Lattice QCD Workshop, Santa Fe, August 26-30 2019

Neutrino-less double beta decay

Vincenzo Cirigliano
Los Alamos National Laboratory

Outline

- Introduction:
    - Neutrino mass and Lepton Number Violation
    - EFT framework for LNV and $0\nu\beta\beta$
- $0\nu\beta\beta$ from light Majorana ν exchange (LNV @ dim 5)
- $0\nu\beta\beta$ from (multi)TeV-scale dynamics (LNV @ dim 7,9)

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- Introduction:
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- $0\nu\beta\beta$ from (multi)TeV-scale dynamics (LNV @ dim 7,9)

5-slide talk?

Credits

- Results based on following papers

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud,
Phys.Rev. C97 (2018) no.6, 065501

S. Pastore, J. Carlson, V. C., W. Dekens, E. Mereghetti, R. Wiringa,
1710.05026, Phys.Rev. C97 (2018) no.1, 014606

V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck,
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

V. C. , W. Dekens, M. Graesser, E. Mereghetti, J. de Vries,
1806.02780, JHEP 1812 (2018) 097

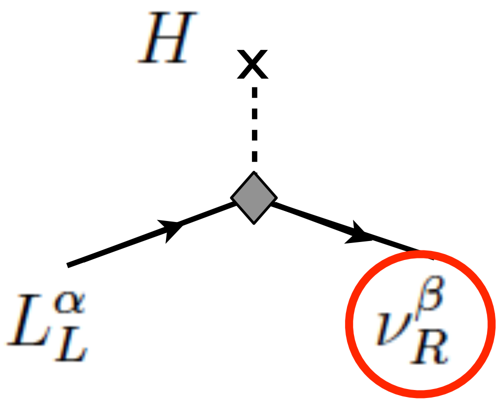
V. C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa,
1907.11254

Neutrino mass and new physics

- Neutrino mass requires introducing new degrees of freedom

Dirac mass:

$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$



- Violates $L_{e,\mu,\tau}$, conserves L

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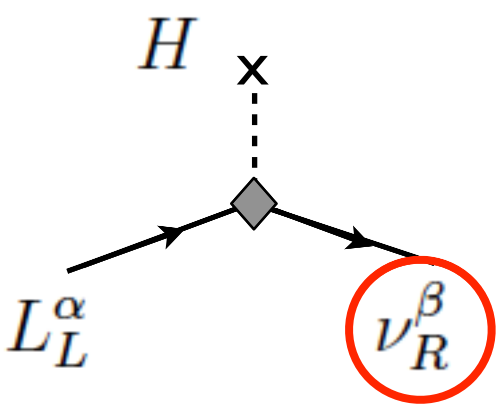
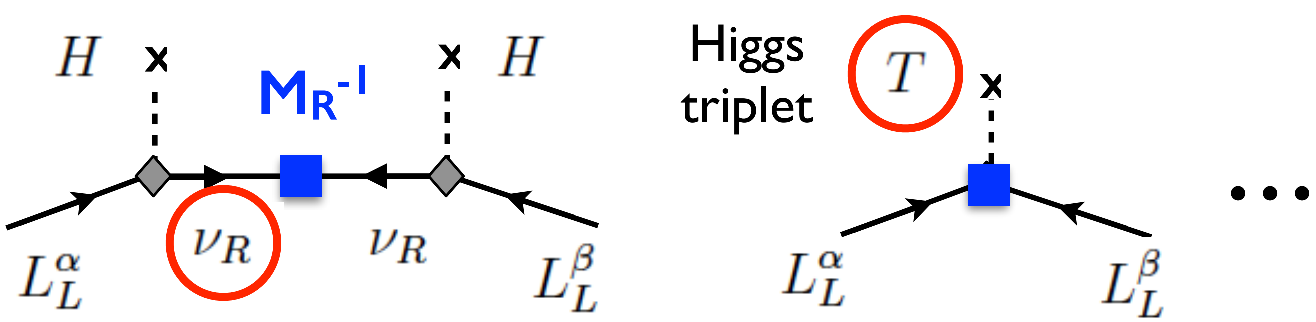


- Violates $L_{e,\mu,\tau}$, conserves L

Majorana mass:

$$m_M \, \psi_L^T \, C\psi_L \; + \; \text{h.c.}$$



- Violates $L_{e,\mu,\tau}$ and L ($\Delta L=2$)

Neutrino mass and new physics

- Neutrino mass requires introducing new degrees of freedom

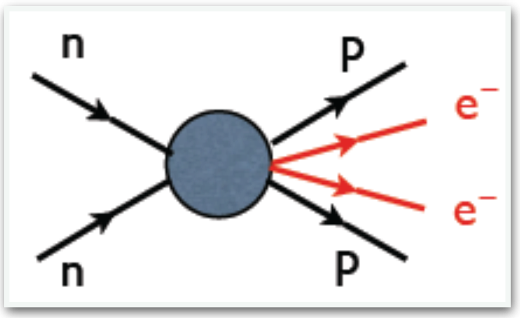
$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}} + \ldots$$

- Key question:
  - Are neutrino Majorana particles? Or equivalently:
  - Is Lepton Number a good symmetry of the new dynamics?

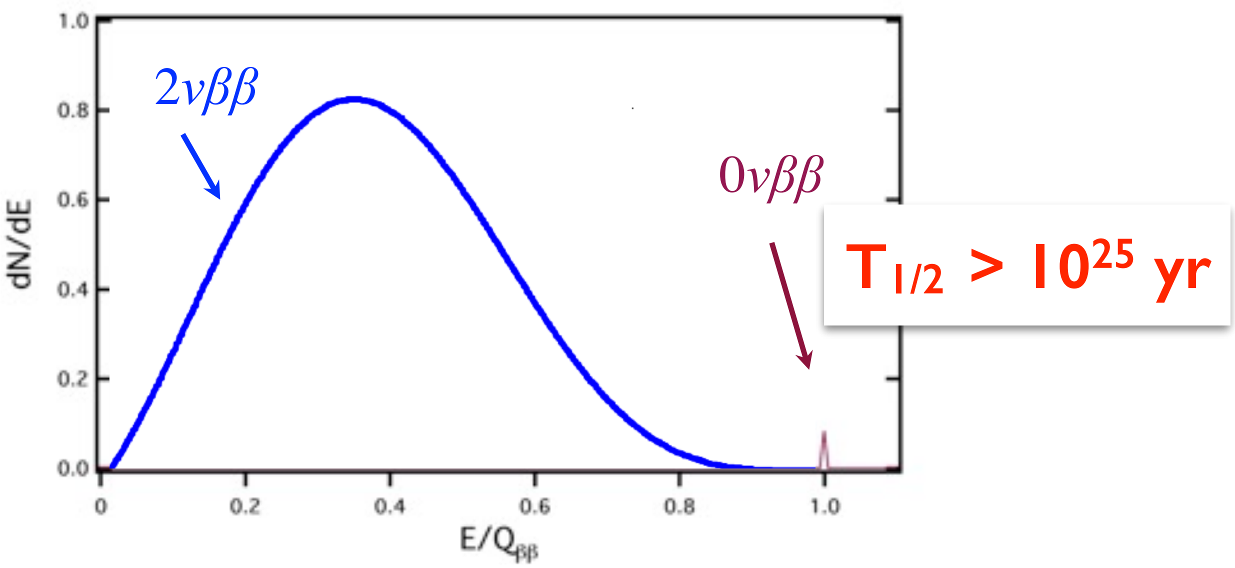
- Most promising probe of LNV is neutrino-less double beta decay (0νββ)

Neutrinoless double beta decay ($0\nu\beta\beta$)

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



Lepton number changes by two units: $\Delta L=2$



- Observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), for which single beta decay is energetically forbidden

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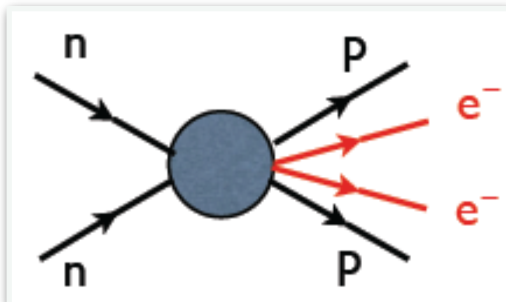
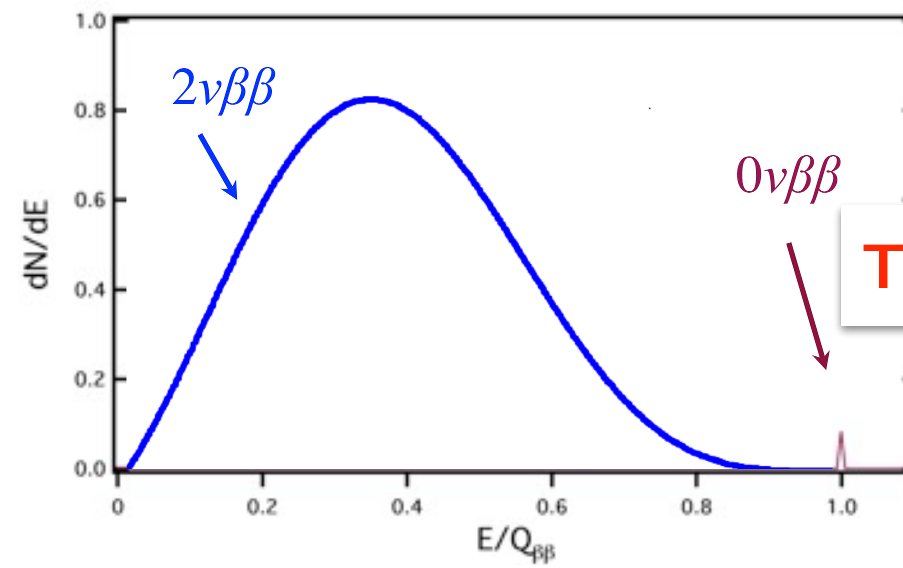
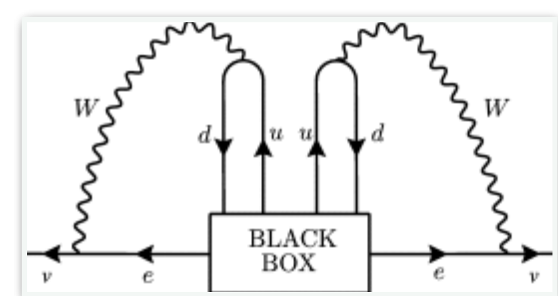


Lepton number changes by two units: ΔL=2



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

- Observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), for which single beta decay is energetically forbidden
- B-L conserved in SM → 0νββ observation would signal new physics
  - Demonstrate that neutrinos are Majorana fermions
  - Establish a key ingredient to generate the baryon asymmetry via leptogenesis

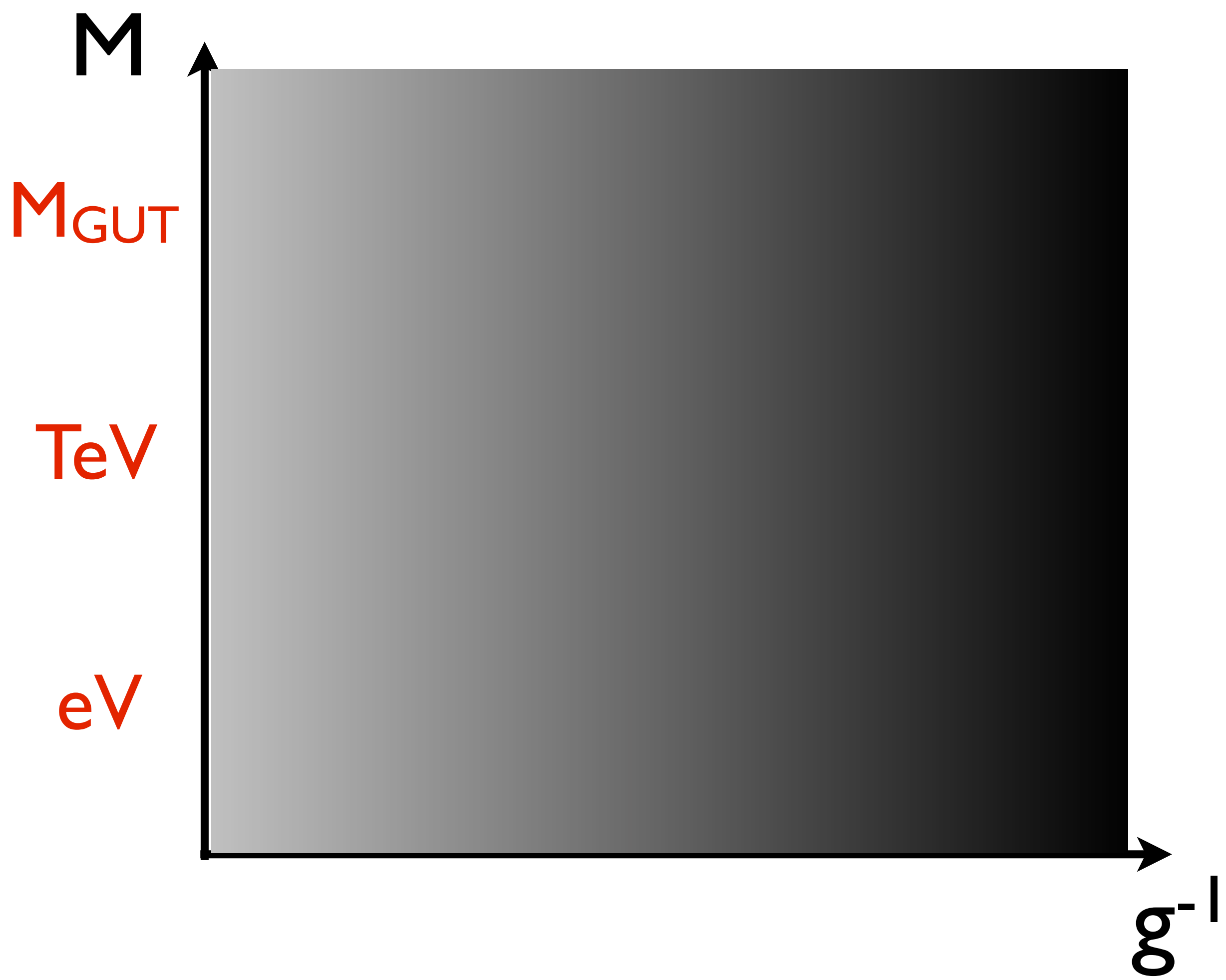


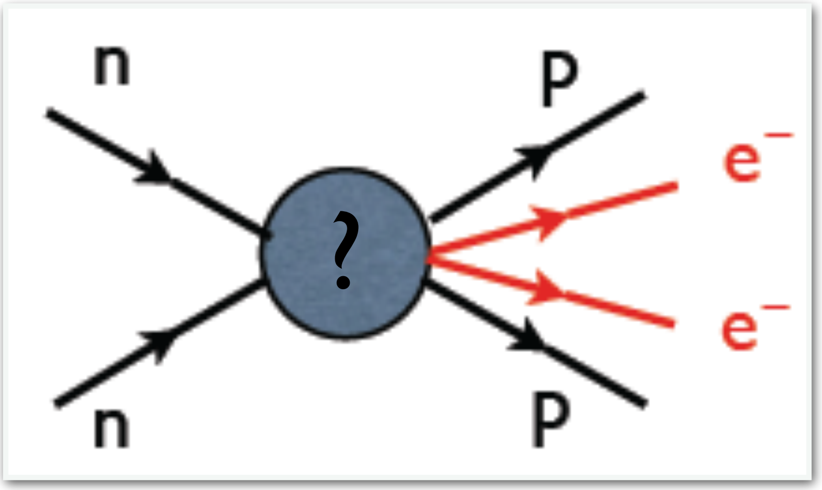
Shechter-Valle 1982

Fukujgita-Yanagida 1987

0νββ physics reach

- Next generation "ton scale" searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe LNV from a variety of mechanisms





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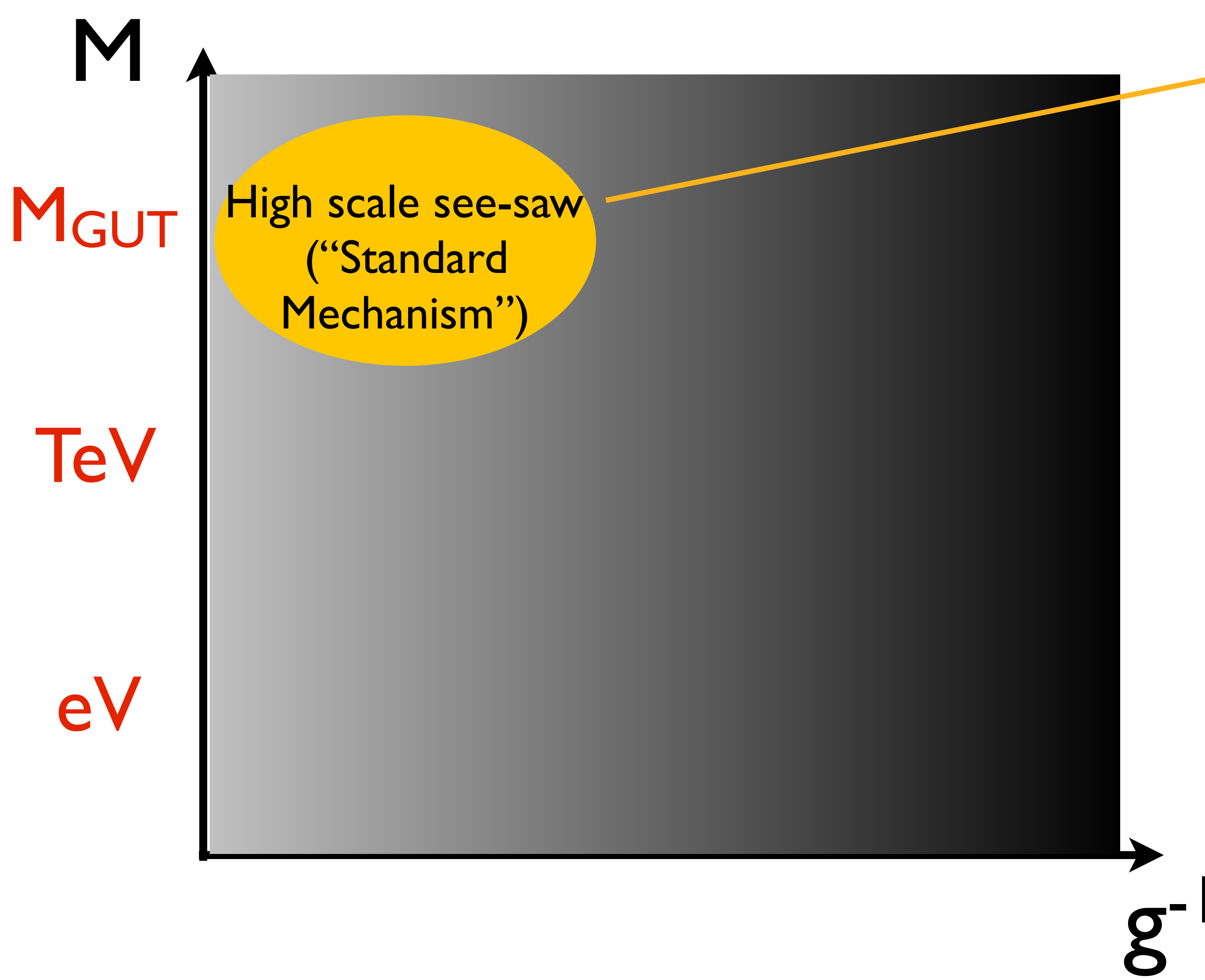
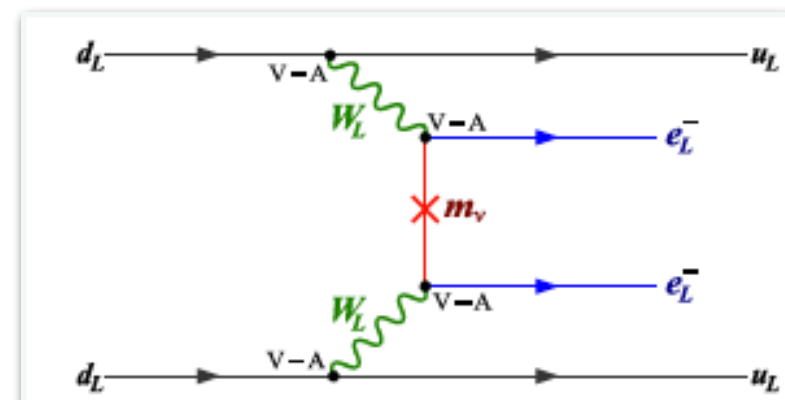


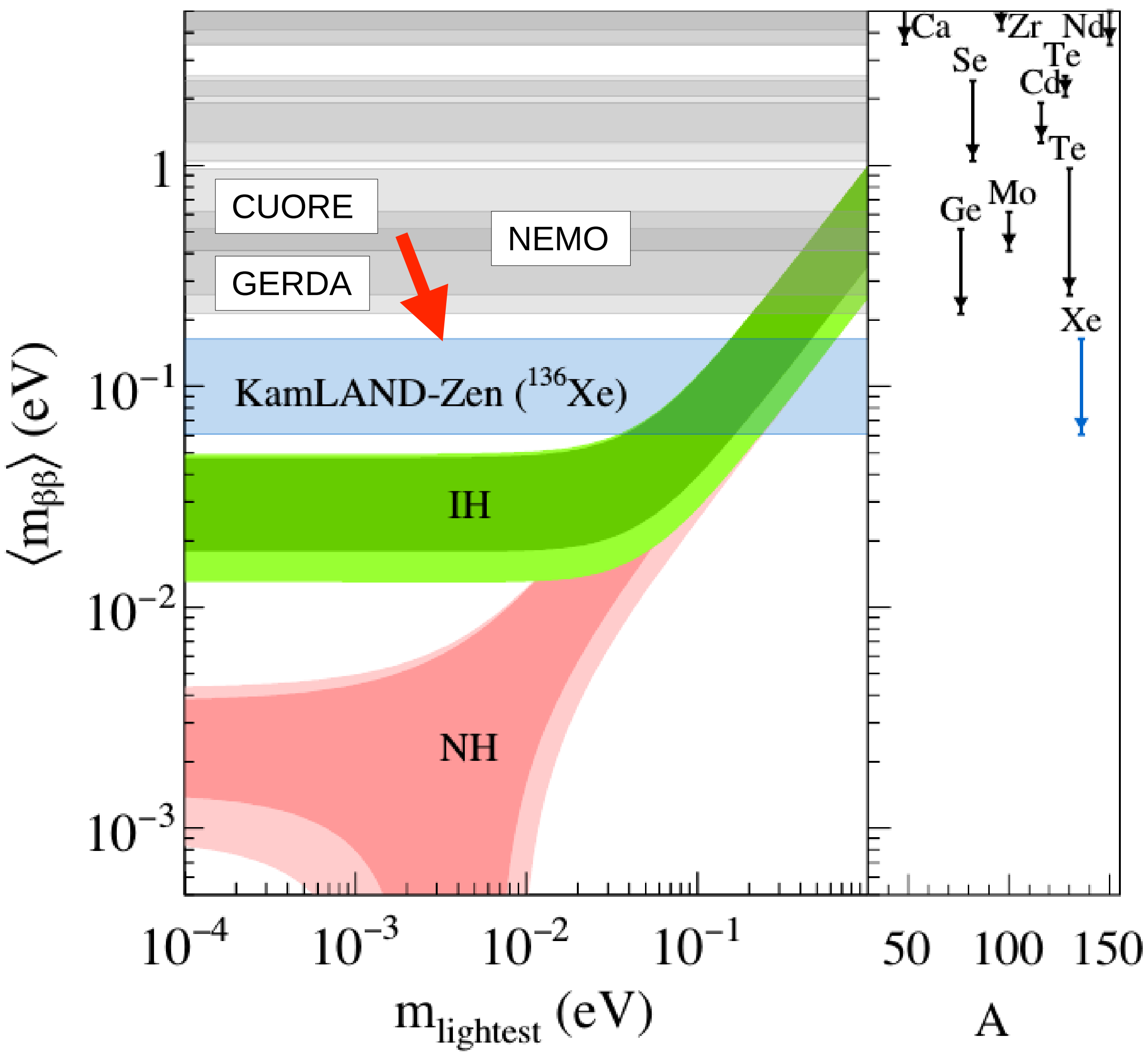
LNV dynamics at M >> TeV:
leaves as only low-energy footprint light
Majorana neutrinos



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

0νββ physics reach

- Next generation "ton scale" searches ($T_{1/2}$ >10^{27-28} yr) will probe LNV from a variety of mechanisms



