism

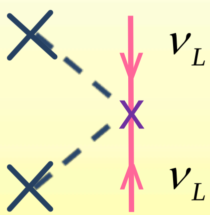


More generally, independent on details of high-energy physics:

2) dimension-five operator

Weinberg '79
Weldon + Zee '80
...

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\text{dim}=5} + \ldots \qquad \mathcal{L}_{\text{dim}=5} = \frac{c_5}{M_{\not{L}}}\left[\left(\ell^T C \tilde{\varphi}\right)\left(\tilde{\varphi}^T \ell\right) + \text{H.c.}\right]$$



$$= \frac{c_5 v^2}{2M_{\not{L}}}\left(\overline{\nu}_L \nu_R^c + \text{H.c.}\right) + \ldots$$

Majorana mass

$|\Delta L| = 2$

$m_\nu \sim 0.1\,\text{eV} \Rightarrow M_{\not{L}} \sim c_5 \cdot 10^{15}\ \text{GeV}$

NDA: $c_5 = \mathcal{O}(4\pi\alpha)$

comparable to GUT scale!

coincidence?

Not exclusive mechanisms!

- B, L accidental symmetries at classical level
- non-perturbative effects break B+L, but conserve B-L
- unless B-L is exact, dim-5 op is allowed and will be there; it should be the most important effect of new physics

→ coincidence that it can explain shortcoming of the SM?

N.B. In some models, $c_5 \sim y_e^2 \sim 10^{-11}$

→ higher-dim ops could be important

Talk by Dekens next week

...
Prézeau, Ramsey-Musolf + Vogel '09
...
Graesser '17
Cirigliano *et al.* '17'18

Here: only light neutrinos and dim-5 op

neutrino oscillations: $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$ not a symmetry

is $U(1)_{B-L}$?

0ν2ß decay

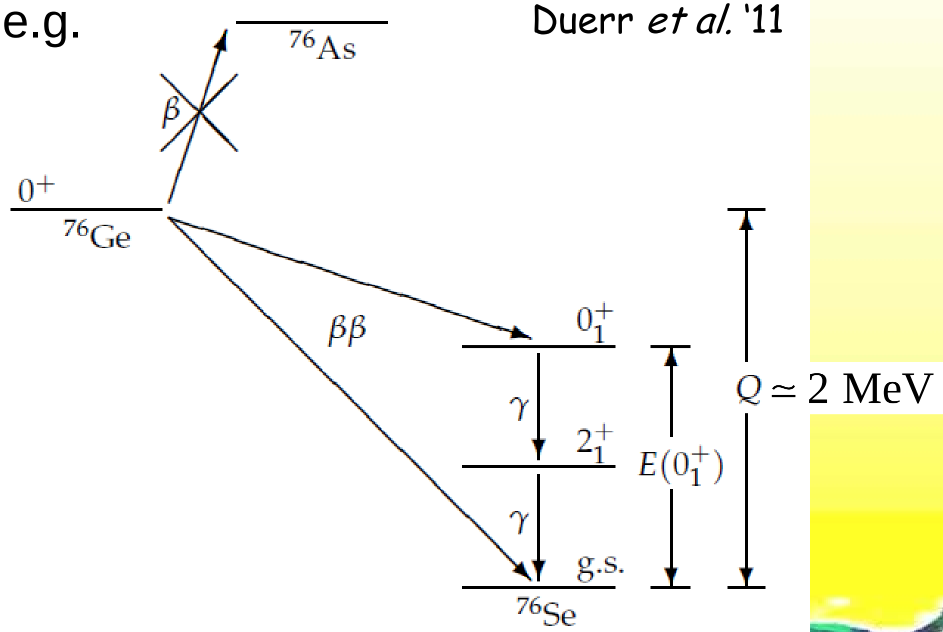
lots of nucleons for lots of time ⟹ most sensitive probe of B-L violation

single-beta decay $\quad {}^{A}Z \rightarrow {}^{A}(Z+1) + e^{-} + \overline{\nu}_{e} \quad \left(T_{1/2}^{(\beta)}\right)^{-1} \propto \left(G_F\, f_\pi^2\right)^2$

two-neutrino double-beta decay $\quad {}^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-} + 2\overline{\nu}_{e} \quad \left(T_{1/2}^{(2\nu 2\beta)}\right)^{-1} \propto \left(G_F\, f_\pi^2\right)^4$

e.g.

Duerr *et al.* '11



too small to measure except when single-beta decay kinematically forbidden

$$T_{1/2}^{(2\nu 2\beta)}\left({}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}\right) = 1.84_{-0.10}^{+0.14} \cdot 10^{21}\,\mathrm{y}$$

GERDA Collab. '15

Table 1 $\beta^-\beta^-$ decay transitions for naturally occurring parent isotopes*

Transition	T_0 (keV)	Abundance (%)	Excitation energy of first 2^+ state (keV)**
^{46}Ca → ^{46}Ti	985	0.0035	889
^{48}Ca → ^{48}Ti†	4272	0.187	984
^{70}Zn → ^{70}Ge	1001	0.62	—
^{76}Ge → ^{76}Se	2045	7.8	559
^{80}Se → ^{80}Kr	136	49.8	—
^{82}Se → ^{82}Kr	3005	9.2	776
^{86}Kr → ^{86}Sr	1249	17.3	1077
^{94}Zr → ^{94}Mo	1148	17.4	871
^{96}Zr → ^{96}Mo†	3350	2.8	778
^{98}Mr → ^{98}Ru	111	24.1	—
^{100}Mo → ^{100}Ru	3033	9.6	540
^{104}Ru → ^{104}Pd	1301	18.7	556
^{110}Pd → ^{110}Cd	2014	11.8	658
^{114}Cd → ^{114}Sn	540	28.7	—
^{116}Cd → ^{116}Sn	2808	7.5	1294
^{122}Sn → ^{122}Te	358	4.56	—
^{124}Sn → ^{124}Te	2278	5.64	603
^{128}Te → ^{128}Xe	869	31.7	443
^{130}Te → ^{130}Xe	2533	34.5	536
^{134}Xe → ^{134}Ba	843	10.4	605
^{136}Xe → ^{136}Ba	2481	8.9	819
^{142}Ce → ^{142}Nd	1414	11.1	—
^{146}Nd → ^{146}Sm‡	61	17.2	—
^{148}Nd → ^{148}Sm	1928	5.7	550
^{150}Nd → ^{150}Sm	3367	5.6	334
^{154}Sm → ^{154}Gd	1250	22.6	123
^{160}Gd → ^{160}Dy	1731	21.8	87
^{170}Er → ^{170}Yb	655	14.9	84
^{176}Yb → ^{176}Hf	1077	12.6	88
^{186}W → ^{186}Os	489	28.6	137
^{192}Os → ^{192}Pt	408	41.0	317
^{198}Pt → ^{198}Hg	1043	7.2	412
^{204}Hg → ^{204}Pb	414	6.9	—
^{232}Th → ^{232}U§	850	100	48
^{238}U → ^{238}Pu¶	1146	99.275	44

$$Q \geq 2m_e$$

pairing

⬇

parent : even-even, $J^P = 0^+$

daughter: even-even,

typically $J^P = 0^+$ (g.s.)

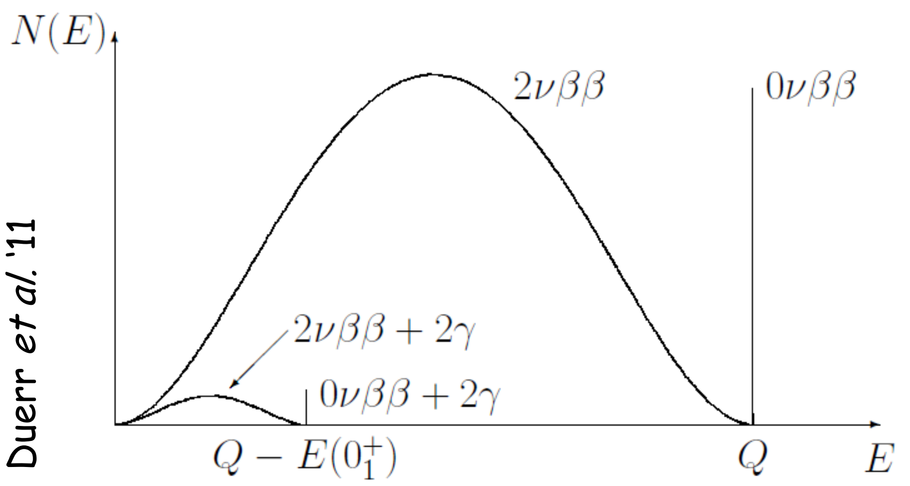
$$\Delta I = 2$$

Haxton + Stephenson '84

Racah '37
Furry '39
...

