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EFT approach to neutrino-less double beta decay

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Outline

- "End-to-end" Effective Field Theory (EFT) *framework* for Lepton Number Violation (LNV) and $0\nu\beta\beta$ and its benefits

- $0\nu\beta\beta$ from light Majorana ν exchange mechanism

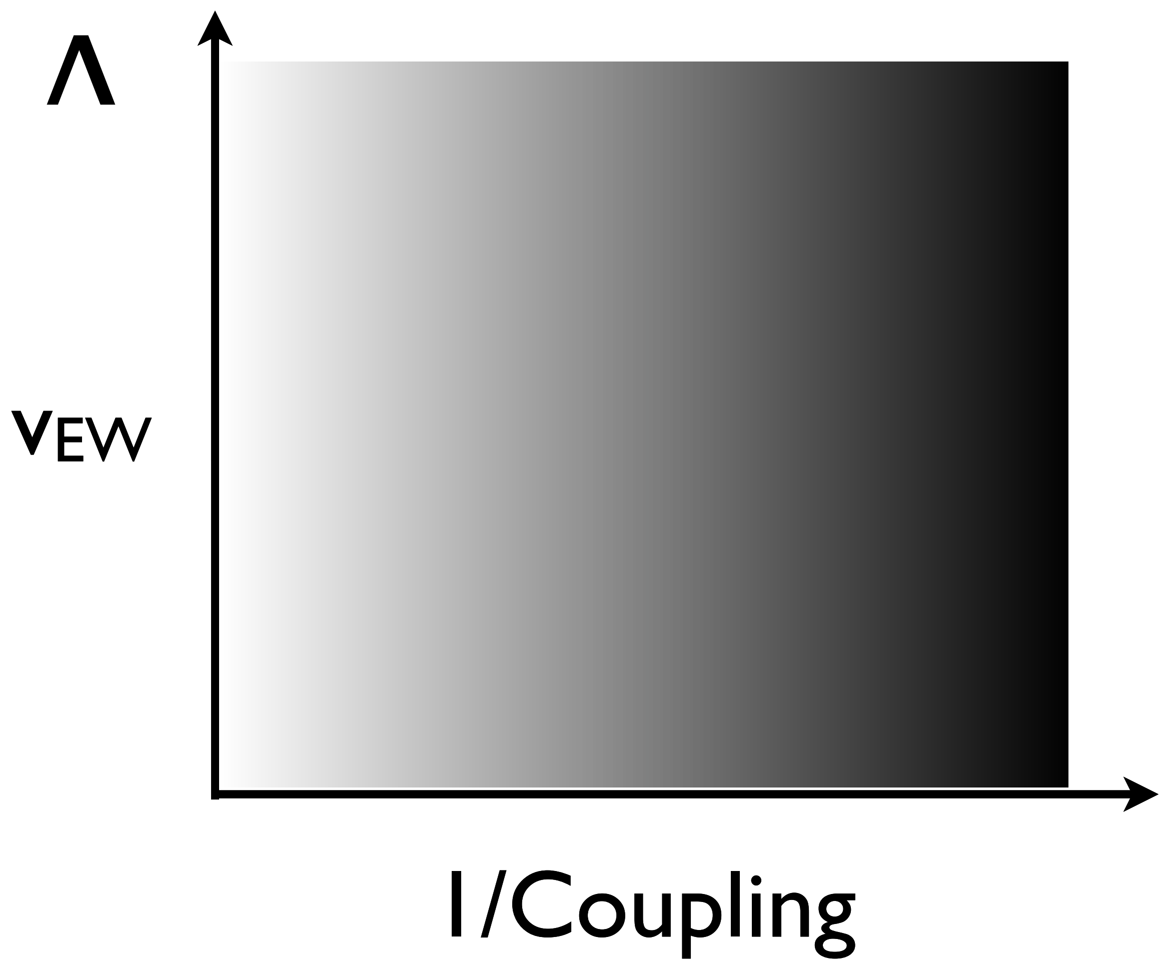
- $0\nu\beta\beta$ from (multi)TeV-scale dynamics [if time permits]

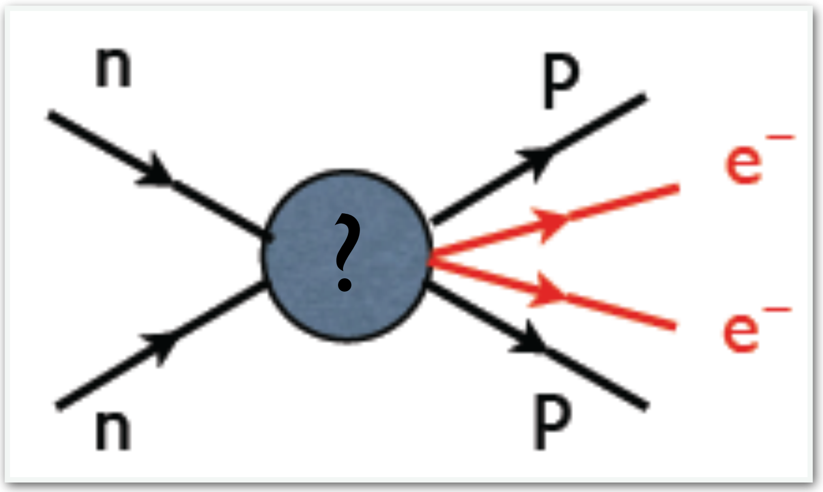
Special thanks to collaborators:
W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck, A. Walker-Loud

EFT framework for LNV and neutrino-less double beta decay

0νββ physics reach

- Ton-scale 0νββ searches ($T_{1/2}$ >$10^{27\text{-}28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms





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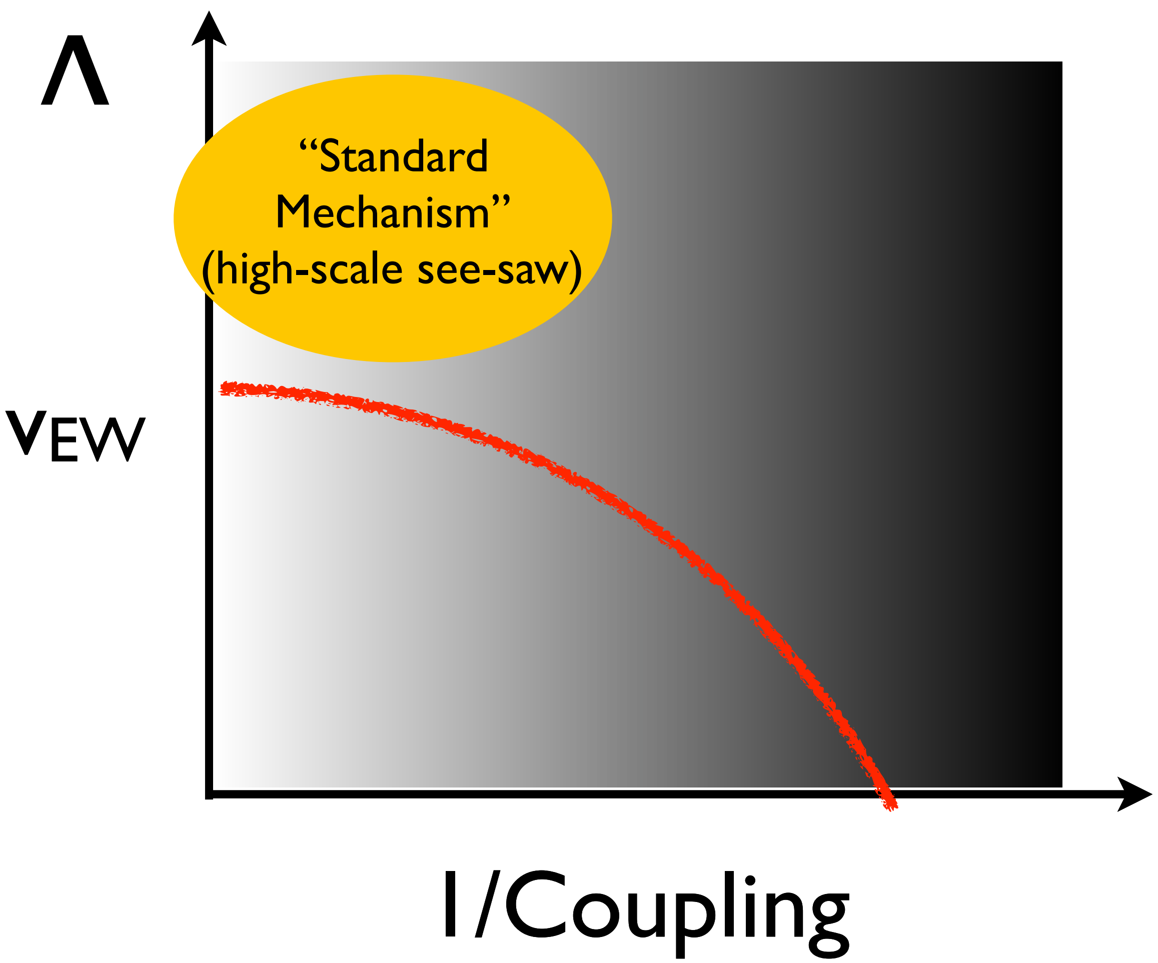

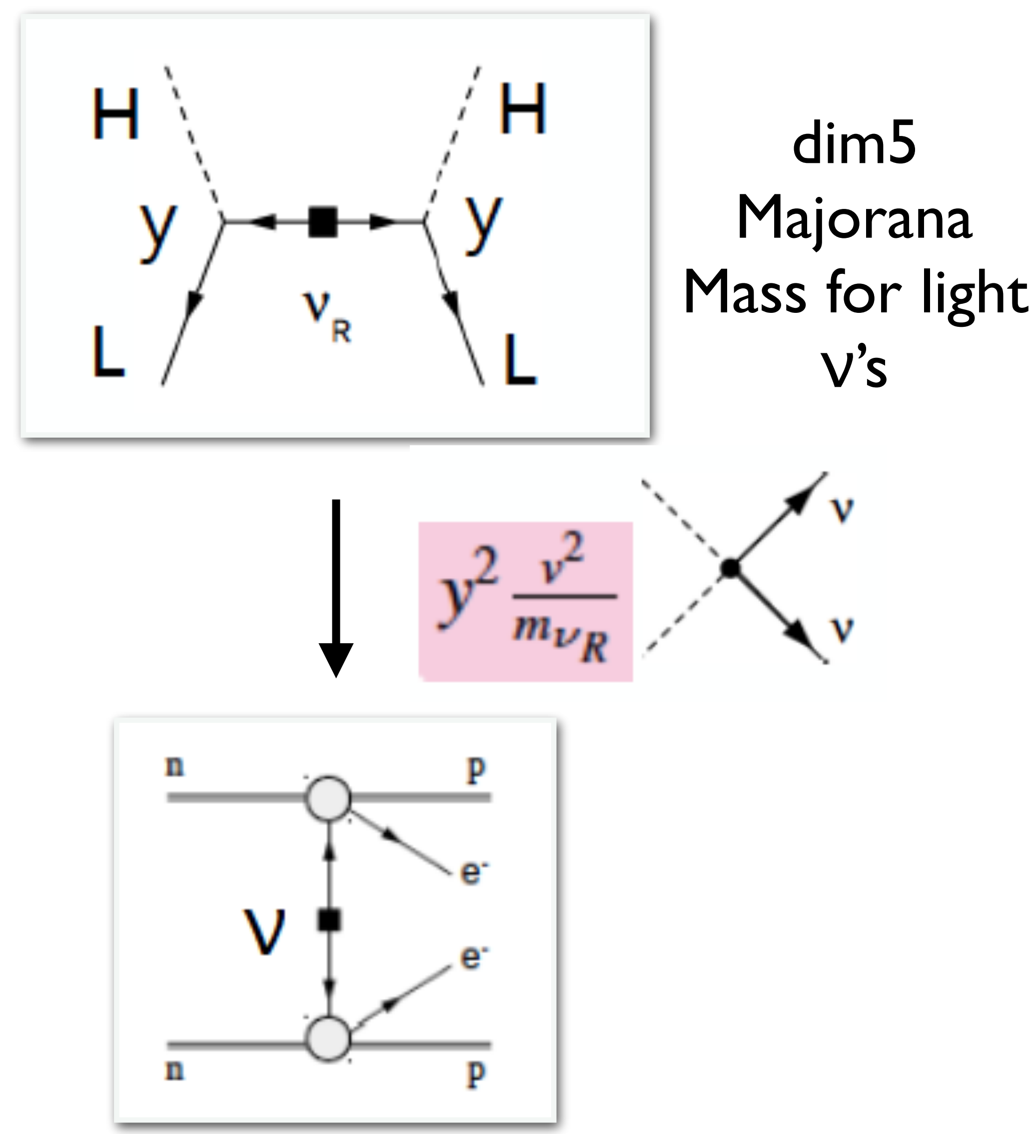

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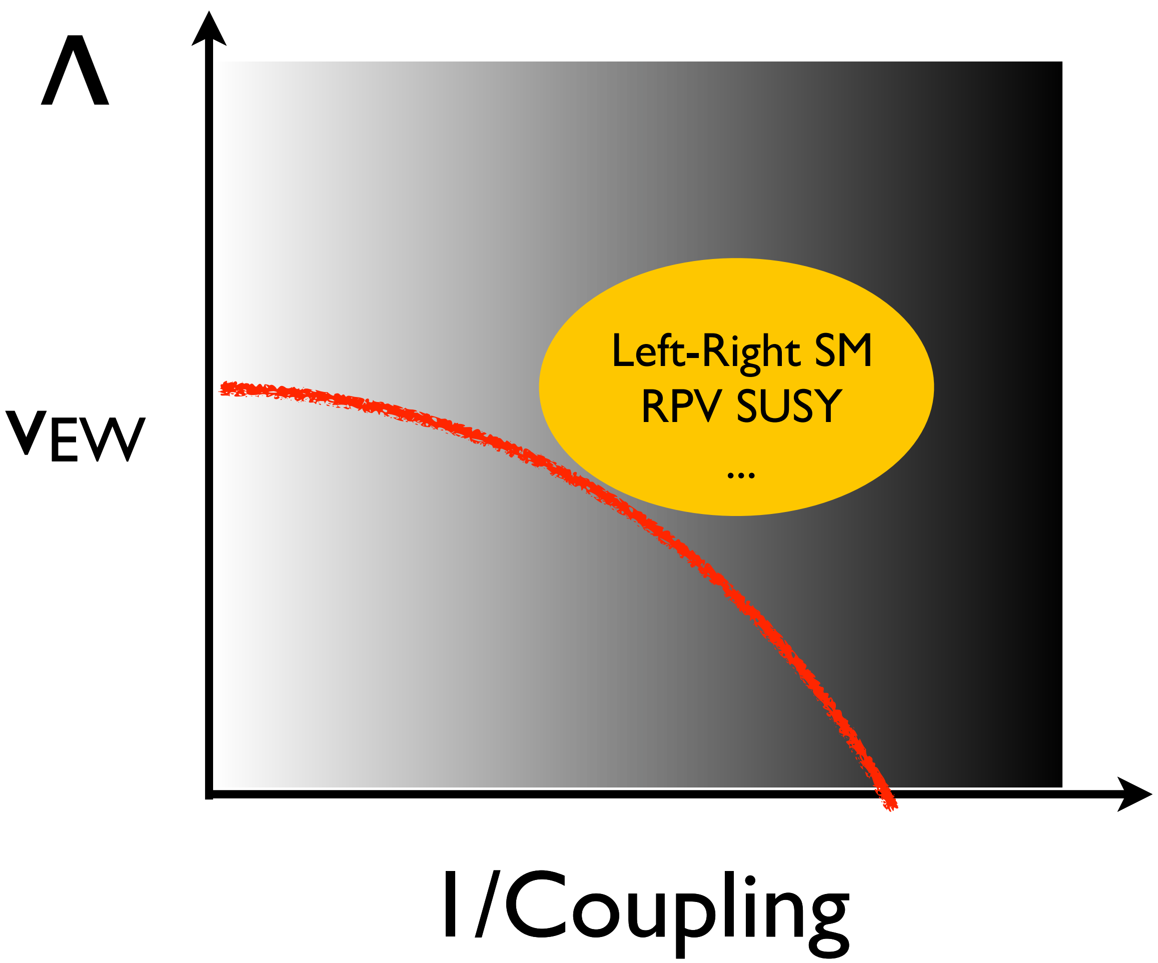