KamLAND-Zen coll., '16

LNV dynamics at M >> TeV:
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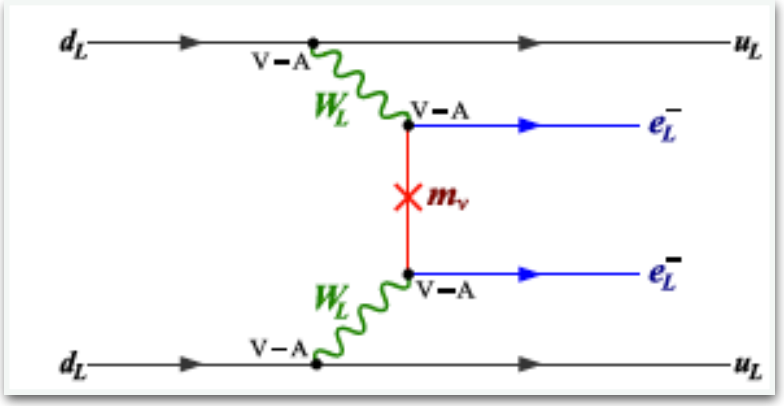
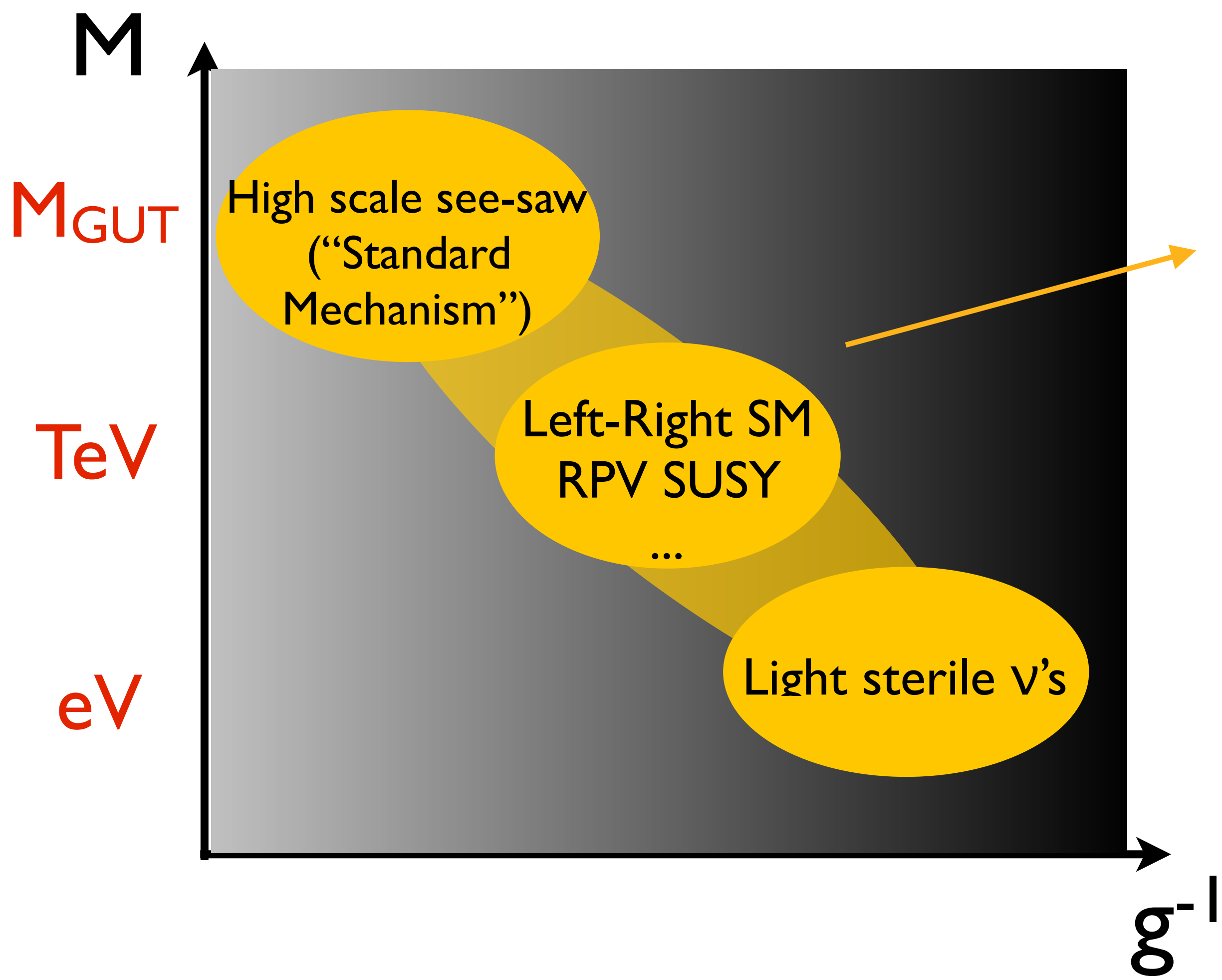


$$A \propto m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i$$

Clear interpretation framework and sensitivity goals ("inverted hierarchy").
Requires difficult nuclear matrix elements: O(100%) uncertainty (spread)

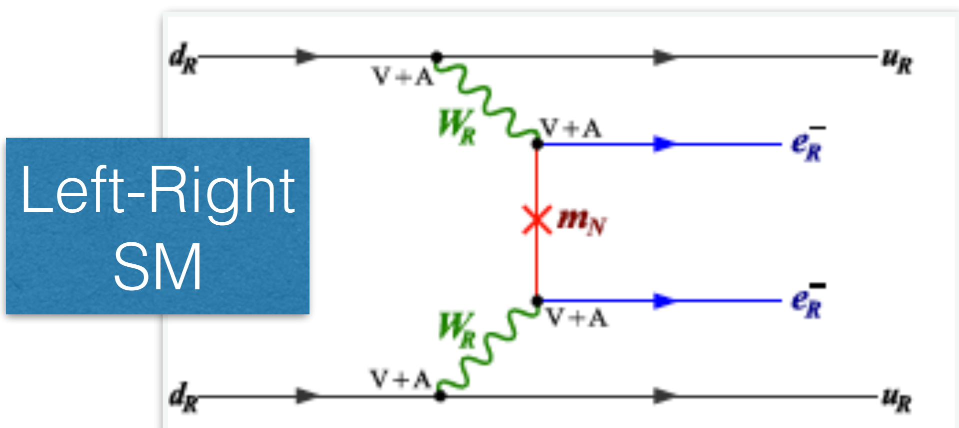
0νββ physics reach

- Next generation "ton scale" searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe LNV from a variety of mechanisms



LNV dynamics could be at any scale > eV.

For M ~ 1-100 TeV one expects
(i) New contributions to 0νββ not directly related to light neutrino mass;
(ii) Collider signatures, such as pp → eejj



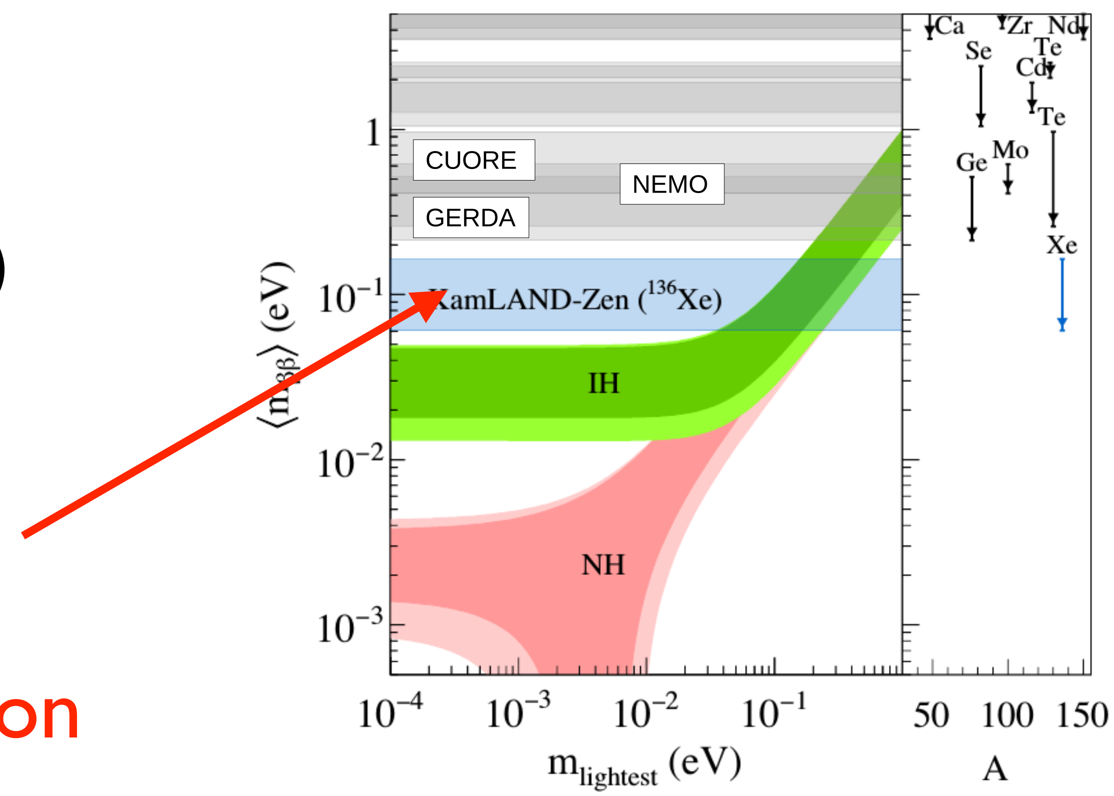
Decay rate depends on a
different set of (equally uncertain) hadronic and nuclear matrix elements

EFT framework

- Impact of $0\nu\beta\beta$ searches most efficiently analyzed in EFT framework, connecting LNV scale to nuclear scales

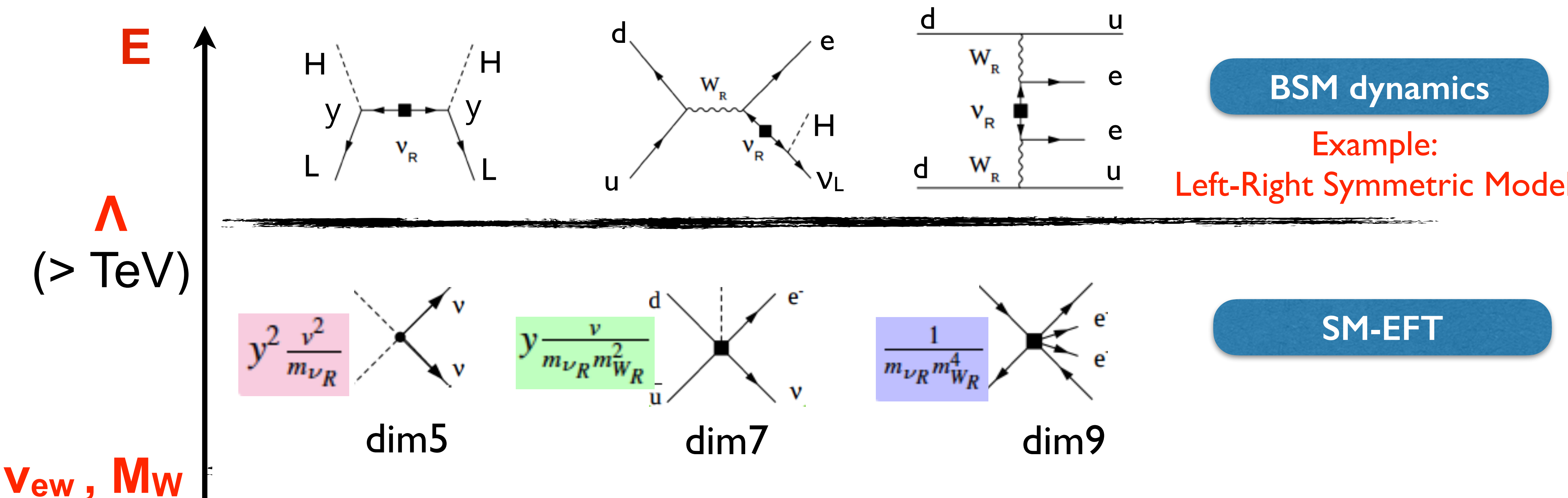
1. Classify sources of Lepton Number Violation and relate $0\nu\beta\beta$ to other LNV processes (such as pp → eejj at the LHC)

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



KamLAND-Zen coll., '16

EFT framework

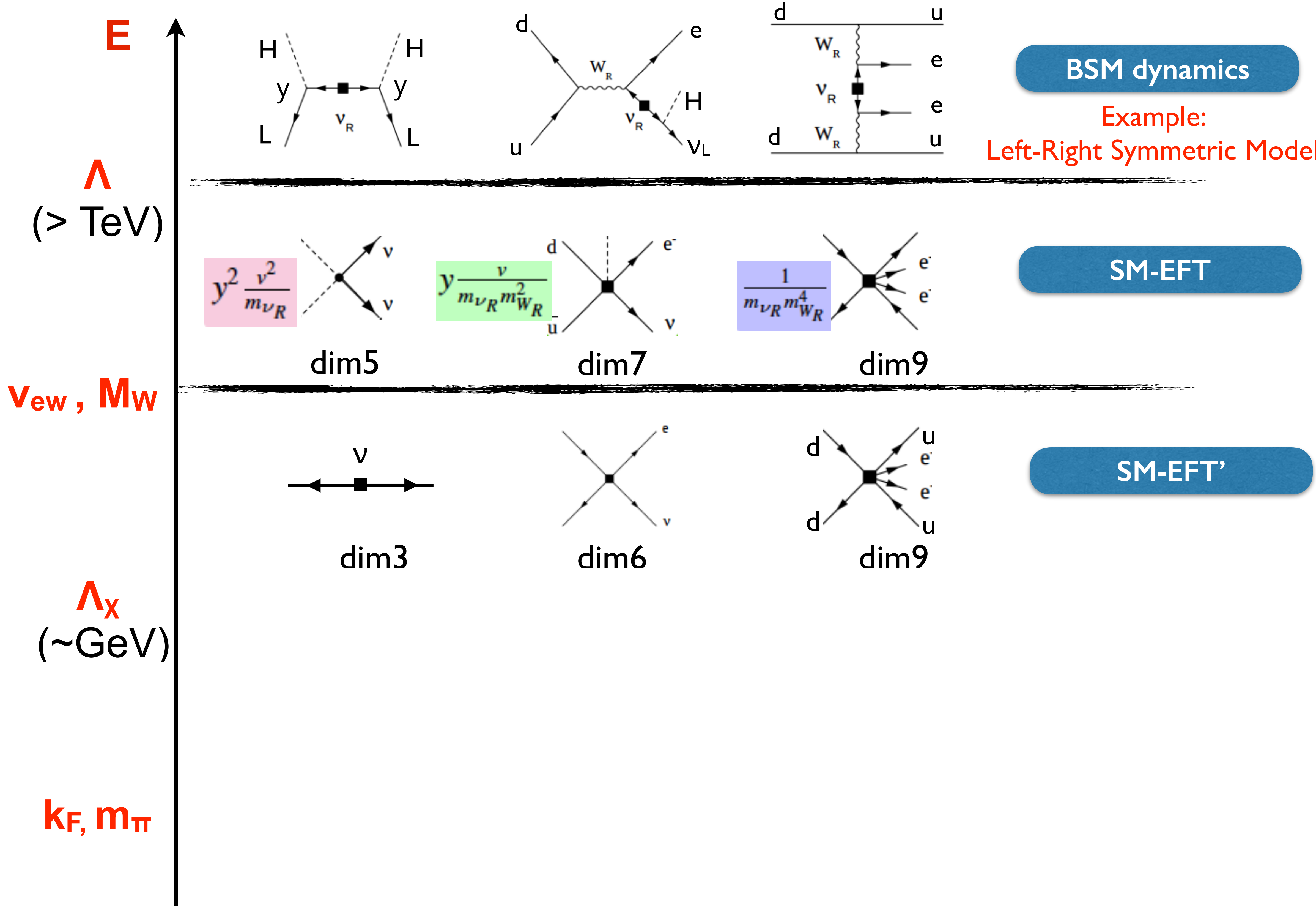


Λ_χ
(~GeV)

k_F, m_π

- ΔL=2 operators appear only at odd dimension — A. Kobach 1604.05726
- Insertions of small dimensionless (Yukawa) coupling can make dim=5,,7,9 operators equally important for Λ~ TeV
- ν_R with mass < Λ can be included in the framework

EFT framework



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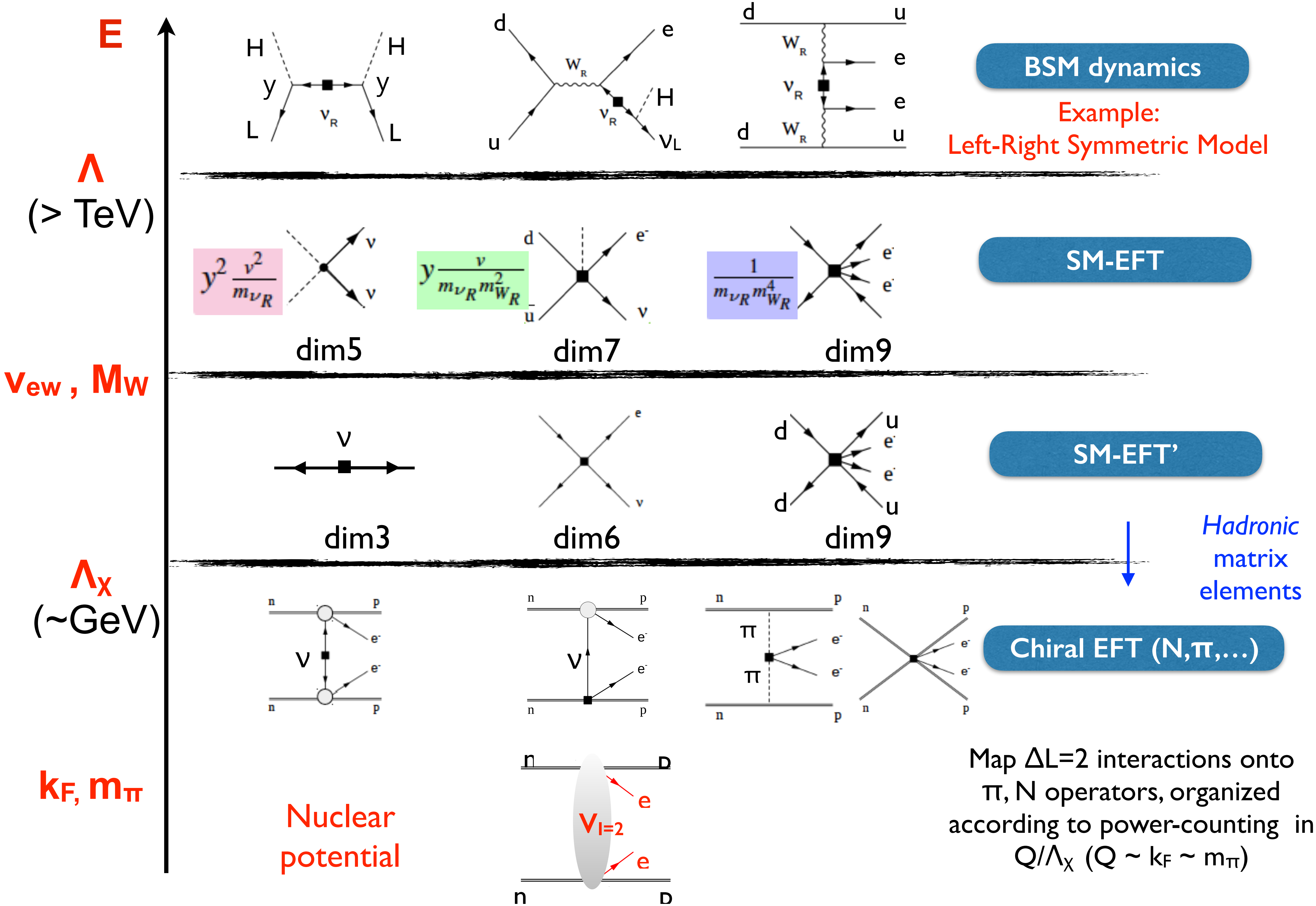

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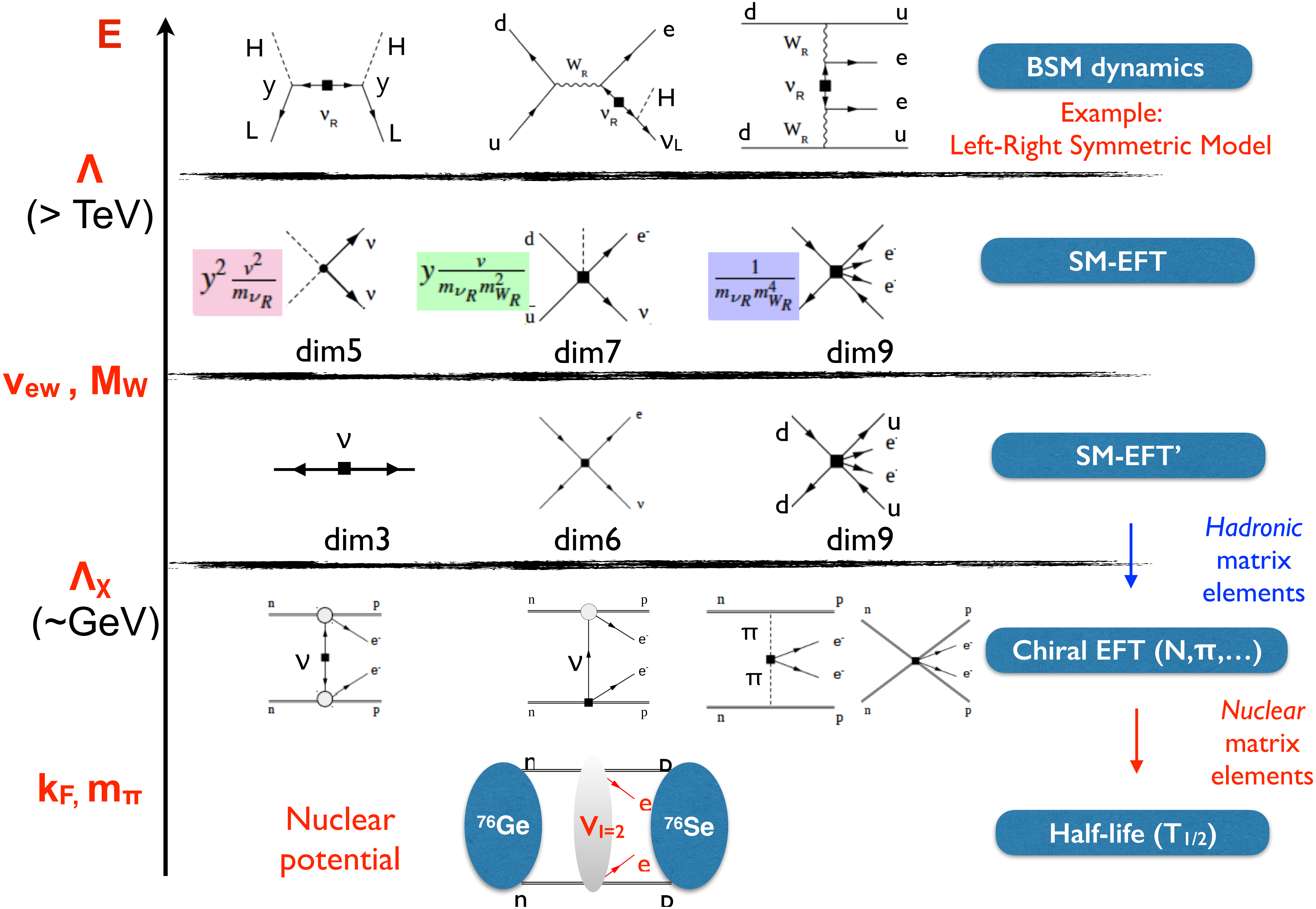
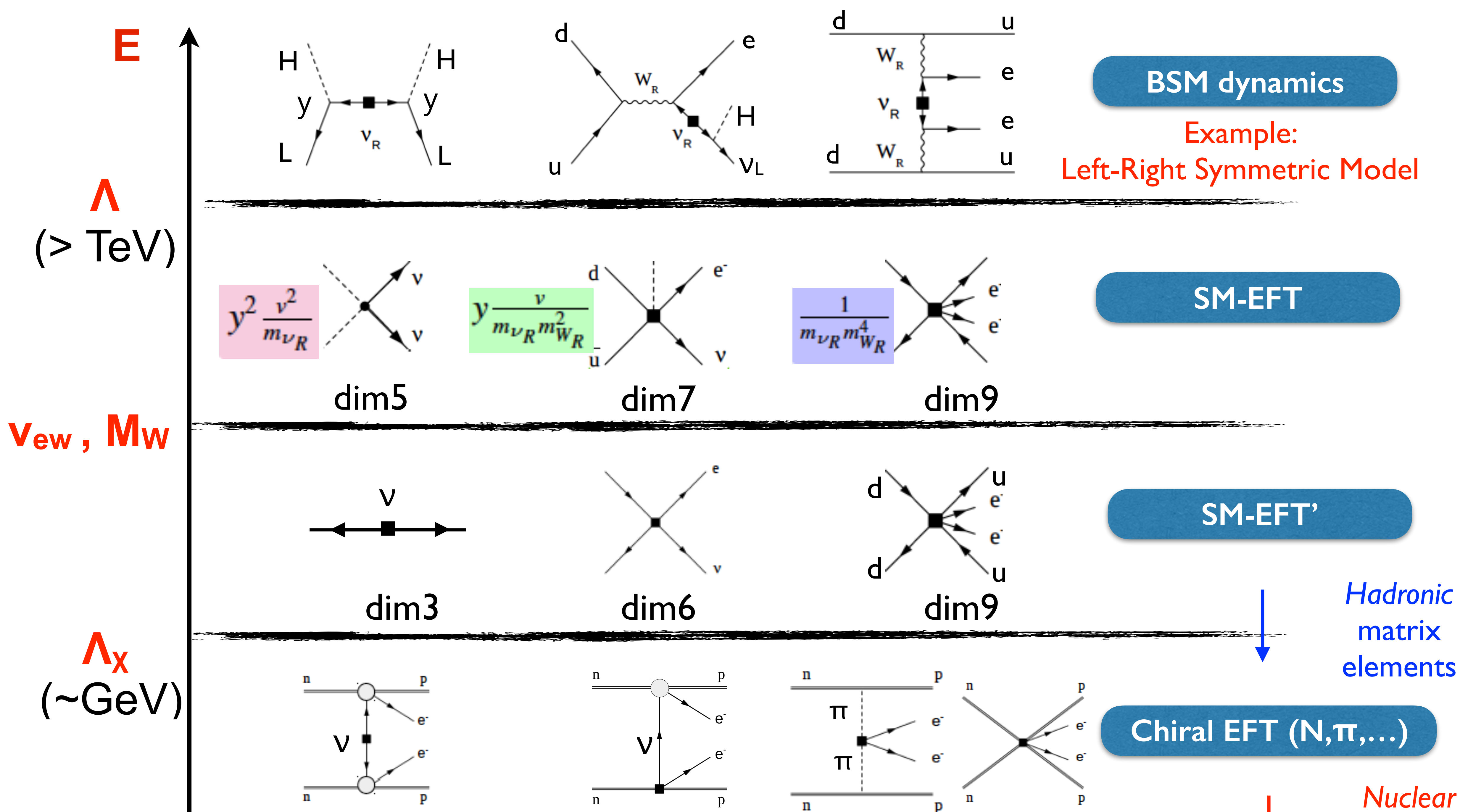