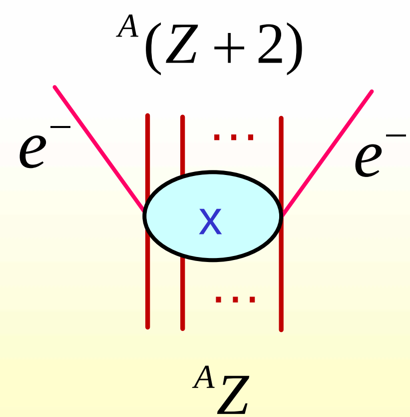
neutrinoless double-beta decay

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



Duerr *et al.* '11

$$ \Delta L = 2 $$



even rarer: e.g., $T_{1/2}^{(0\nu 2\beta)}\left({}^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}\right) > 8.0 \cdot 10^{25}\,\mathrm{y}$

GERDA-II Collab. '18

e.g. Haxton + Stephenson '84

$$m_{\nu i} \lesssim M_{nuc} \Rightarrow \left(T_{1/2}^{(0\nu 2\beta)}\right)^{-1} \propto \left|M^{(0\nu)}\right|^2 \left|m_{\beta\beta}\right|^2$$

nuclear matrix element

effective Majorana mass

$$m_{\beta\beta} \equiv \sum_{i=1}^{n} U_{ei}^2 m_{\nu i}$$

PMNS matrix elements

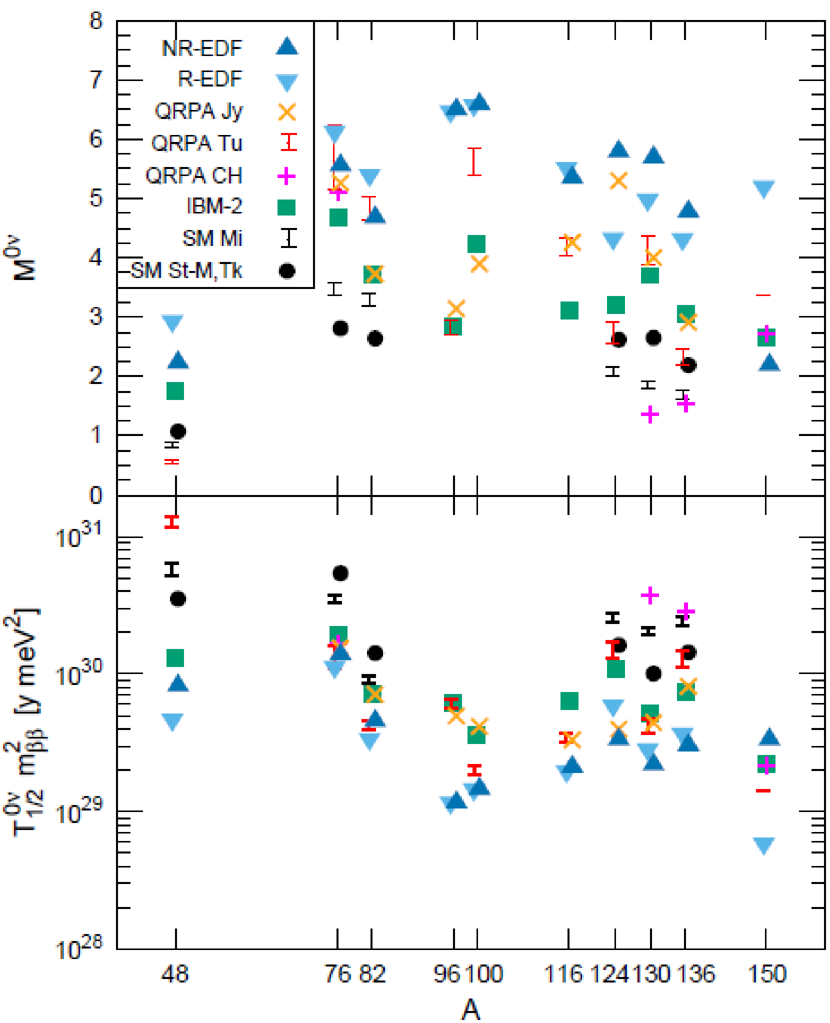
neutrino masses

$$\begin{cases} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{cases}$$

Majorana phases

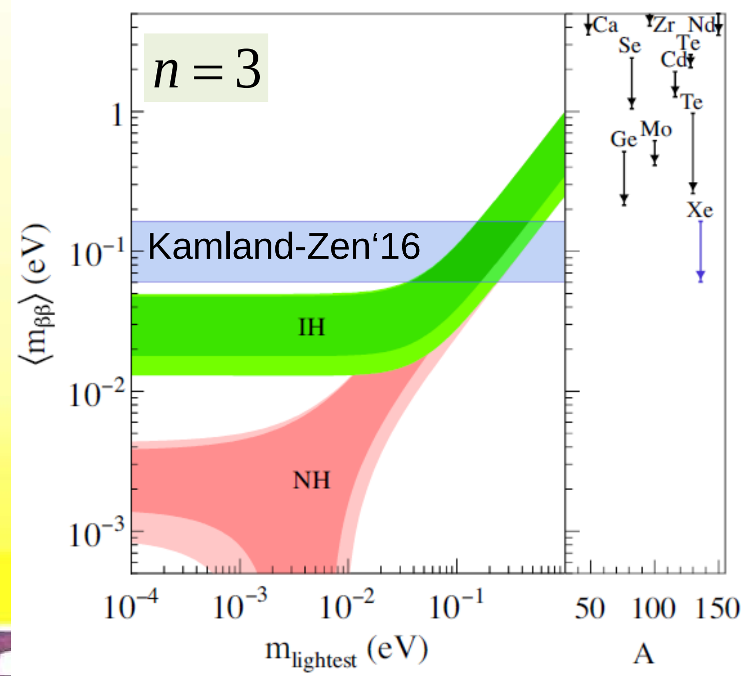
Dirac phase

$$m_{\beta\beta} = m_{\nu 1}\, c_{12}^2 c_{13}^2 + m_{\nu 2}\, s_{12}^2 c_{13}^2\, e^{i\alpha_{21}} + m_{\nu 3}\, s_{13}^2\, e^{i(\alpha_{31}-2\delta)}$$



next-gen expts

Engel + Menéndez '17



major uncertainty: nuclear matrix element

↑

uncontrolled many-body approximations

enormous progress in *ab initio* calculations:
^{48}Ca in horizon

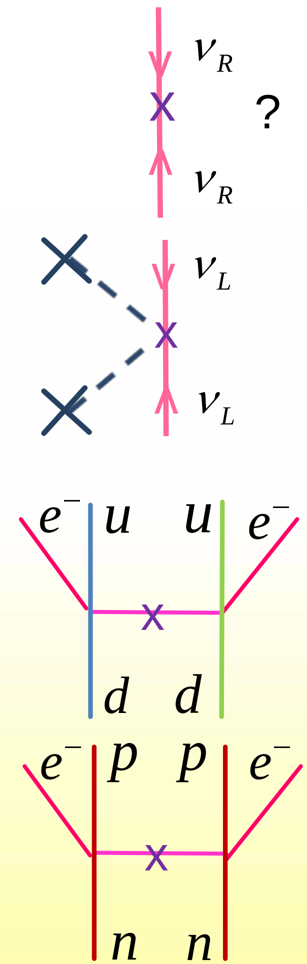
input?

Chiral or Pionless EFT

The Way of EFT

Q

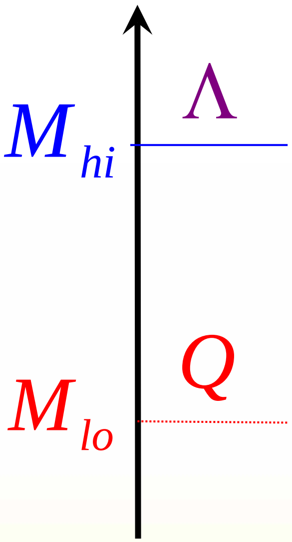
$M_{\not L} \sim ?$	unknown physics
$M_{EW} \sim v, m_Z, m_W$ ~ 100 GeV	Standard Model + higher-dim
$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$ ~ 1 GeV	QCD
$M_{nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$ ~ 100 MeV	Chiral EFT (χPT)
$\aleph \sim 1/a_{NN}$ ~ 30 MeV	Pionless EFT



run RG

match with lattice, ...

Effective Field Theory



arbitrary
UV regulator

non-analytic functions,
from solution of dynamical eq.
(*e.g.* Lippmann-Schwinger)

$$T^{(\bar{\nu})}(Q \sim M_{lo} \ll M_{hi}) \propto \sum_{\nu=0}^{\bar{\nu}} \left[\frac{Q}{M_{hi}}\right]^{\nu} F^{(\nu)}\left(\frac{Q}{M_{lo}}, \frac{Q}{\Lambda}; \gamma_i^{(\nu)}\left(\frac{\Lambda}{M_{lo}}, \frac{M_{lo}}{M_{hi}}\right)\right)$$

$$+\mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}+1}}, \frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}}\Lambda}\right)$$

“low-energy constants”

$N^{\bar{\nu}}LO$

(unfortunately not the usage by potential modelers)

controlled

RG invariance

(absent for “chiral potentials”)

(OTHERWISE, CUTOFF DEP NOT ERROR ESTIMATE)

$$\frac{\Lambda}{T^{(\bar{\nu})}} \frac{\partial T^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}}\Lambda}\right)$$

to minimize cutoff errors, $\Lambda \gtrsim M_{hi}$

for realistic error estimate, $\Lambda \in [M_{hi}, \infty)$

model independent

(OTHERWISE, SENSITIVE TO HIGH-MOM DETAILS)

QCD (-LITE)

$Q \ll M_{EW}$

d.o.f.s quarks: $q = \begin{pmatrix} u \\ d \end{pmatrix}$ gluons: G_μ^a (+ photon: A_μ)

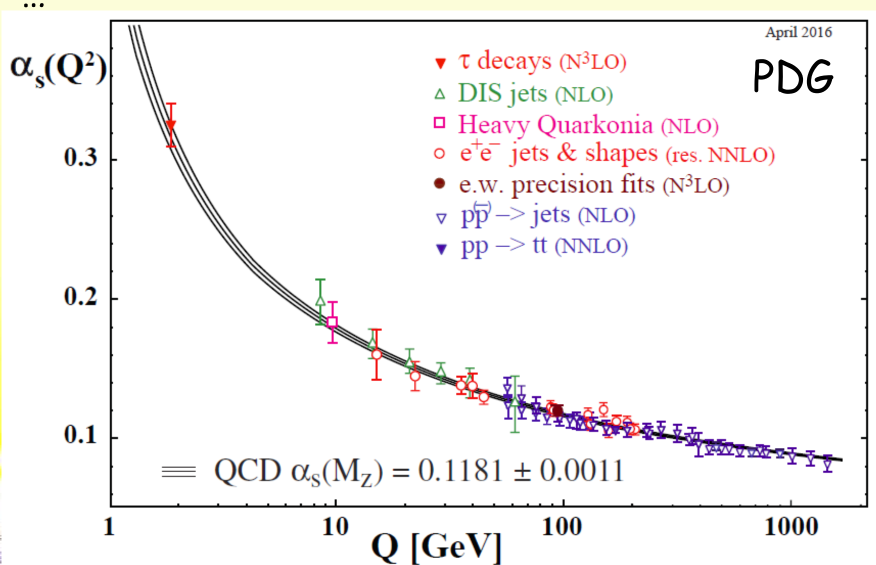
symmetries SO(3,1) global, $SU(3)_c$ $(+U(1)_{em})$ gauge