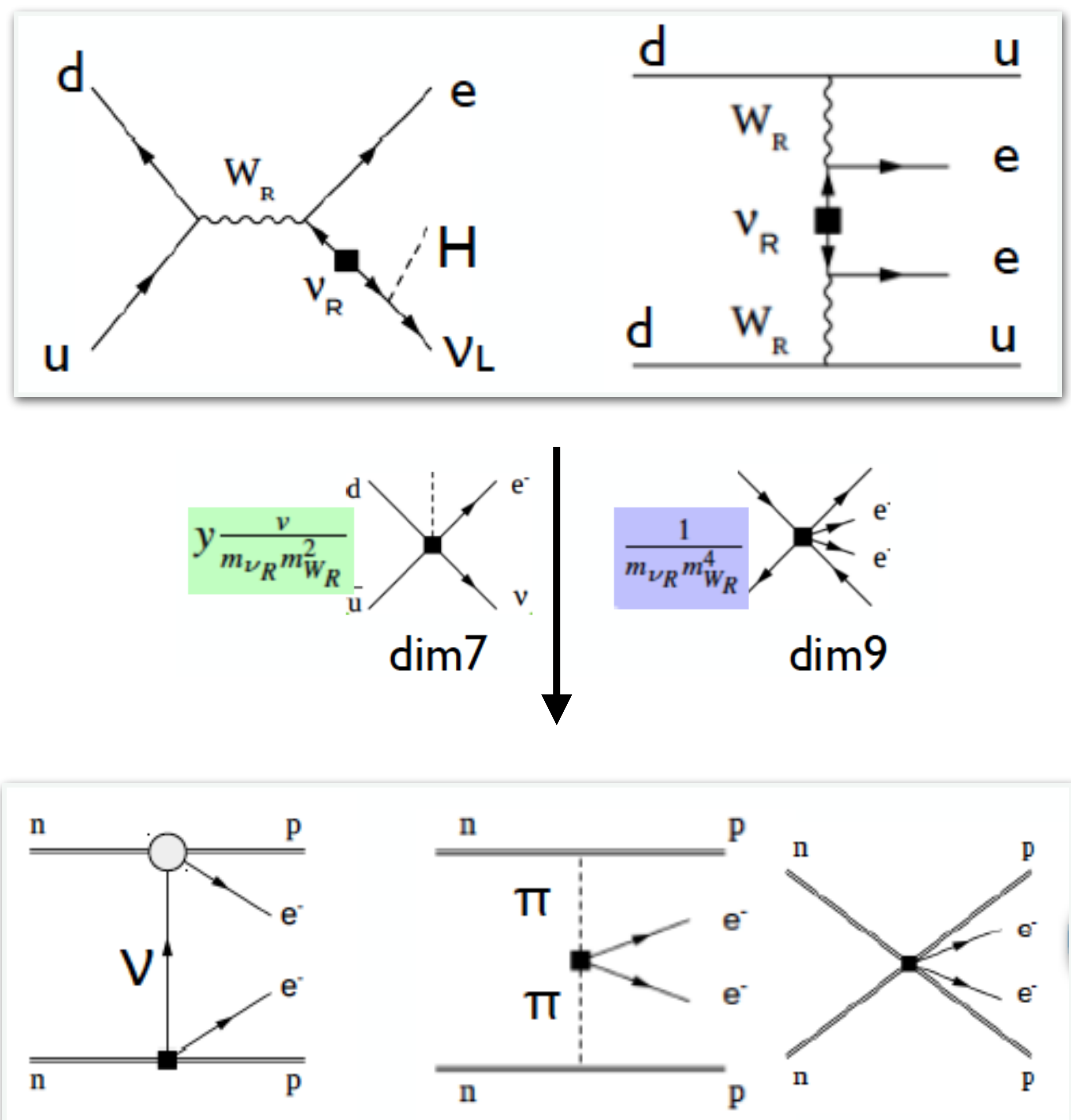

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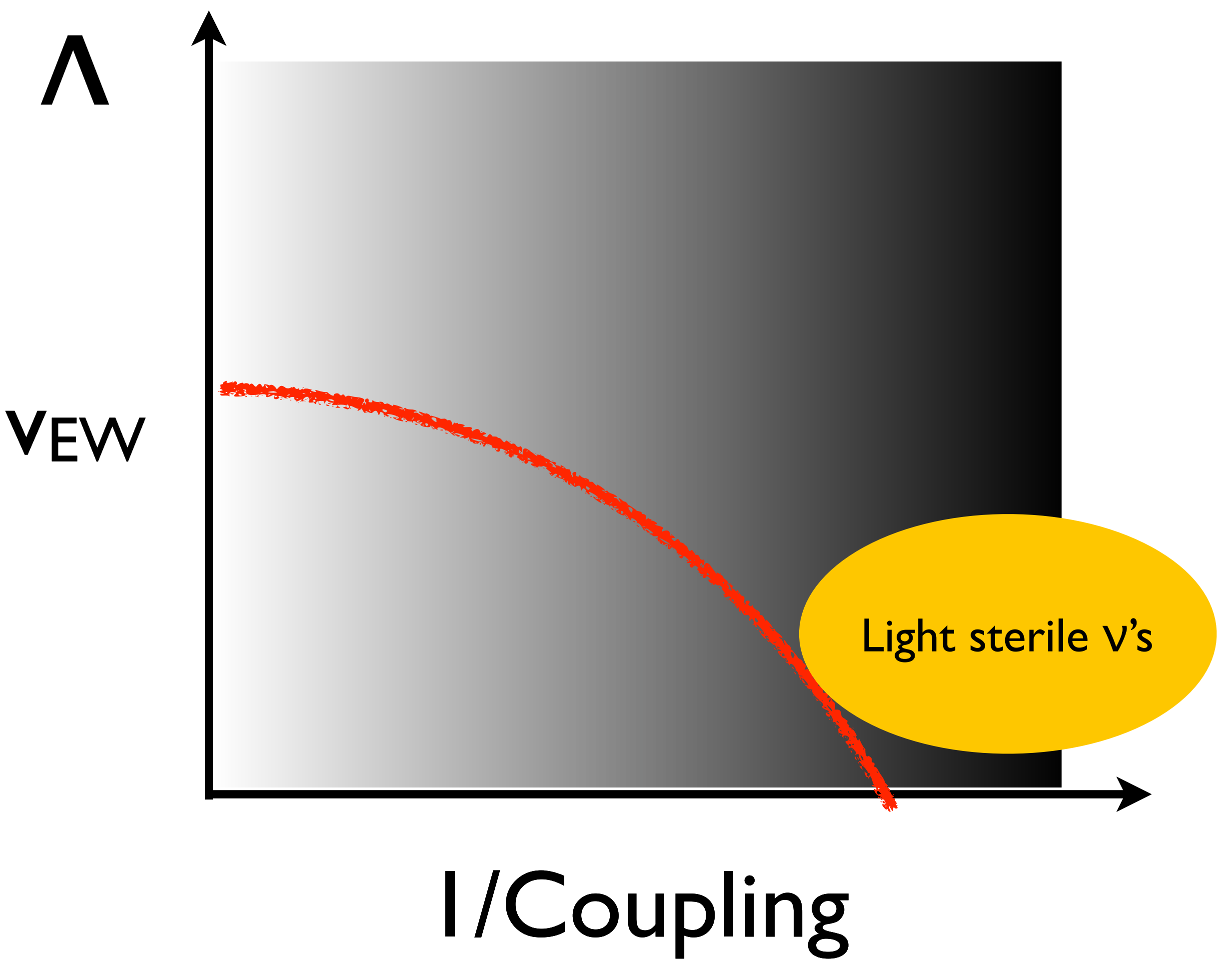
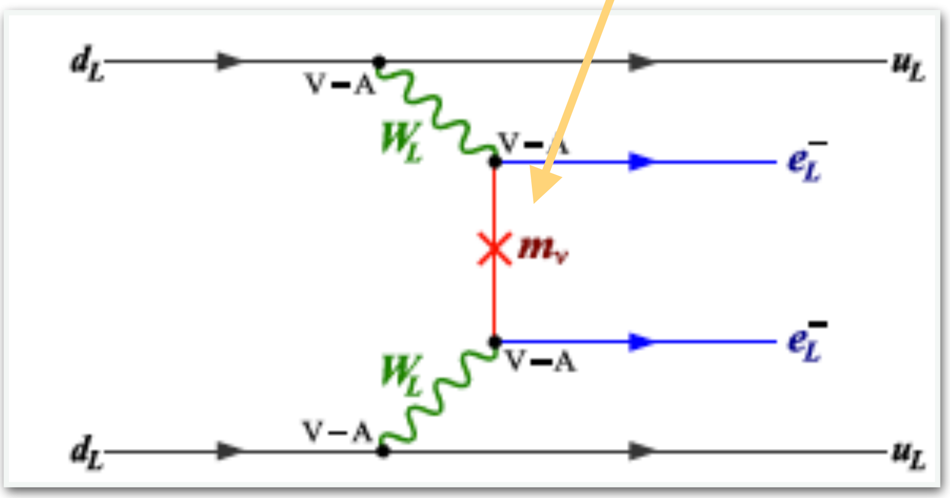
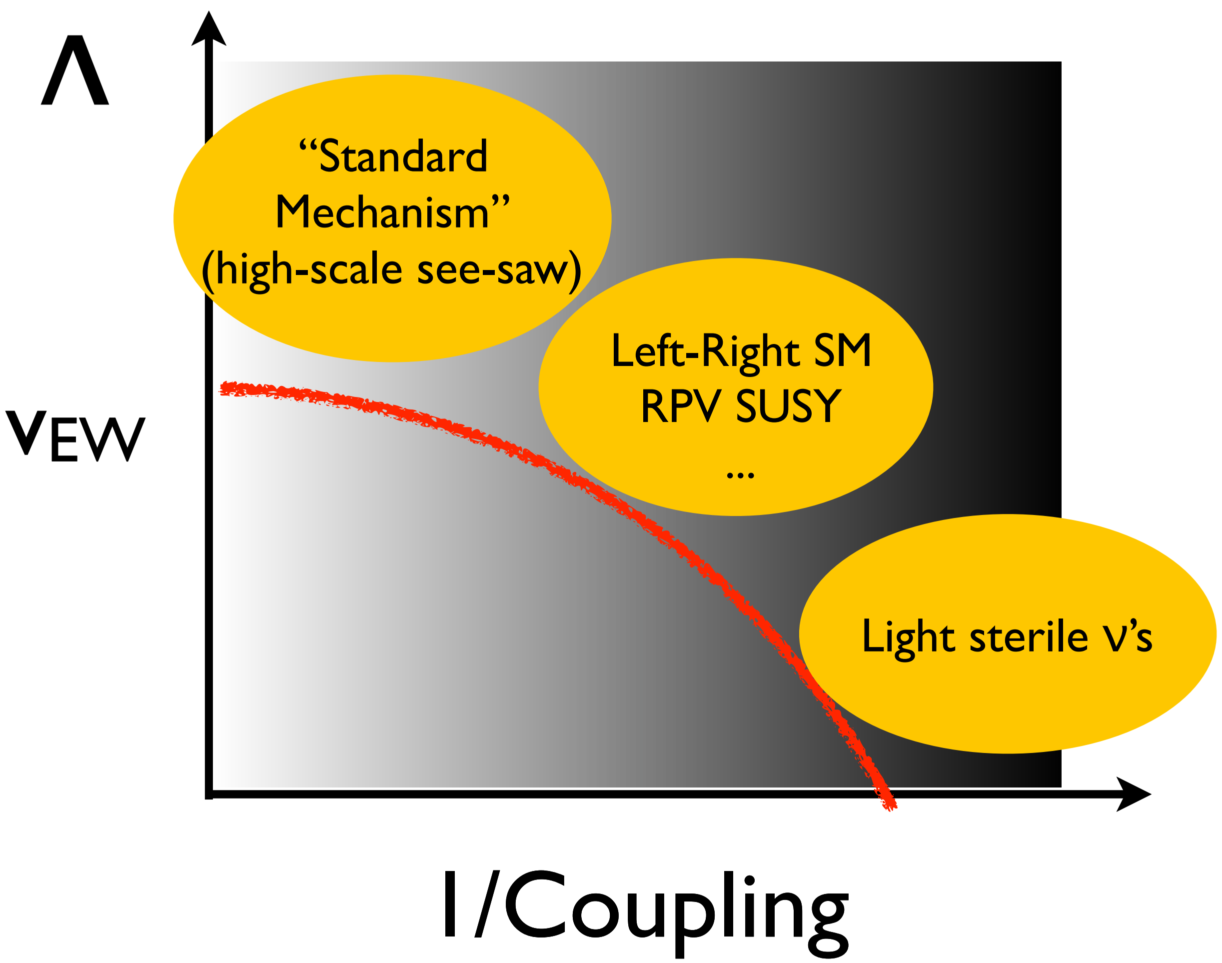


Light right-handed Majorana neutrinos:
M_R ~ eV → GeV:



$0\nu\beta\beta$ physics reach

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms

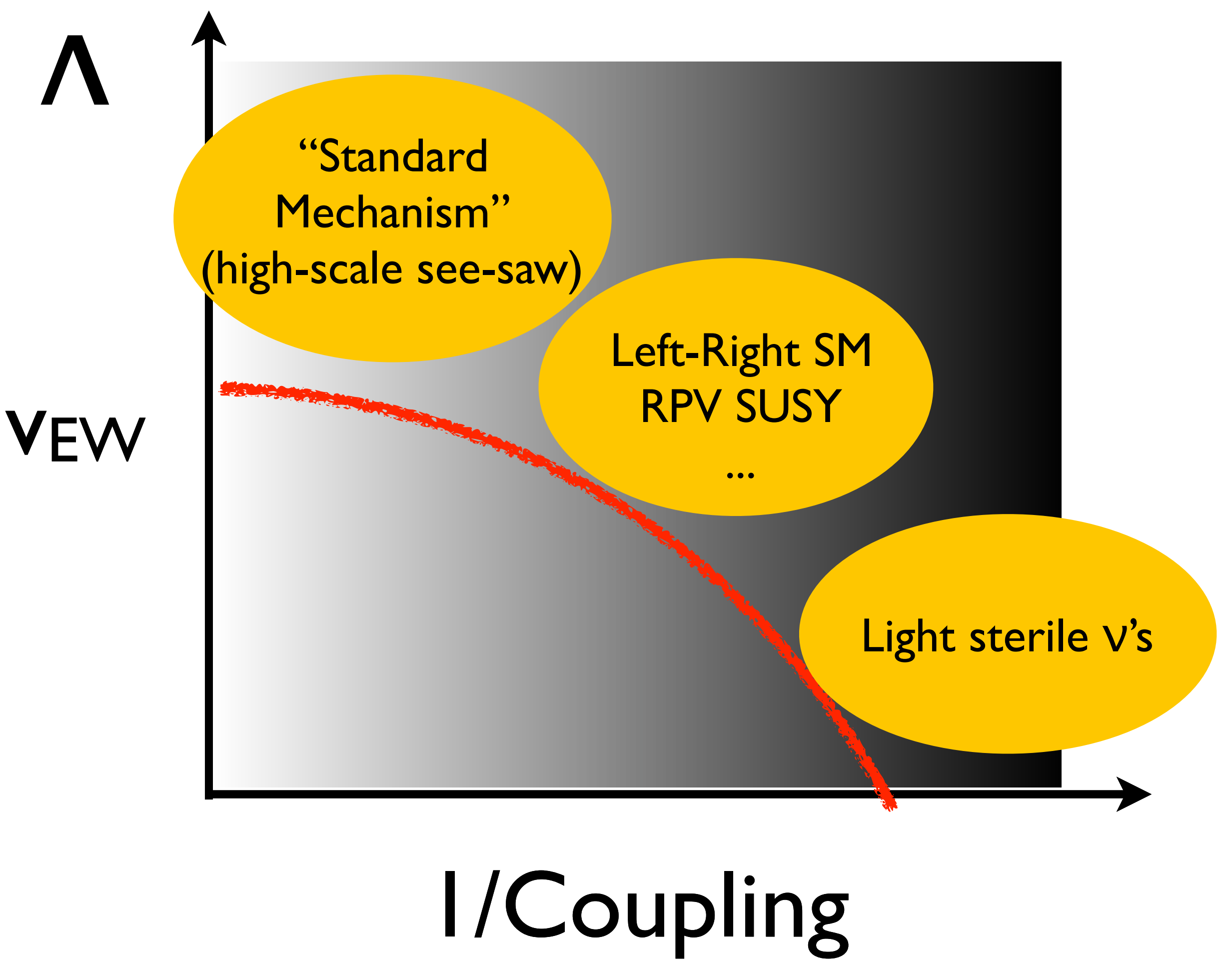


Impact of $0\nu\beta\beta$ searches most efficiently analyzed in a BSM-EFT framework, encompassing a large class of underlying models

Hadronization of resulting quark-level operators is most efficiently and rigorously achieved using chiral EFT techniques

0νββ physics reach

- Ton-scale 0νββ searches ($T_{1/2}$ >$10^{27\text{-}28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms

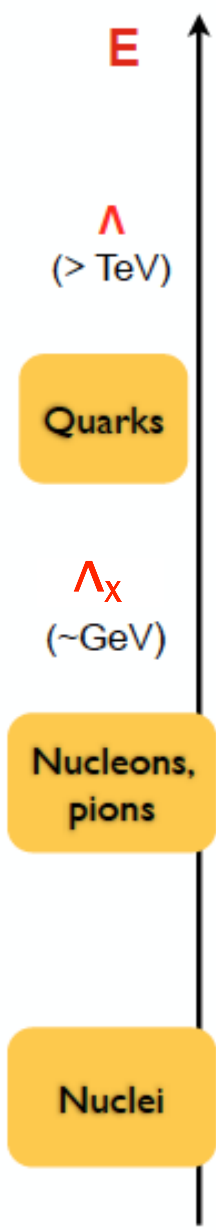


Impact of 0νββ searches most efficiently analyzed in a BSM-EFT framework, encompassing a large class of underlying models

Hadronization of resulting quark-level operators is most efficiently and rigorously achieved using chiral EFT techniques

"End-to-end" EFT framework:
connecting LNV scale Λ to nuclear scales, with controllable uncertainties