EFT framework



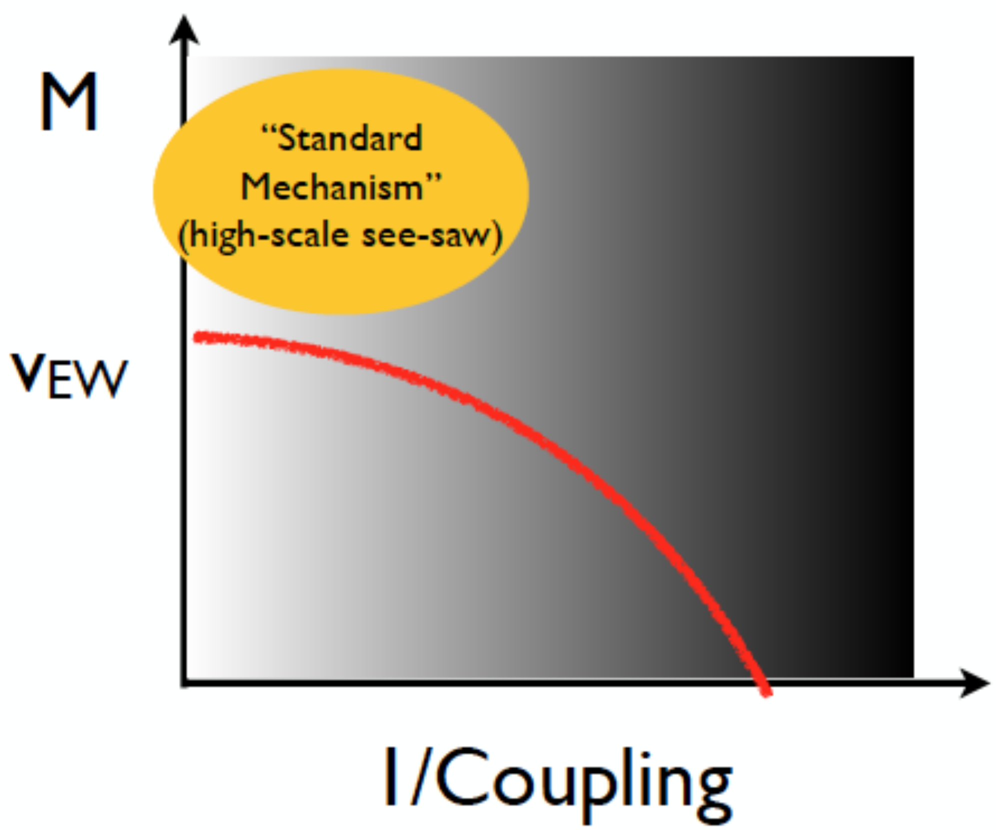
Chain of EFTs +

lattice QCD &

many-body methods

$T_{1/2} \sim (m_W/\Lambda)^A \ (\Lambda_\chi/m_W)^B \ (k_F/\Lambda_\chi)^C$

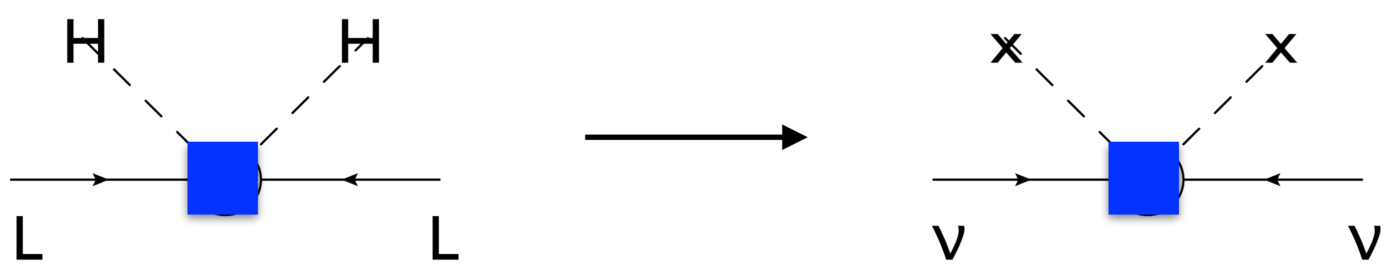
0νββ from light Majorana neutrino (dim-5 operator)



High-scale effective Lagrangian

- Standard Model + Weinberg dim-5 operator

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left\{ \frac{u_{\alpha\beta}}{\Lambda_{\text{LNV}}} \epsilon_{ij}\epsilon_{mn} L_i^{T\alpha} C L_m^{\beta} \, H_j H_n + \text{h.c.} \right\}$$



- Model-independent seesaw leading to Majorana mass for neutrinos

$$m_{\alpha\beta} = -u_{\alpha\beta}(v^2/\Lambda_{\text{LNV}})$$

$$v = (\sqrt{2}G_F)^{-1/2} \simeq 246 \text{ GeV}$$

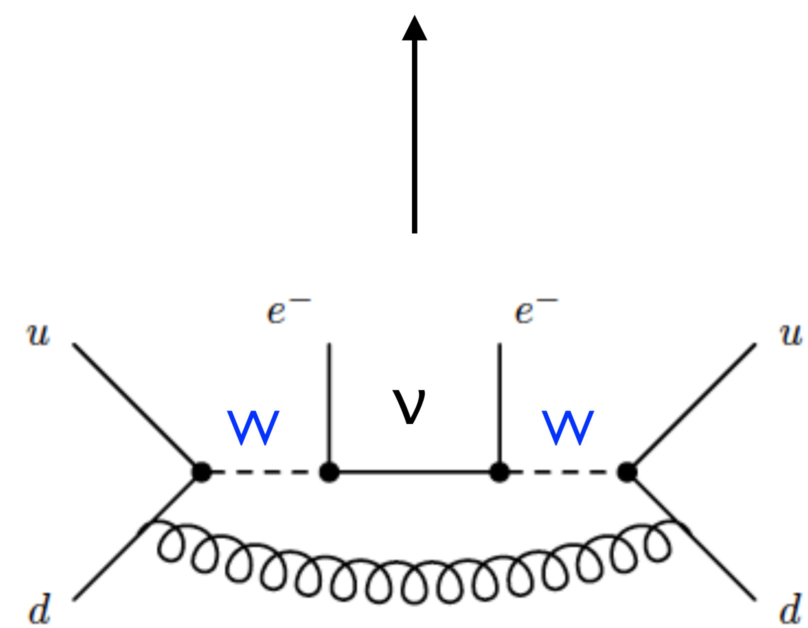
GeV-scale effective Lagrangian

- QCD + Fermi theory + Majorana mass + local operator

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \left\{ 2\sqrt{2} G_F V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} + \frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL} - C_L\, O_L + \text{h.c.} \right\}$$

$$O_L = \bar{e}_L e_L^c\ \bar{u}_L \gamma_\mu d_L\ \bar{u}_L \gamma^\mu d_L \qquad C_L = (8 V_{ud}^2 G_F^2 m_{\beta\beta})/M_W^2 \times (1 + \mathcal{O}(\alpha_s/\pi))$$

- Effect of local operator highly suppressed at nuclear level ~ O($(k_F/M_W)^2$)



ΔL=2 amplitudes

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

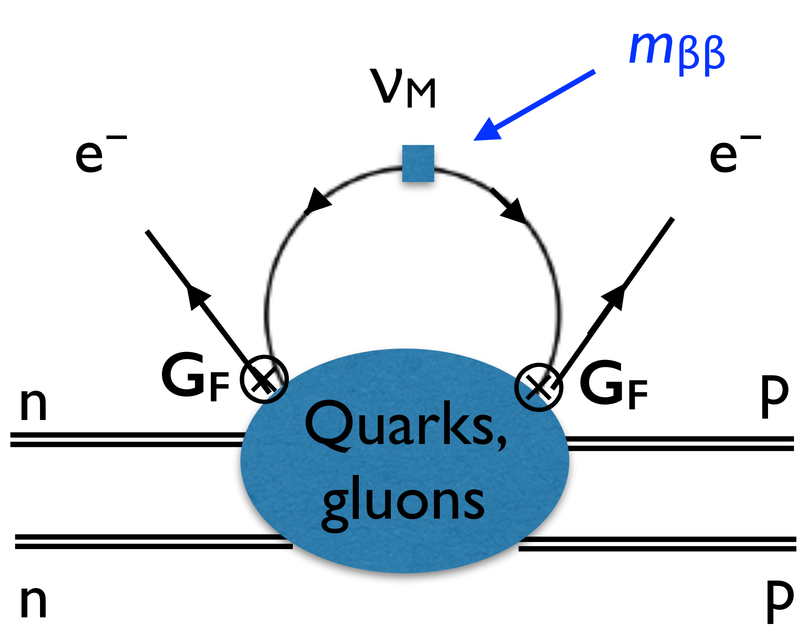
- Determined by neutrino-less non-local effective action

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

Scalar massless propagator

$|p_1 - p_2|/k_F \ll 1.$

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



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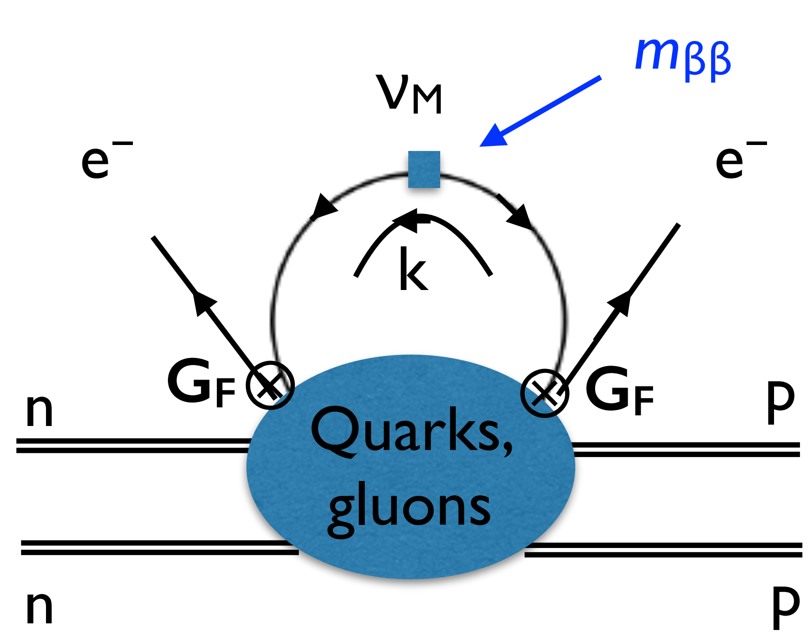
$$\langle e_1 e_2 h_f | S_{\text{eff}}^{\Delta L=2} | h_i \rangle = \frac{8 G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x \, \langle e_1 e_2 | \bar{e}_L(x) e_L^c(x) | 0 \rangle \int \frac{d^4k}{(2\pi)^4} \frac{g^{\mu\nu} \hat{\Pi}_{\mu\nu}^{++}(k,x)}{k^2 + i\epsilon},$$

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

Momentum space representation

LNV hadronic amplitudes such as nn → ppee receive contributions from all neutrino virtual momenta (k)



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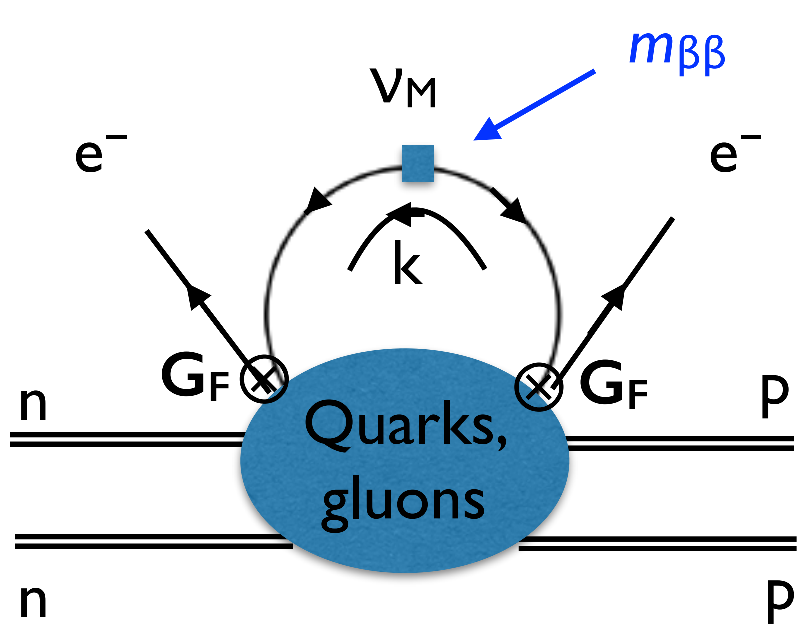
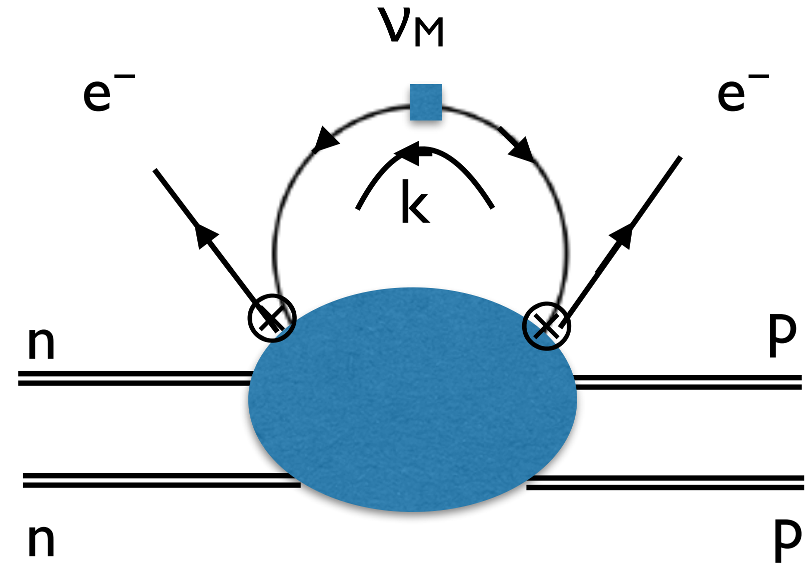
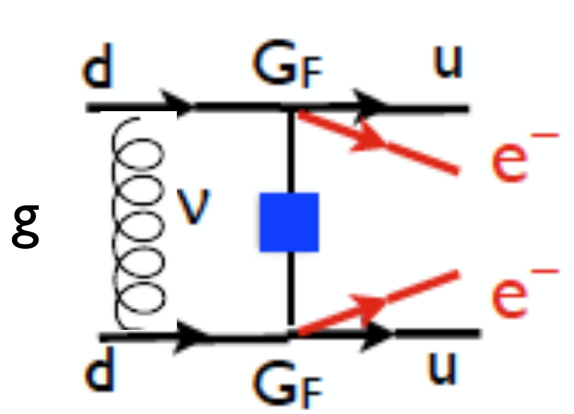


Chiral EFT captures contributions from all relevant momentum regions

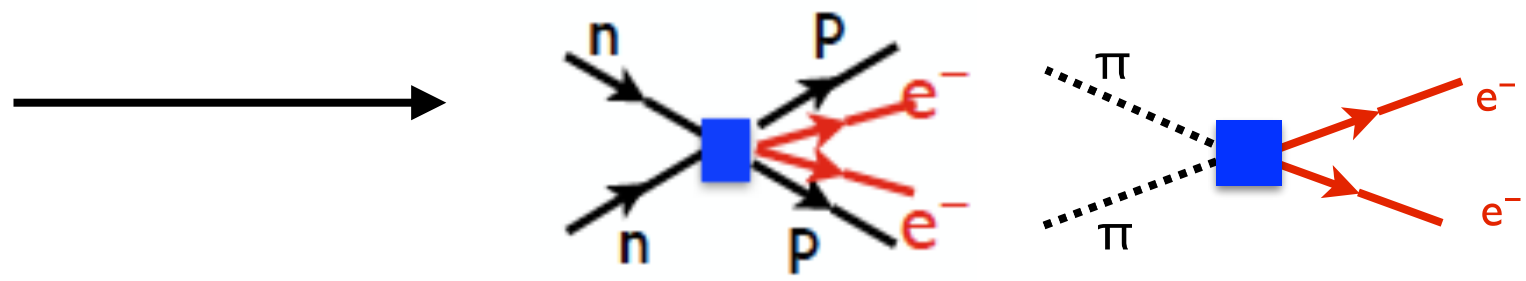
ΔL=2 amplitudes in EFT



"Hard neutrinos":
E, |**k**| > $\Lambda_\chi \sim m_N \sim$ GeV

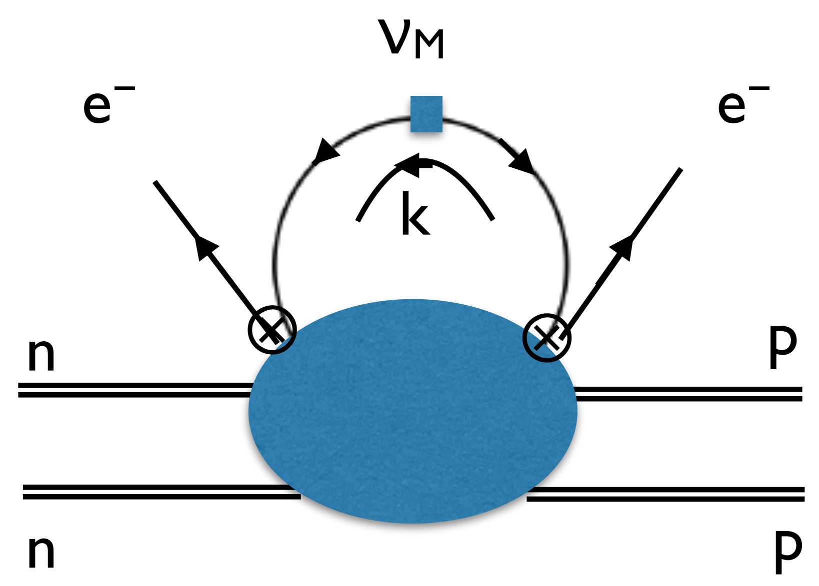


Short-range ΔL=2 operators at the hadronic level, *still proportional to $m_{\beta\beta}$*



Short- and pion-range contributions to "Neutrino potential" mediating nn→pp

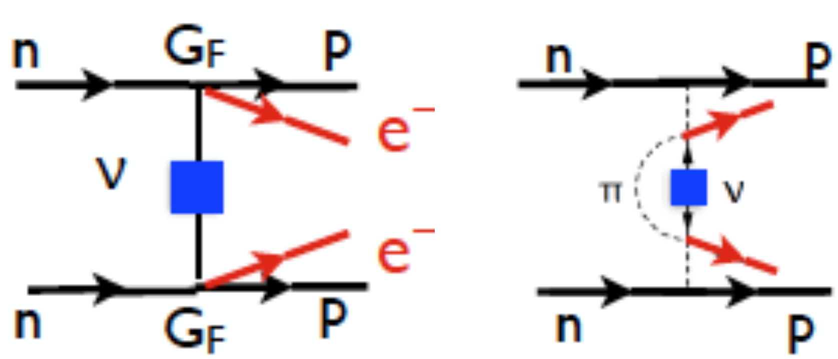
ΔL=2 amplitudes in EFT

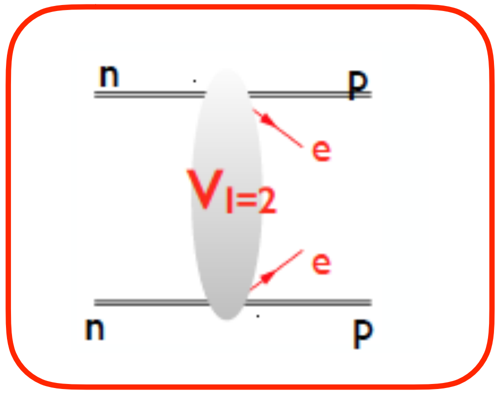


"Soft" & "Potential" neutrinos:

$(E, |\mathbf{k}|) \sim Q \sim k_F \sim m_\pi$

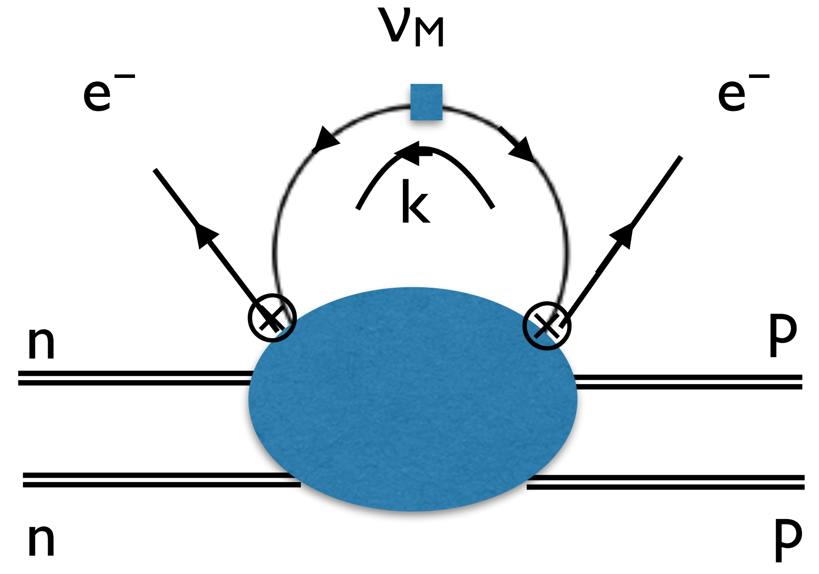
$(E, |\mathbf{k}|) \sim (Q^2/m_N, Q)$



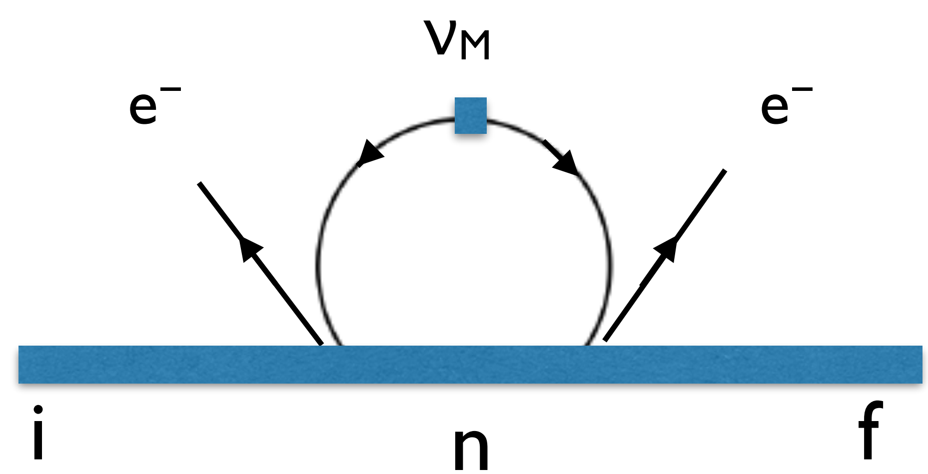


Calculable long- and pion-range contributions to "Neutrino potential" mediating nn→pp