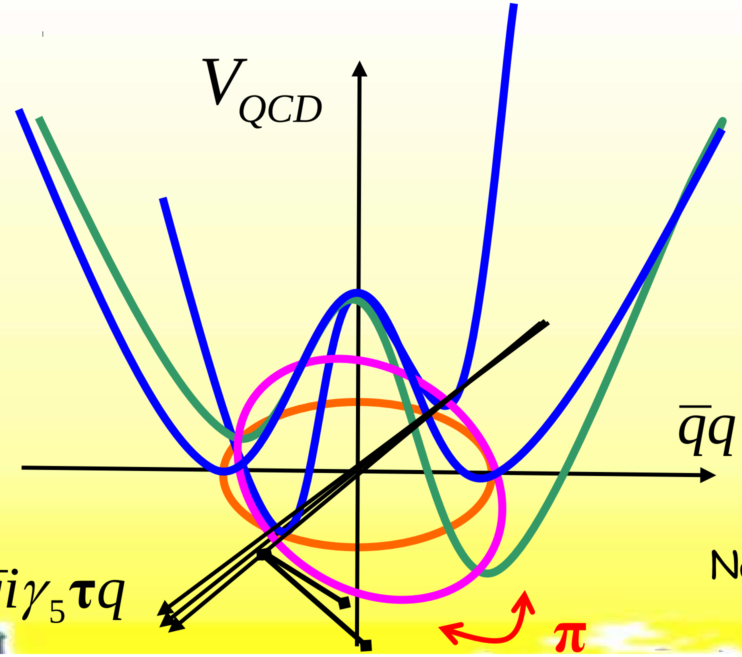
$$\mathcal{L}_{QCD} = \underbrace{\bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu}}_{M_{QCD} \sim m_N,\, m_\rho,\, 4\pi f_\pi,\, \ldots \sim 1\ \mathrm{GeV}} + \underbrace{\bar{m}\,\bar{q}\left(1 - \varepsilon\tau_3\right)q}_{m_\pi \sim \sqrt{\bar{m} M_{QCD}} \simeq 140\ \mathrm{MeV}} + \ldots$$

Basic mass scales

$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots \sim 1\ \mathrm{GeV}$ $\quad m_\pi \sim \sqrt{\bar{m} M_{QCD}} \simeq 140\ \mathrm{MeV}$

Gross + Wilczek '73
Politzer '73
...

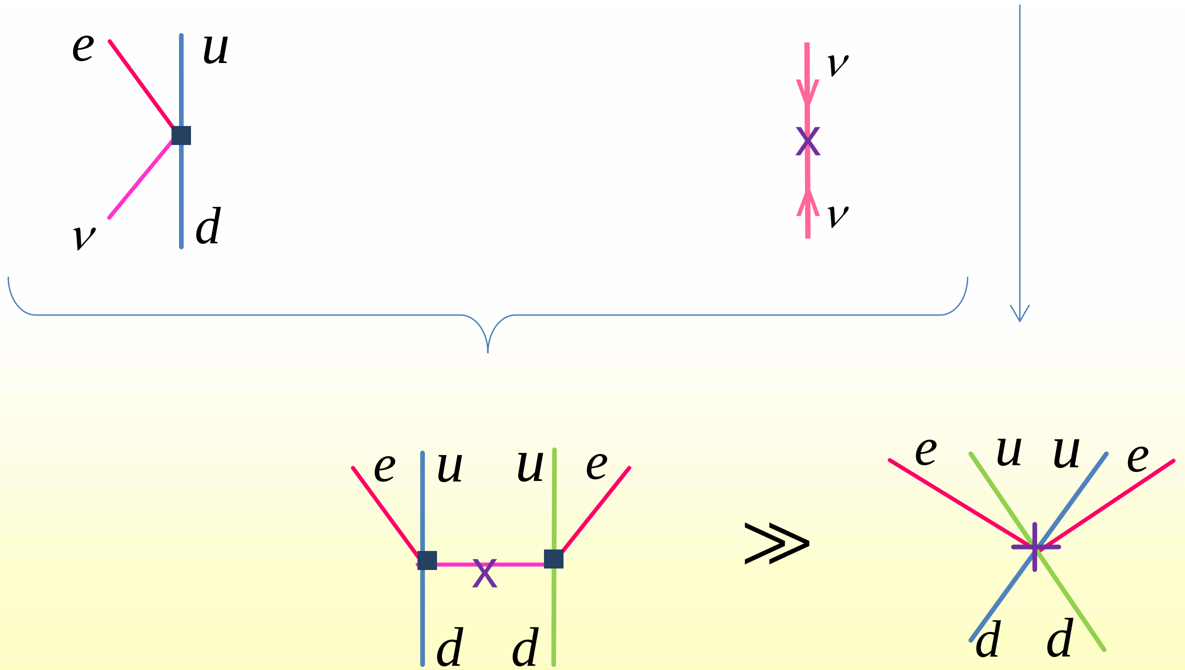




Nambu '64
...

$f_\pi \sim M_{QCD}/4\pi + \mathcal{O}(\bar{m}) \simeq 100\ \mathrm{MeV}$

$$\mathcal{L}_{QCD} = \ldots + \frac{G_F}{\sqrt{2}} V_{ud} \left(\bar{e}_L \gamma_\mu \nu_{eL} \, \bar{u}_L \gamma^\mu d_L + \text{H.c.} \right) - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \ldots$$

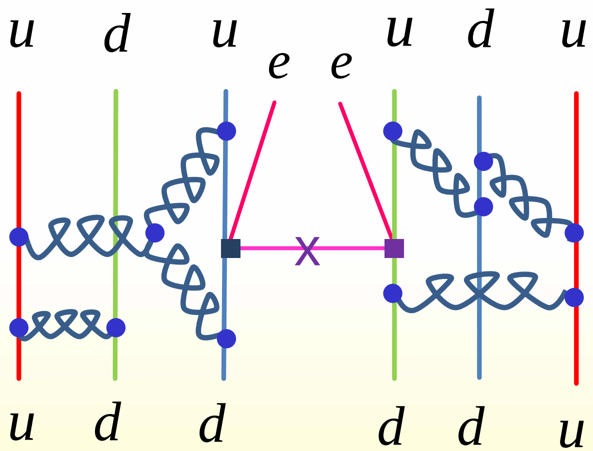


$$\propto G_F^2 \frac{m_{\beta\beta}}{Q^2}$$

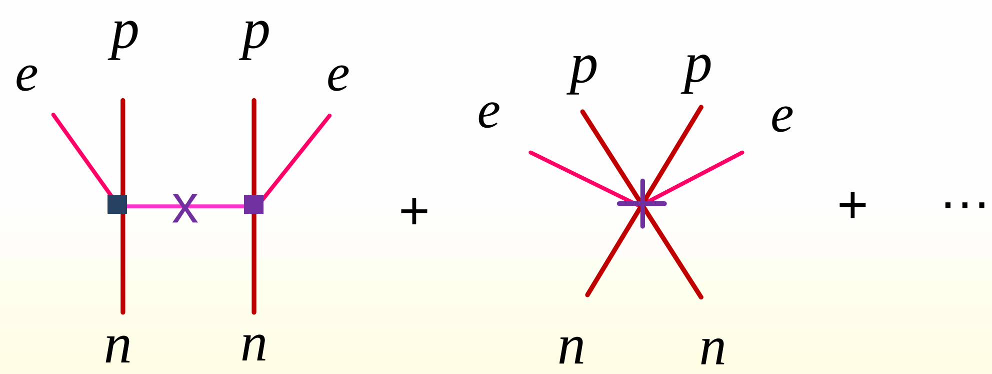
$$\propto G_F^2 \frac{m_{\beta\beta}}{M_{EW}^2}$$

$Q \sim M_{QCD}$

$Q \ll M_{QCD}$



$\longrightarrow$



$\propto G_F^2 \frac{m_{\beta\beta}}{Q^2}$

$\propto G_F^2 \frac{m_{\beta\beta}}{?^2}$

Chiral EFT

$Q \sim m_\pi \ll M_{QCD}$

d.o.f.s

nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ pions: $\boldsymbol{\pi} = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix}$ (+ photon: A_μ)

+ Deltas + Roper + ...?

symmetries

SO(3,1) global, $SU(3)_c$ (+$U(1)_{em}$) gauge, ~~SU(2)×SU(2) global~~

(trivial)

$$\mathcal{L}_{\chi EFT} = \frac{1}{2}\left(\partial_\mu \boldsymbol{\pi} \cdot \partial^\mu \boldsymbol{\pi} - m_\pi^2 \boldsymbol{\pi}^2\right) + N^\dagger \left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right) N + \frac{g_A}{2 f_\pi} N^\dagger \vec{\sigma} \boldsymbol{\tau} N \cdot \cdot \vec{\nabla} \boldsymbol{\pi}$$

$$+ C_0 \, N^\dagger N \, N^\dagger N + \ldots$$

other spin/isospin,
chiral partners,
more derivatives and fields,
powers of pion mass

expansion in:

$$\frac{Q}{M_{QCD}} \sim \begin{cases} Q/m_N & \text{non-relativistic} \\ Q/m_\rho, \ldots & \text{multipole} \\ Q/4\pi f_\pi & \text{pion loop} \end{cases}$$