EFT framework for 0νββ



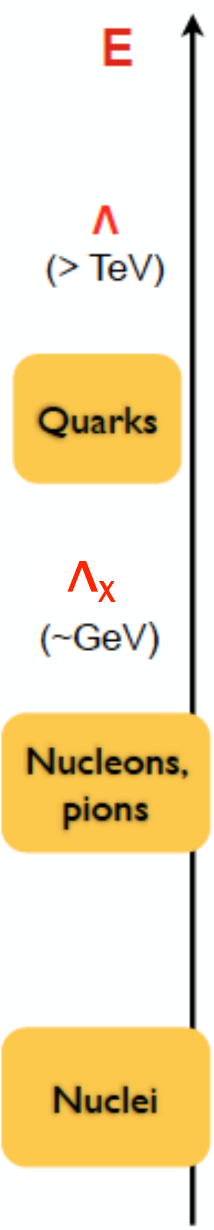
$$\mathcal{L}_{\rm BSM}$$

↓ Integrate out heavy particles

$$\mathcal{L}_{\rm eff} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

LNV in the
"Standard Model EFT":
only dim=5,7,9,…

EFT framework for 0νββ



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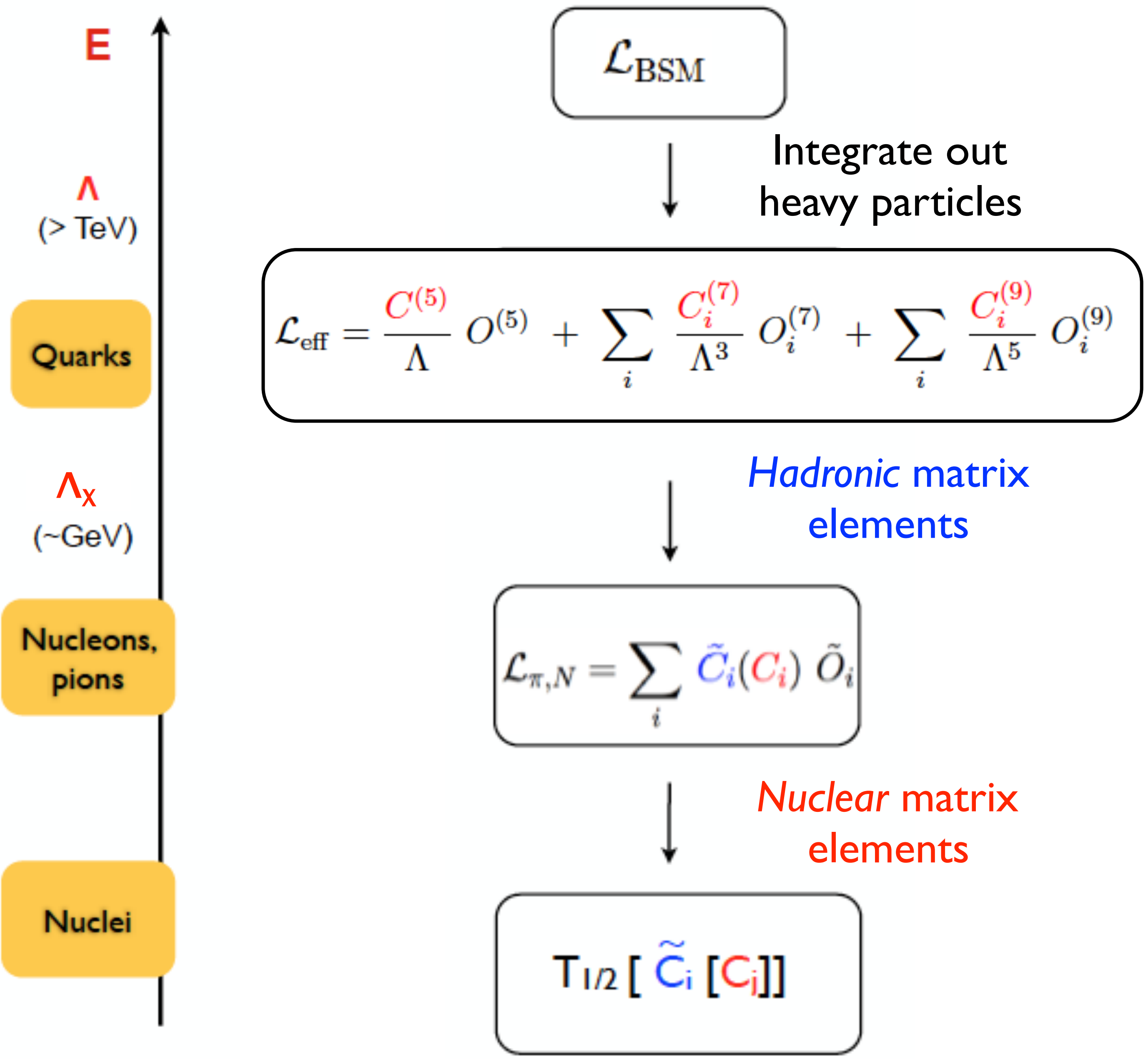
↓ *Hadronic* matrix elements

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

Chiral EFT:

Map ΔL=2 interactions onto π, N operators, organized according to power-counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$)

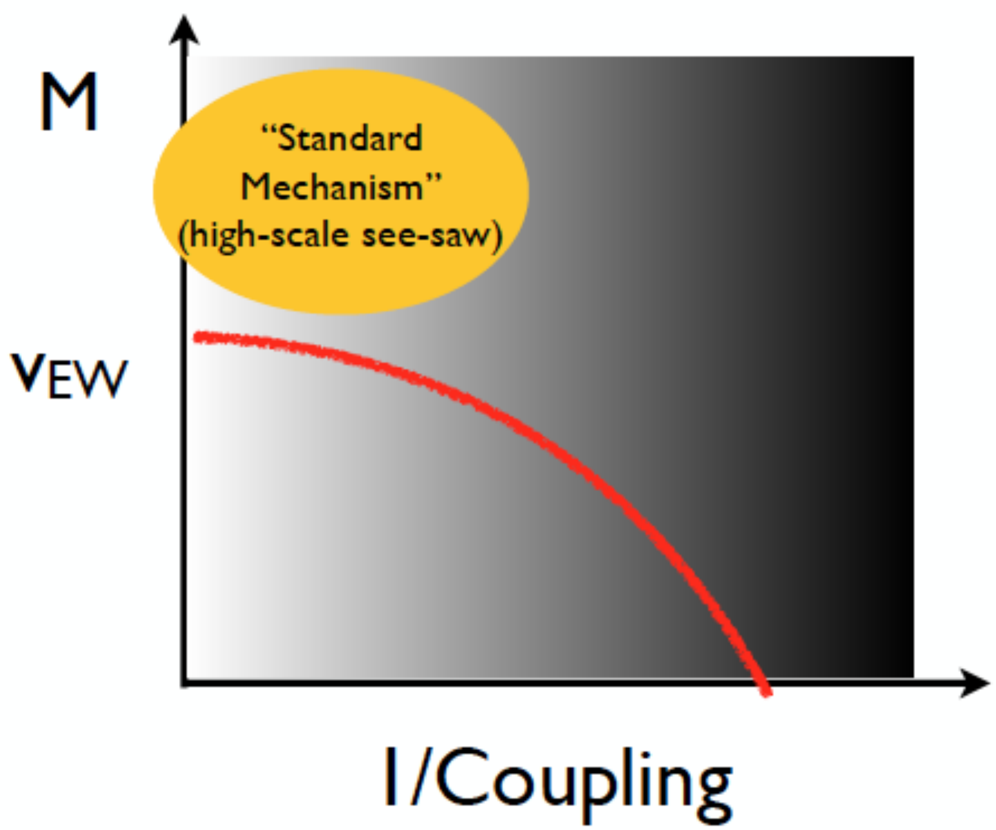
EFT framework for 0νββ



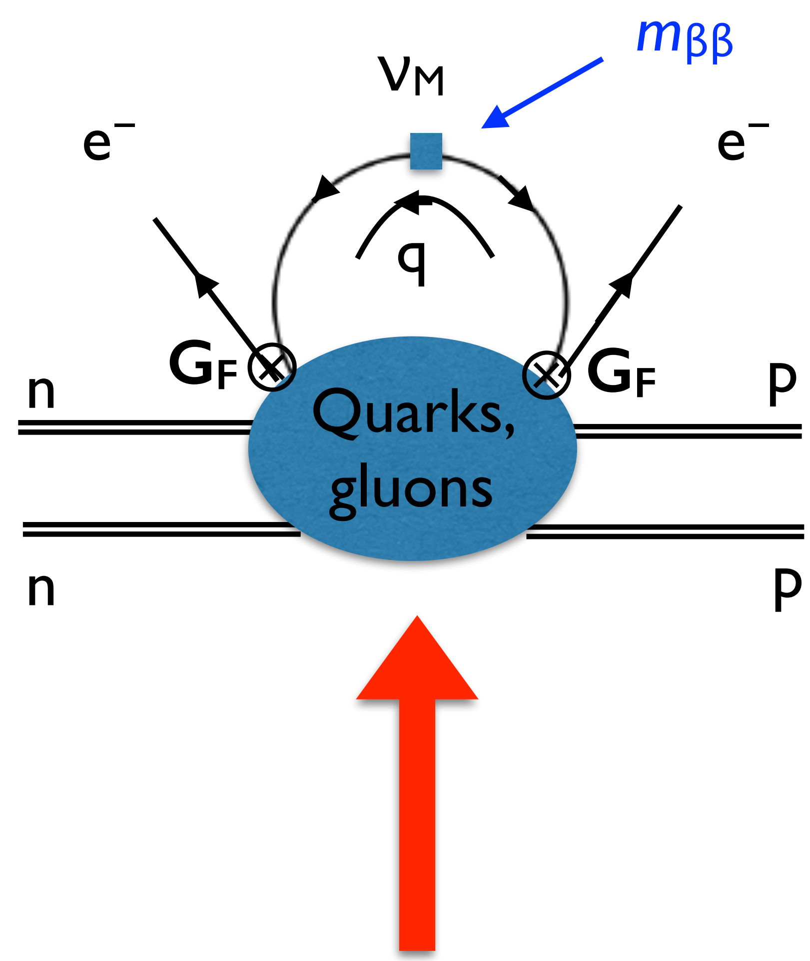
Chain of EFTs +
lattice QCD & many-body methods

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

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



Hadronic ΔL=2 amplitudes in EFT



Effective Lagrangian just below the weak scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} - \frac{4G_F}{\sqrt{2}} V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2}\, \nu_{eL}^T C \nu_{eL} + \text{H.c.}$$

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729, Phys.Rev. C97 (2018) no.6, 065501

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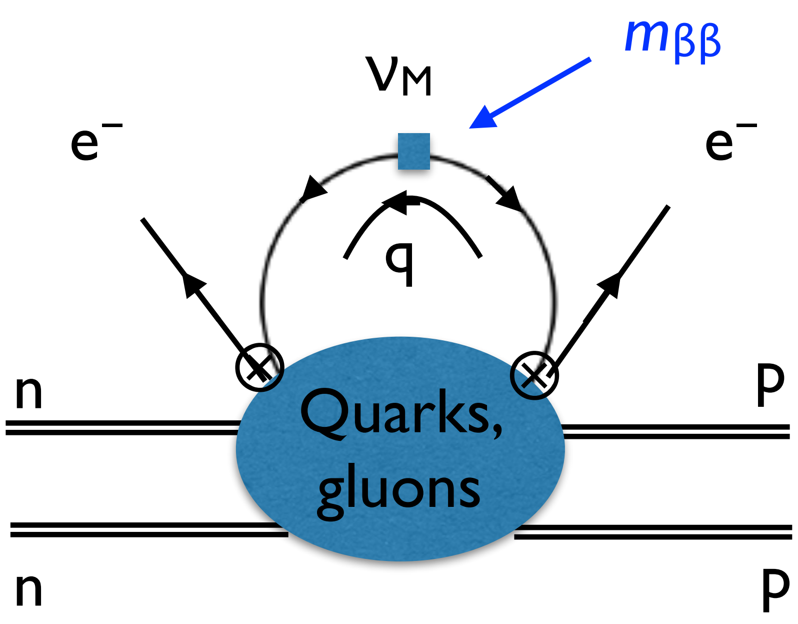

LNV hadronic amplitudes such as nn → ppee receive contributions from broad range of neutrino virtual momenta (q)

Chiral EFT captures contributions from all momentum regions

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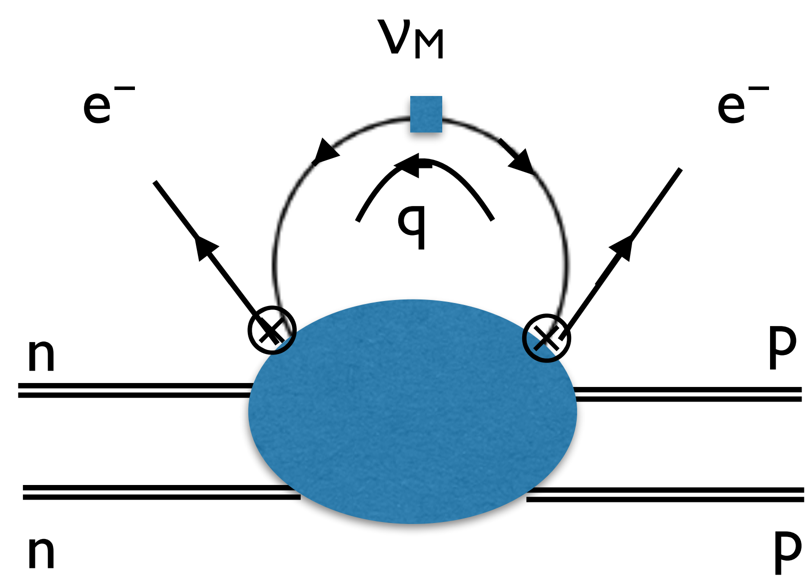
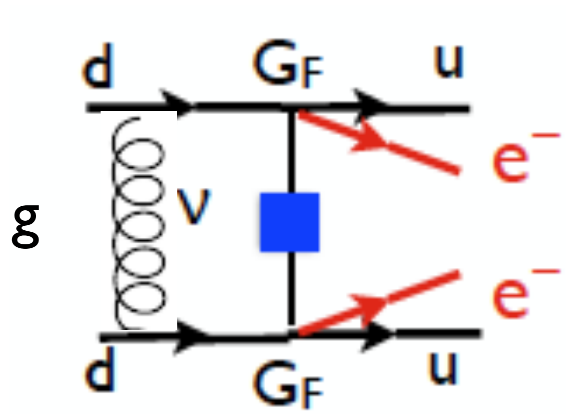
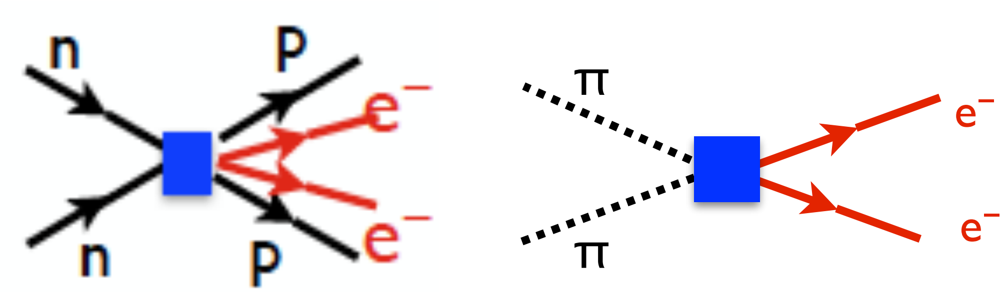


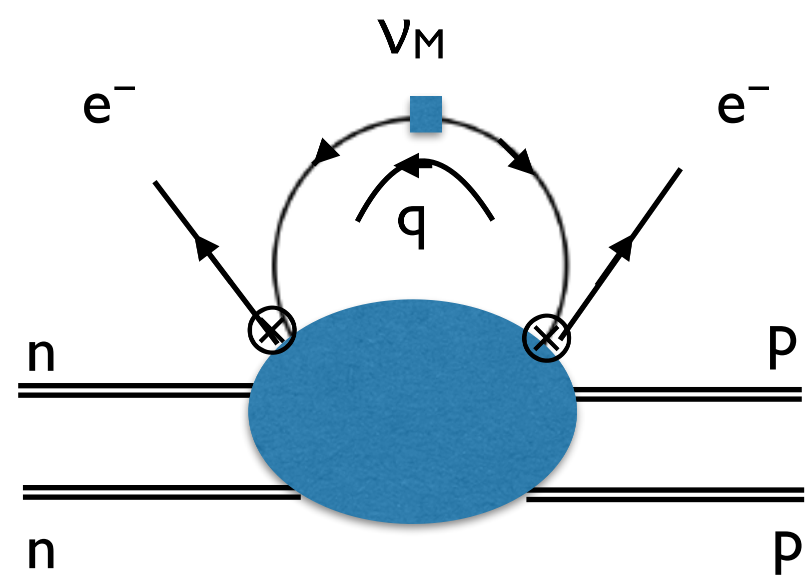
"Hard neutrinos":
E, |**q**| > Λ_χ ~ m_N ~ GeV





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

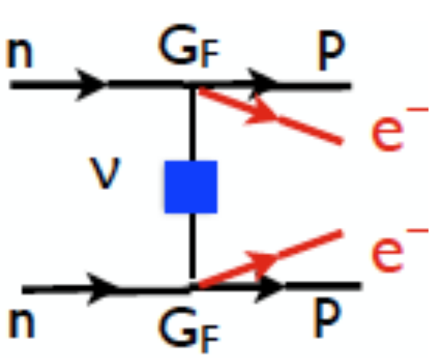
Hadronic ΔL=2 amplitudes in EFT

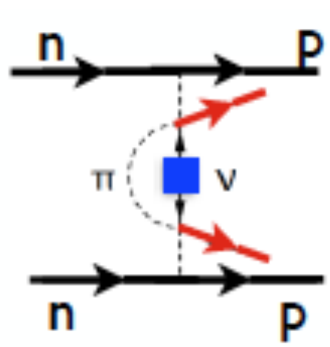


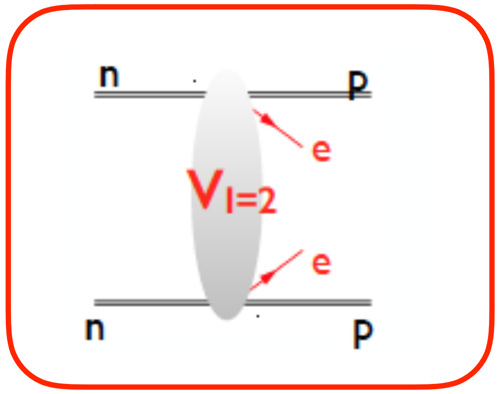
“Soft” & “Potential” neutrinos:

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

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



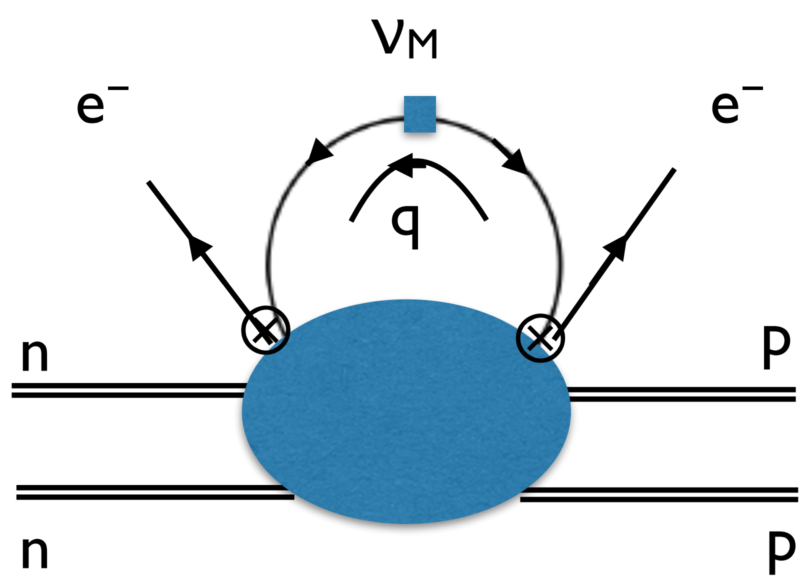




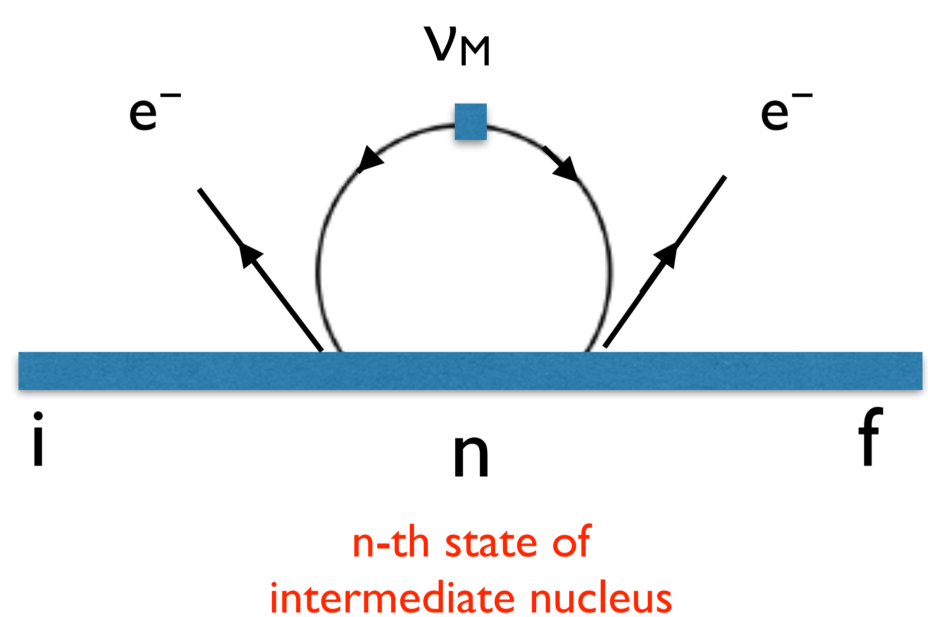
Non-local “Neutrino potential”

(long- and pion-range) mediating nn→pp

Hadronic ΔL=2 amplitudes in EFT



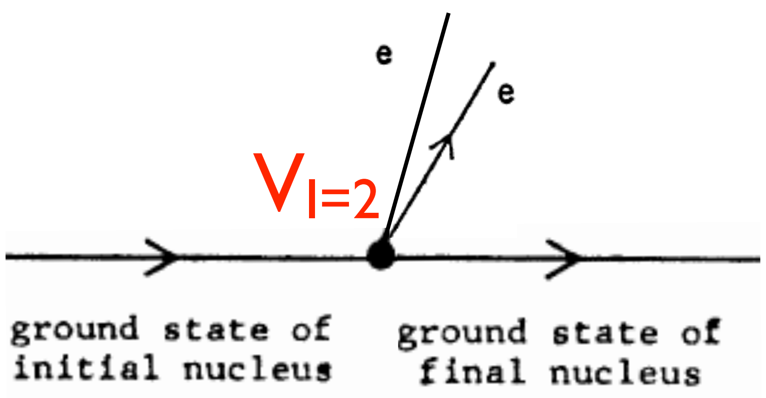
"UltraSoft" neutrinos:
(E, |**q**|) << k_F



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

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

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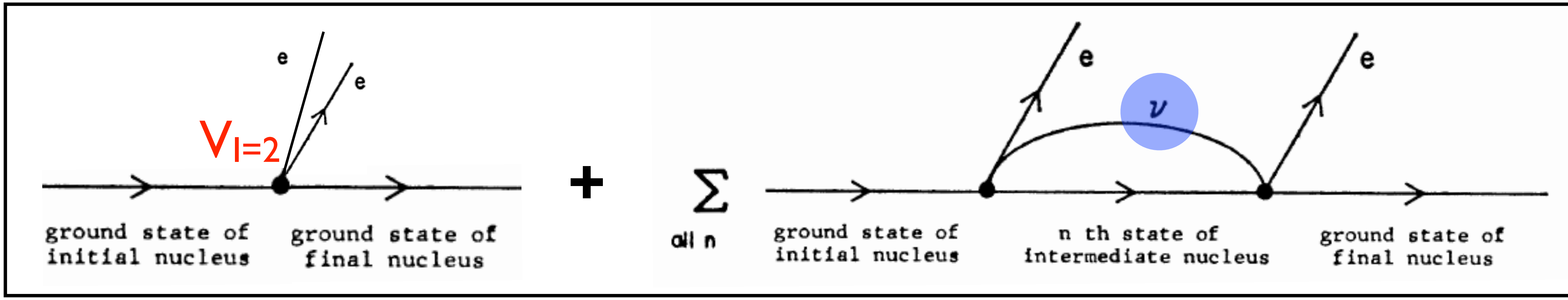

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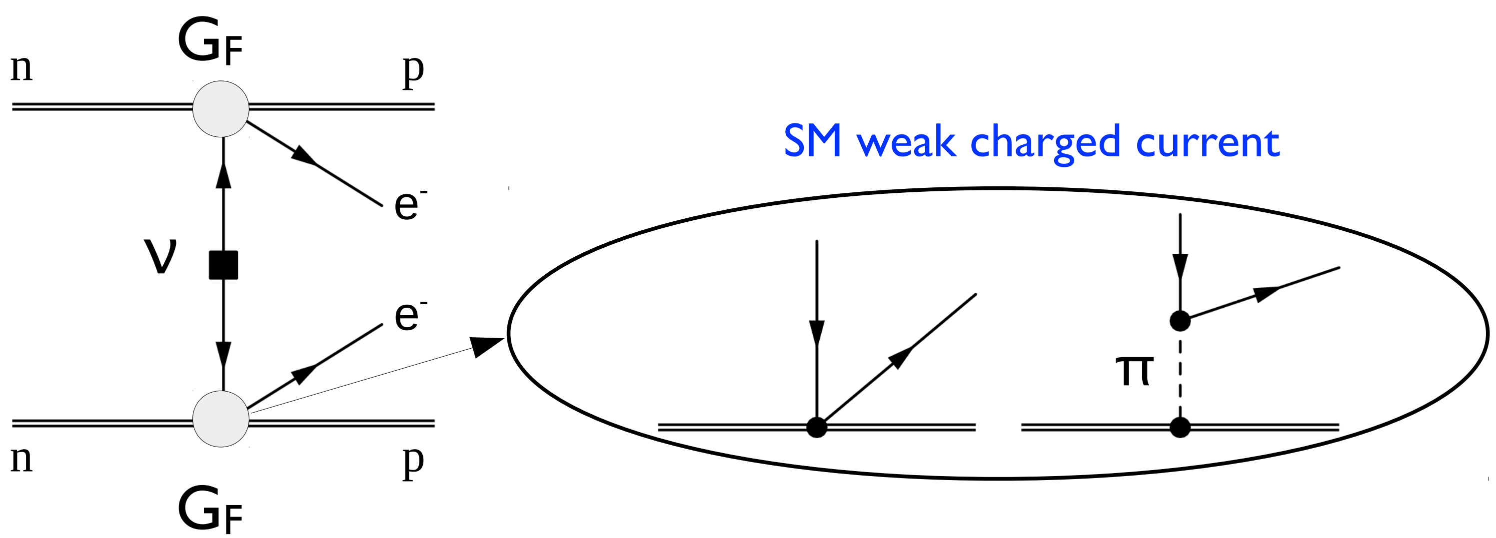
Ultrasoft ν

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

EFT justifies the "closure approximation" and quantifies corrections to it

Leading order 0νββ potential

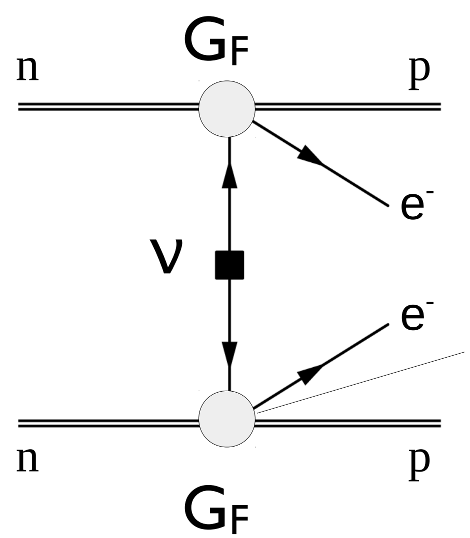


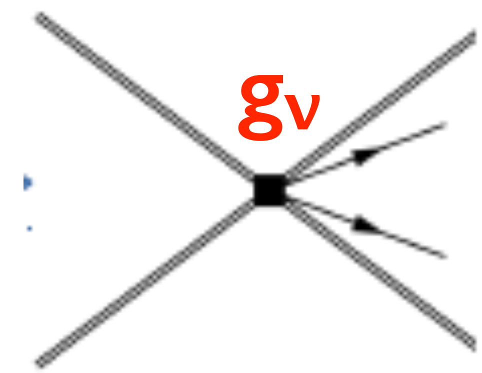
- Tree-level exchange of Majorana neutrinos

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

Hadronic input: g_A

Leading order 0νββ potential





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Hadronic input: g_A

- Symmetries allow one to write down a contact term

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

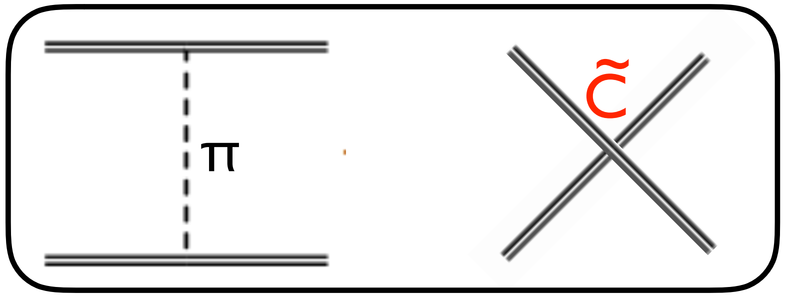
$g_\nu \sim 1/(4\pi F_\pi)^2$ in NDA / Weinberg counting (and hence sub-leading)

But is it?

Scaling of contact term

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}

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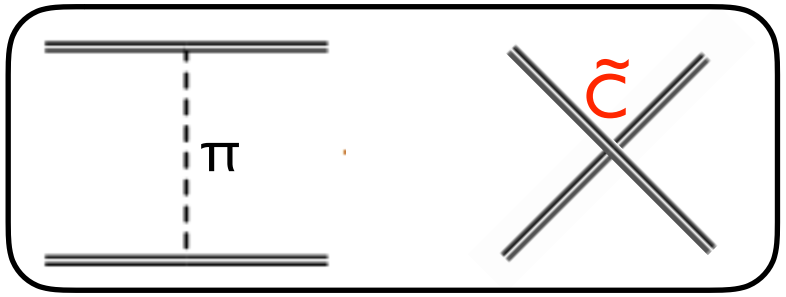

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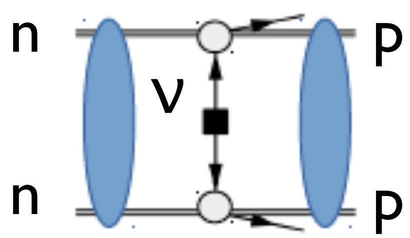

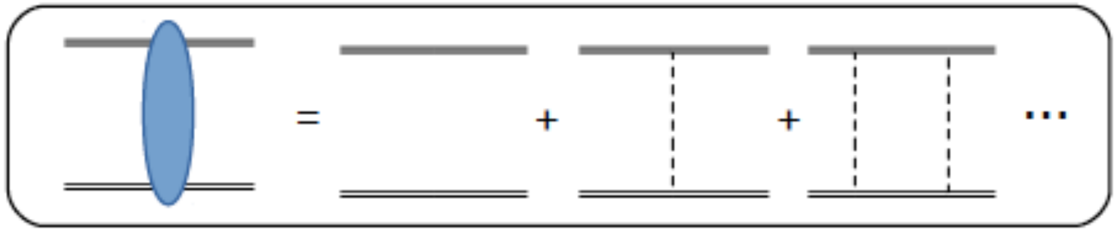

UV finite

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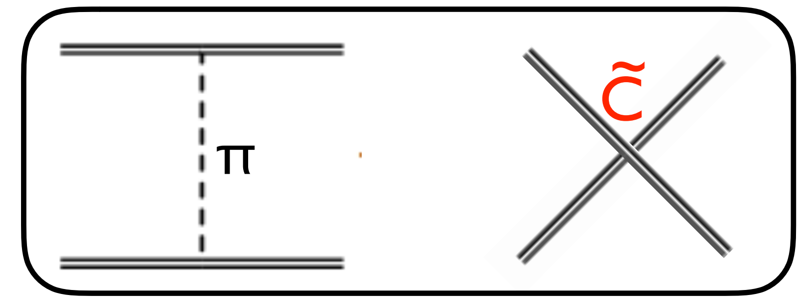

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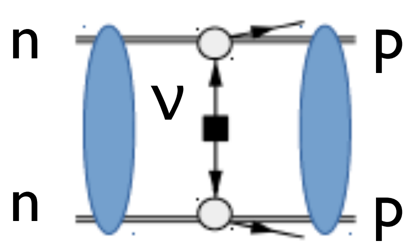

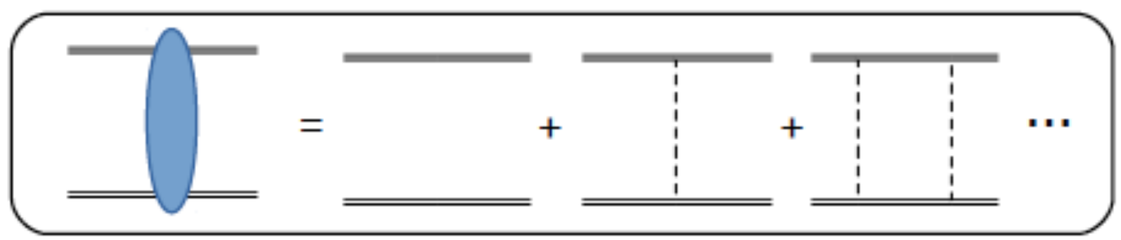

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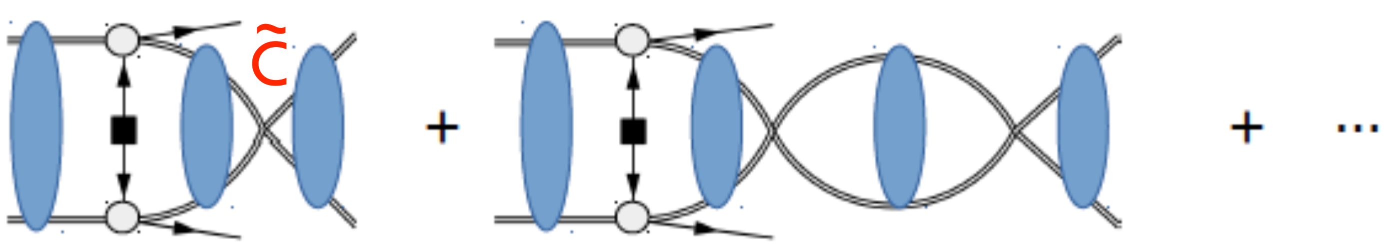

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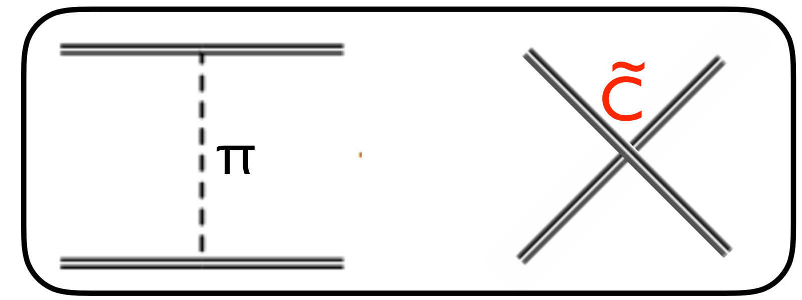

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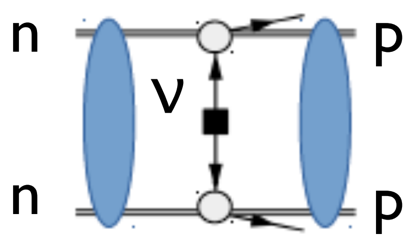