ΔL=2 amplitudes in EFT



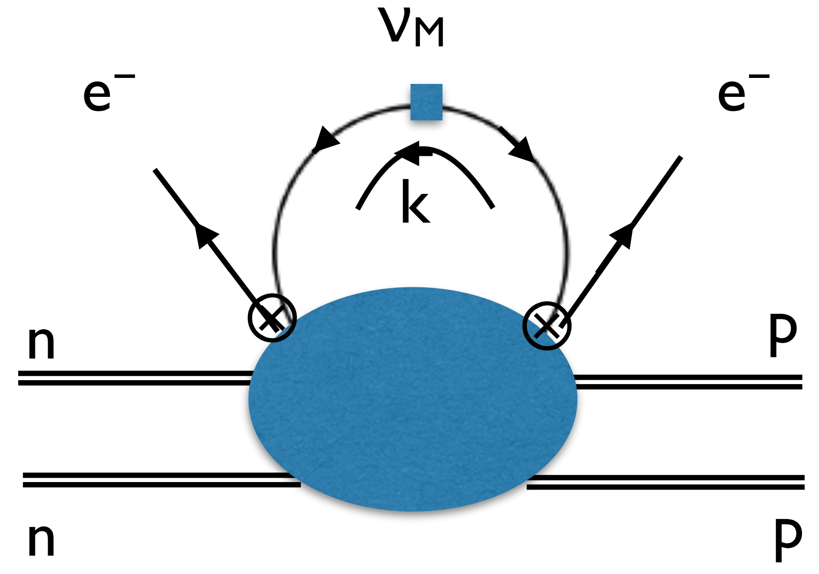
"UltraSoft" neutrinos:
$(E, |k|) \ll k_F$



n-th state of
intermediate nucleus

Double insertions of the weak current at the hadronic / nuclear level

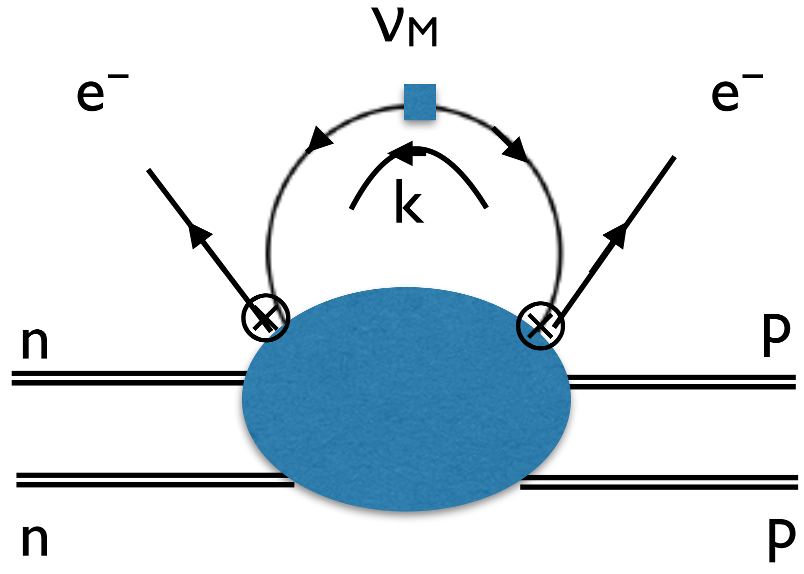
Nuclear scale effective Hamiltonian



Kinetic terms and strong NN potential

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

Nuclear scale effective Hamiltonian



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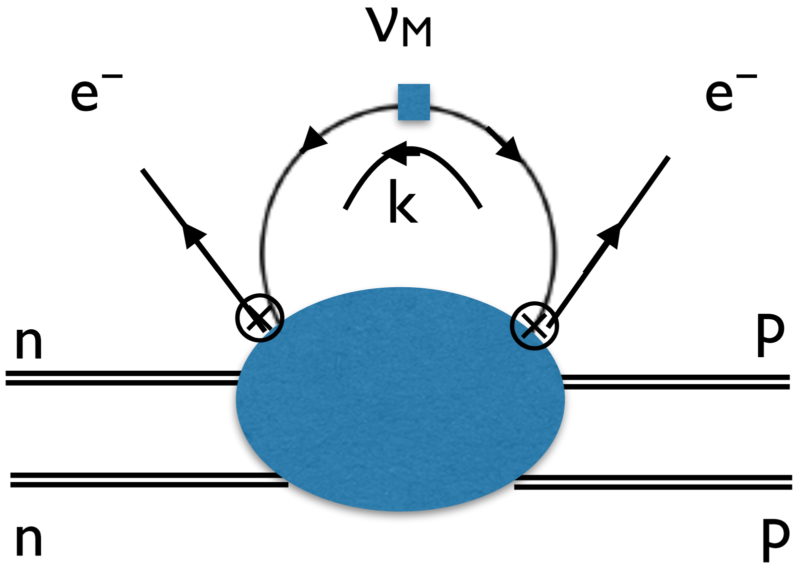
"Ultra-soft" (e, ν) with |**p**|, E << k_F
cannot be integrated out

Nuclear scale effective Hamiltonian



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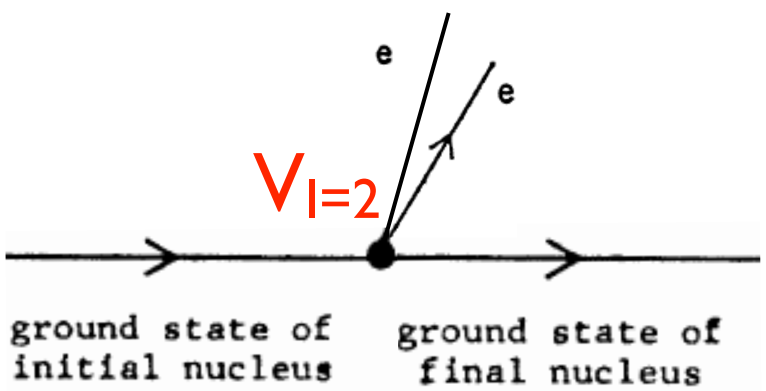
"Ultra-soft" (e, ν) with **|p|**, E << k_F cannot be integrated out

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

Anatomy of 0νββ amplitude

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a \neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \ldots \right)$$

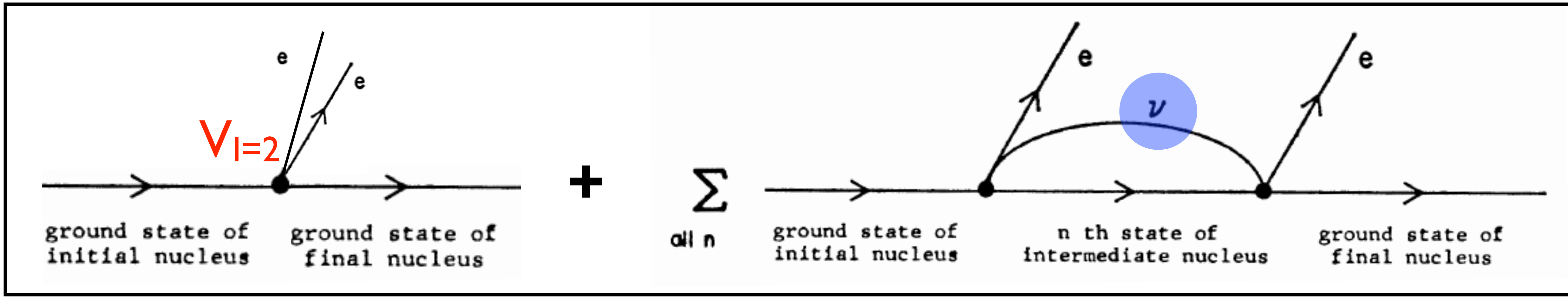
$V_\nu \sim 1/Q^2$, $1/(\Lambda_\chi)^2, \ldots$

↑ LO

↑ N^2LO

Anatomy of 0νββ amplitude

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a \neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \dots \right)$$

$V_\nu \sim 1/Q^2\ ,\ 1/(\Lambda_\chi)^2, \dots$

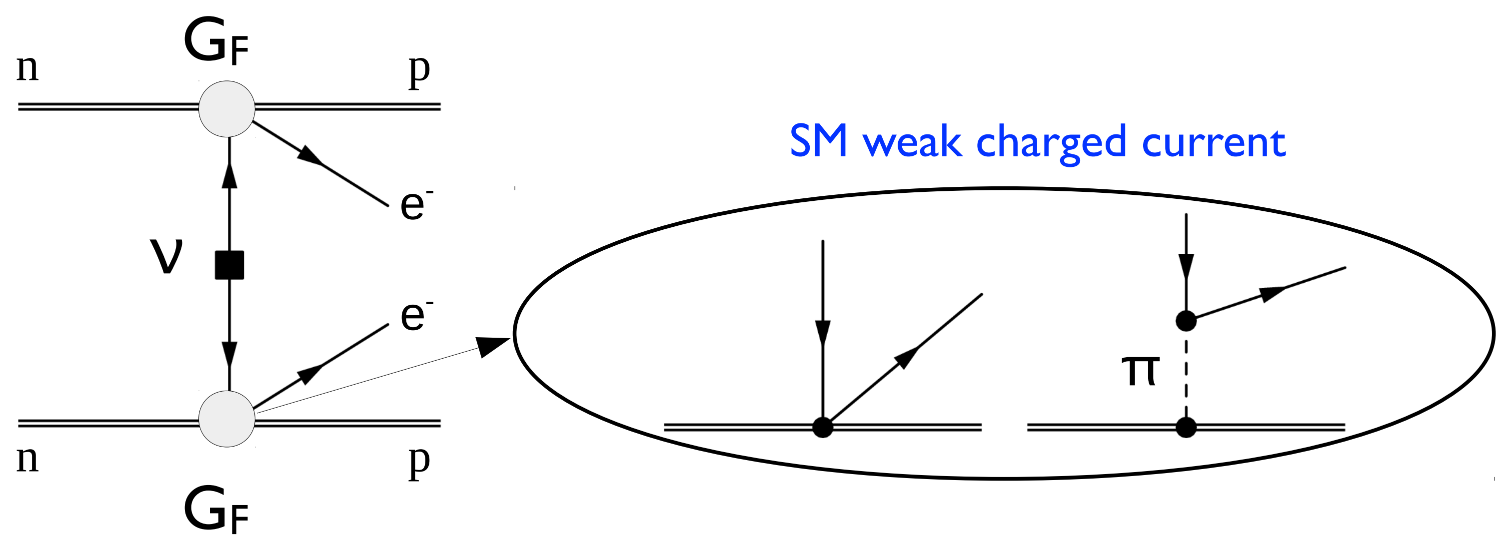
↑ LO ↑ N^2LO

Ultrasoft ν

Loop calculable in terms of $E_n - E_i$ and $\langle f\,|J_\mu|\,n\rangle\langle n\,|J^\mu|\,i\rangle$, that also control 2νββ.

Contributes to the amplitude at N^2LO

Leading order 0νββ potential

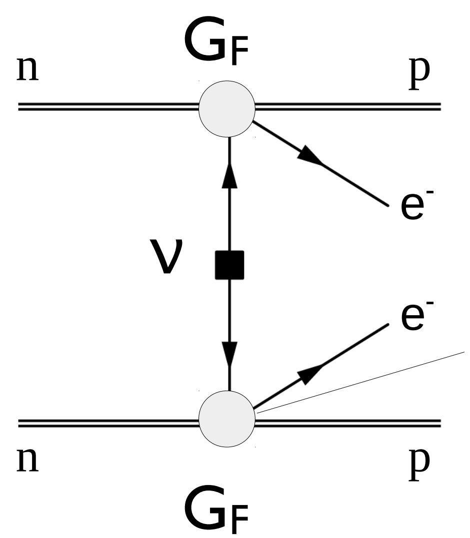


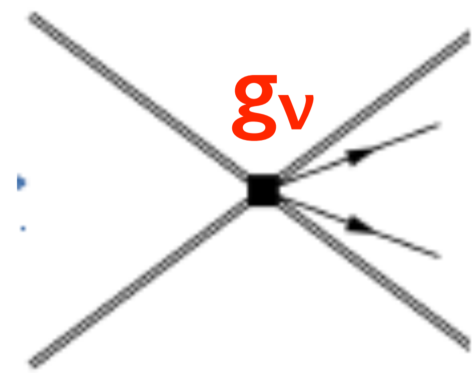
- Tree-level ν_M exchange

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

Hadronic input: g_A

Leading order 0νββ potential





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Hadronic input: g_A

- Short-range coupling $g_\nu \sim 1/Q^2 \sim 1/k_F^2$ (only in $^1S_0$ channel) required by renormalization of nn→ppee amplitude

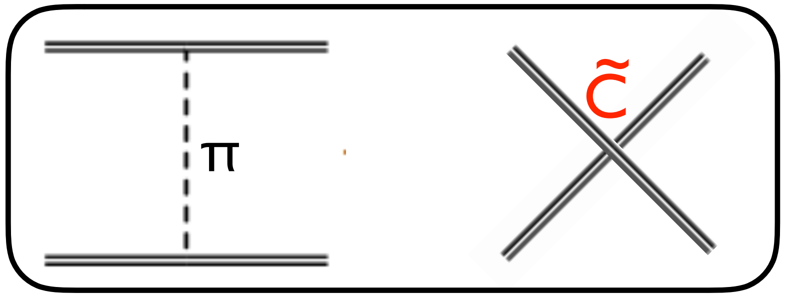
$$V_{\nu,CT}^{(a,b)} = -2\, g_\nu\, \tau^{(a)+}\tau^{(b)+}$$

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

Scaling of contact term

Weinberg 1991, Kaplan-Savage-Wise 1996

- Study nn→ppee amplitude (in $^1S_0$ channel) with LO strong potential



$\tilde{C} \sim 4\pi/(m_N Q) \sim 1/F_\pi^2$ from fit to a_{NN}

Scaling of contact term

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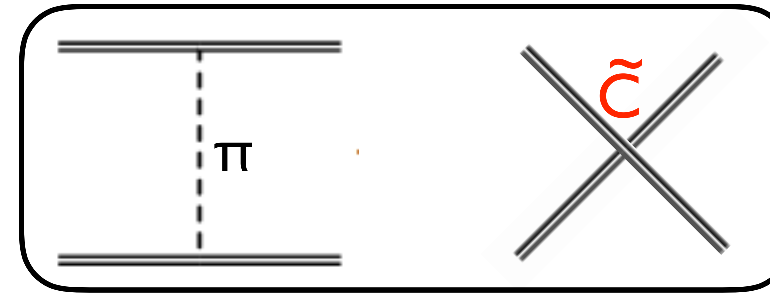

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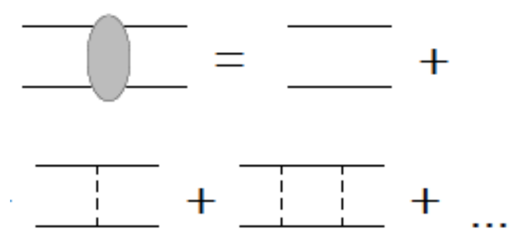
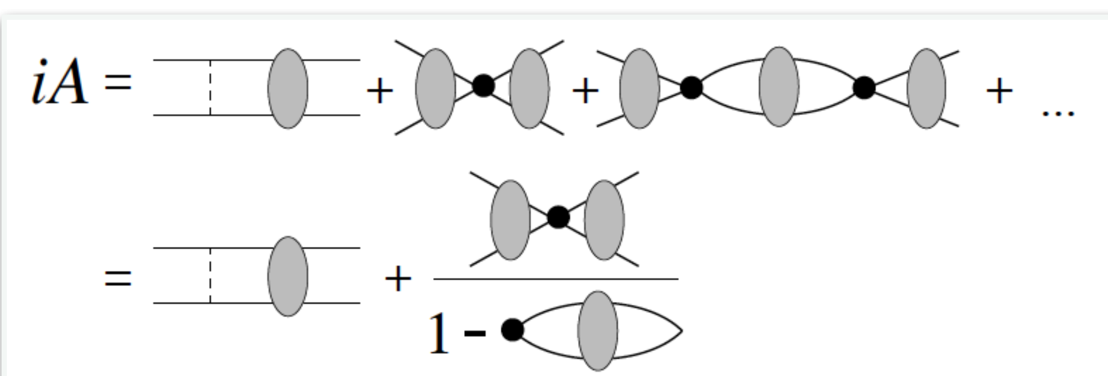
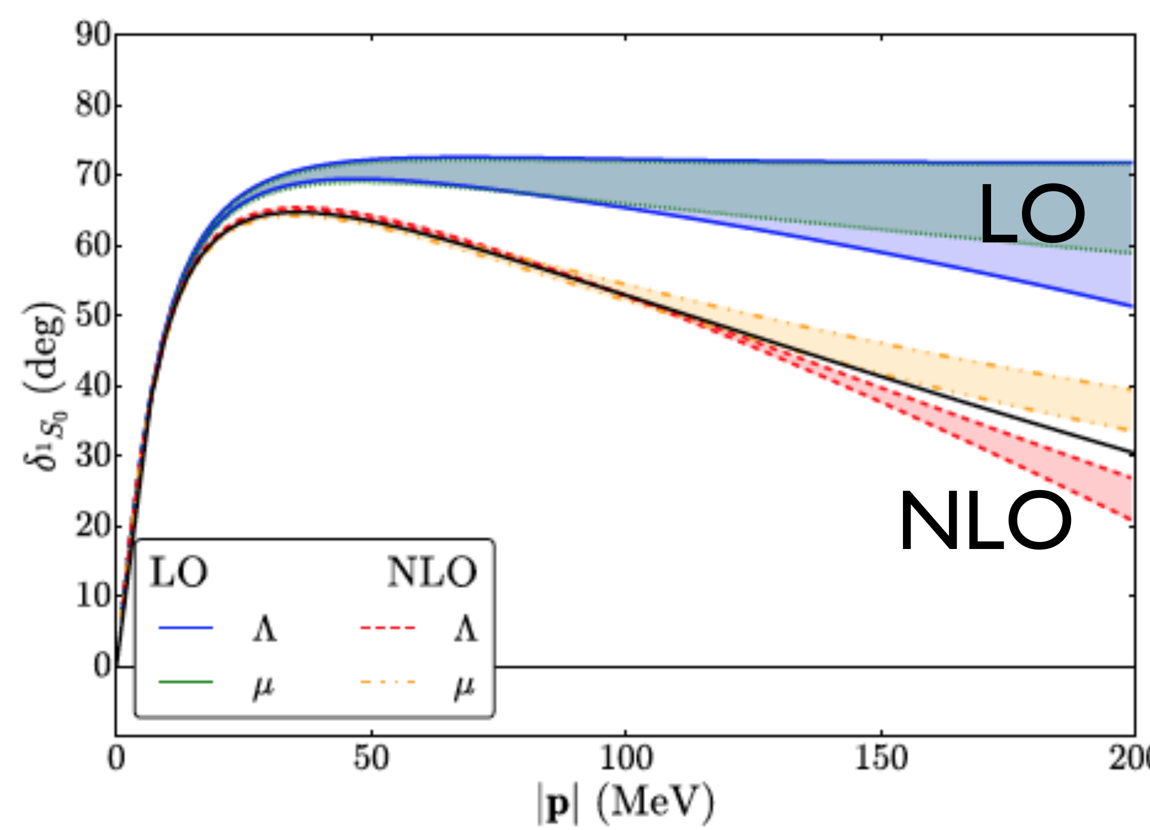




Kaplan-Savage-Wise nucl-th/9605002



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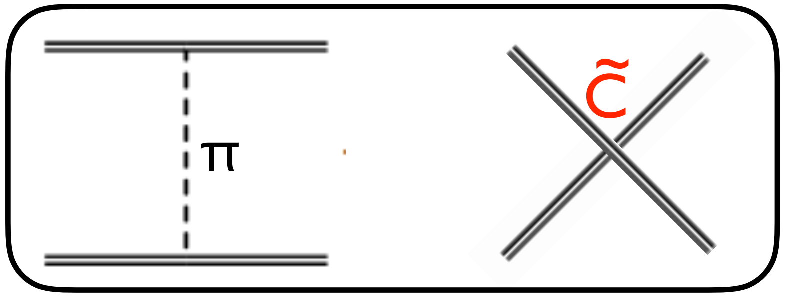

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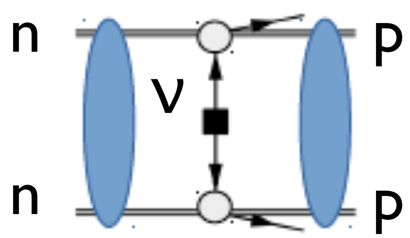

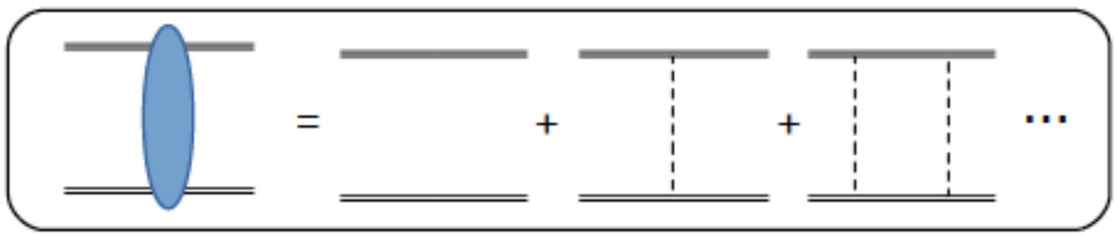

UV finite

Scaling of contact term

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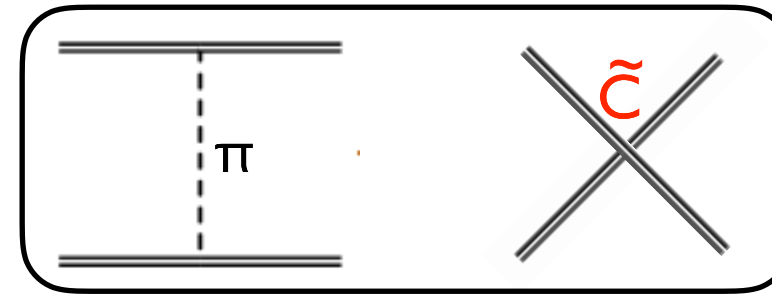
- Study nn→ppee amplitude (in $^1S_0$ channel) with LO strong potential



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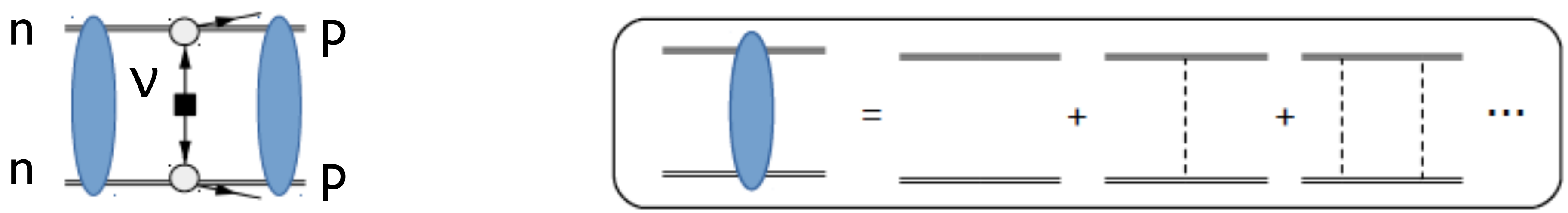

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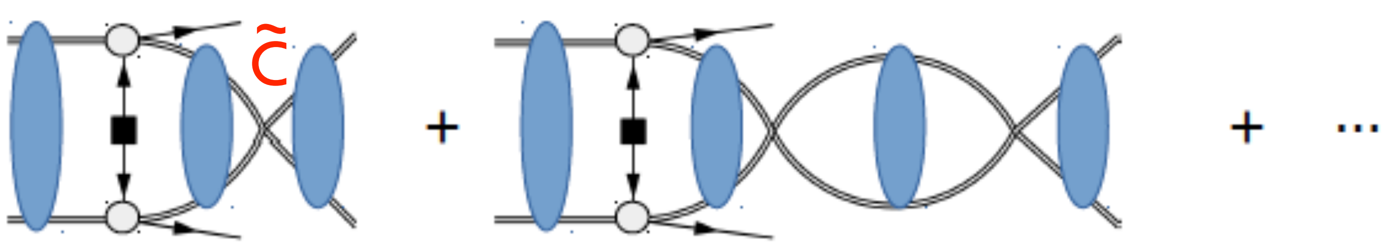

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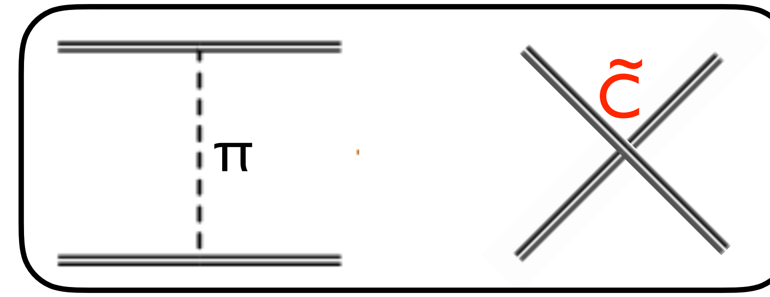