$Q \ll m_\pi$

Pionless EFT

d.o.f.s nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ photon: A_μ)

symmetries $SO(3,1)$ global, $SU_c(3)$ $(+U_{em}(1))$ gauge

(trivial)

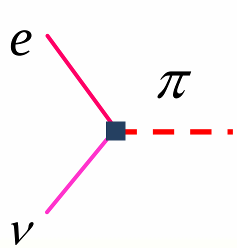
$$\mathcal{L}_{\not\pi EFT} = N^+\left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right)N + C_0\, N^+N\, N^+N + D_0\, N^+N\, N^+N\, N^+N + \ldots$$

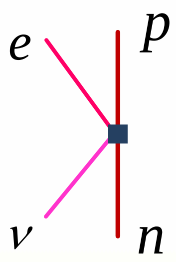
more derivatives and fields, isospin violation

Classically the same as Chiral EFT minus pions, but renormalization different in general

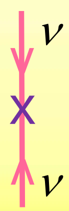
Chiral EFT for definiteness:

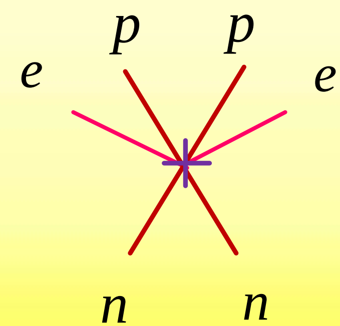
$$\mathcal{L}_{\chi EFT} = \ldots + \sqrt{2} G_F V_{ud} \left\{ \bar{e}_L \gamma_\mu \nu_{eL} \left[f_\pi \partial^\mu \pi^- - N^\dagger \left(\delta_0^\mu - g_A \delta_i^\mu \sigma^i \right) \tau^+ N \right] + \text{H.c.} \right\} + \ldots$$

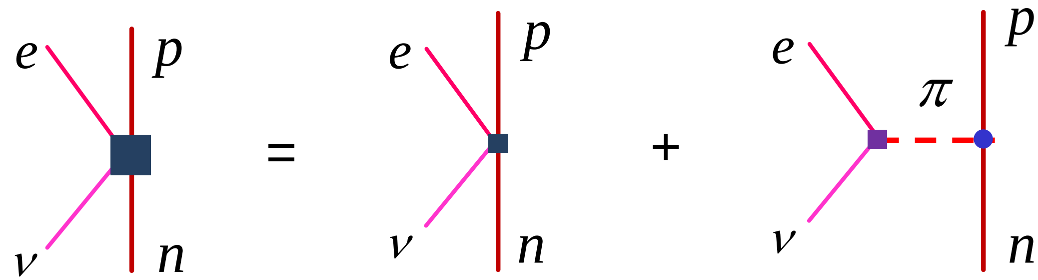




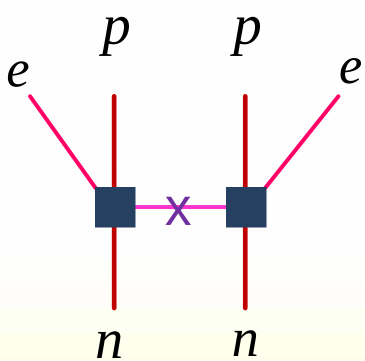
$$\mathcal{L}_{\chi EFT} = \ldots - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + g_\nu G_F^2 V_{ud}^2 m_{\beta\beta} \left\{ \bar{e}_L C \bar{e}_L^T N^\dagger \tau^+ N N^\dagger \tau^+ N + \text{H.c.} \right\} + \ldots$$







$G_F V_{ud}$ $\qquad$ $G_F V_{ud}\, f_\pi Q \,\frac{1}{Q^2}\,\frac{Q}{f_\pi}$

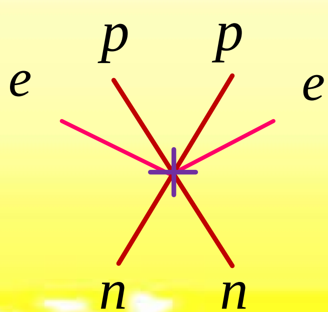


$$\propto 2\, G_F^2\, V_{ud}^2\, m_{\beta\beta}\, V_\nu^{(0)}(\vec{q})$$

$$S_{12}(\hat{q}) \equiv \vec{\sigma}_1 \cdot \hat{q}\, \vec{\sigma}_2 \cdot \hat{q} - \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2$$

$$V_\nu^{(0)}(\vec{q}) = \frac{\tau_1^+ \tau_2^+}{\vec{q}^{\,2}} \left\{ 1 + g_A^2 \left[S_{12}(\hat{q}) - \frac{2}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 \right] - \frac{g_A^2 m_\pi^4}{(\vec{q}^{\,2} + m_\pi^2)^2} \left[S_{12}(\hat{q}) + \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 \right] \right\}$$

Cirigliano *et al.* ‘17



$$\propto 2\, G_F^2\, V_{ud}^2\, m_{\beta\beta}\, V_{\rm ct}^{(?)}(\vec{q})$$

$$V_{\rm ct}^{(?)} = -g_\nu\, \tau_1^+ \tau_2^+$$

Georgi + Manohar '86

naïve dimensional analysis (NDA)

perturbative renormalization ⇒

$$c_i = \mathcal{O}\left(\frac{(4\pi)^{N-2}}{M^{D-4}} c_i^{\text{red}} \right)$$

number of fields in operator

dimension of operator

$$c_i^{\text{red}} = \mathcal{O}\left(\left(g^{\text{red}} \right)^{\#} \right)$$

reduced coupling

reduced underlying theory parameter

insertions

e.g.

$$g_\nu G_F^2 V_{ud}^2 m_{\beta\beta} = \mathcal{O}\left(\frac{(4\pi)^4}{M_{QCD}^5} \left(g_\nu G_F^2 V_{ud}^2 m_{\beta\beta} \right)^{\text{red}} \right)$$

$$\left(g_\nu G_F^2 V_{ud}^2 m_{\beta\beta} \right)^{\text{red}} = \mathcal{O}\left(\left(G_F^2 V_{ud}^2 \right)^{\text{red}} \left(m_{\beta\beta} \right)^{\text{red}} \right)$$

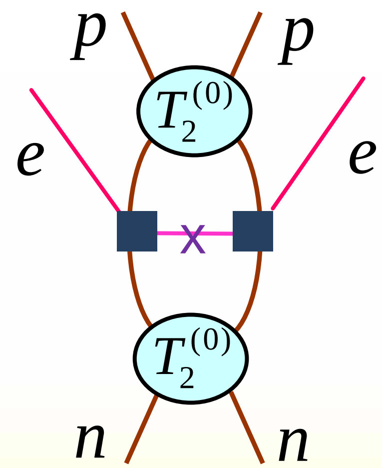
$$\left(G_F V_{ud} \right)^{\text{red}} = \mathcal{O}\left(\frac{M_{QCD}^2}{(4\pi)^2} G_F V_{ud} \right) \qquad \left(m_{\beta\beta} \right)^{\text{red}} = \mathcal{O}\left(\frac{m_{\beta\beta}}{M_{QCD}} \right)$$

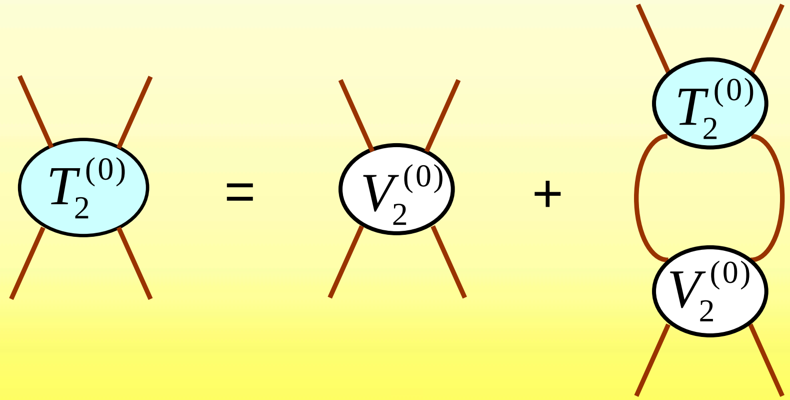
$$\Rightarrow \quad g_\nu = \mathcal{O}\left(\frac{1}{M_{QCD}^2} \right)$$

BUT… NUCLEAR AMPLITUDES NONPERTURBATIVE!