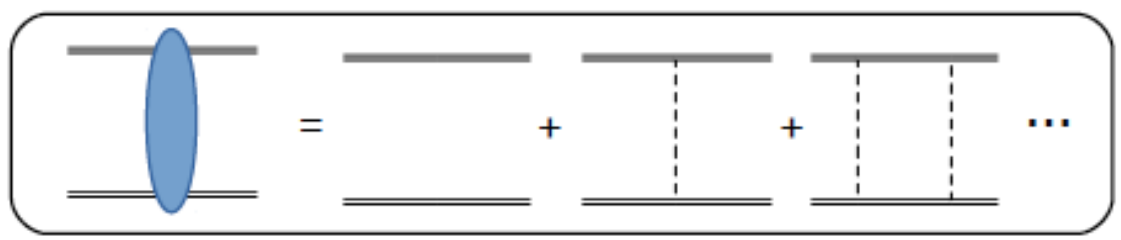

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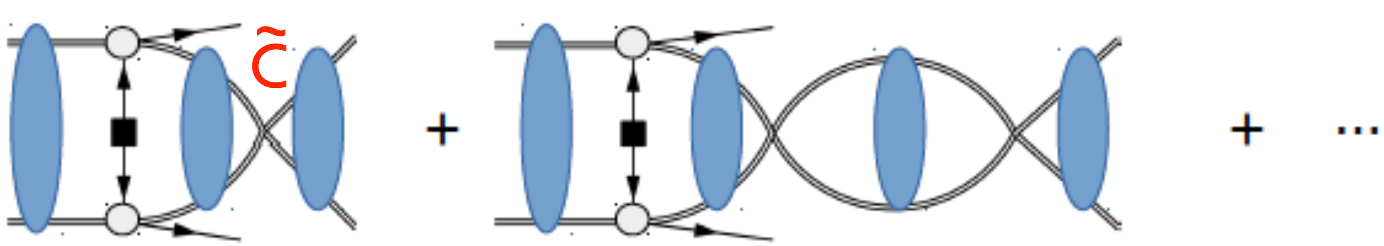

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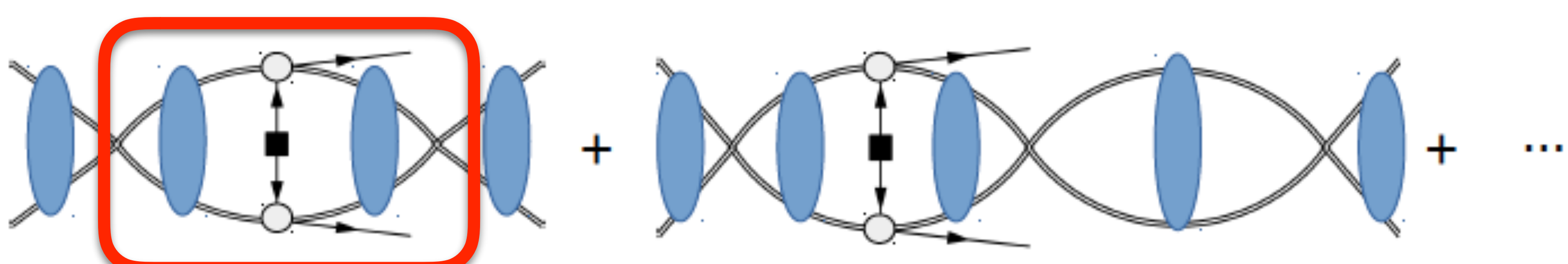
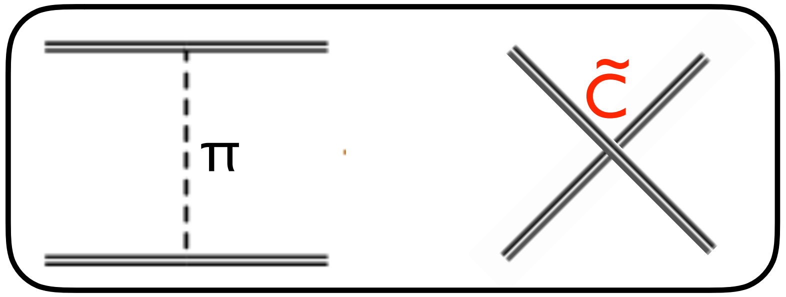


2-loop diagram is UV divergent!

Scaling of contact term

Weinberg 1991, Kaplan-Savage-Wise 1996

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



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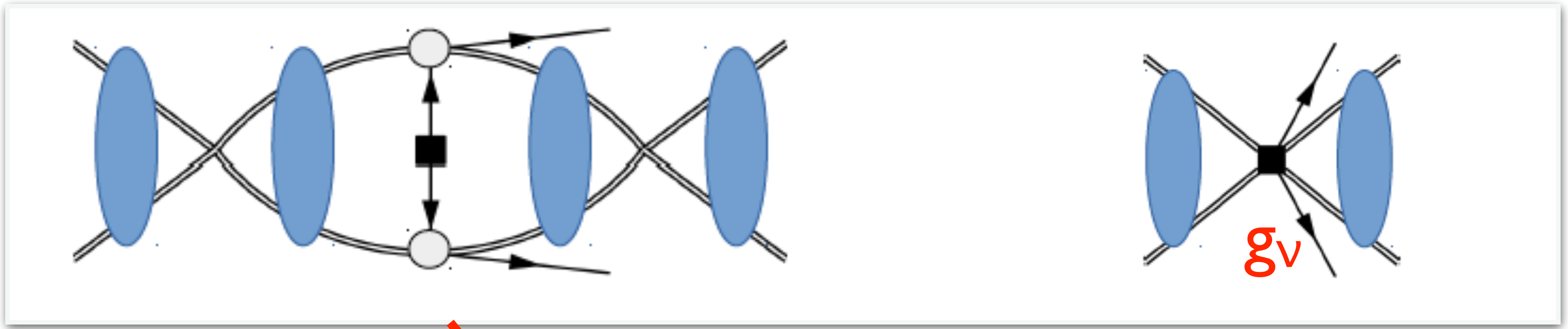
- Renormalization requires contact LNV operator at LO!



V. Cirigliano, 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 $g_\nu \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$, same order as $1/q^2$ from tree-level neutrino exchange

If you don't like Feynman diagrams...

- Same conclusion obtained by solving the Schroedinger equation
  - Use smeared delta function to regulate short range strong potential: $\tilde{C} \to \tilde{C}\,(R_S) \sim 1/F_\pi^2$

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

  - Compute amplitude

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

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

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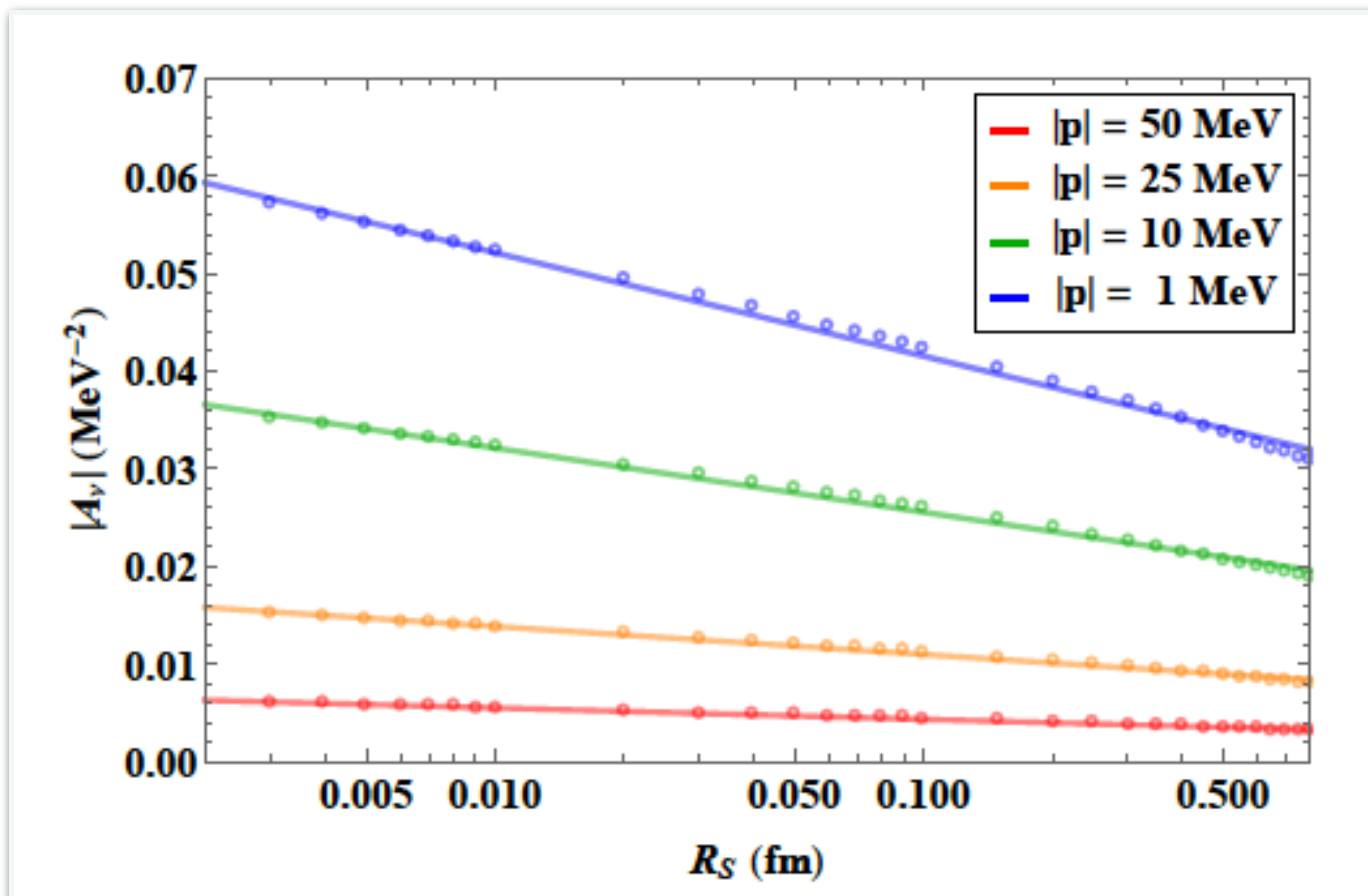
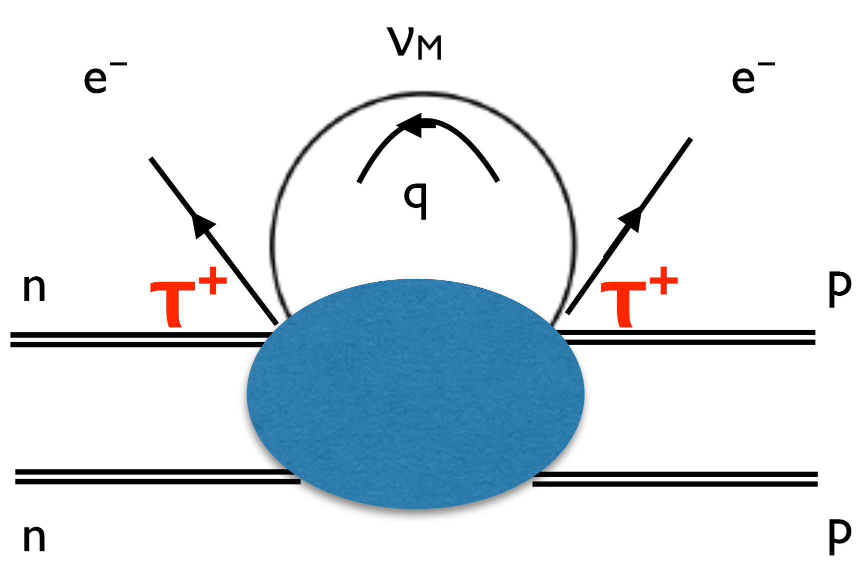
- Logarithmic dependence on R_S ⇒

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



Estimating finite part of g_ν

- Long term: compute $nn \to pp$ in lattice QCD and match to EFT



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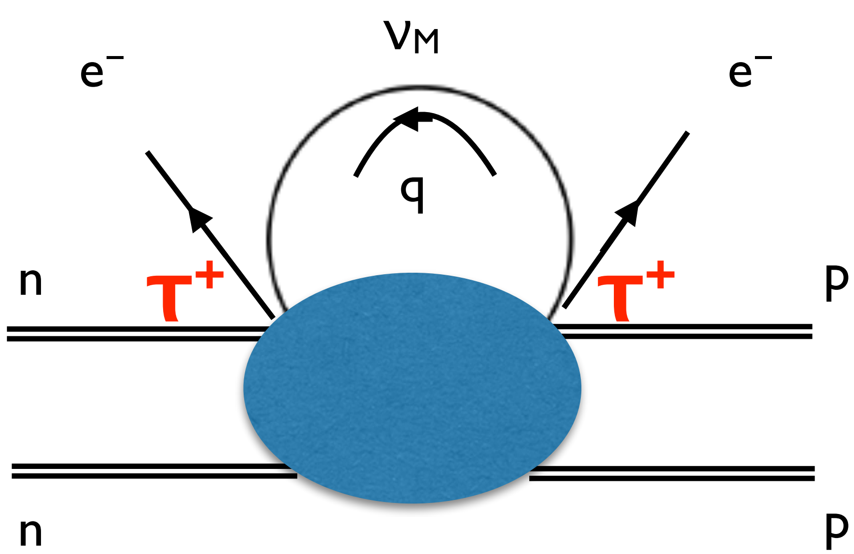
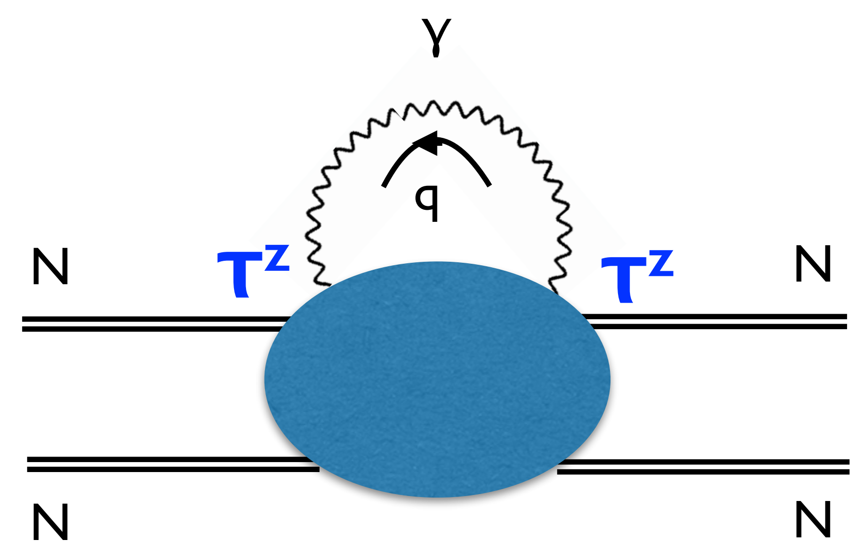
- Chiral symmetry relates g_ν to one of two I=2 EM LECs (hard γ's vs ν's)





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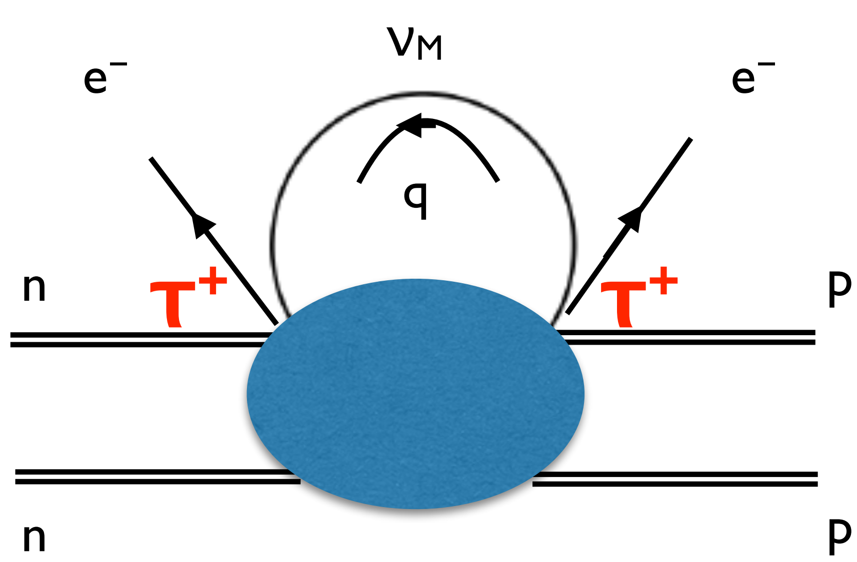
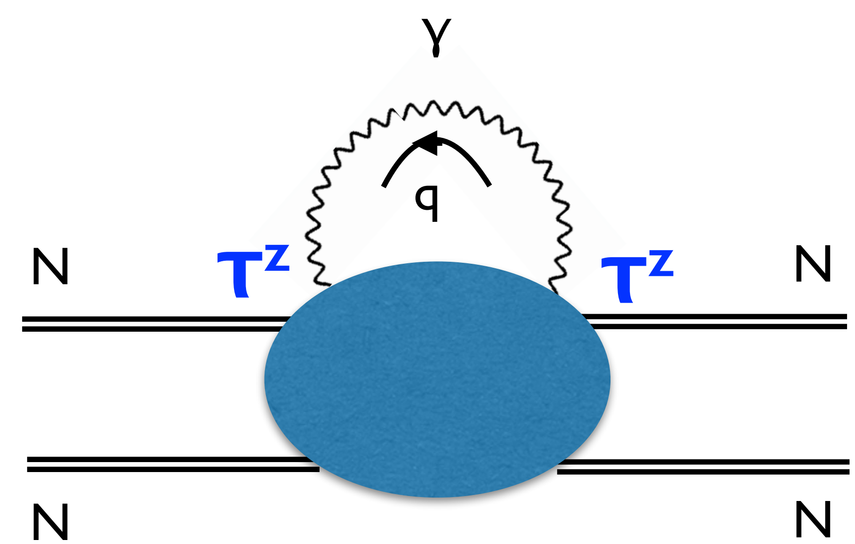