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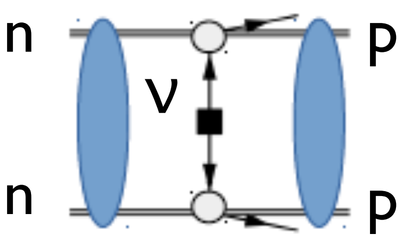
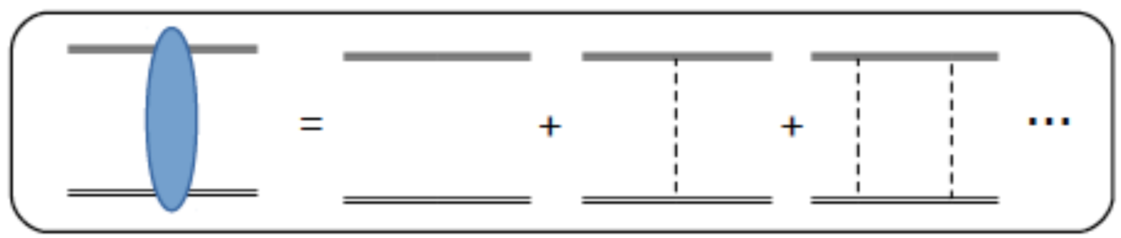
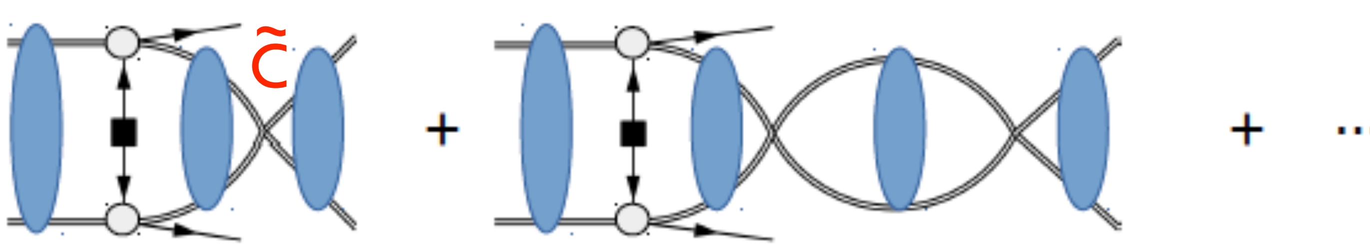
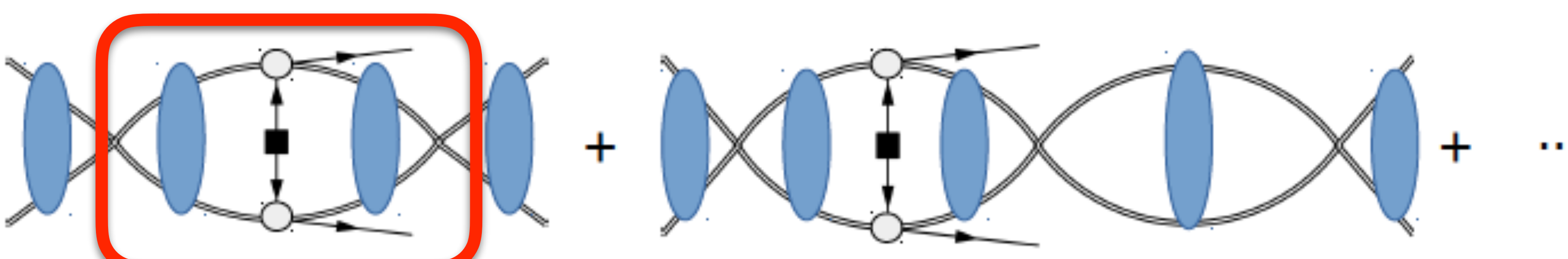




UV finite



UV finite

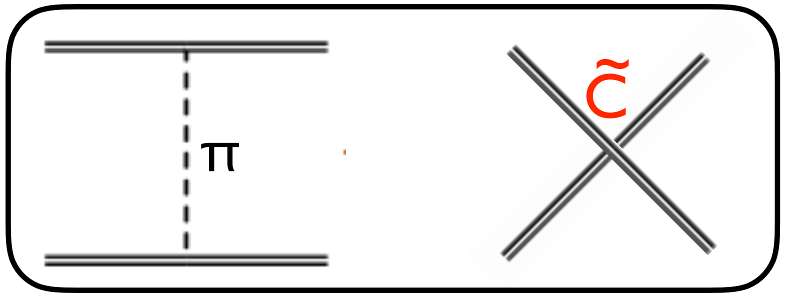


2-loop diagram is UV divergent!

Scaling of contact term

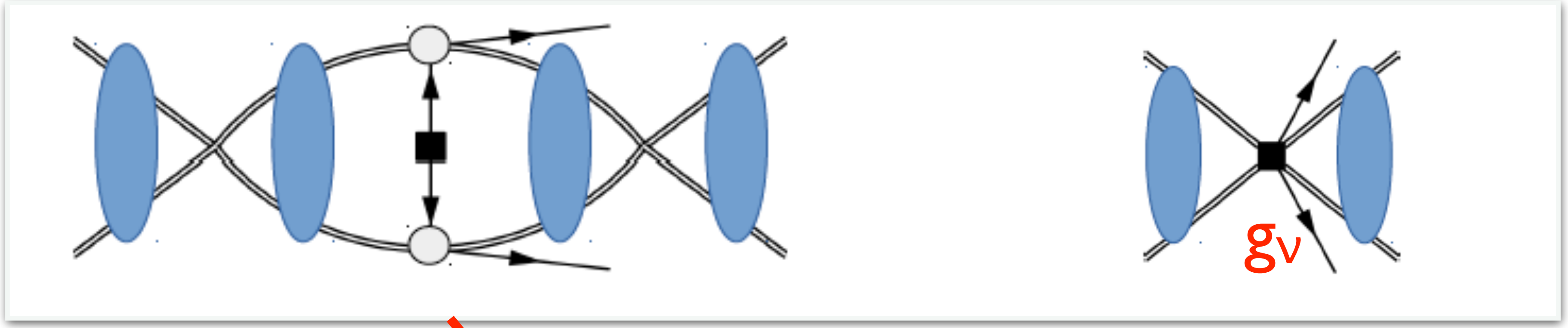
Weinberg 1991, Kaplan-Savage-Wise 1996

- Study nn→ppee amplitude (in $^1S_0$ channel) with LO strong potential



$\tilde{C} \sim 4\pi/(m_N Q) \sim 1/F_\pi^2$ from fit to a_{NN}

- Renormalization requires contact LNV operator at LO!



V. C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

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

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

Use different regulator and scheme

- Same conclusion obtained by solving the Schroedinger equation
  - Use smeared delta function to regulate short range strong potential: $\tilde{C} \to \tilde{C}\,(R_S)$

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

  - Compute amplitude

$$\mathcal{A}_\nu = \int d^3\mathbf{r}\ \psi^-_{\mathbf{p}'}(\mathbf{r})\, V_{\nu,0}(\mathbf{r})\, \psi^+_{\mathbf{p}}(\mathbf{r})$$

Scattering states "fully correlated" according to the leading order strong potential in the $^1S_0$ channel

Use different regulator and scheme

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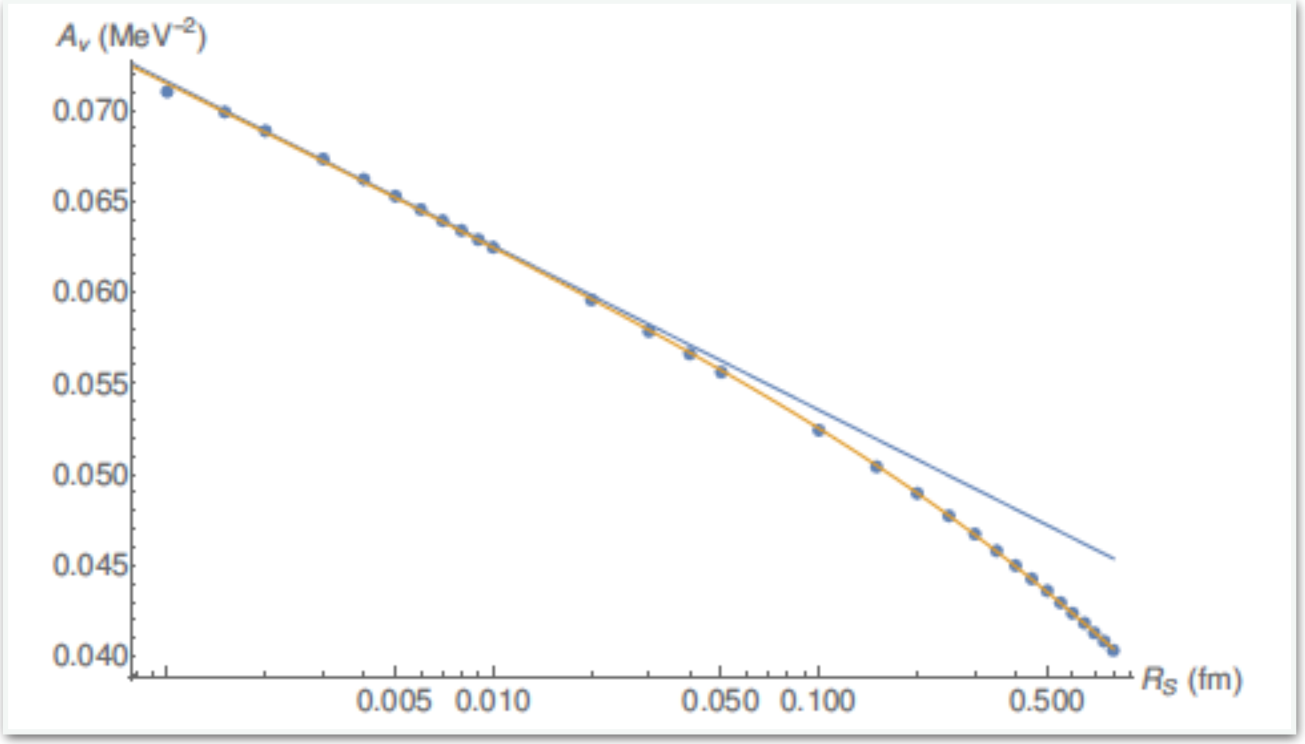
$$\mathcal{A}_\nu = \int d^3\mathbf{r}\;\psi^-_{\mathbf{p}'}(\mathbf{r})\,V_{\nu,0}(\mathbf{r})\,\psi^+_{\mathbf{p}}(\mathbf{r})$$

- Logarithmic dependence on R_S $\Rightarrow$

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



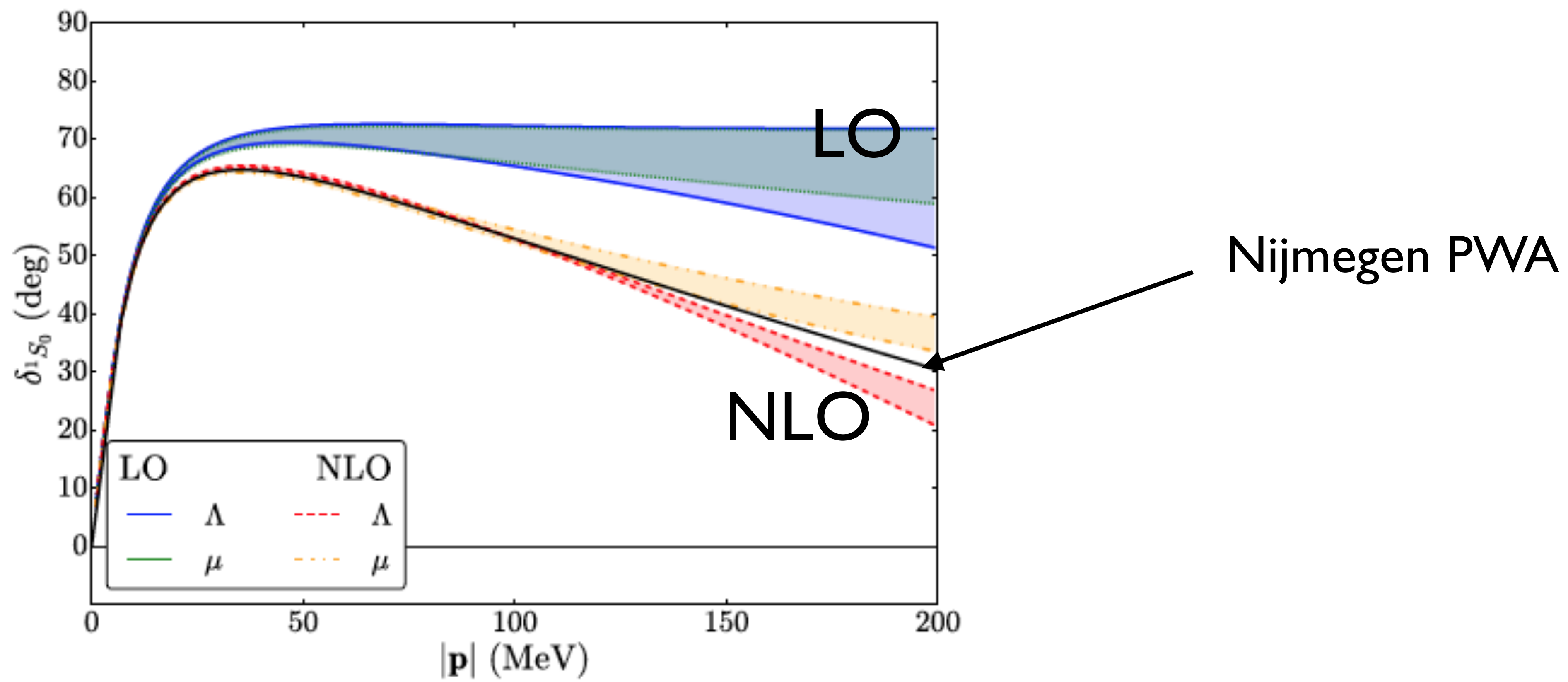
NLO 0νββ potential ($^1S_0$)

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254

- Introduce $V_{Strong,1} \sim C_2\ N D^2 N\ NN$ with $C_2 \sim 4\pi/(MQ^2\Lambda)$

Long-Yang 1202.4053

Improved description of phase shifts



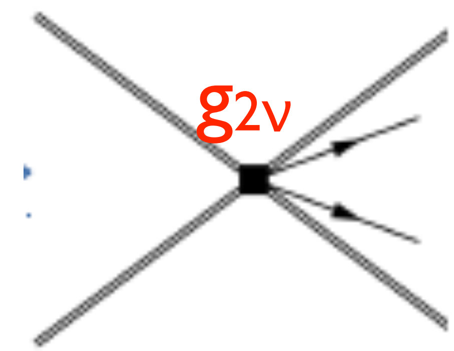
NLO $0\nu\beta\beta$ potential ($^1S_0$)

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254

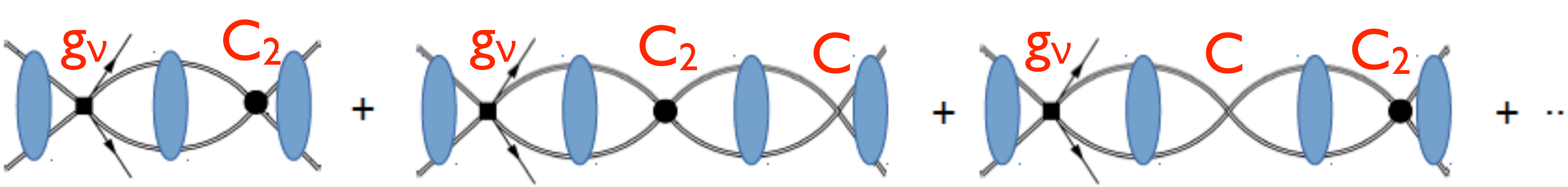
- Introduce $V_{\mathrm{Strong},1} \sim C_2\, N D^2 N\, NN$ with $C_2 \sim 4\pi/(MQ^2\Lambda)$

Long-Yang 1202.4053

- Do we need new short range parameter at NLO? ($V_{\nu,1} \sim g_{2\nu}\, N D^2 N\, NN$)



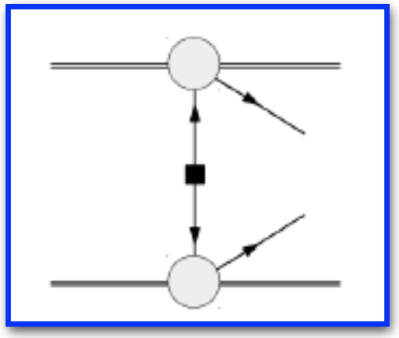
- RGE imply that $g_{2\nu}$ has an "NLO" term $\sim 1/(\Lambda Q^3)$ determined by LO couplings and effective range parameter + unknown N2LO piece



No new parameter needed at NLO

N^2LO 0νββ potential

- Known factorizable corrections
  to 1-body currents (radii, …)



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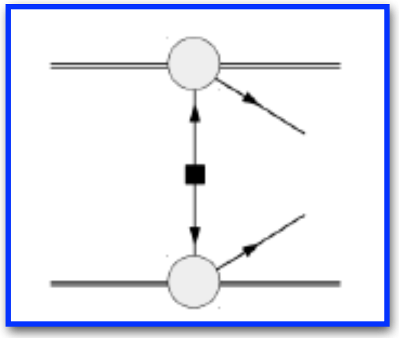
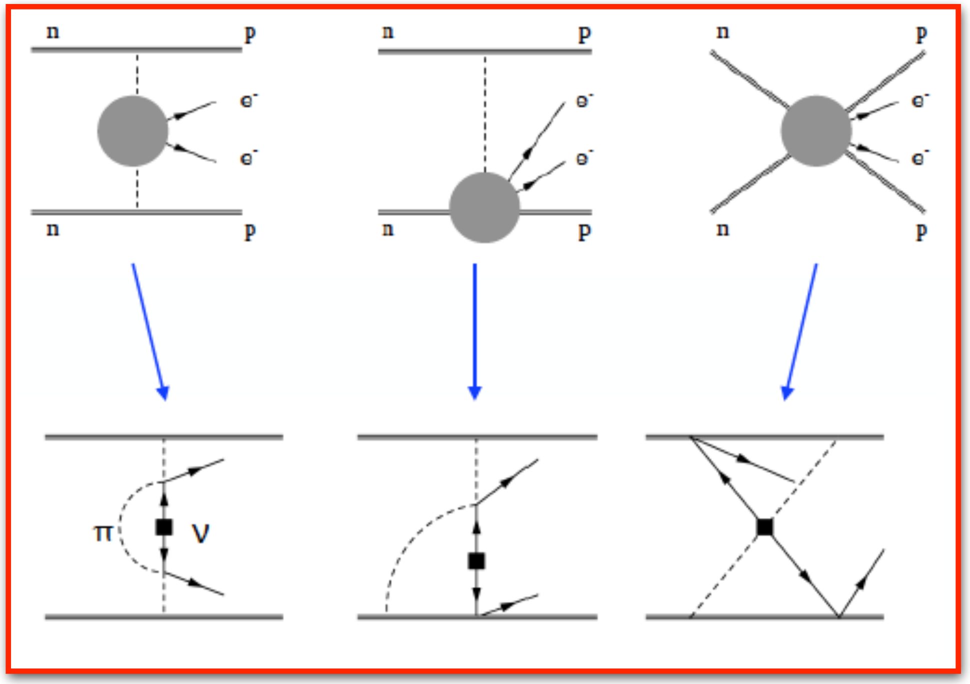


- New non-factorizable contributions to $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$ [π-N loops and new contact terms]



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

N^2LO $0\nu\beta\beta$ potential

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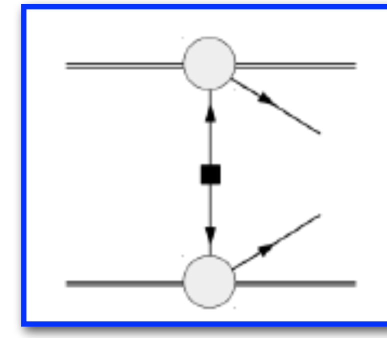

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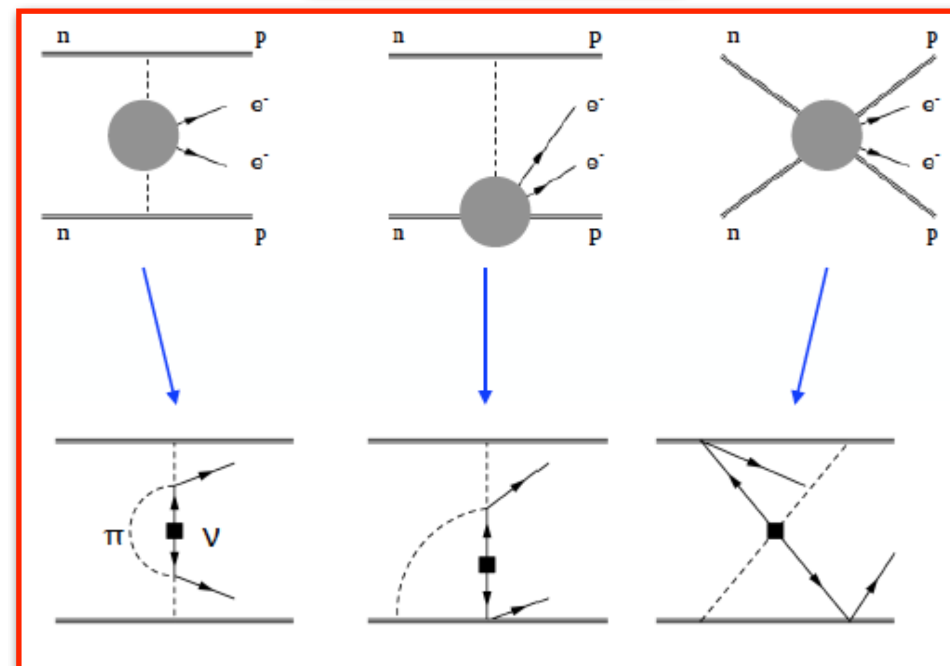
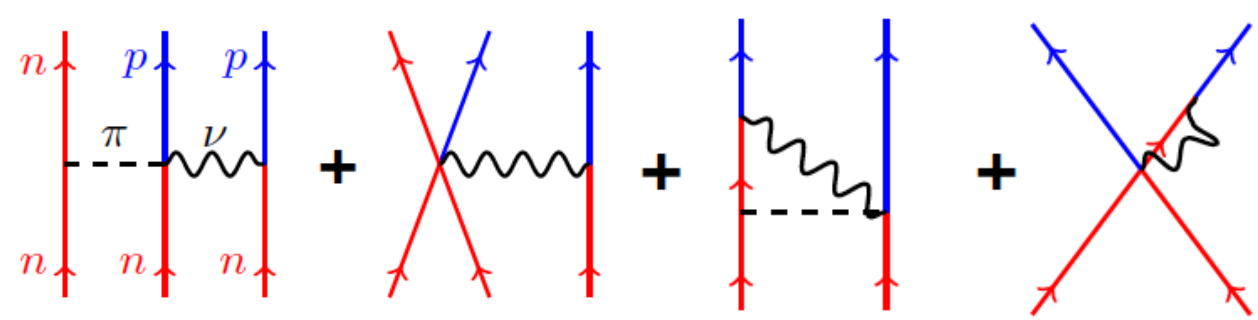


V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- 2-body x 1-body current
  (and another contact…)



Wang-Engel-Yao 1805.10276

N^2LO $0\nu\beta\beta$ potential

Calculations of these effects in light and heavy nuclei show O(10%) corrections

S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026   V.C., J. Engel, E. Mereghetti, in preparation

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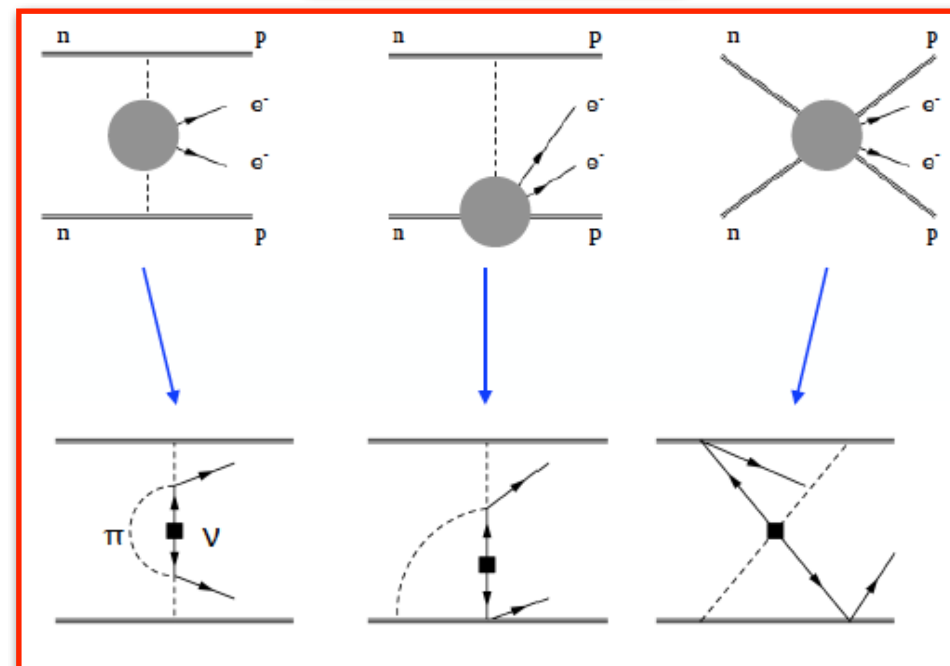