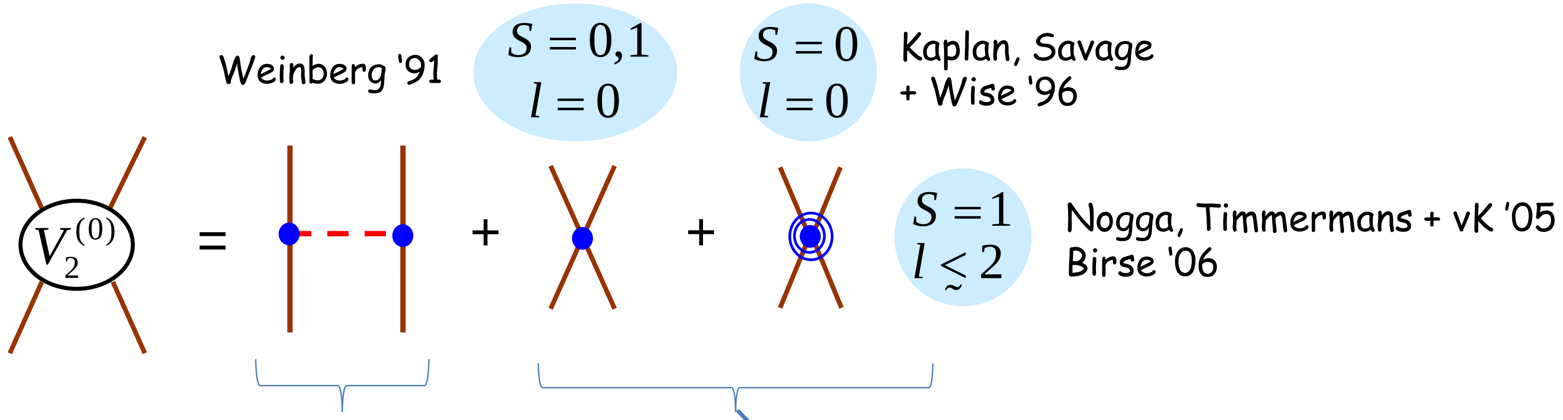
Renormalization

LO





LO



$$= \frac{4\pi}{m_N M_{NN}} \boldsymbol{\tau}_1 \bullet \boldsymbol{\tau}_2 \left[S_{12}(\hat{q}) + \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 \right] \left[1 - \frac{m_\pi^2}{\vec{q}^{\,2} + m_\pi^2} \right]$$

singular, requires counterterms
in waves where it is iterated

$$= \frac{4\pi}{m_N M_{NN}} \left\{ C_0\left({}^3S_1\right) + C_0\left({}^1S_0\right) + \frac{m_\pi^2}{M_{NN}^2} D_2\left({}^1S_0\right) + \frac{p'p}{M_{NN}^2}\left[C_2\left({}^3P_0\right) + C_2\left({}^3P_2\right) \right] + ? \right\}$$

larger than NDA!

$$M_{NN} \equiv \frac{4\pi f_\pi}{g_A^2 m_N} f_\pi \sim f_\pi$$

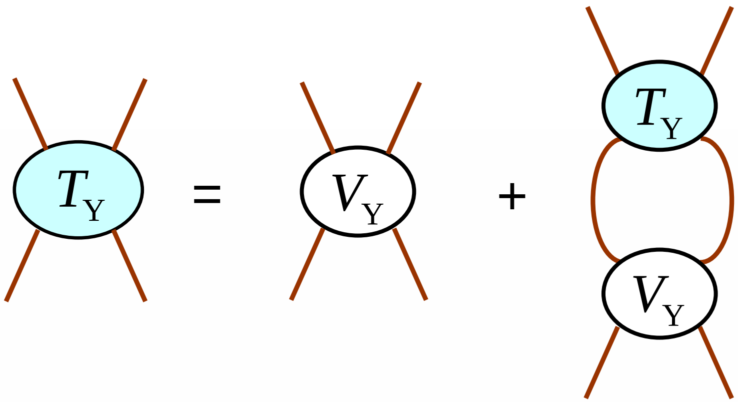
Kaplan, Savage + Wise '98

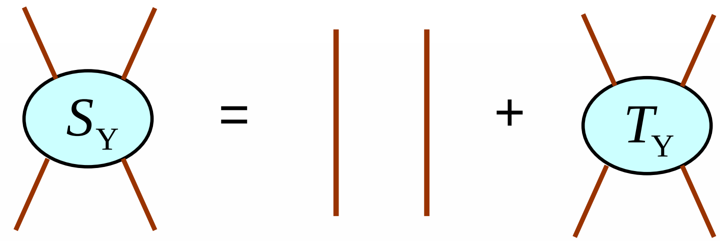
subLOs NDA relative to LO (except spin-singlet *S* wave)

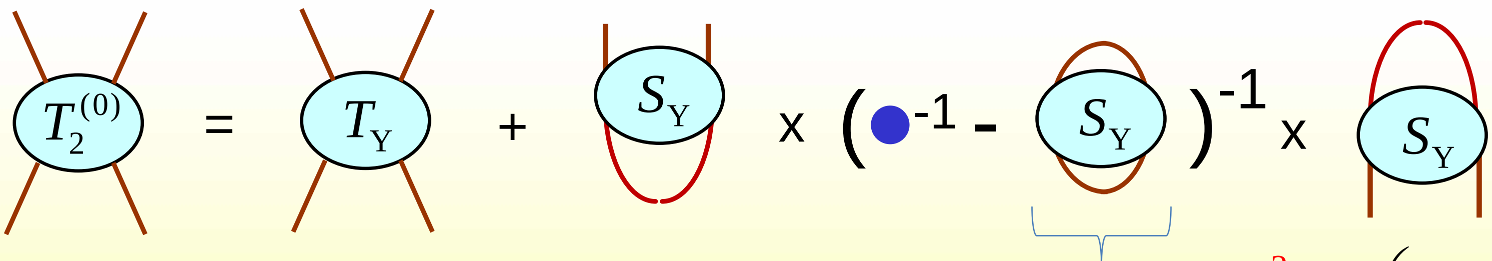
Long + vK '07
Long + Yang '12

$^1S_0$ $V_2^{(0)}(\vec{q}) = \frac{4\pi}{m_N M_{NN}}\left[C_0\left({}^1S_0\right) + \frac{m_\pi^2}{M_{NN}^2} D_2\left({}^1S_0\right) + 1 - \frac{m_\pi^2}{\vec{q}^{\,2}+m_\pi^2}\right] \equiv \frac{4\pi}{m_N M_{NN}}\tilde{C} + V_Y(\vec{q})$

singular regular







Kaplan, Savage + Wise '96
Long + Yang '13

well-defined well-defined

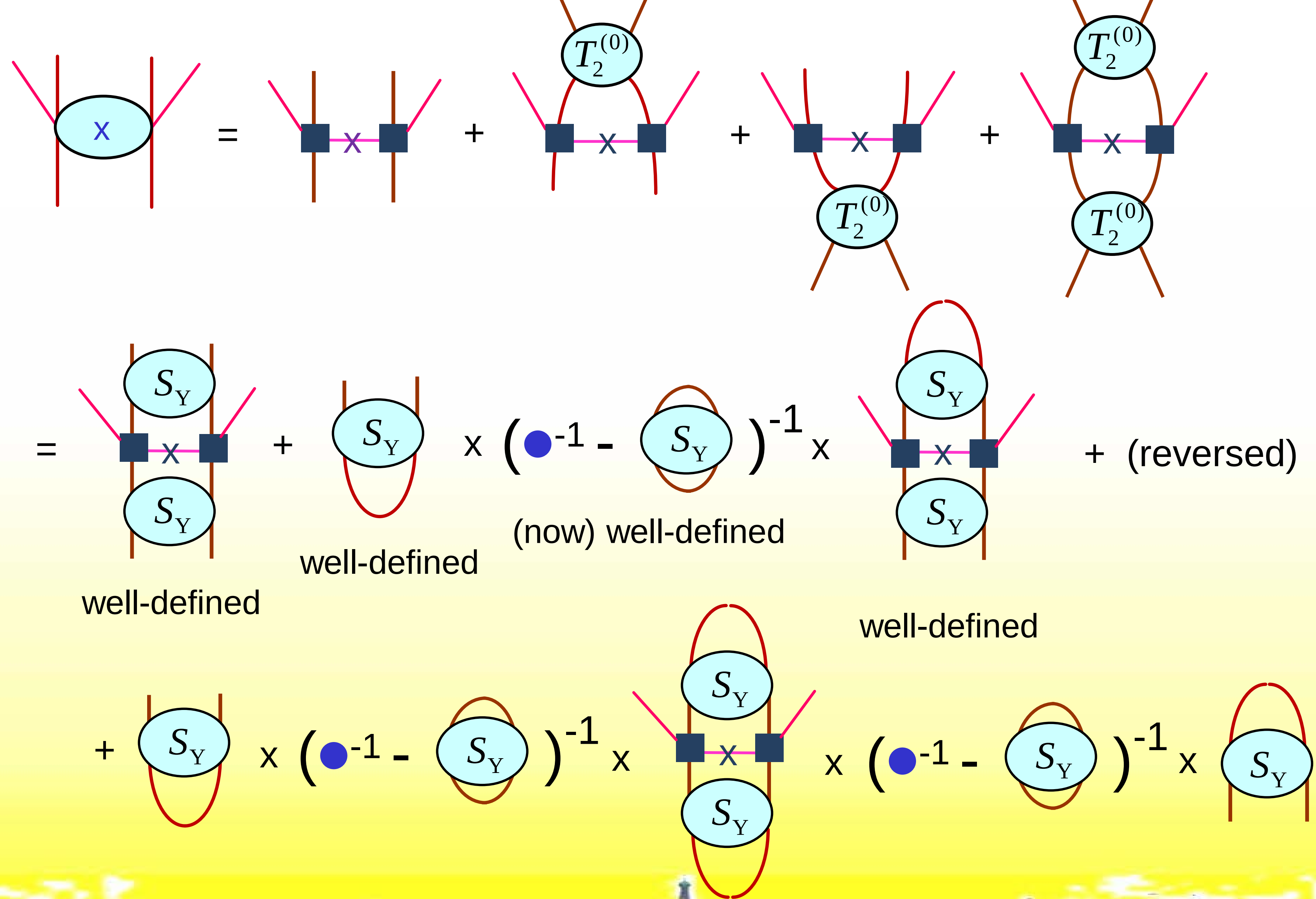
$\propto \Lambda + \# \frac{m_\pi^2}{M_{NN}} \ln\left(\frac{\Lambda}{M_{NN}}\right) + \# \frac{k^2}{\Lambda} + \ldots$

need for counterterms: two at LO one at NLO

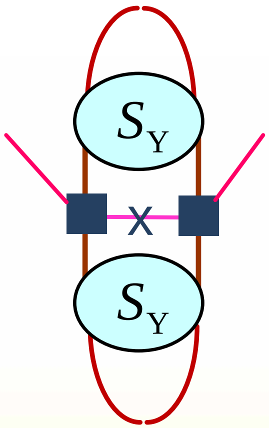
LO dim reg with min sub: $\tilde{C}^{-1}(\mu) = -\# \frac{m_\pi^2}{M_{NN}} \ln\left(\frac{\mu}{\mu_*}\right) + \ldots$

determined from scattering length at physical pion mass

Cirigliano *et al.* '18



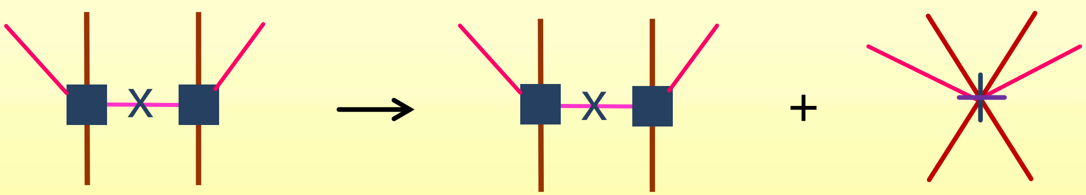
$$V_\nu^{(0)}(\vec{q}) = \frac{\tau_1^+\tau_2^+}{\vec{q}^{\,2}}\left\{1+2g_A^2+\frac{g_A^2 m_\pi^4}{(\vec{q}^{\,2}+m_\pi^2)^2}\right\}$$