g_ν | $g_\nu = C_1$ | C_1 $(J_L J_L)$ | C_2 $(J_L J_R)$

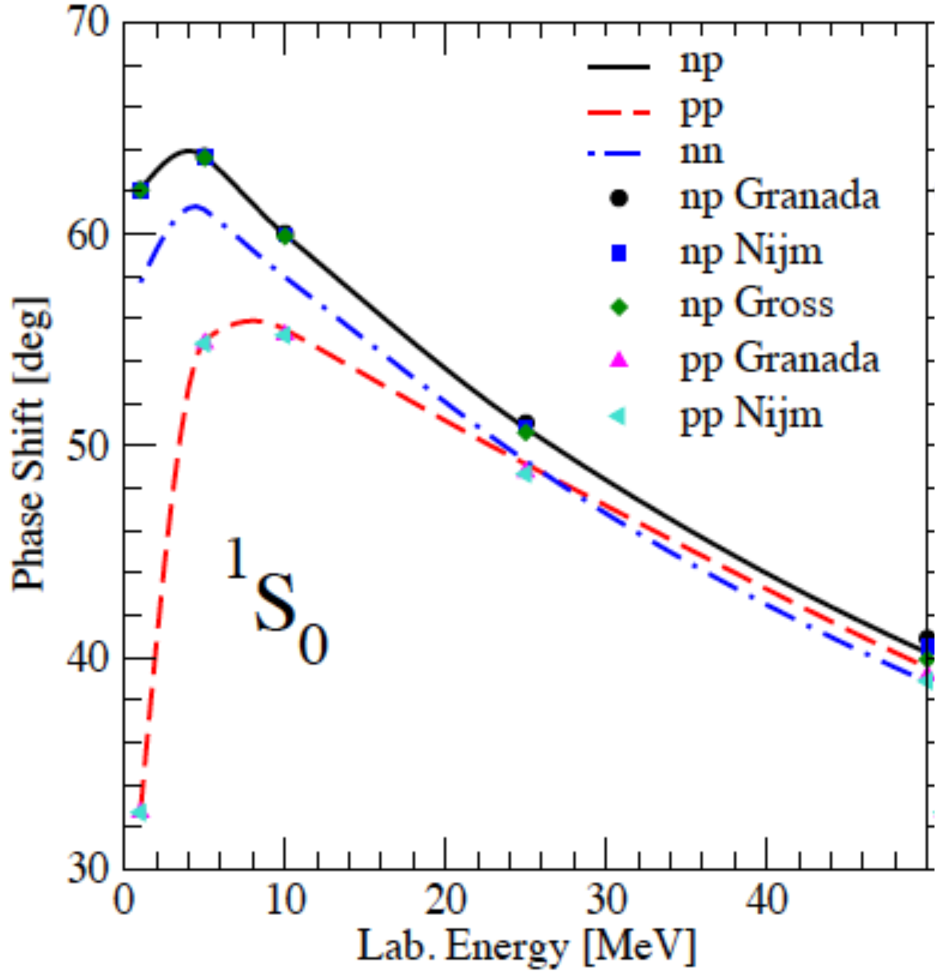
0νββ vs EM isospin breaking

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

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

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

Piarulli et al, 1412.6446



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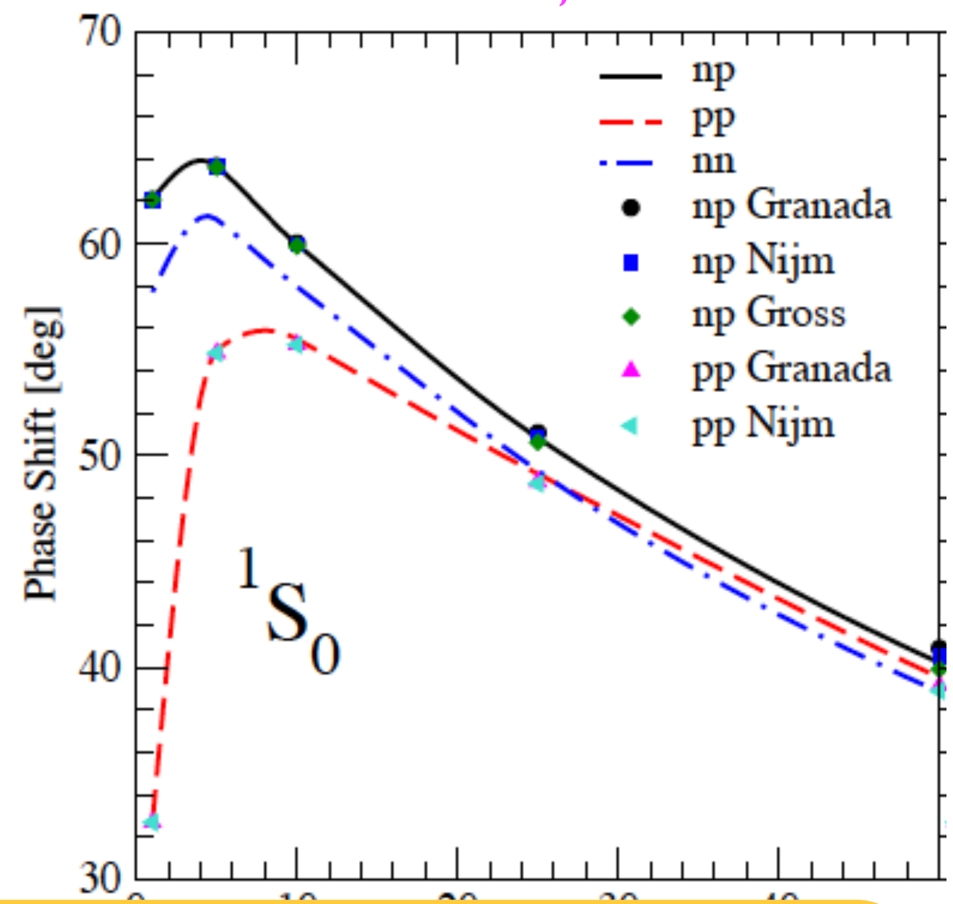

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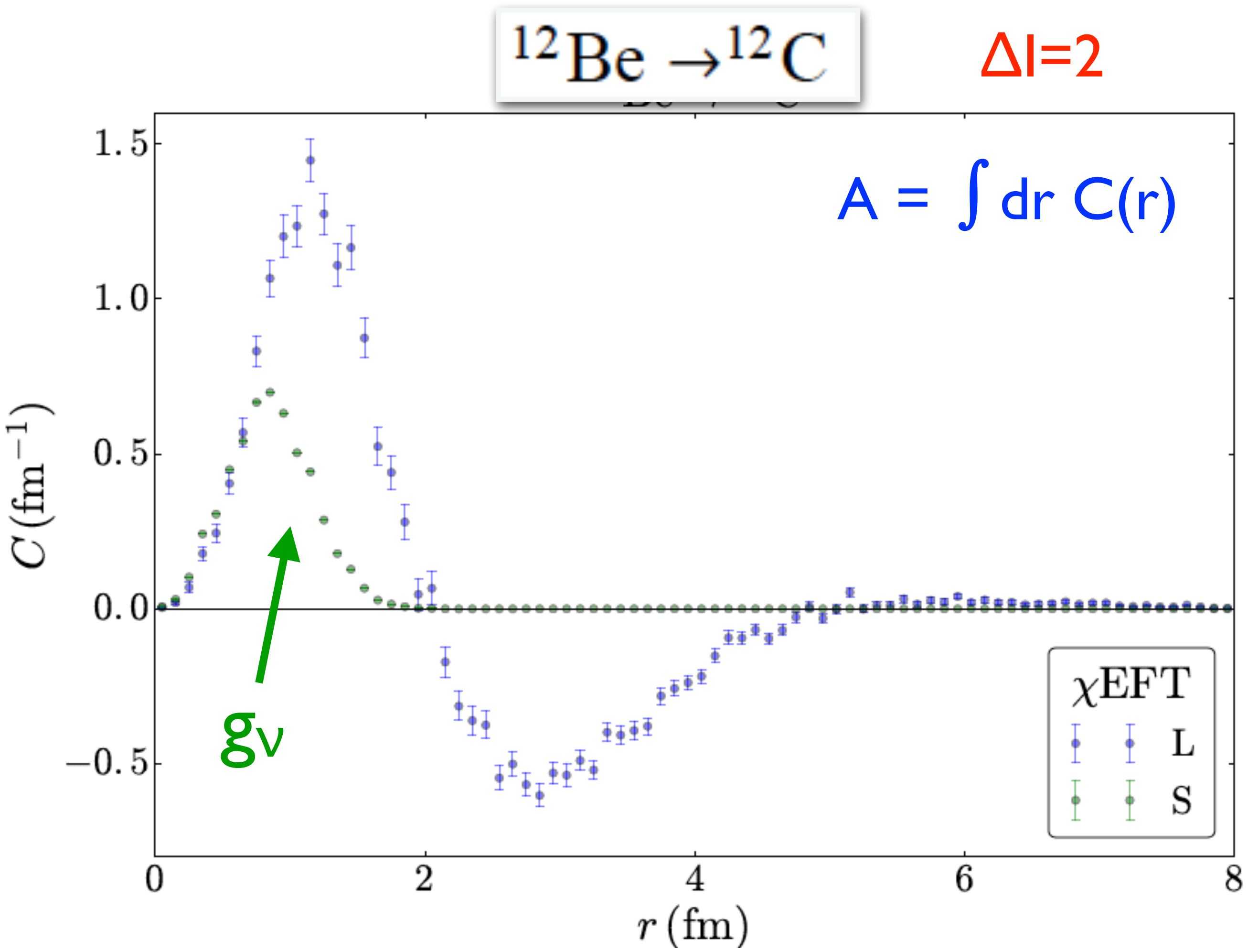
The EFT analysis survives comparison with data!

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

Guesstimating numerical impact

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1906.xxxxx



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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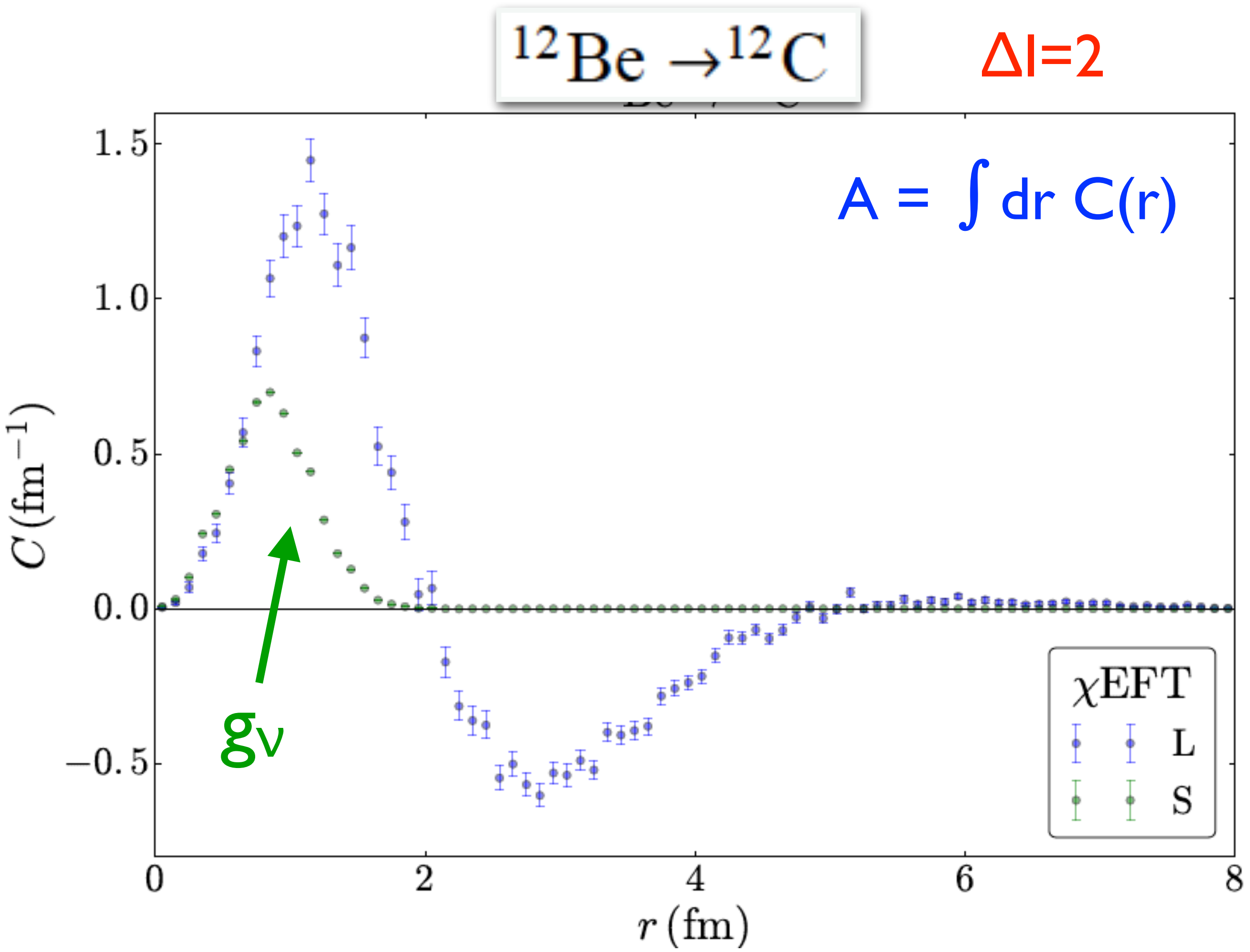

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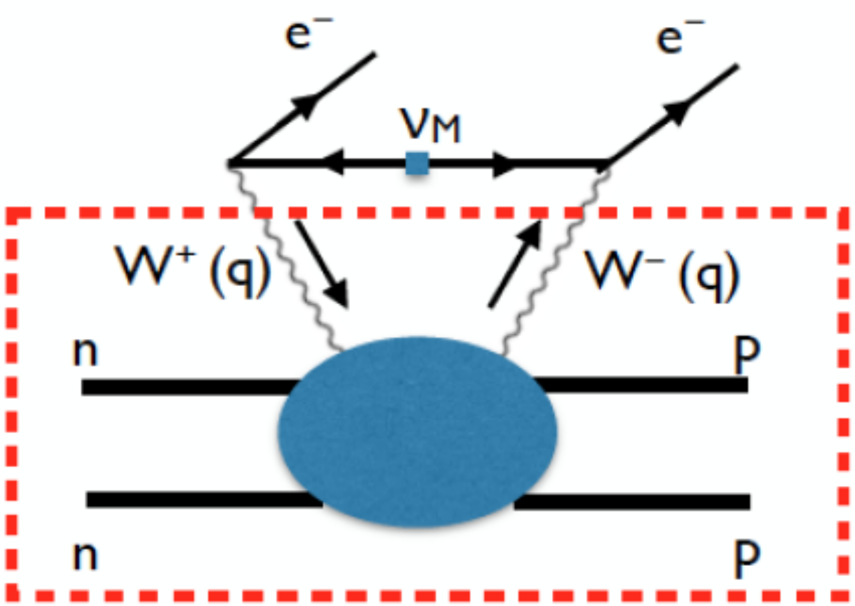
Transitions of experimental interest (^{76}Ge→ ^{76}Se, …) have ΔI=2 (and node) ⇒ expect significant effect!