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

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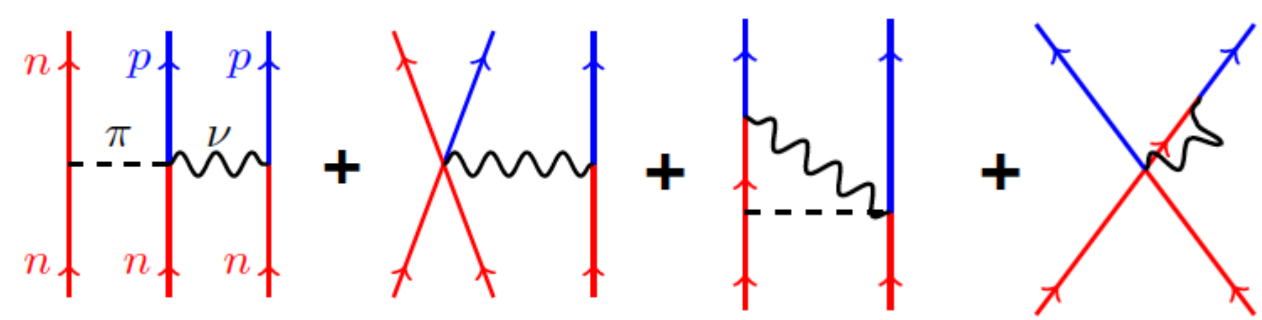
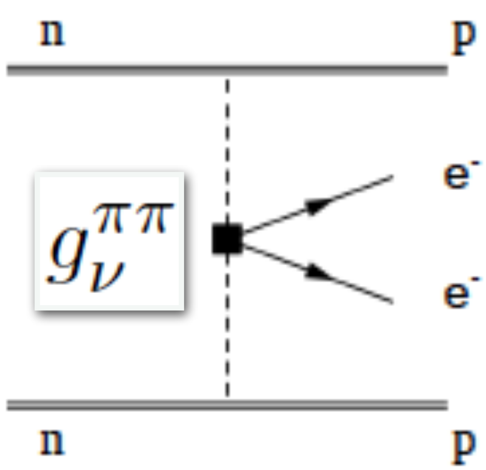
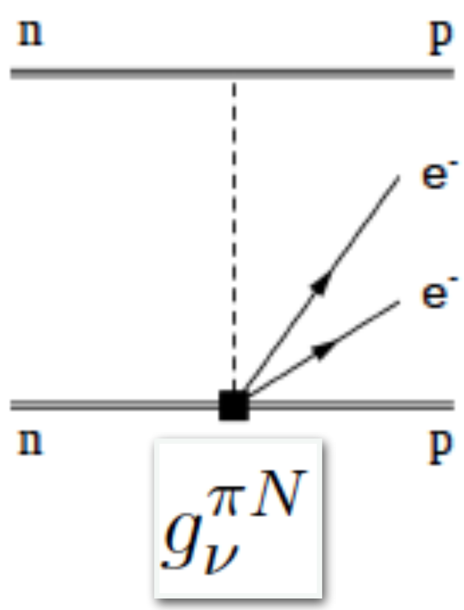


Wang-Engel-Yao 1805.10276

Estimating the LECs



N2LO



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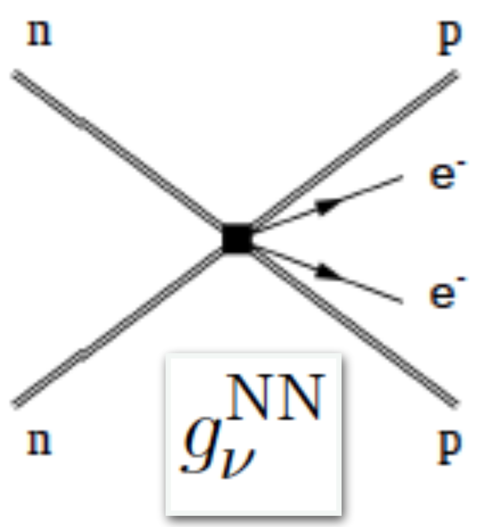

LO

Estimating the LECs

1. Compute $\pi^- \rightarrow \pi^+$, $nn \rightarrow pp$, … in lattice QCD and match to EFT

$$S_{\text{eff}}^{\Delta L=2} = i4G_F^2 V_{ud}^2 m_{\beta\beta} \int d^4x \, \bar{e}_L(x) e_L^c(x) \int d^4y \, S(x-y) \, g^{\mu\nu} \, T\Big(\bar{u}_L \gamma_\mu d_L(x) \, \bar{u}_L \gamma_\nu d_L(y)\Big)$$

Remnant of ν propagator

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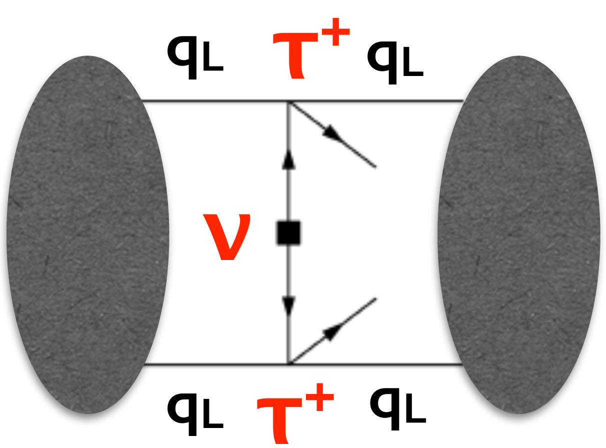
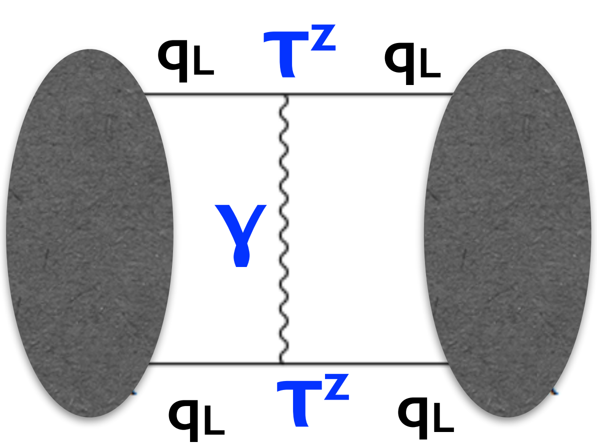
Remnant of ν propagator
~ γ propagator in Feynman gauge

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

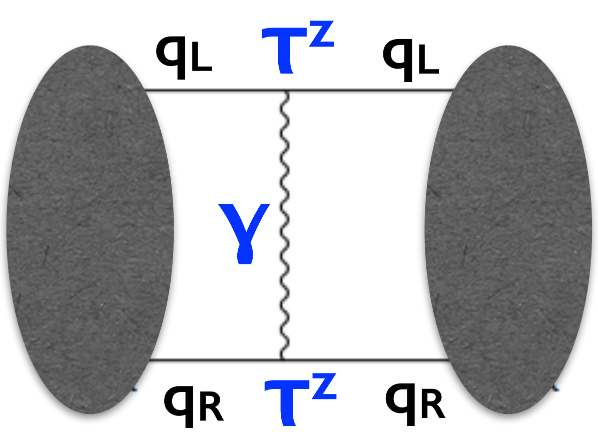
2. Chiral symmetry relates $(g_\nu)^{AB}$ to one of two I=2 EM LECs (hard γ's vs ν's)



g_ν



C_1



C_2

Estimating the LECs

1. Compute $\pi^- \to \pi^+$, $nn \to pp$, … in lattice QCD and match to EFT

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Remnant of ν propagator
~ γ propagator in Feynman gauge

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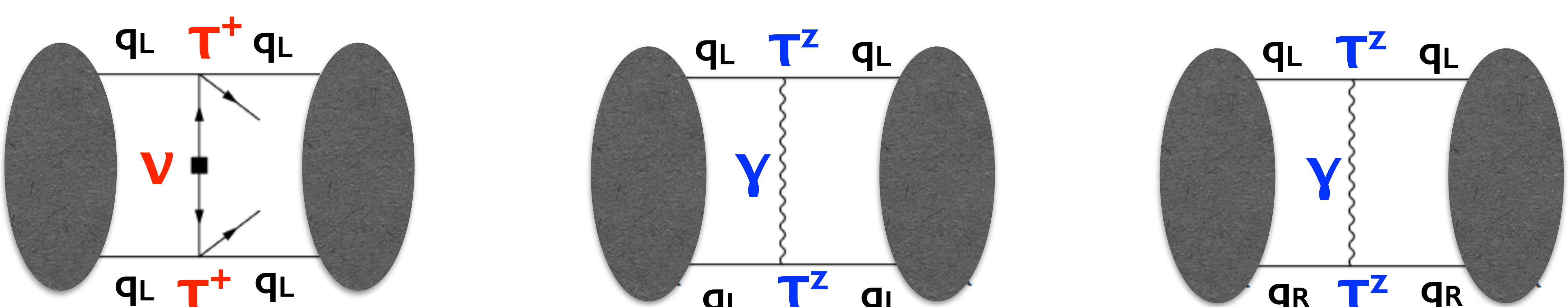

g_ν $\quad g_\nu = C_1$ $\quad C_1$ $\quad C_2$

ππ coupling

- I=2 operators involving pions

EM case

$Q_L = \frac{\tau^z}{2}, Q_R = \frac{\tau^z}{2}$

$$\mathcal{L}^{\pi\pi}_{e^2} = -e^2 F_\pi^2 \, \kappa_3 \left[\mathrm{Tr}(\mathcal{Q}^{\mathrm{em}}_L u^\mu)\, \mathrm{Tr}(\mathcal{Q}^{\mathrm{em}}_L u_\mu) - \frac{1}{3} \mathrm{Tr}\left(\mathcal{Q}^{\mathrm{em}}_L \mathcal{Q}^{\mathrm{em}}_L\right) \mathrm{Tr}\left(u^\mu u_\mu\right) + (L \to R) \right]$$

ΔL=2 case

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

$$\mathcal{L}^{\pi\pi}_{|\Delta L|=2} = \left(2\sqrt{2} G_F V_{ud}\right)^2 m_{\beta\beta} \, \bar{e}_L C \bar{e}_L^T \, \frac{5 g_\nu^{\pi\pi}}{3(16\pi)^2} F_\pi^2 \times \left[\mathrm{Tr}(\mathcal{Q}^{\mathrm{w}}_L u^\mu)\, \mathrm{Tr}(\mathcal{Q}^{\mathrm{w}}_L u_\mu) - \frac{1}{3} \mathrm{Tr}\left(\mathcal{Q}^{\mathrm{w}}_L \mathcal{Q}^{\mathrm{w}}_L\right) \mathrm{Tr}\left(u^\mu u_\mu\right) \right] + \mathrm{H.c.}$$

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

- Estimates of k_3 in large-N_C inspired resonance approach ⇒

Ananthanarayan & Moussallam hep-ph/0405206

$$g_\nu^{\pi\pi}(\mu = m_\rho) = -7.6$$

~30% uncertainty

ππ coupling

- I=2 operators involving pions

EM case

$Q_L = \frac{\tau^z}{2},\ Q_R = \frac{\tau^z}{2}$

$$\mathcal{L}^{\pi\pi}_{e^2} = -e^2 F_\pi^2\, \kappa_3 \left[\mathrm{Tr}(\mathcal{Q}_L^{\rm em} u^\mu)\, \mathrm{Tr}(\mathcal{Q}_L^{\rm em} u_\mu) - \frac{1}{3} \mathrm{Tr}\left(\mathcal{Q}_L^{\rm em} \mathcal{Q}_L^{\rm em}\right)\, \mathrm{Tr}\left(u^\mu u_\mu\right) + (L \to R) \right]$$

ΔL=2 case

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

$$\mathcal{L}^{\pi\pi}_{|\Delta L|=2} = \left(2\sqrt{2}\, G_F V_{ud}\right)^2 m_{\beta\beta}\, \bar{e}_L C \bar{e}_L^T\, \frac{5 g_\nu^{\pi\pi}}{3(16\pi)^2} F_\pi^2 \times \left[\mathrm{Tr}(\mathcal{Q}_L^{\rm w} u^\mu)\, \mathrm{Tr}(\mathcal{Q}_L^{\rm w} u_\mu) - \frac{1}{3} \mathrm{Tr}\left(\mathcal{Q}_L^{\rm w} \mathcal{Q}_L^{\rm w}\right)\, \mathrm{Tr}\left(u^\mu u_\mu\right) \right] + \mathrm{H.c.}$$

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

- Estimates of k_3 in large-N_C inspired resonance approach ⇒

Ananthanarayan & Moussallam hep-ph/0405206

$$g_\nu^{\pi\pi}(\mu = m_\rho) = -7.6$$

~30% uncertainty

- Good agreement with LQCD range*

$$g_\nu^{\pi\pi}(\mu = m_\rho) \in [-12, -8.5]$$

* Xu Feng et al., 1809.10511

For related work see Detmold-Murphy 1811.0554

NN coupling

- Two I=2 operators involving four nucleons

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

EM case

$Q_L = \frac{\tau^z}{2}, Q_R = \frac{\tau^z}{2}$

$$\frac{e^2 C_1}{4}\left(\bar{N}Q_L N \bar{N} Q_L N - \frac{\mathrm{Tr}[Q_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

$$\frac{e^2 C_2}{4}\left(\bar{N}Q_L N \bar{N} Q_R N - \frac{\mathrm{Tr}[Q_L Q_R]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

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ΔL=2 case

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

$$8G_F^2 V_{ud}^2 m_{\beta\beta}\bar{e}_L e_L^c \, \frac{g_\nu}{4}\left(\bar{N}Q_L N \bar{N} Q_L N - \frac{\mathrm{Tr}[Q_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L \to R\right)$$

- Chiral symmetry ⇒ $g_\nu = C_1$

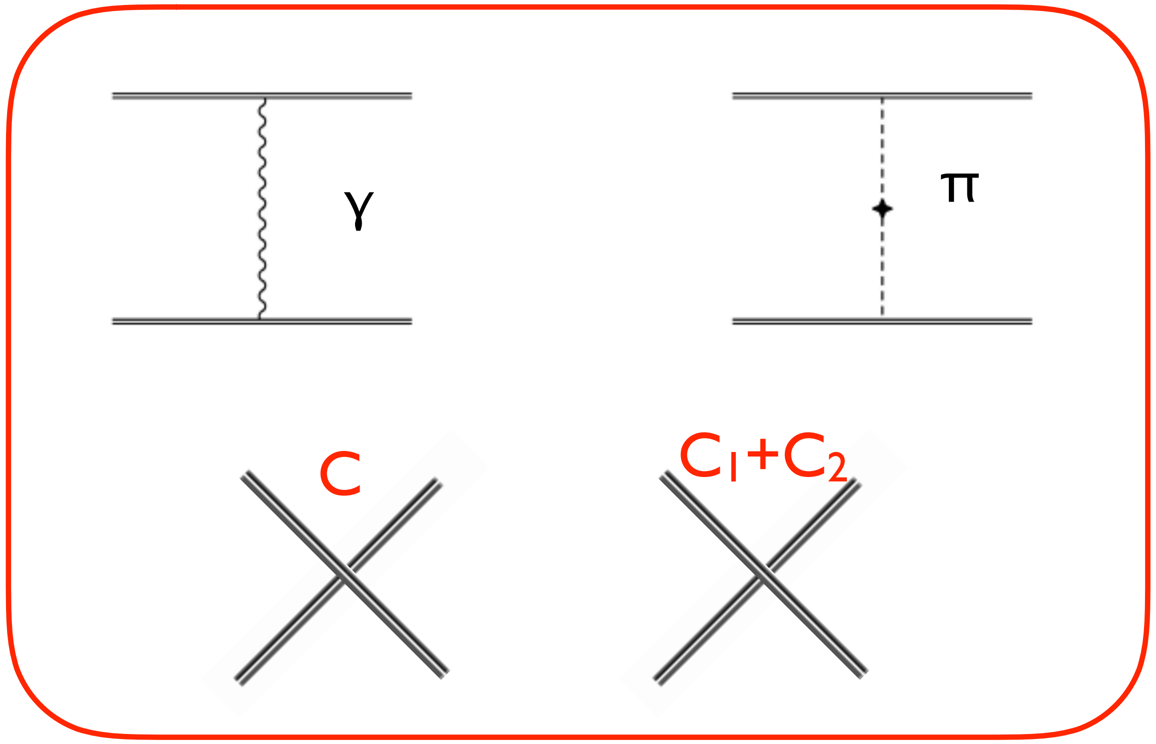
- Can we get C_1 from experiment ?

Connection with data

$$a_{np} = -23.7 \pm 0.02 \text{ fm}\,, \qquad a_{nn} = -18.90 \pm 0.40 \text{ fm}\,, \qquad a_C = -7.804 \pm 0.005 \text{ fm}\,.$$

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

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



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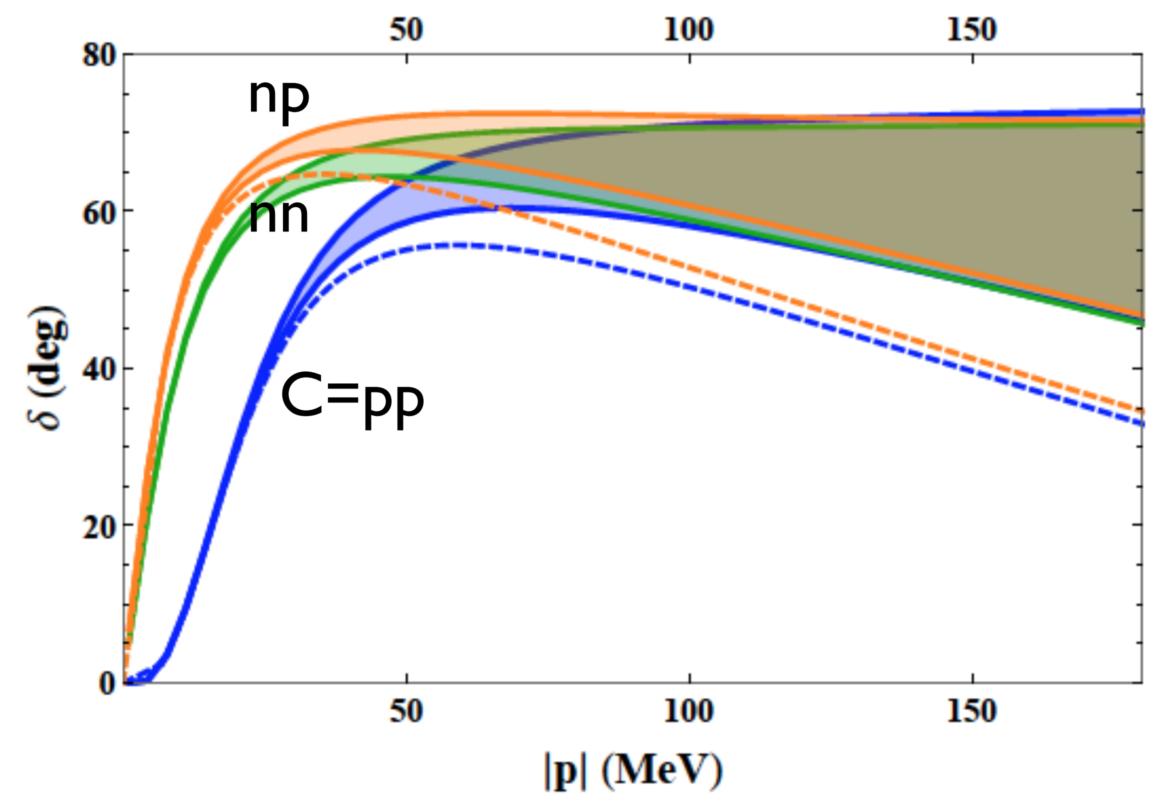

$$\frac{\mathcal{C}_1 + \mathcal{C}_2}{2} \equiv \left(\frac{m_N C}{4\pi}\right)^2 \left(2.5 - 1.8\,\ln(m_\pi/\mu)\right)$$

$$C = -\frac{1}{\tilde{\Lambda}^2}$$

$$\tilde{\Lambda}(\mu = m_\pi) = O(100\text{ MeV})$$

Connection with data

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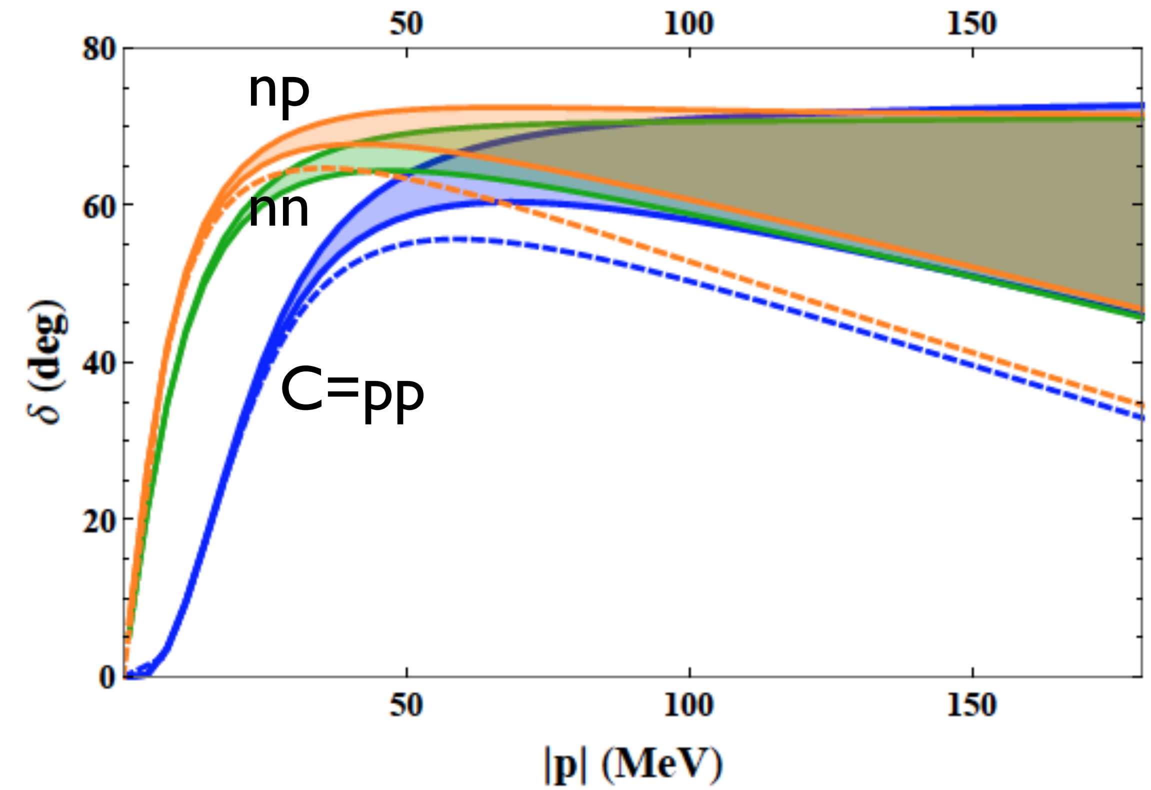


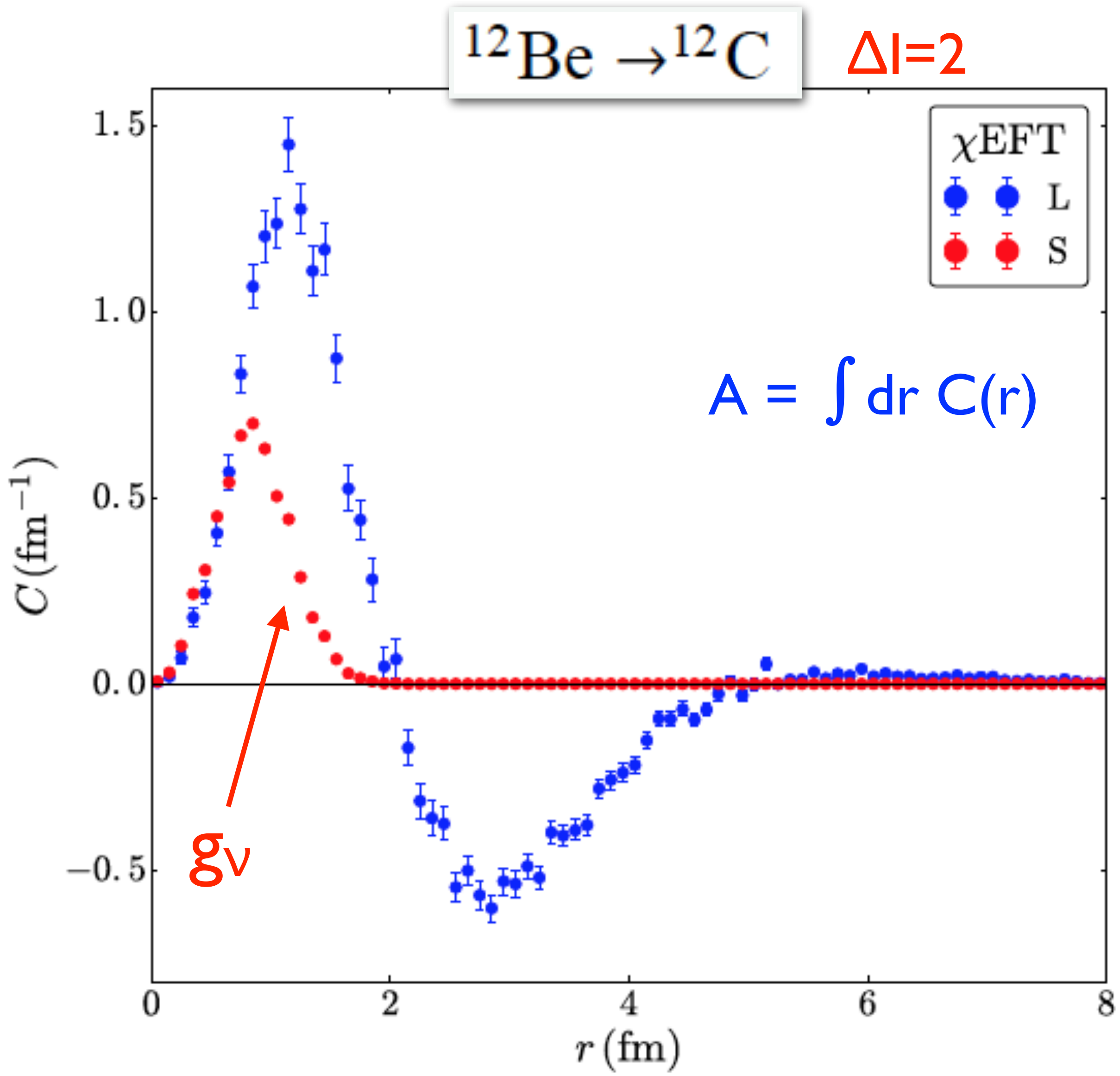
The EFT analysis survives comparison with data!