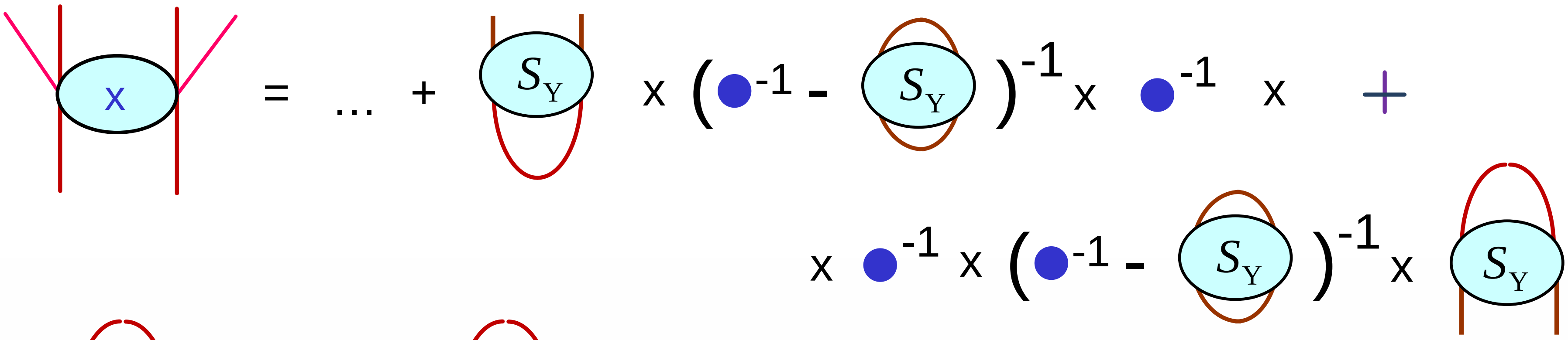
$$= -\left(\frac{m_N}{4\pi}\right)^2 \frac{1+2g_A^2}{2}\left[\Delta + \ln\frac{\mu^2}{-\left(|\vec{p}|+|\vec{p}\,'|\right)^2+i0^+}\right]+\dots$$

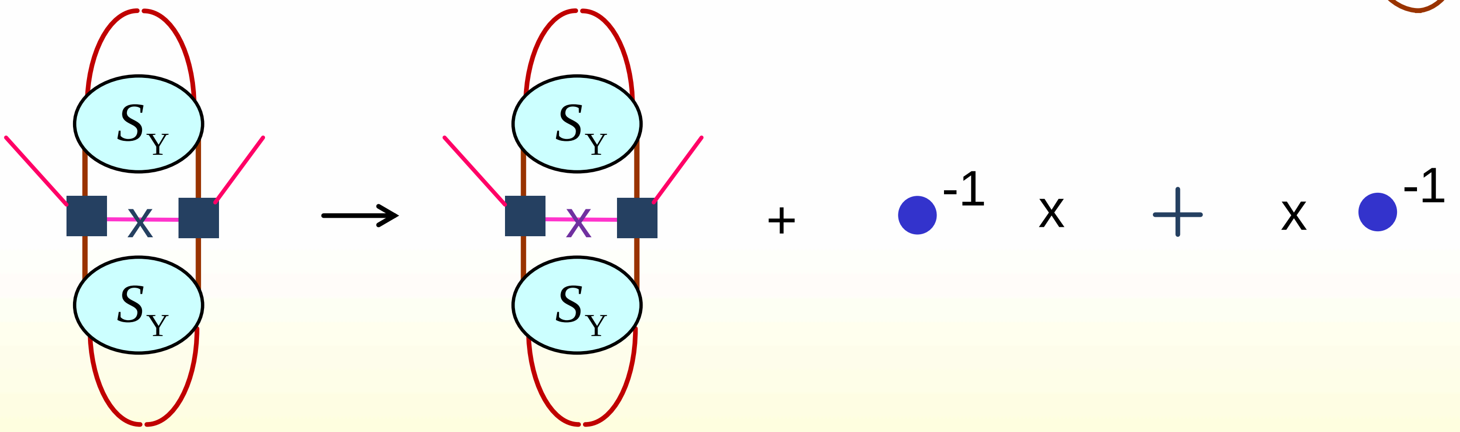
$$\Delta = \frac{1}{d-4} - C_E + \ln(4\pi) + 1$$

counterterm needed!



$$V_{\mathrm{ct}}^{(0)} = -g_\nu\, \tau_1^+\tau_2^+$$





dim reg with
min sub

$$= \left(\frac{m_N}{4\pi}\right)^2 \left[\frac{M_{NN}^2 g_\nu(\mu)}{\tilde{C}^2(\mu)} - \frac{1+2g_A^2}{2} \ln \frac{\mu^2}{-\left(|\vec{p}|+|\vec{p}'|\right)^2 + i0^+} \right] + \dots$$

$$\Rightarrow \mu \frac{d}{d\mu} \frac{M_{NN}^2 g_\nu(\mu)}{\tilde{C}^2(\mu)} = 1 + 2g_A^2 \quad \Rightarrow \quad g_\nu = \mathcal{O}\left(\frac{1}{M_{NN}^2}\right) \gg \mathcal{O}\left(\frac{1}{M_{QCD}^2}\right)$$

Alternative: numerical solution of Schrödinger equation in coordinate space

$$\tilde{C}\,\delta^{(3)}(\vec{r}) \to \tilde{C}(R)\,\delta_R^{(3)}(\vec{r}) \quad \Rightarrow \quad \tilde{C}(R) = \#R + \#\frac{m_\pi^2}{M_{NN}} R^2 \ln\left(\frac{R}{R_*}\right) + \ldots$$

Beane, Bedaque, Savage + vK '02

here $\delta_R^{(3)}(\vec{r}) = \dfrac{e^{-r^2/R^2}}{\pi^{3/2} R^3}$

determined from scattering length

$$g_\nu\,\delta^{(3)}(\vec{r}) \to g_\nu(R)\;\delta_R^{(3)}(\vec{r})$$

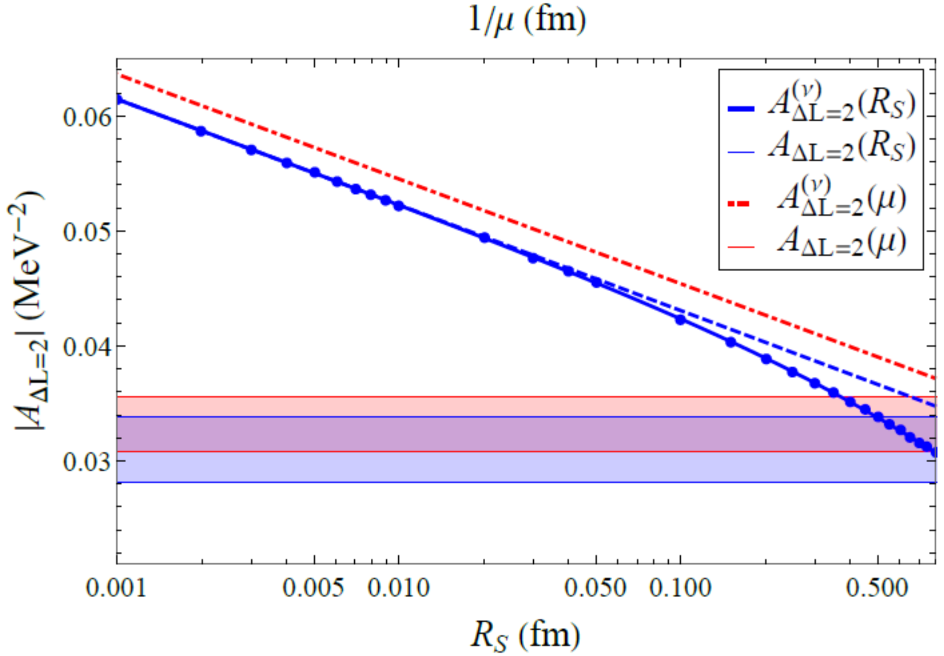
$$A^{(\nu)}_{\Delta L=2} = -\int d^3r\;\psi^-_{\vec{p}'}(\vec{r})\;V^{(0)}_\nu(\vec{r})\,\psi^+_{\vec{p}}(\vec{r})$$

$$A^{(NN)}_{\Delta L=2} = -\int d^3r\;\psi^-_{\vec{p}'}(\vec{r})\;V^{(0)}_{\rm ct}(\vec{r})\,\psi^+_{\vec{p}}(\vec{r})$$

$$A_{\Delta L=2} = A^{(\nu)}_{\Delta L=2} + A^{(NN)}_{\Delta L=2}$$

$$\frac{M_{NN}^2\, g_\nu(\mu)}{\tilde{C}^2(\mu)} \simeq -\left(1+2g_A^2\right)\ln\left(\frac{R}{R_\nu}\right) + \#R + \ldots$$

determined how?