Strategies to determine g_ν

- Long term → (1) Lattice QCD;
  (2) Processes sensitive to I=2 interactions with pions and nucleons (get C_1 and C_2)

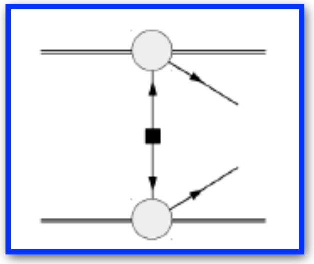


- Short term → explore methods to evaluate the forward amplitude $W^+(q)nn \to W^-(q)pp$ for a broad range of q

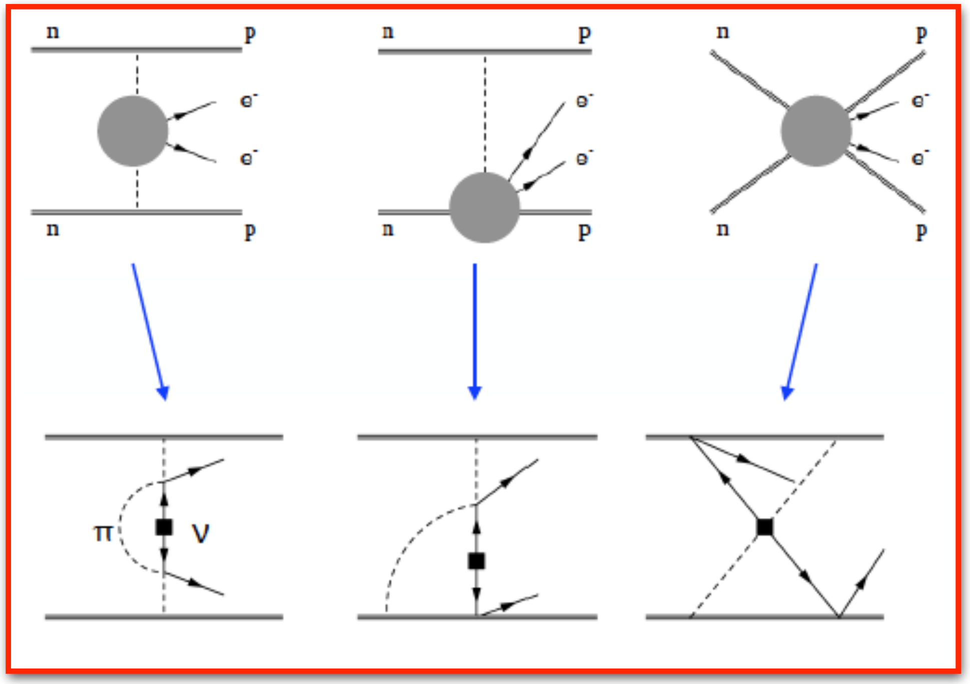
- Experimental input on (C_1+C_2) from CIB in NN scattering can be used to validate the method

N^2LO 0νββ potential

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

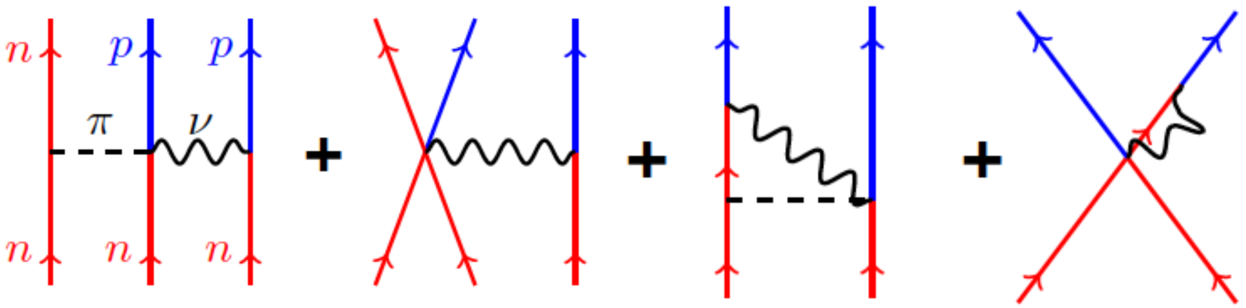


- New non-factorizable contributions
  to $V_{\nu,2} \sim V_{\nu,0} (k_F/4\pi F_\pi)^2$ [π-N loops
  and <u>new contact terms</u>]



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

- 2-body x 1-body current
  (and <u>another contact</u>…)



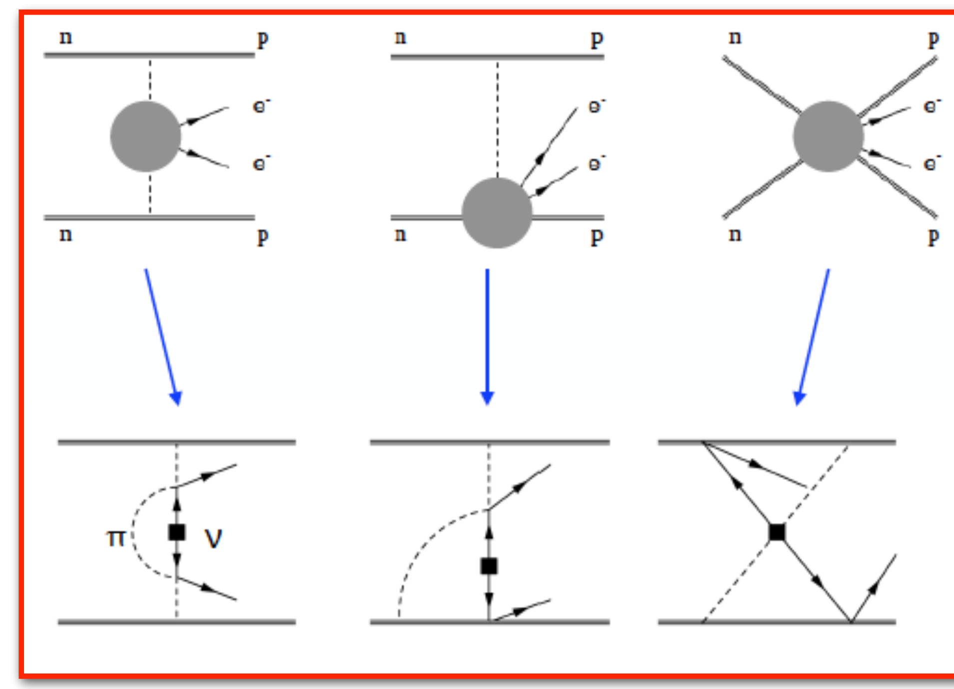
Wang-Engel-Yao 1805.10276

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

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

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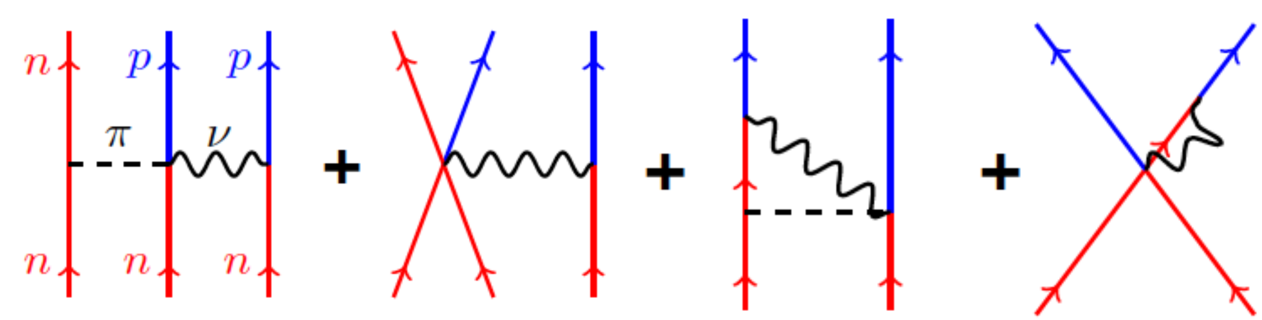
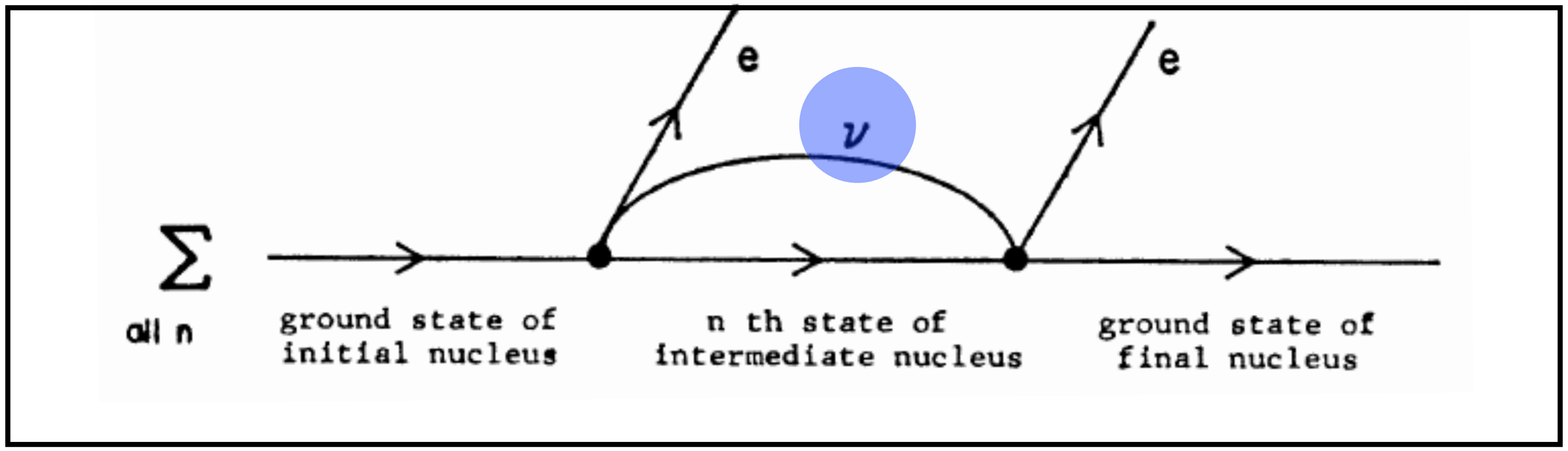


Wang-Engel-Yao 1805.10276

Ultrasoft neutrino contributions

Figure adapted from Primakoff-Rosen 1969

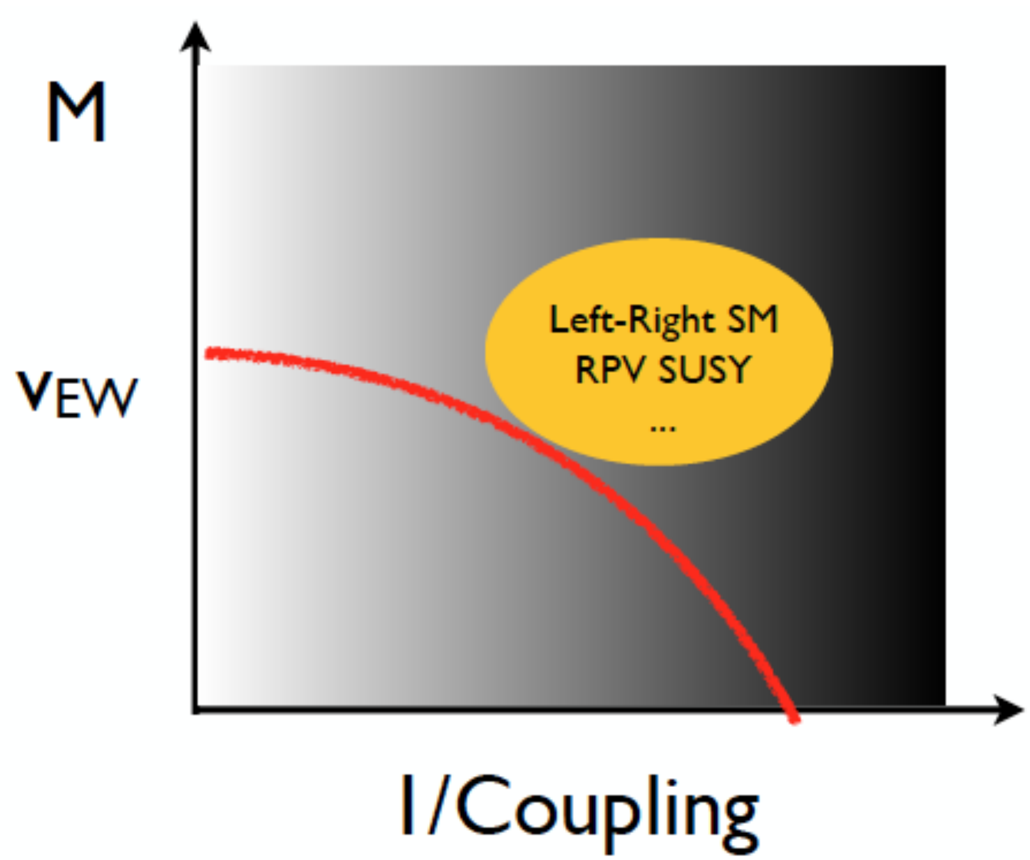


$$T_{\text{usoft}}(\mu_{\text{us}}) = \frac{T_{\text{lept}}}{8\pi^2} \sum_n \langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle \left\{ (E_2+E_n-E_i)\left(\log\frac{\mu_{\text{us}}}{2(E_2+E_n-E_i)}+1\right)+1 \leftrightarrow 2 \right\}$$

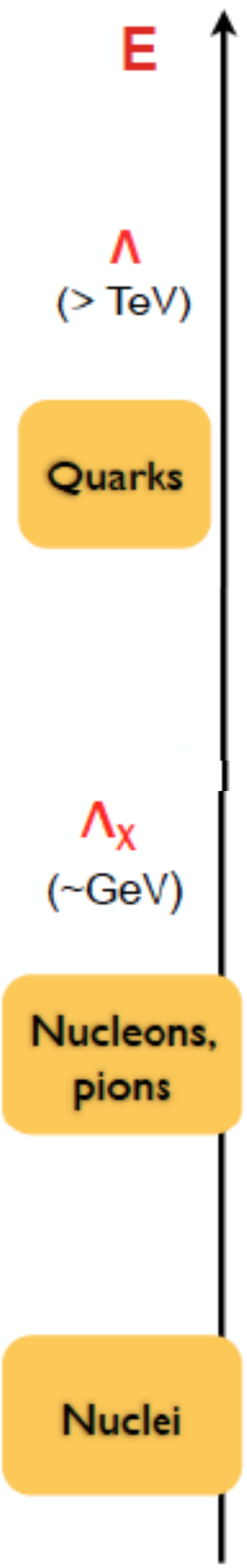
V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- 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
- $T_{usoft}/T_0 \sim (E_n - E_i)/(4\pi k_F)$ → N2LO contribution
- μ_{us} dependence cancels with $V_{\nu,2.}$: consistency check

$0\nu\beta\beta$ from multi-TeV scale dynamics (dim-7, 9, …operators)