The analog of $e^2(C_1+C_2)$ is included in all high-quality potentials (AV18, CD-Bonn, chiral, …)

MeV)

Guesstimating numerical impact

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254



Assume $g_\nu \sim (C_1+C_2)/2$ with (C_1+C_2) taken from fit to NN data

Evaluate impact in light nuclei using Variational Monte Carlo, with wavefunctions corresponding to the Norfolk chiral potential [1606.06335]

g_ν contribution sizable in ΔI=2 transition (due to node): for A=12, A_S/A_L = 0.75

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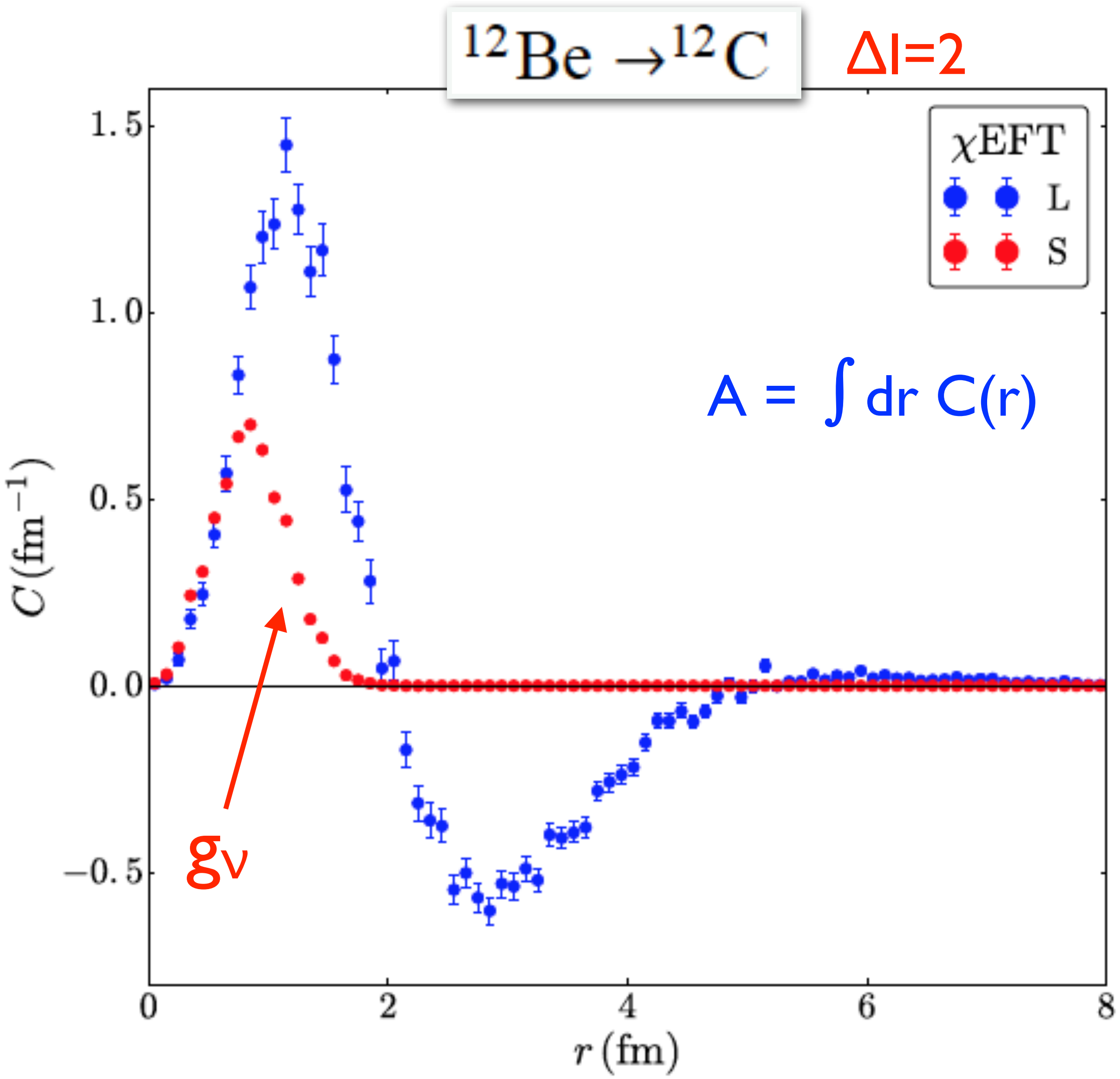

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Transitions of experimental interest ($^{76}Ge \to {}^{76}Se$, …) have ΔI=2 (and node) ⇒ expect significant effect!

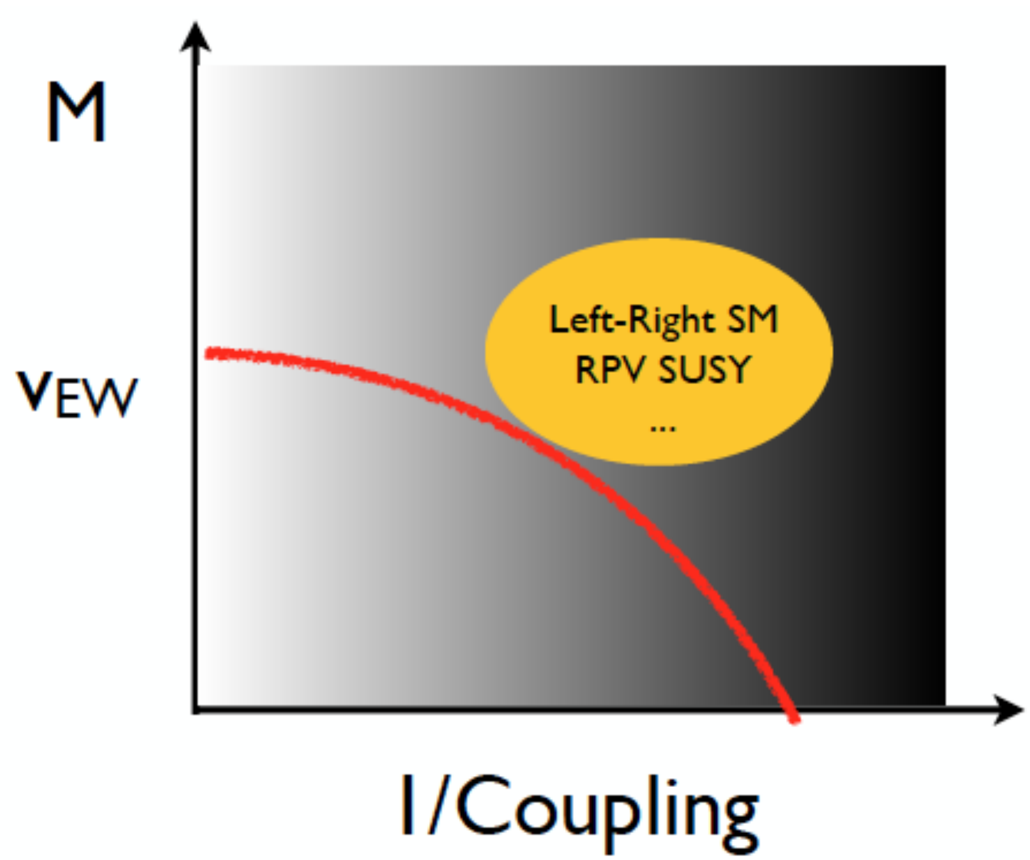
Conclusions & Outlook

- Ton-scale $0\nu\beta\beta$ searches will probe LNV from a broad variety of mechanisms — high discovery potential, far reaching implications

- EFT approach provides a general framework to:
  1. Relate $0\nu\beta\beta$ to underlying LNV dynamics (and collider & cosmology)
  2. Organize contributions to hadronic and nuclear matrix elements
     - Identified new leading order short-range contributions
     - Implications for $m_{\beta\beta}$ not yet clear (size of g_ν & relative sign)

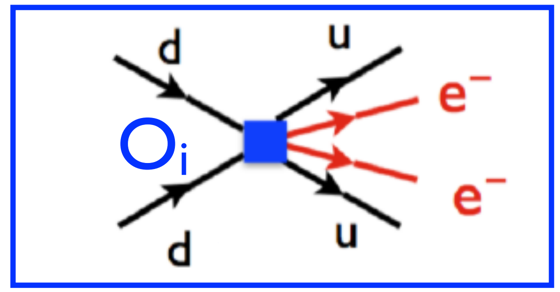
Improving the theory uncertainty is challenging, but there are good prospects thanks to advances in EFT, lattice QCD, and nuclear structure

0νββ from multi-TeV scale dynamics (dim-7, 9, …operators)

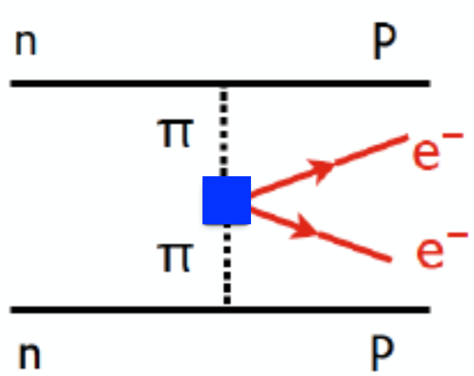


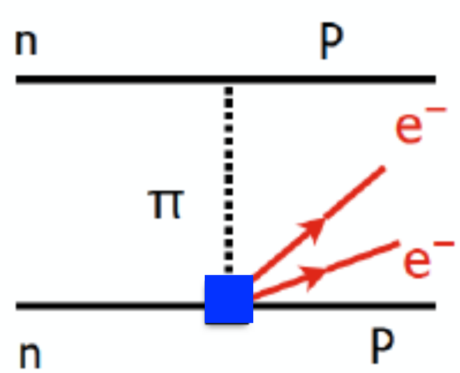
Chiral realization of dim-9 operators

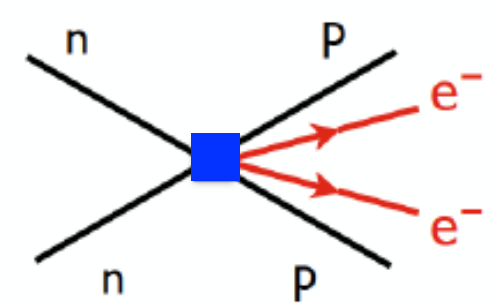
Pion-range effects



Short-range effects

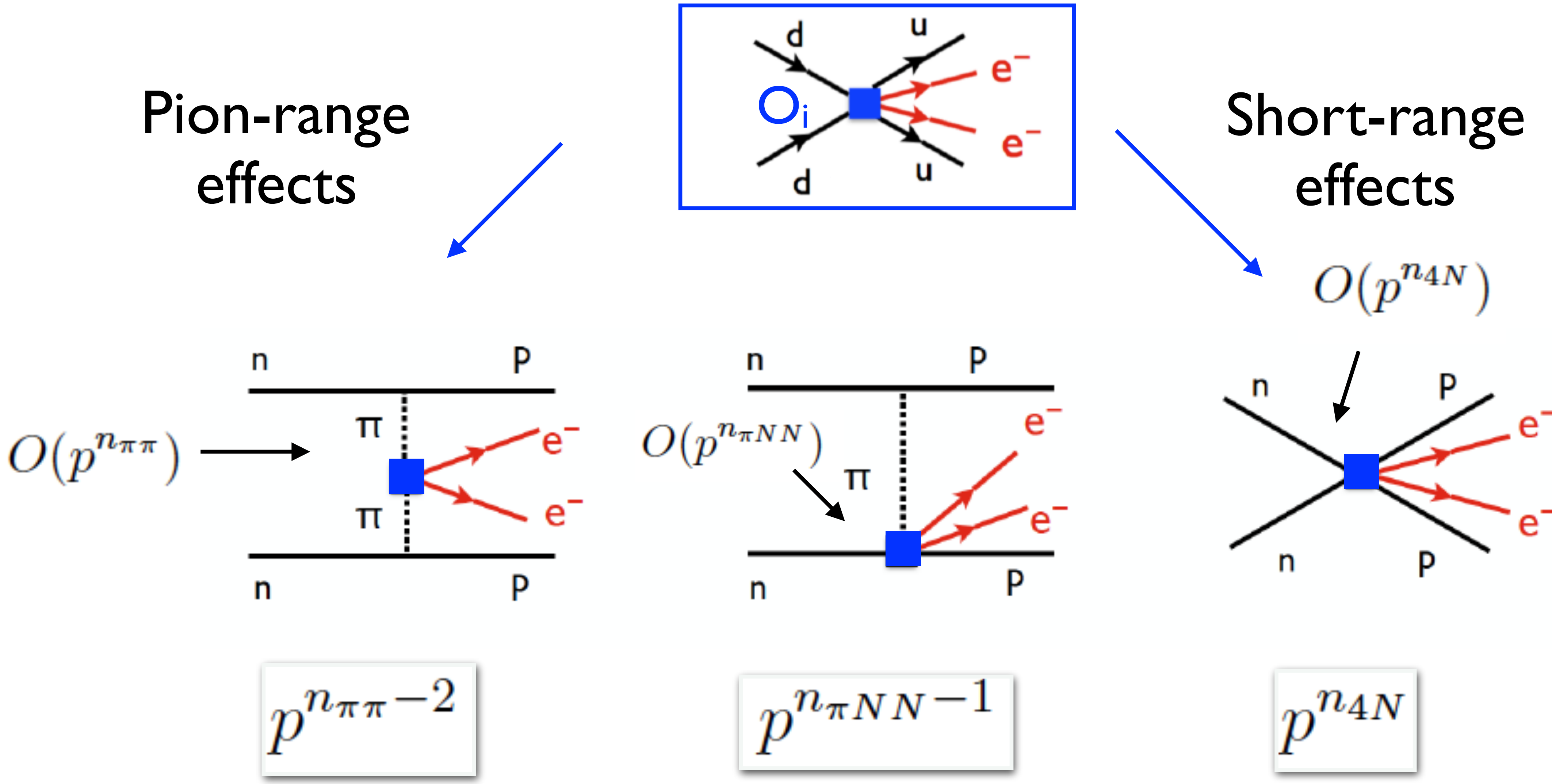






Vergatos 1982, Faessler, Kovalenko, Simkovic, Schweiger 1996
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Chiral realization of dim-9 operators

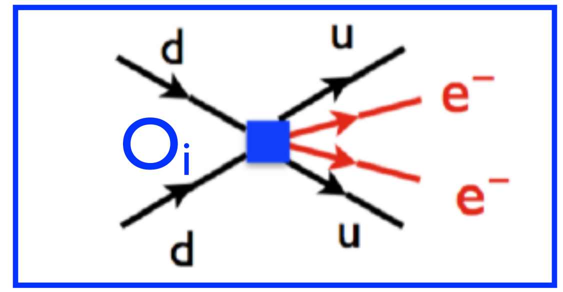


p ~ Q

Naive dimensional analysis → $V_{\pi\pi}$ dominates for all but one operator

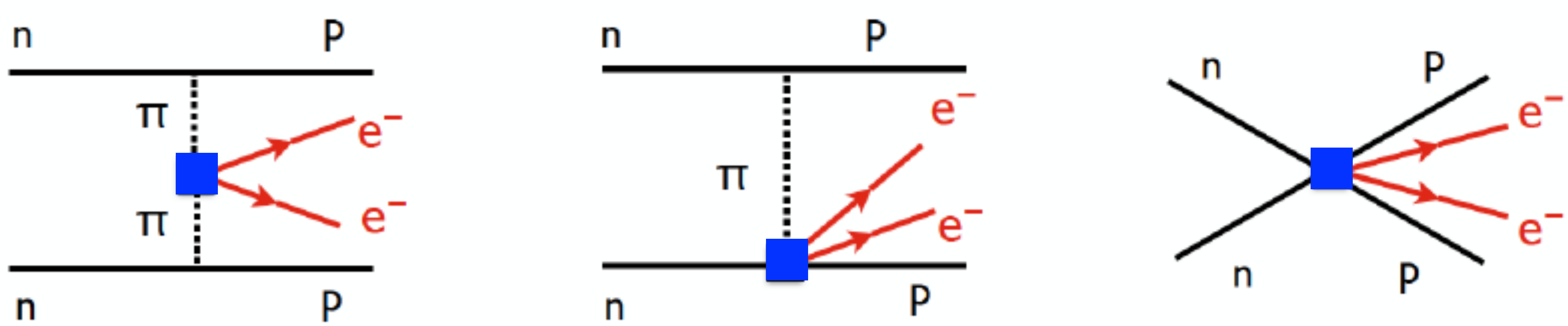
Vergatos 1982, Faessler, Kovalenko, Simkovic, Schweiger 1996
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Chiral realization of dim-9 operators



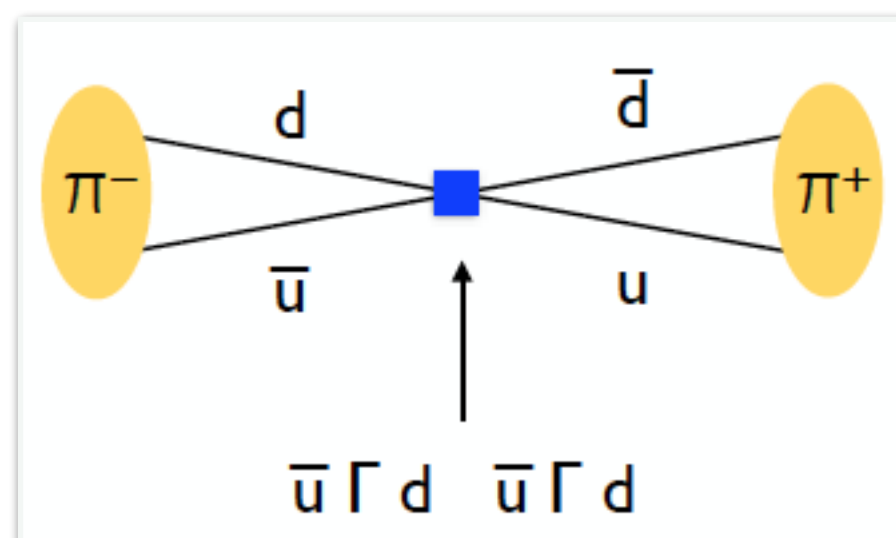
Pion-range effects

Short-range effects



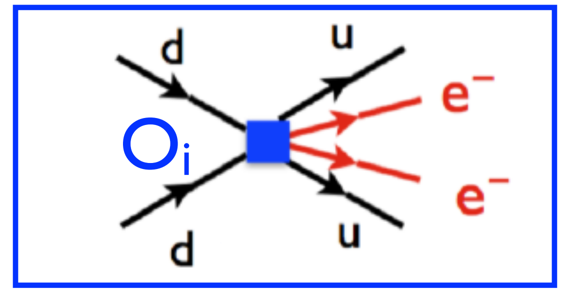
- Two recent developments:

  1. ππ matrix elements now precisely know via direct and indirect lattice QCD calculations



Nicholson et al., 1805/02634

Chiral realization of dim-9 operators



Pion-range effects

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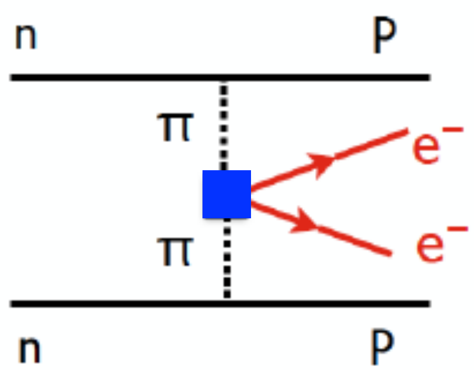

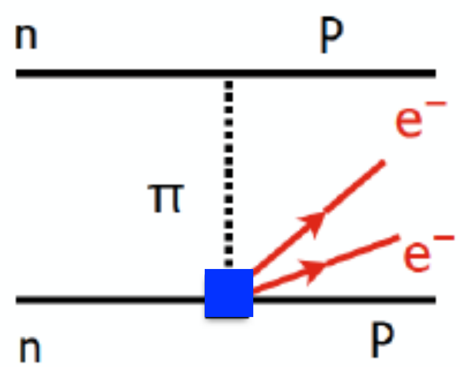

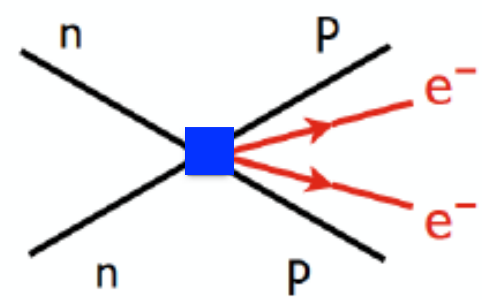

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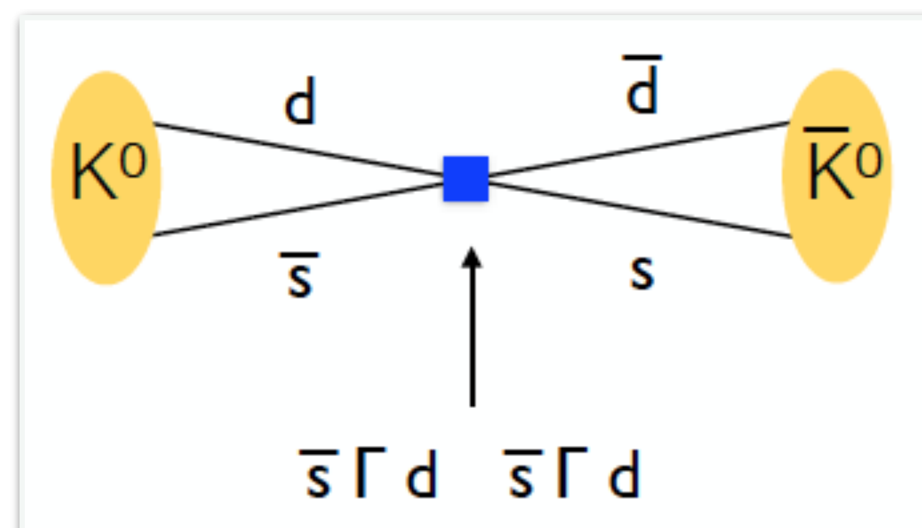

VC, Dekens, Graesser, Mereghetti, 1701.01443

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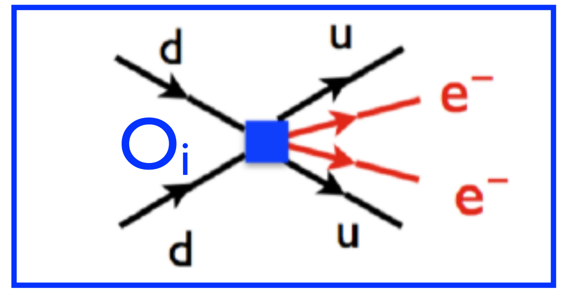