$|\vec{p}| = 1$ MeV $\quad |\vec{p}'| = 38$ MeV $\quad \vec{p}_{e1} = \vec{p}_{e2} = 0$

higher waves   well defined without enhanced counterterms

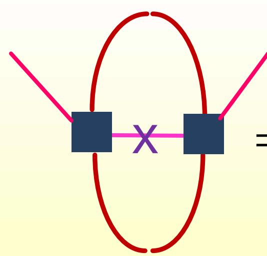
Perturbative pions?   LO same as Pionless EFT

Renormalization in Pionless EFT

Cirigliano *et al.* ‘18

$$V_2^{(0)} = \frac{4\pi}{m_N M_{lo}} C_0$$

$$V_\nu^{(0)}(\vec{q}) = \frac{\tau_1^+ \tau_2^+}{\vec{q}^{\,2}} \left(1+3g_A^2\right)$$



$$= -\left(\frac{m_N}{4\pi}\right)^2 \frac{1+3g_A^2}{2} \left[\Delta + \ln \frac{\mu^2}{-\left(|\vec{p}|+|\vec{p}\,'|\right)^2 + i0^+}\right] + \ldots$$

$$V_{\rm ct}^{(0)} = -g_\nu \, \tau_1^+ \tau_2^+ \;\Rightarrow\; \mu \frac{d}{d\mu} \frac{M_{lo}^2 g_\nu(\mu)}{C_0^2(\mu)} = 1+3g_A^2 \;\Rightarrow\; g_\nu = \mathcal{O}\left(\frac{1}{M_{lo}^2}\right) \gg \mathcal{O}\left(\frac{1}{M_{hi}^2}\right)$$

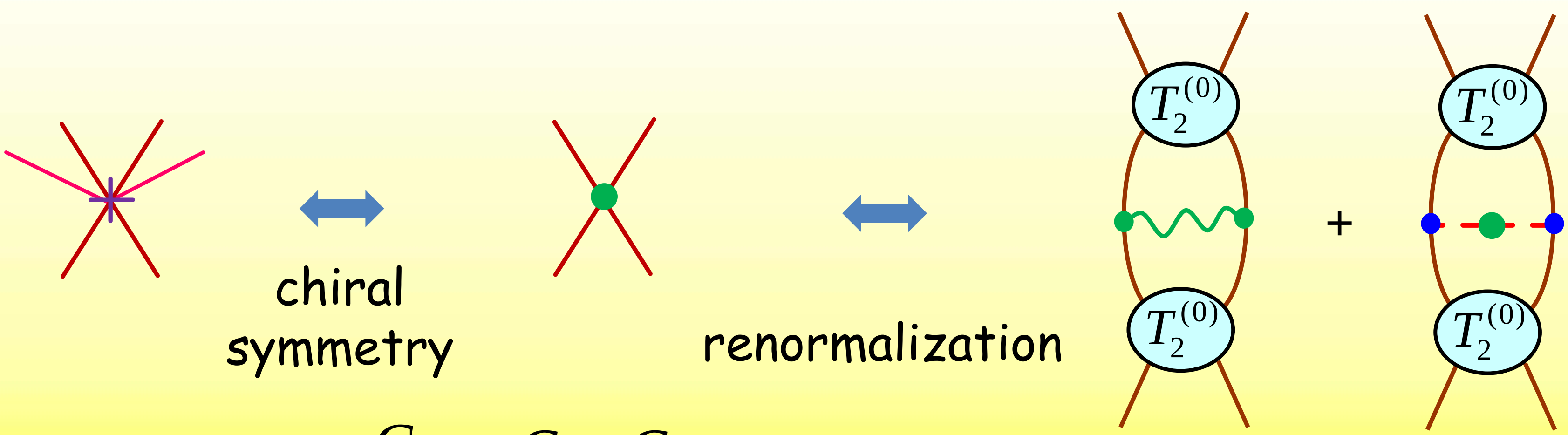
LEC Estimate

cf. Nicholson *et al.* '16'18
Shanahan *et al.* '17

- eventually, match to lattice QCD L-violating amplitude as done in strong-interacting sector

cf. Barnea *et al.* '15
...

- for now, estimate from connection with isospin violation



g_ν $\qquad$ $g_\nu = C_1$ $\qquad$ $C_1 + C_2$

$$g_\nu \propto \left\langle pp \left| \frac{1}{\vec{q}^{\,2}} \right| nn \right\rangle$$ same as electromagnetism for $I = 2$

$$\begin{cases} O_1 = N^\dagger u^\dagger Q_L u N\, N^\dagger u^\dagger Q_L u N - \frac{1}{6}\mathrm{Tr}\left(u^{\dagger 2} Q_L u^2 Q_L\right) N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N + \left(L \leftrightarrow R\right) \\ O_2 = 2\left[N^\dagger u^\dagger Q_L u N\, N^\dagger u Q_R u^\dagger N - \frac{1}{6}\mathrm{Tr}\left(u^{\dagger 2} Q_L u^2 Q_R\right) N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N \right] \end{cases}$$

$$u = \exp\left(i \boldsymbol{\tau} \bullet \boldsymbol{\pi} / 2 f_\pi\right)$$

- E&M: $Q_L = Q_R = \frac{\tau_3}{2}$
- L violation: $Q_L = \tau^+ \quad Q_R = 0$

$$\Rightarrow \quad \mathcal{L}_{\chi EFT} = \ldots + \frac{\pi}{4}\alpha\left(C_1 + C_2\right)\left[N^\dagger \tau_3 N\, N^\dagger \tau_3 N - \frac{1}{3} N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N \right]$$

$$+ G_F^2 V_{ud}^2\, m_{\beta\beta}\, C_1\, \bar{e}_L C \bar{e}_L^T N^\dagger \tau^+ N\, N^\dagger \tau^+ N + \ldots$$

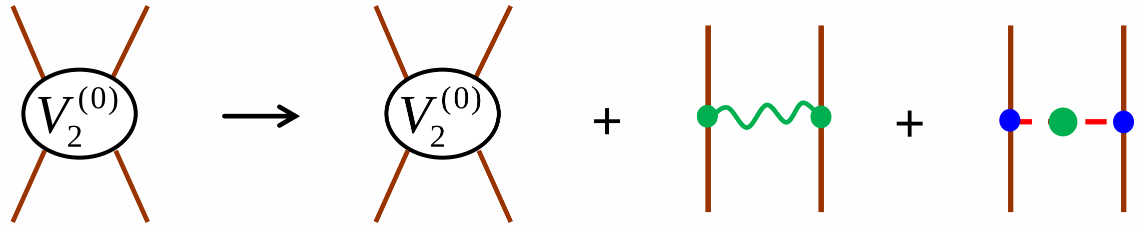
$$= g_\nu$$

multi-pion E&M interactions can separate C_1 and C_2

… but difficult.
for now:

- estimate $C_1 + C_2$ from $a_{\rm CIB} = \frac{a_{pp} + a_{nn}}{2} - a_{np} \simeq 10.3\ {\rm fm}$
- assume $C_1 \sim C_2$

uncontrolled error



vK '93
Friar, Goldman + vK '96
…

$$\frac{4\pi}{m_N M_{NN}} \qquad \frac{4\pi}{m_N M_{NN}} \frac{\alpha m_N M_{NN}}{Q^2} \qquad \left(\frac{Q}{f_\pi}\right)^2 \frac{1}{Q^4} \frac{\alpha M_{QCD}^2}{4\pi} \sim \frac{4\pi}{m_N M_{NN}} \frac{\alpha m_N M_{NN}}{Q^2}$$

LO for $Q \lesssim \sqrt{\alpha m_N M_{NN}} \sim 30\ {\rm MeV}$

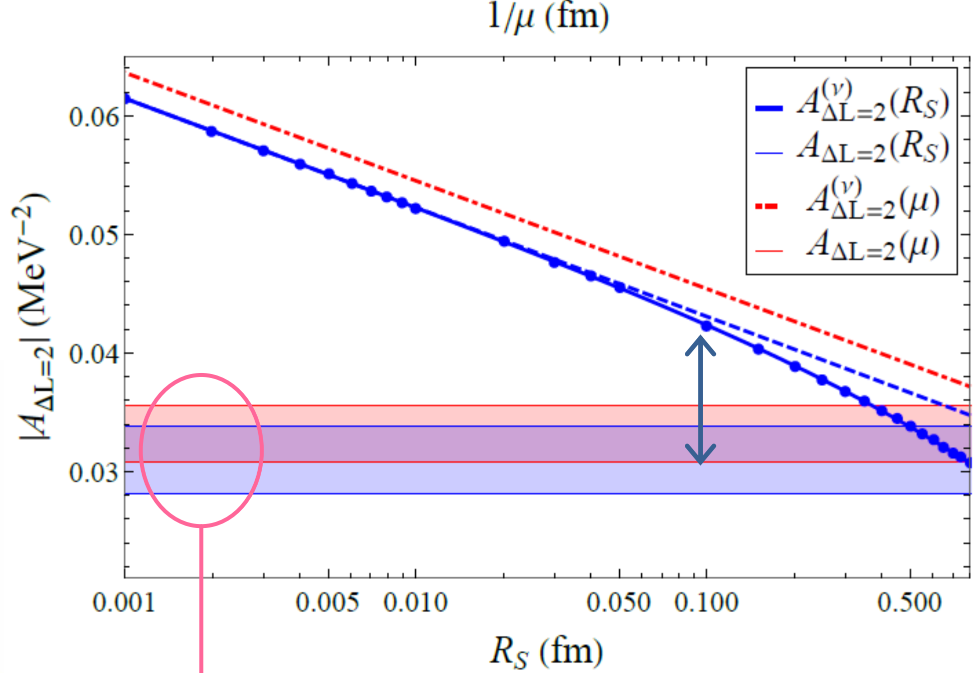
$$\Rightarrow \quad \mu \frac{d}{d\mu}\left[\frac{M_{NN}^2}{\tilde{C}^2(\mu)} \frac{C_1(\mu) + C_2(\mu)}{2}\right] = 1 + g_A^2 \frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{e^2 f_\pi^2}$$

e.g. $\left.\frac{M_{NN}^2}{\tilde{C}^2(\mu)} \frac{C_1(\mu) + C_2(\mu)}{2}\right|_{\mu = m_\pi} \approx 5$ or $\left.\frac{M_{NN}^2}{\tilde{C}^2(\mu)} \frac{C_1(\mu) + C_2(\mu)}{2}\right|_{R = 0.5\ {\rm fm}} \approx 4$