Pion-range effects

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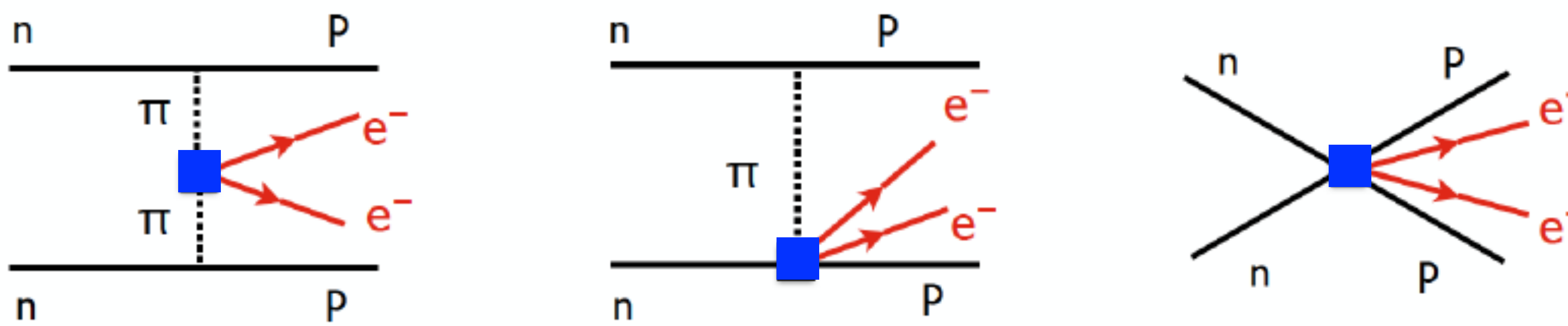
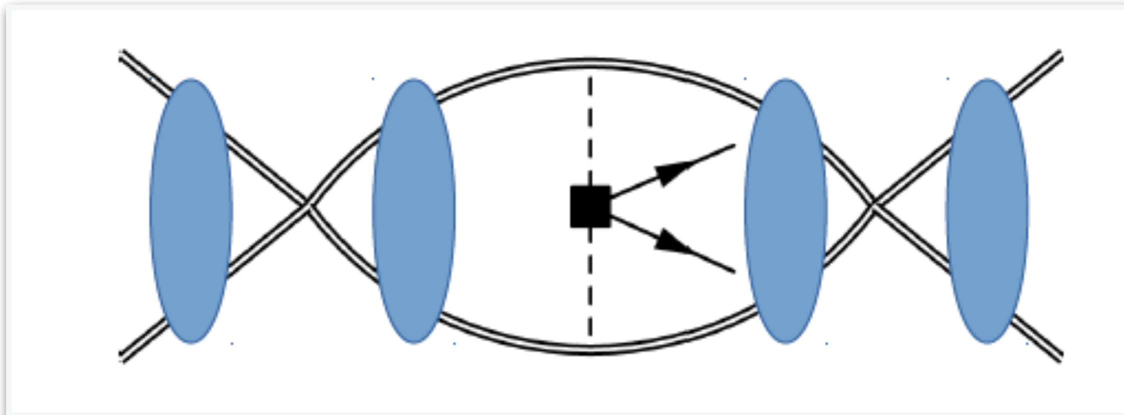


- Two recent developments:

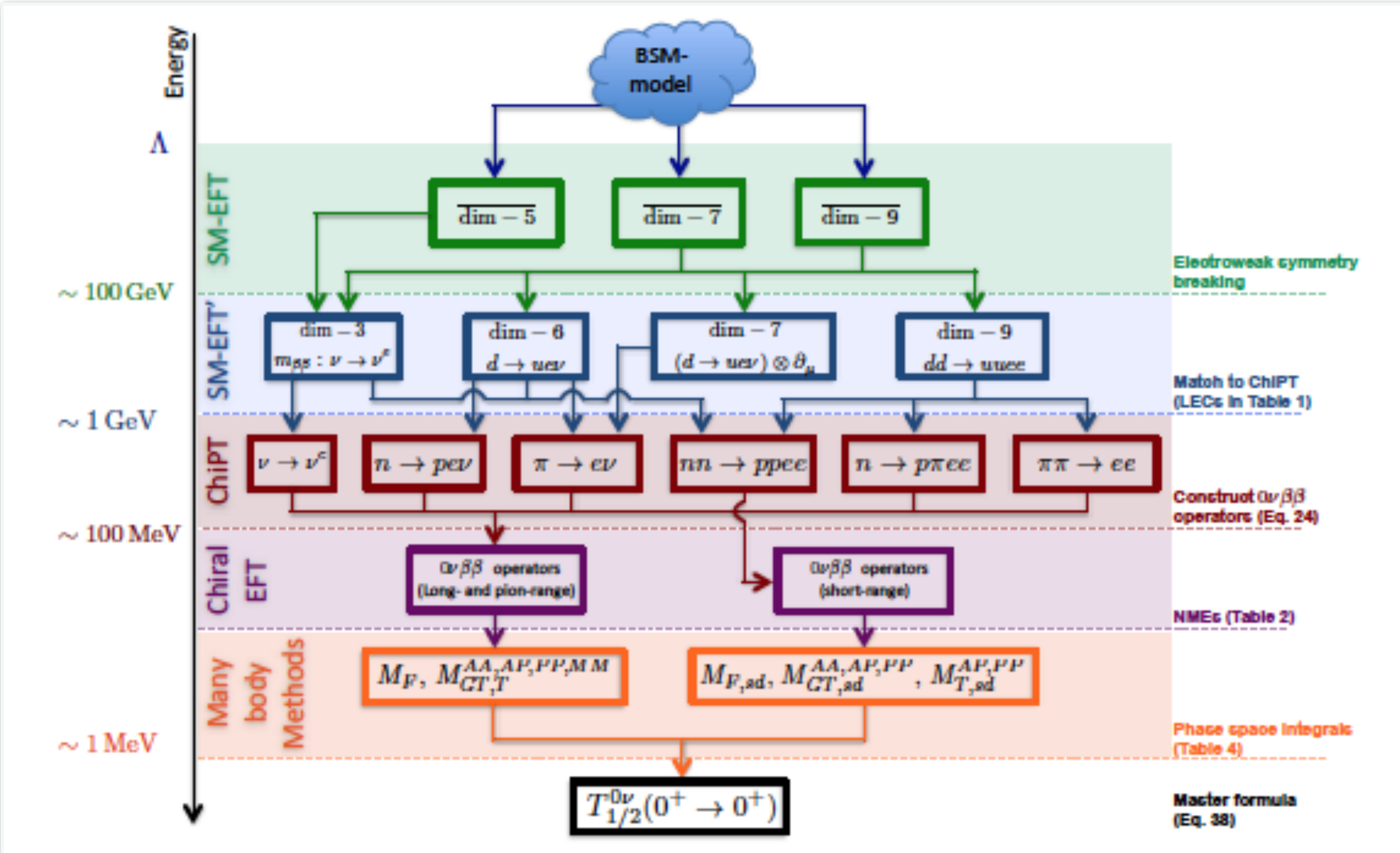
  2. Renormalization → $V_{\pi\pi}$ and V_{NN} are both leading order



V.C, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

EFT-based master formula

- Framework to interpret experiments in terms of high-scale LNV sources



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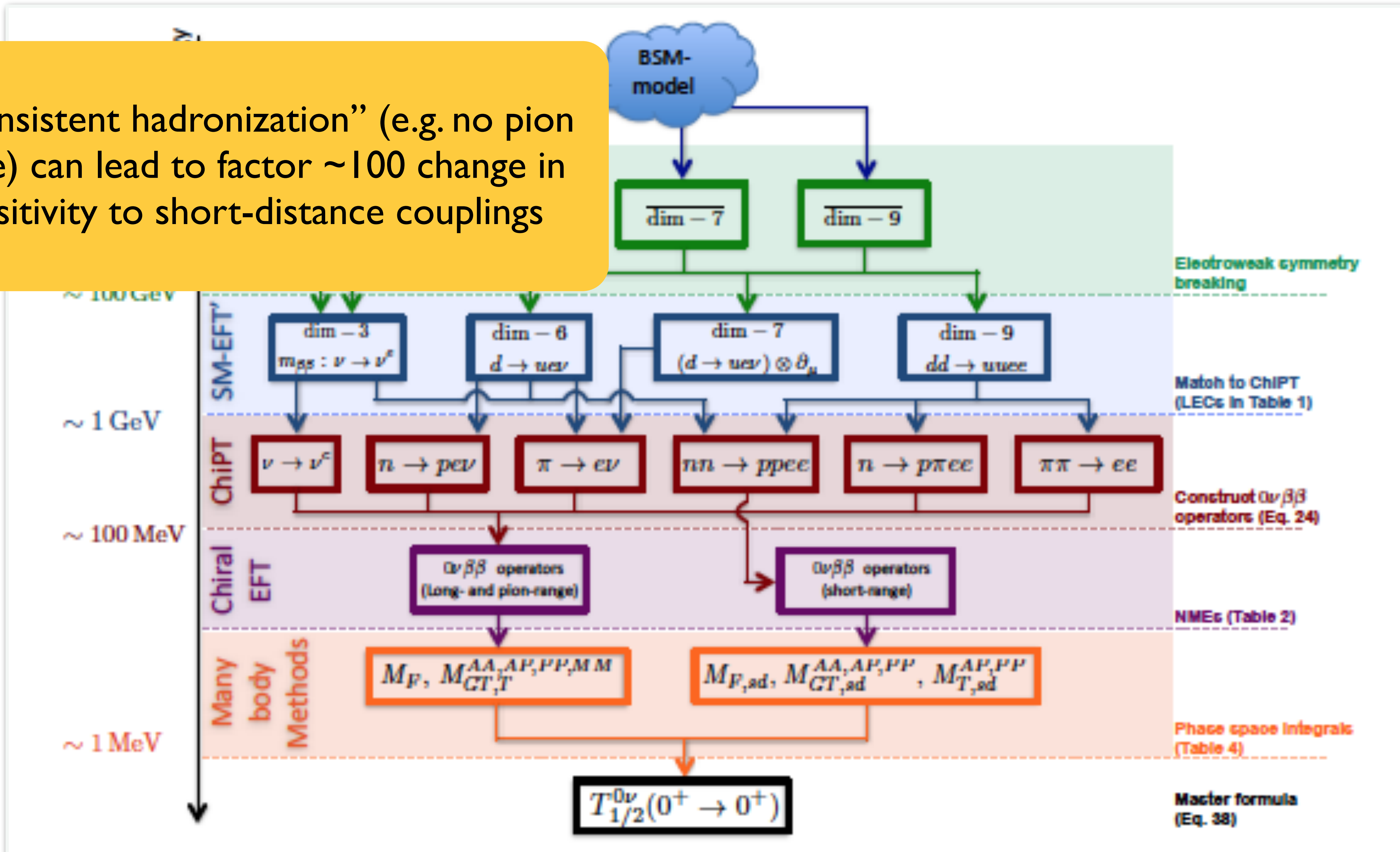

"Inconsistent hadronization" (e.g. no pion range) can lead to factor ~100 change in sensitivity to short-distance couplings

V. C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

EFT-based master formula

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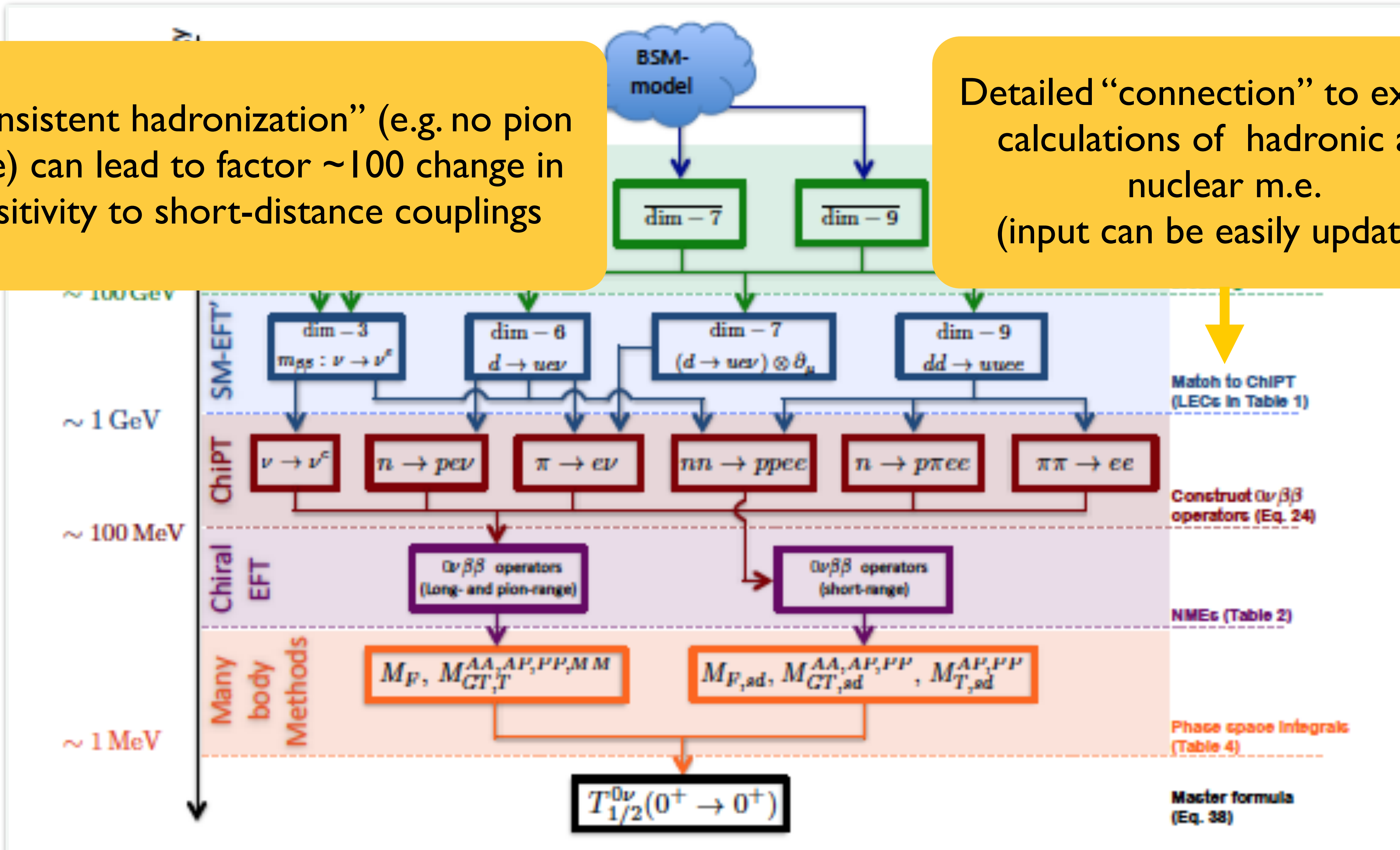
"Inconsistent hadronization" (e.g. no pion range) can lead to factor ~100 change in sensitivity to short-distance couplings

Detailed "connection" to existing calculations of hadronic and nuclear m.e.
(input can be easily updated)



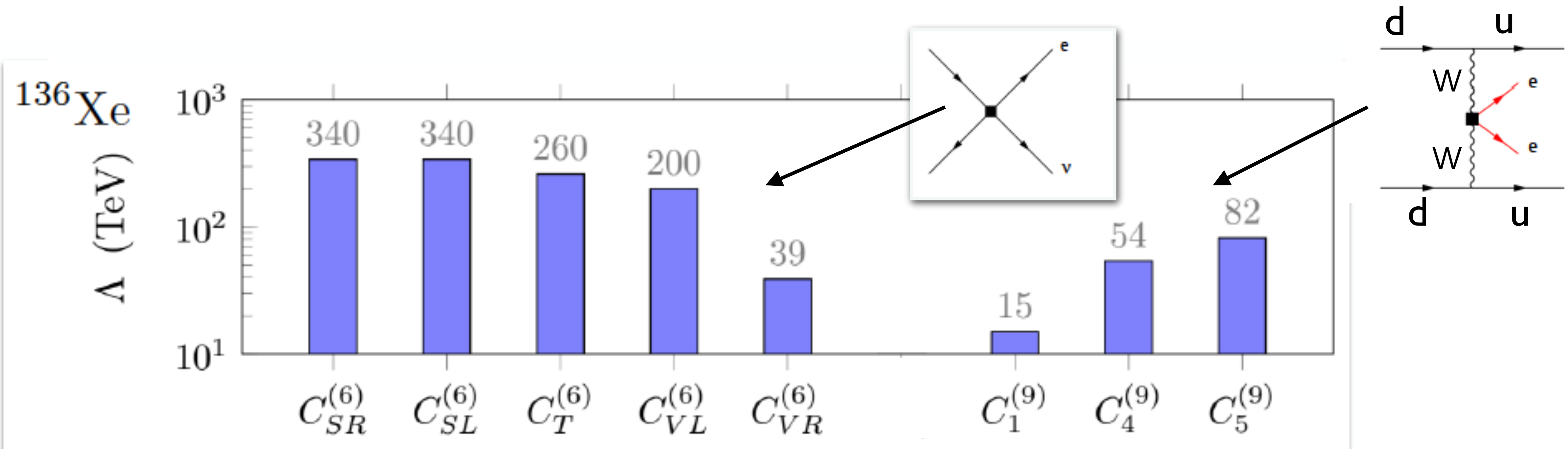
V. C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

What scales are being probed?

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

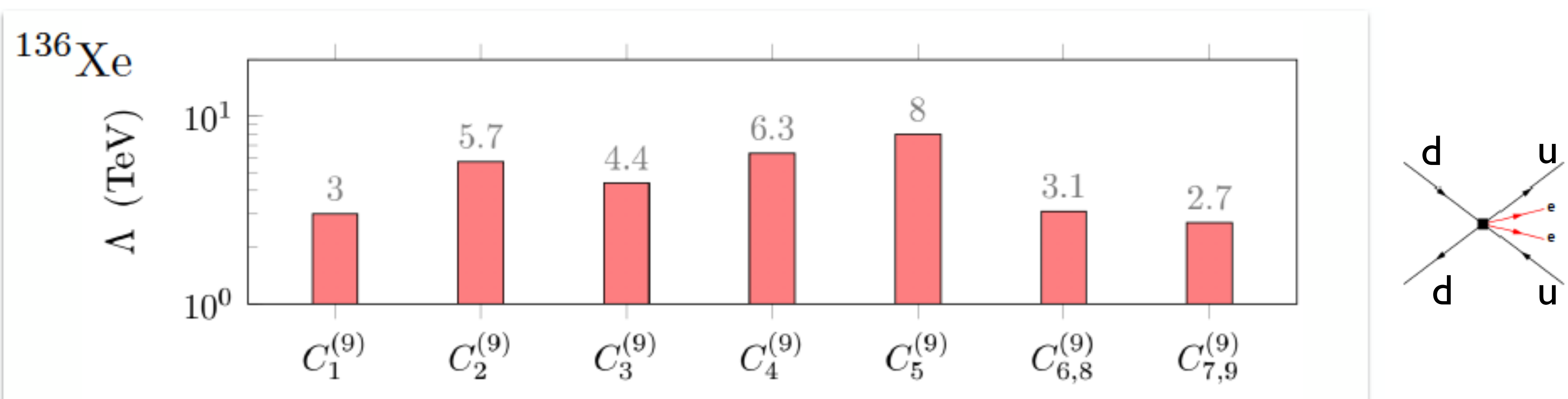
Dim 7 in SM-EFT

$(v/\Lambda)^3$



Dim 9 in SM-EFT

$(v/\Lambda)^5$



Bounds reflect dependence on Λ_X / Λ and Q/Λ_X

Backup

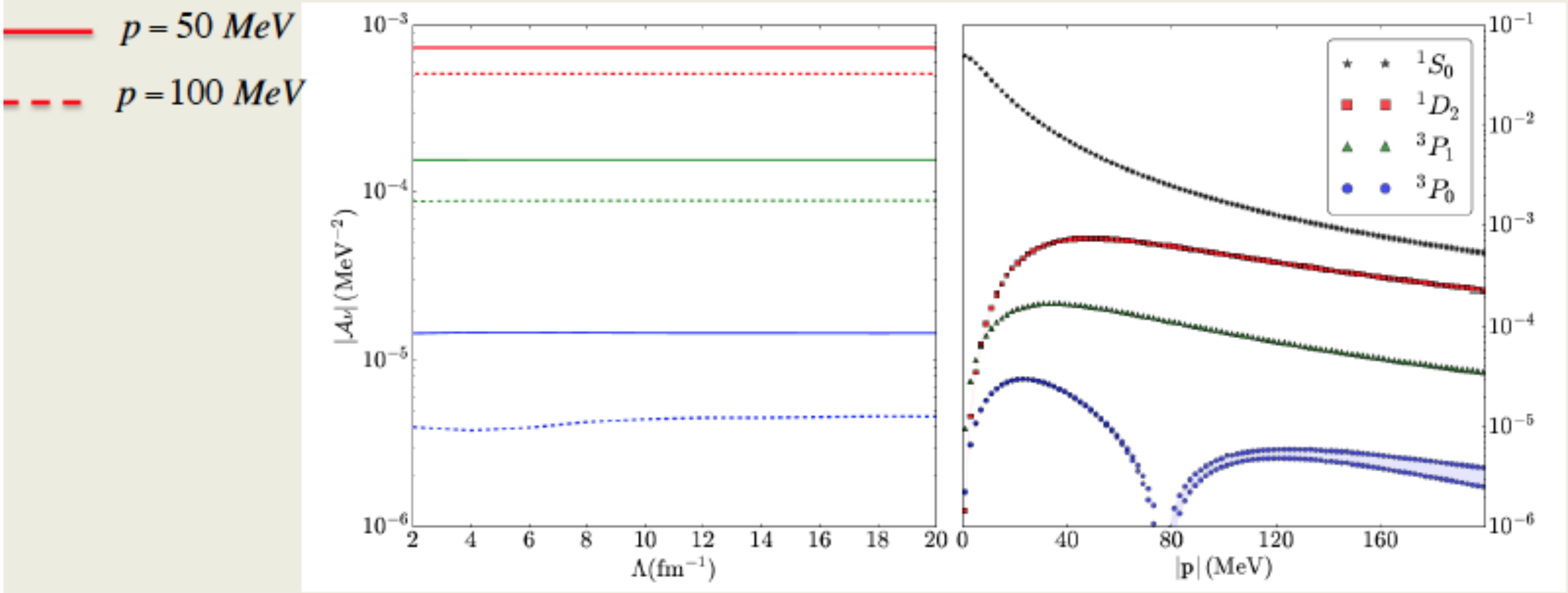
Higher waves

1907.11254

- We studied P- and D-waves in similar fashion

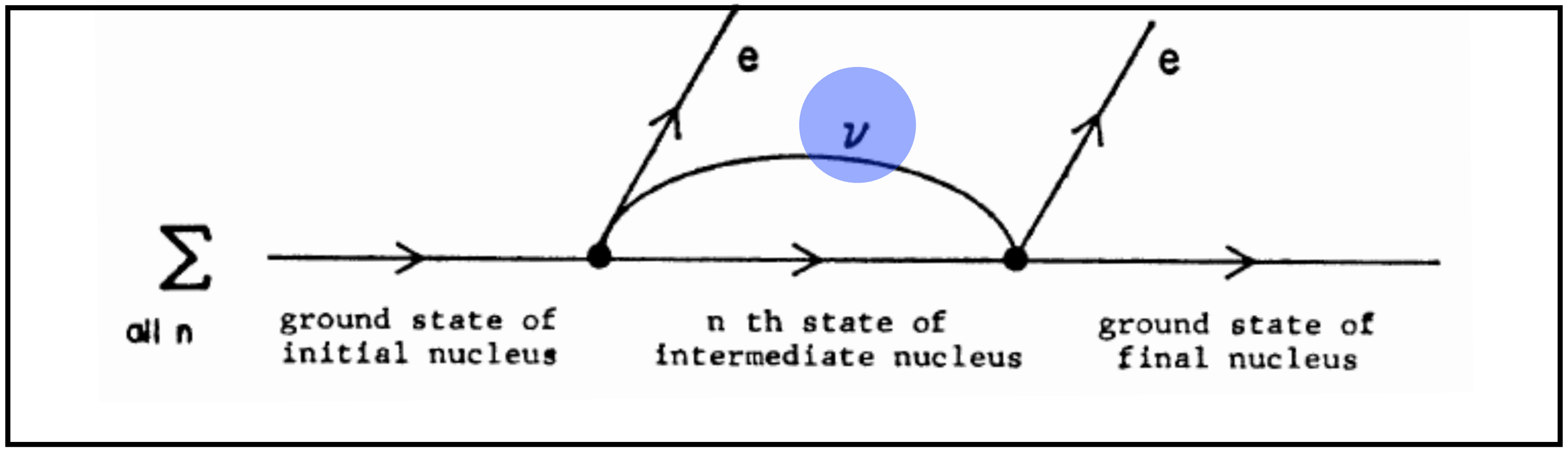
Jordy de Vries

- Strong tensor force attractive in $^3P_0$ and an NN counter term is needed for the strong phase shifts   Nogga et al ‘05
- But once NN force is renormalized so is nn → pp +ee



Ultrasoft neutrino contributions

Figure adapted from Primakoff-Rosen 1969



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

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

- Ultrasoft ν's couple to *nuclear* states: sensitivity to $E_n - E_i$ and $\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle$ that also determine 2νββ amplitude
- $T_{\rm usoft}/T_0 \sim (E_n - E_i)/(4\pi k_F)$ → N2LO contribution
- $\mu_{\rm us}$ dependence cancels with $V_{\nu,2}$: consistency check