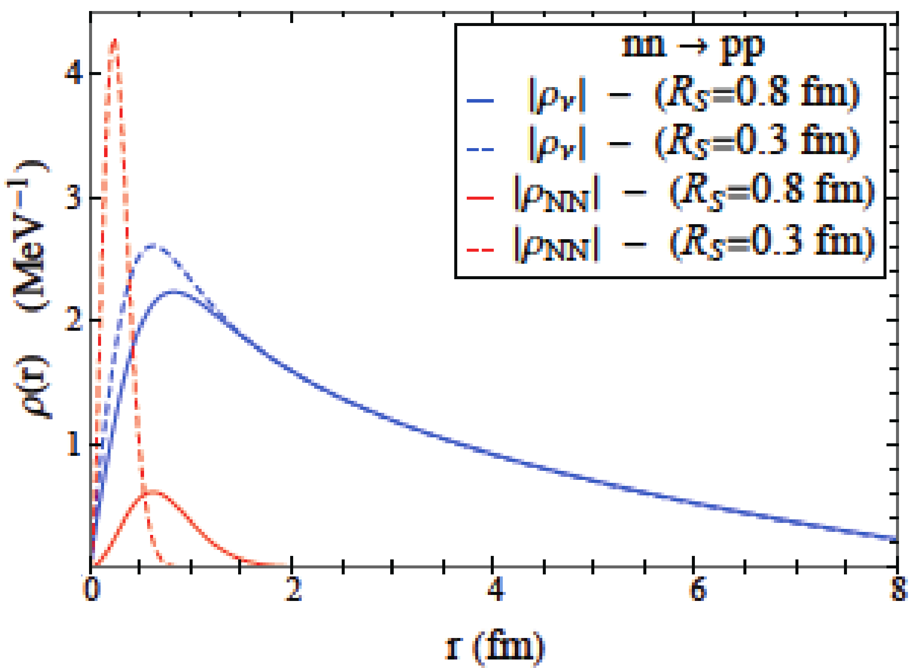
$$A^{(\nu)}_{\Delta L=2} = -\int d^3r\ \psi^{-}_{\vec{p}'}(\vec{r})\ V^{(0)}_{\nu}(\vec{r})\,\psi^{+}_{\vec{p}}(\vec{r})$$

$$A^{(NN)}_{\Delta L=2} = -\int d^3r\ \psi^{-}_{\vec{p}'}(\vec{r})\ V^{(0)}_{\rm ct}(\vec{r})\,\psi^{+}_{\vec{p}}(\vec{r})$$

$$A_{\Delta L=2} = A^{(\nu)}_{\Delta L=2} + A^{(NN)}_{\Delta L=2}$$



$$A_{\Delta L=2} = \int dr\,\rho(r)$$



$C_1(\mu) = C_2(\mu)$ for $\mu \in [0.002, 0.8]$ fm

$$\left.\frac{A^{(NN)}_{\Delta L=2}}{A^{(\nu)}_{\Delta L=2}}\right|_{R=0.1\ \rm fm} \simeq 0.3$$

Ab Initio Example

cf. Pastore *et al.* '18

- Variational Monte Carlo
- AV18+UIX — Wiringa, Stoks + Schiavilla '95; Pieper '08

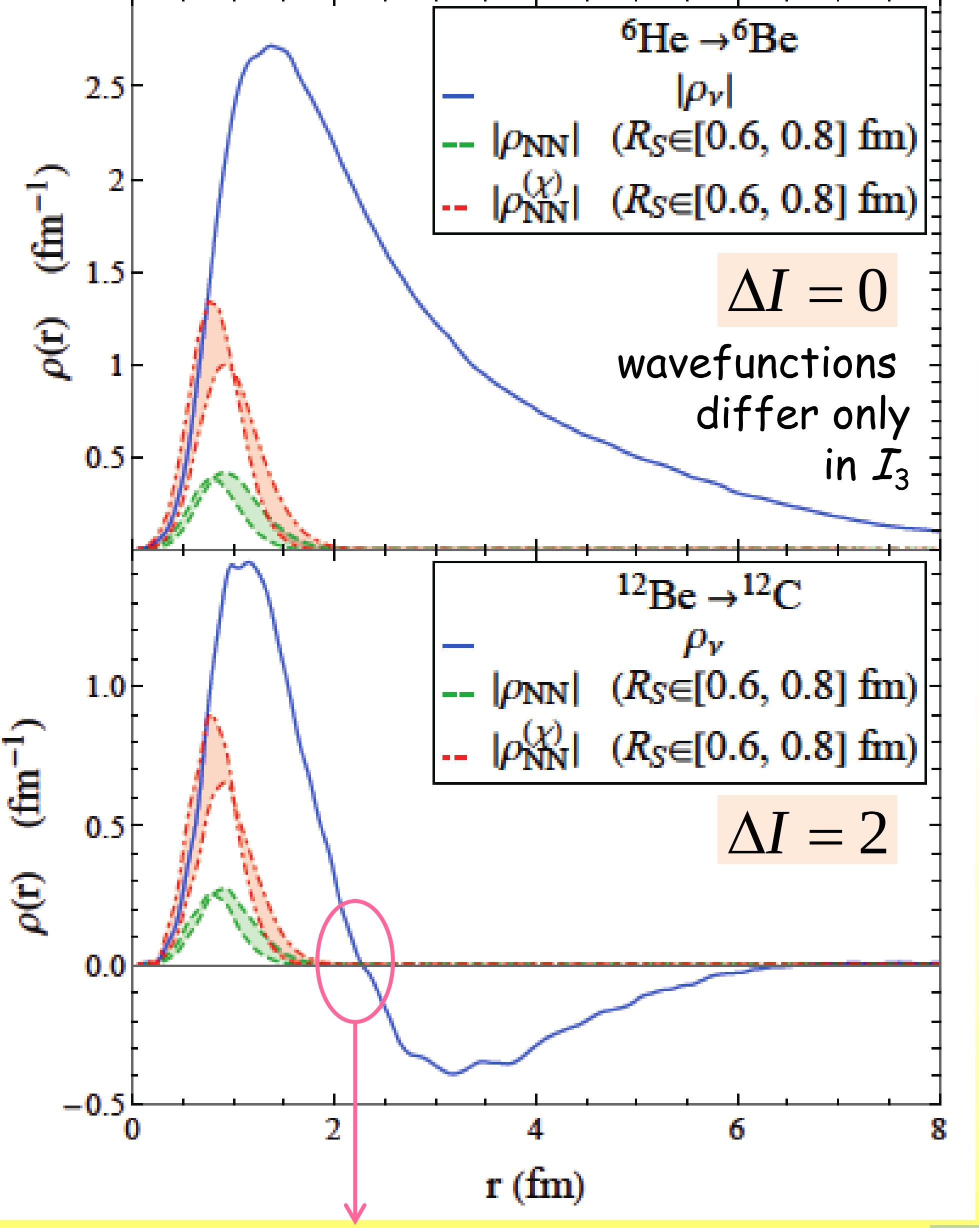
single-beta decay:
agrees with experiment ≲ 10%
for A ≲ 10
Pastore *et al.* '17

uncontrolled error

three strategies for short-range contribution:

- our extraction
- fit to phase shifts from a chiral potential — Piarulli *et al.* '14'16
- replacement with AV18's short-range CIB

similar results



$$\frac{A_{\Delta L=2}^{(NN)}}{A_{\Delta L=2}^{(\nu)}} \approx 0.1$$

$$\frac{A_{\Delta L=2}^{(NN)}}{A_{\Delta L=2}^{(\nu)}} \approx 0.3 - 0.6$$

Šimkovic *et al.* '08
Menéndez *et al.* '09

orthogonality initial/final states

robust feature of realistic transitions

Discussion

❖ why "new"?

- correlations at distances $\lesssim 1/M_{QCD}$
- not accounted for internucleon potential

⇒ not the same as correlations missed in single-particle basis

cf. Miller + Spencer '76 ... Haxton + Stephenson '84 ...

❖ why "leading"? needed for the model-independent definition of light-neutrino exchange

⇒ not the same as a model for a form-factor refinement ... Vergados '81 ...

(e.g. a ~10% in ab initio calculations)

Pastore *et al.* '18

However,
exactly how important depends on
effective scale in (consistently derived)
strong-interaction potential
in many-body environment

N.B.
Range of effect NOT smaller than
that of the internucleon interaction

perspectives for implementation
in realistic nuclei?

Conclusion

Effective field theory allows us to connect
B - L-violating physics beyond the Standard Model
and nuclear physics in a controlled and systematic way

A leading QCD-range contribution to
neutrinoless double-beta decay can be identified
from renormalization

Proper determination requires matching with lattice QCD,
but an estimate can be obtained
from electromagnetic nuclear processes

Ab initio calculations in light nuclei are consistent with
power-counting expectations