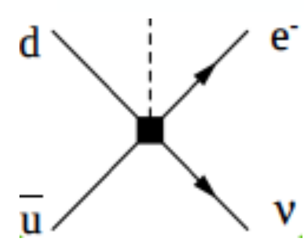
Classifying contributions



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

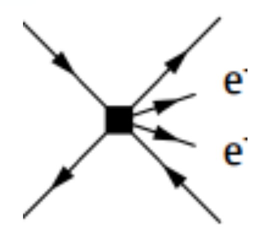
↓ Integrate out heavy particles

$$\mathcal{L}_{\rm eff} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)}$$



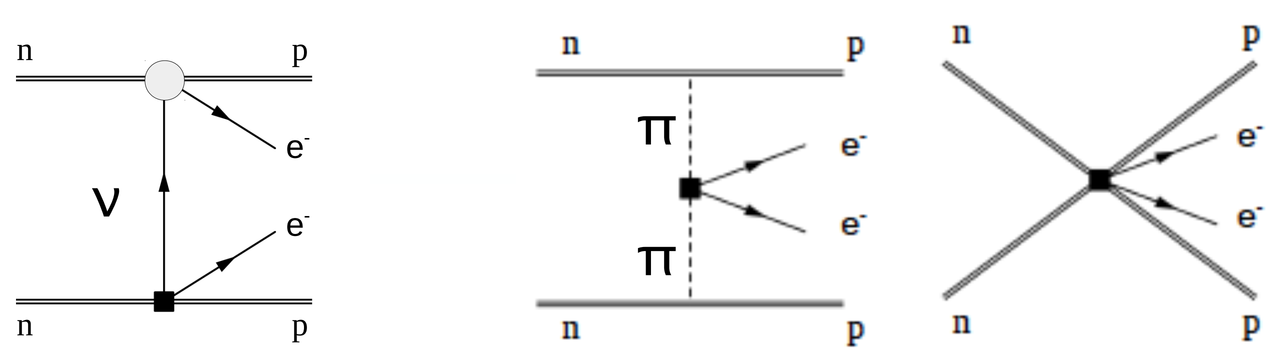
dim7

Lehman 1410.4193

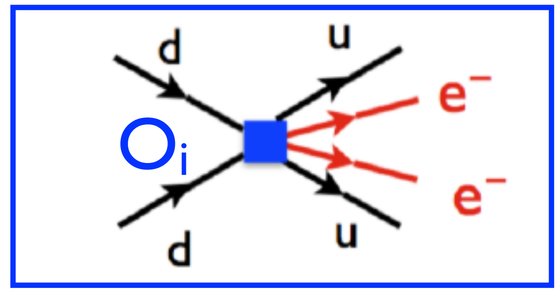


dim9

Graesser 1606.04549

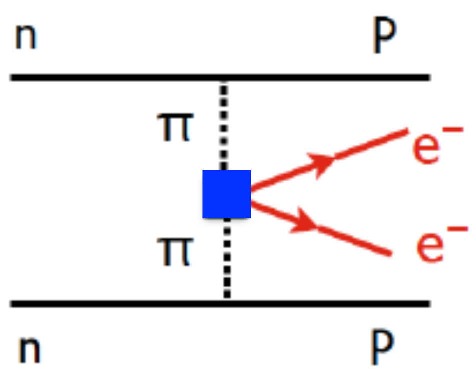


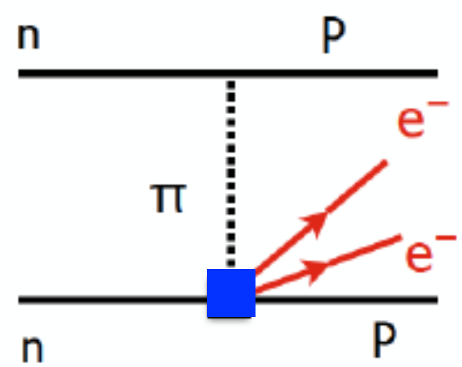
Chiral realization of dim-9 operators

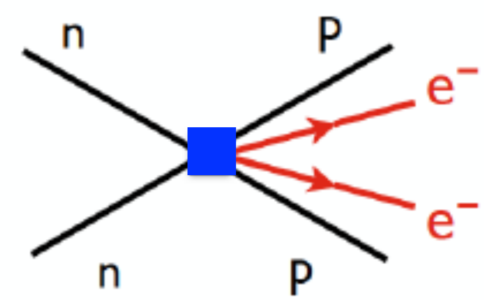


Pion-range effects

Short-range effects







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

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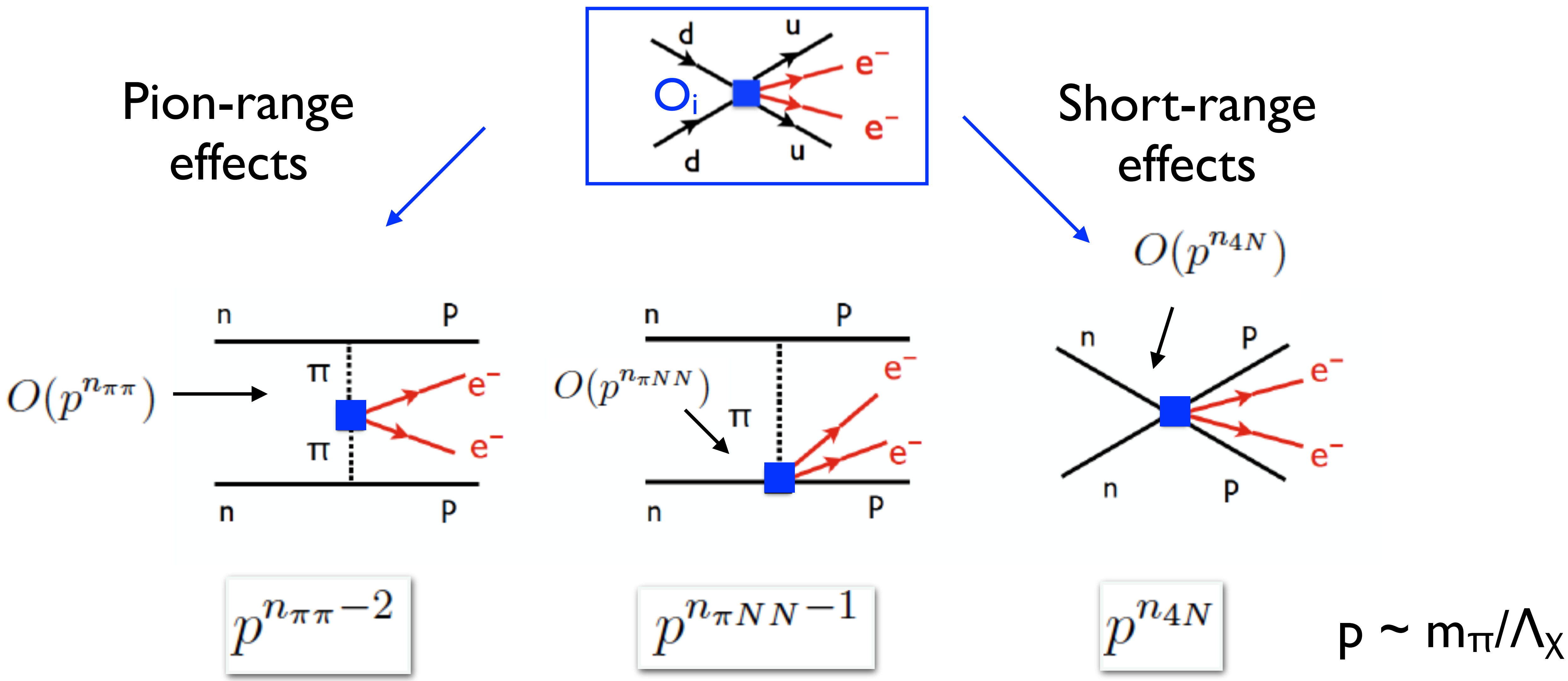
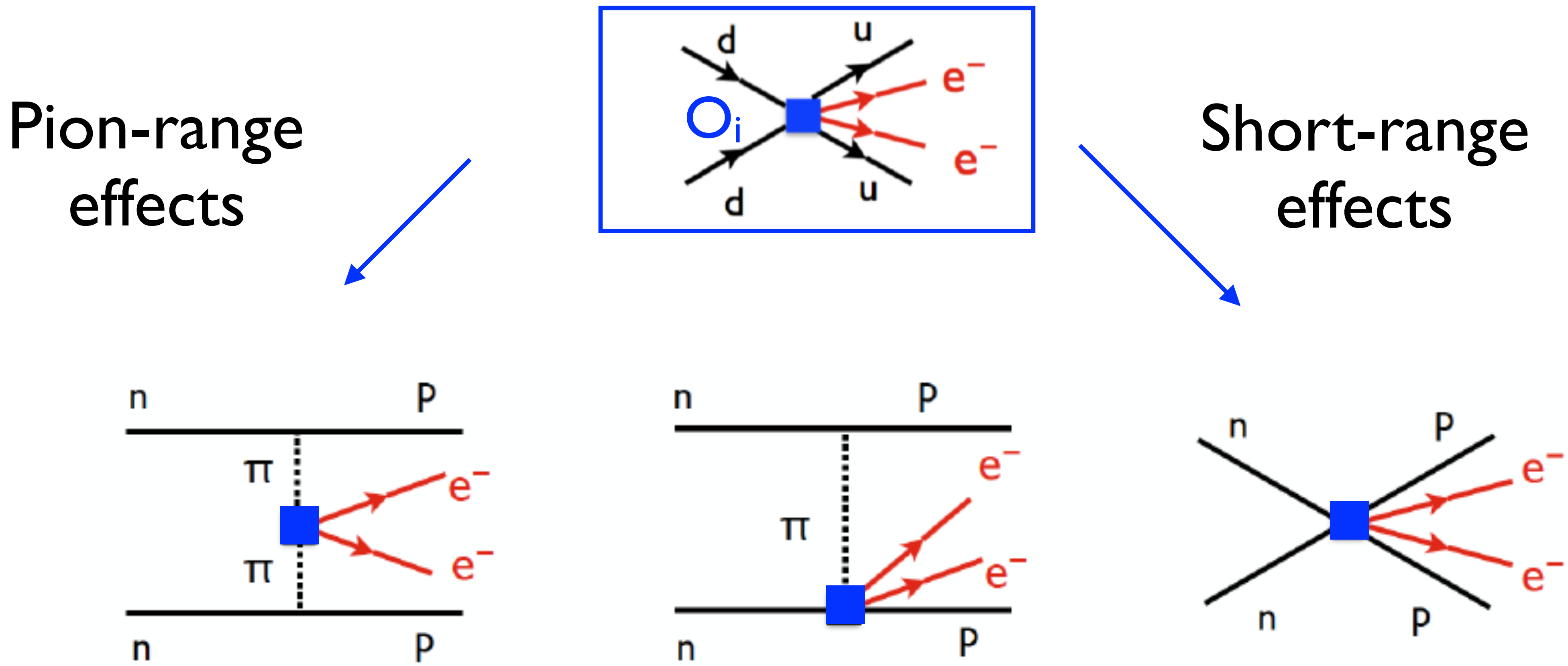


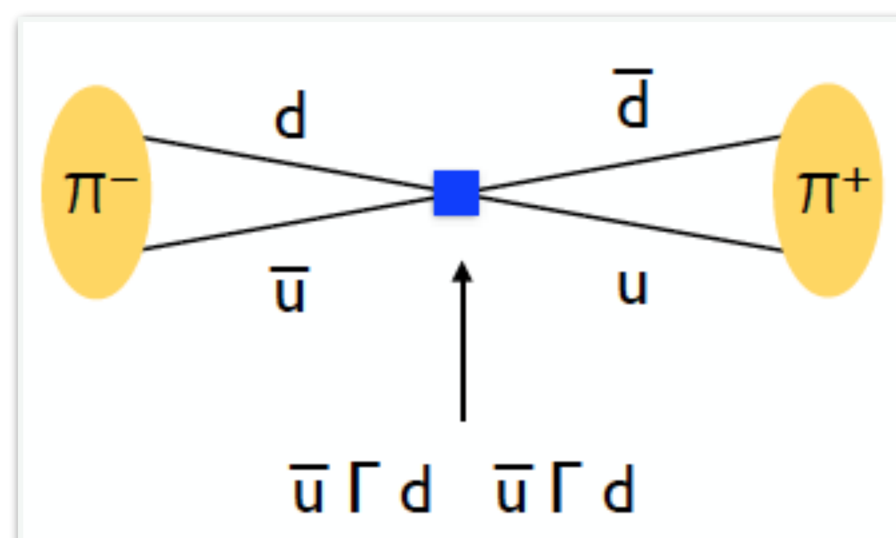
Naive dimensional analysis → $V_{\pi\pi}$ dominates for all but one operator

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

Chiral realization of dim-9 operators



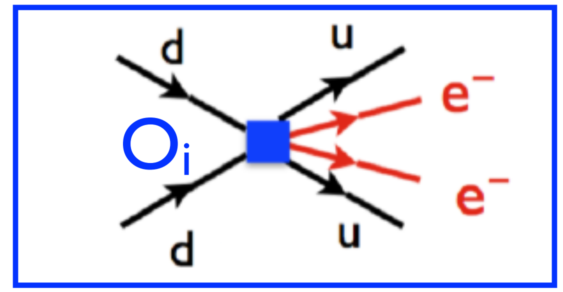
- Two recent developments:
  1. ππ matrix elements now precisely know via direct and indirect lattice QCD calculations



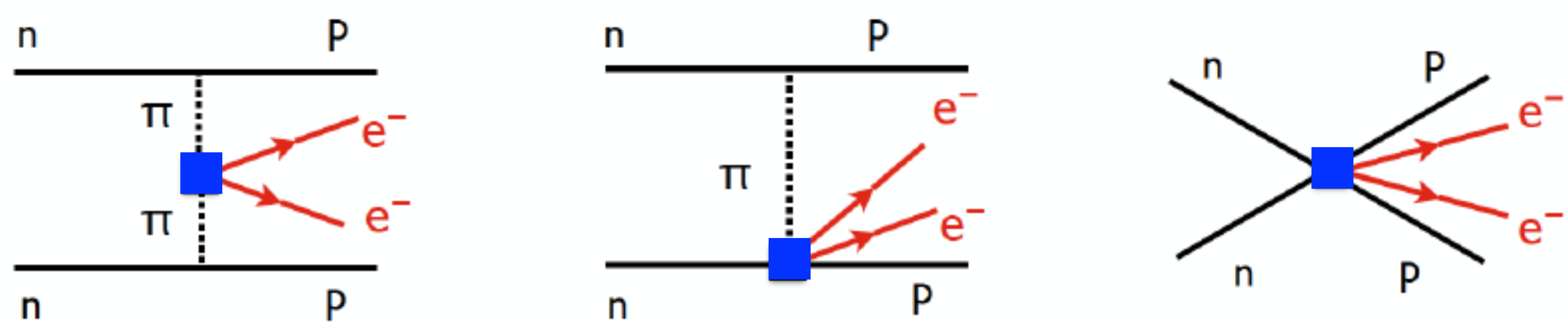
Nicholson et al., 1805/02634

Chiral realization of dim-9 operators

Pion-range effects



Short-range effects



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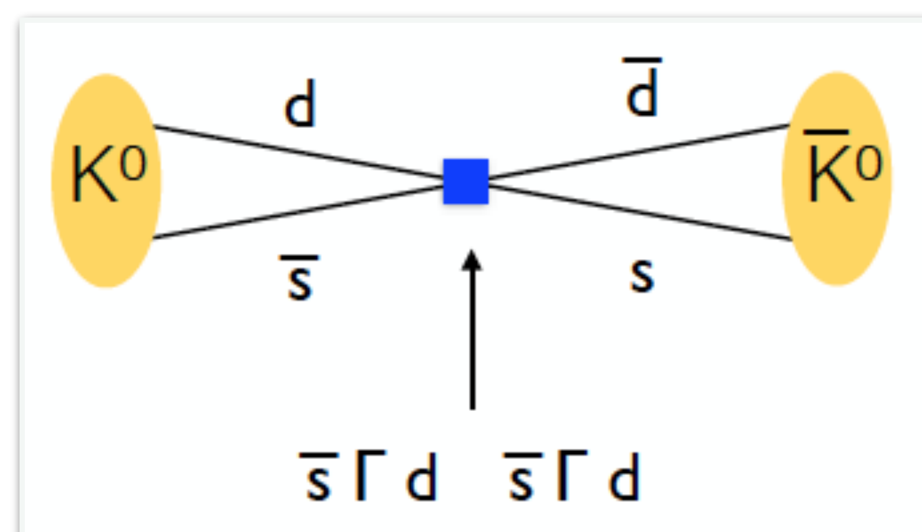
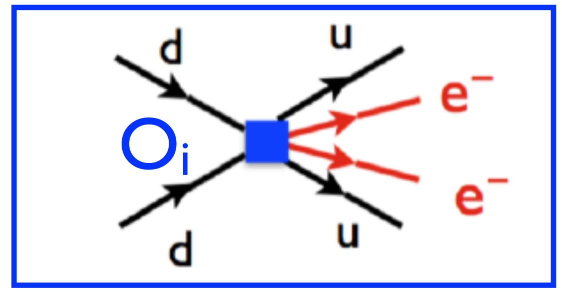


VC, Dekens, Graesser, Mereghetti, 1701.01443

Chiral realization of dim-9 operators



Pion-range effects

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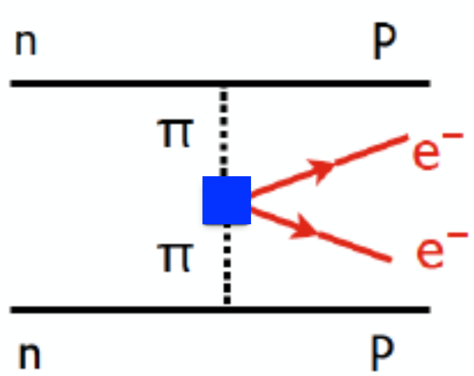
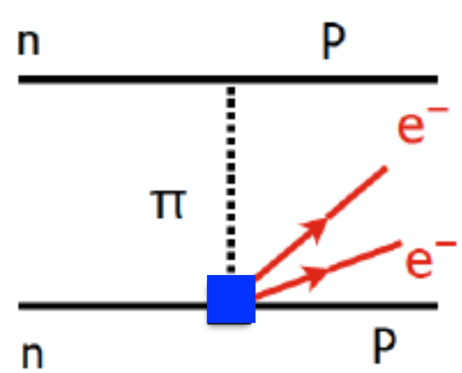
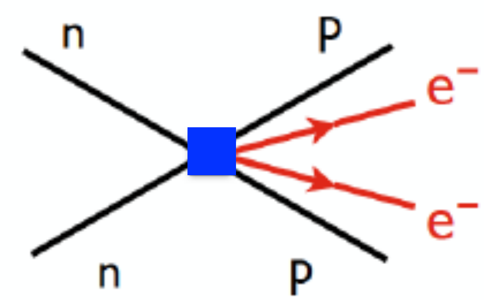
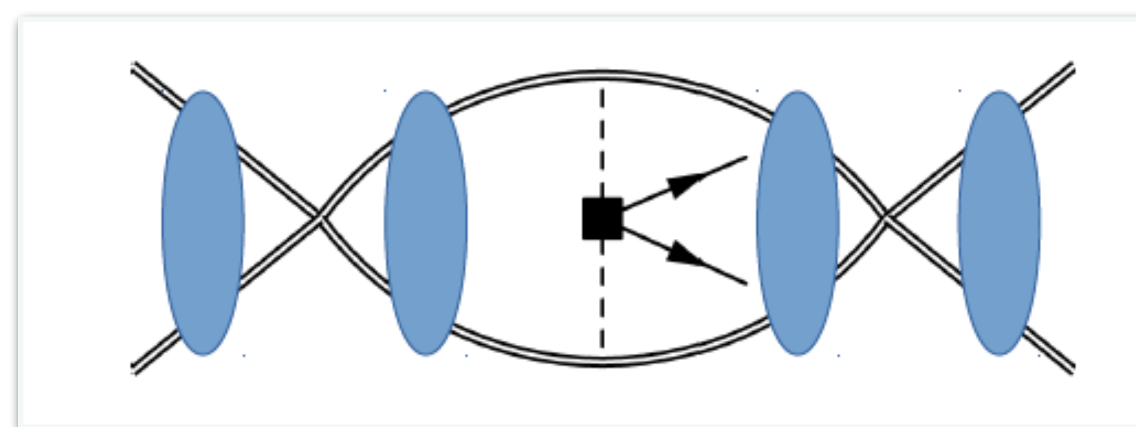






- Two recent developments:

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



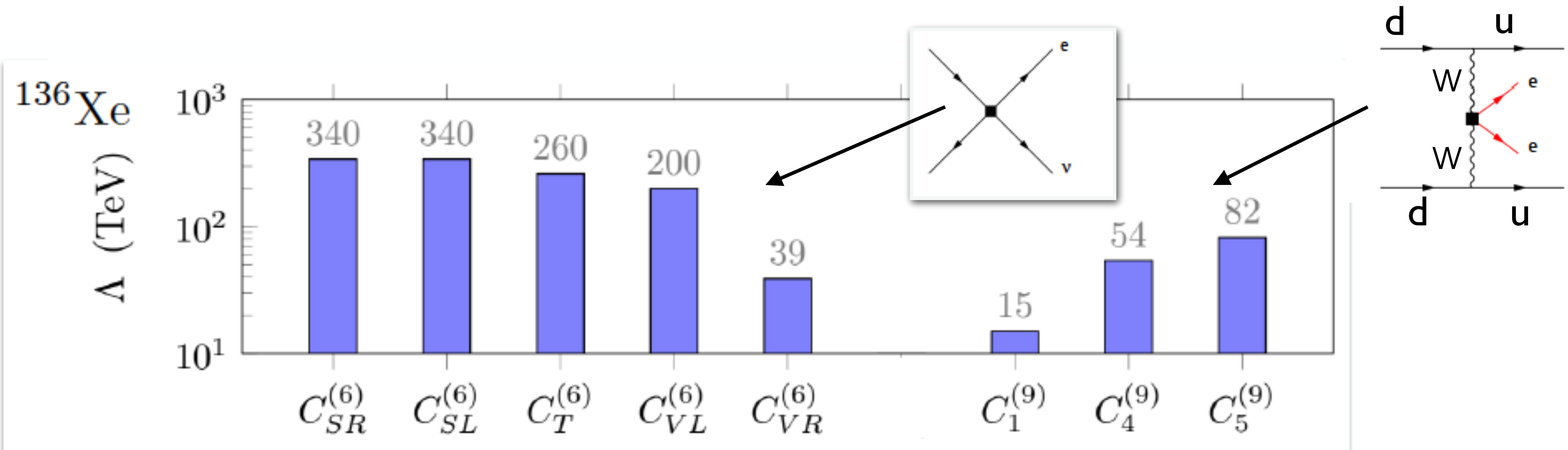
V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

What scales are being probed?

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

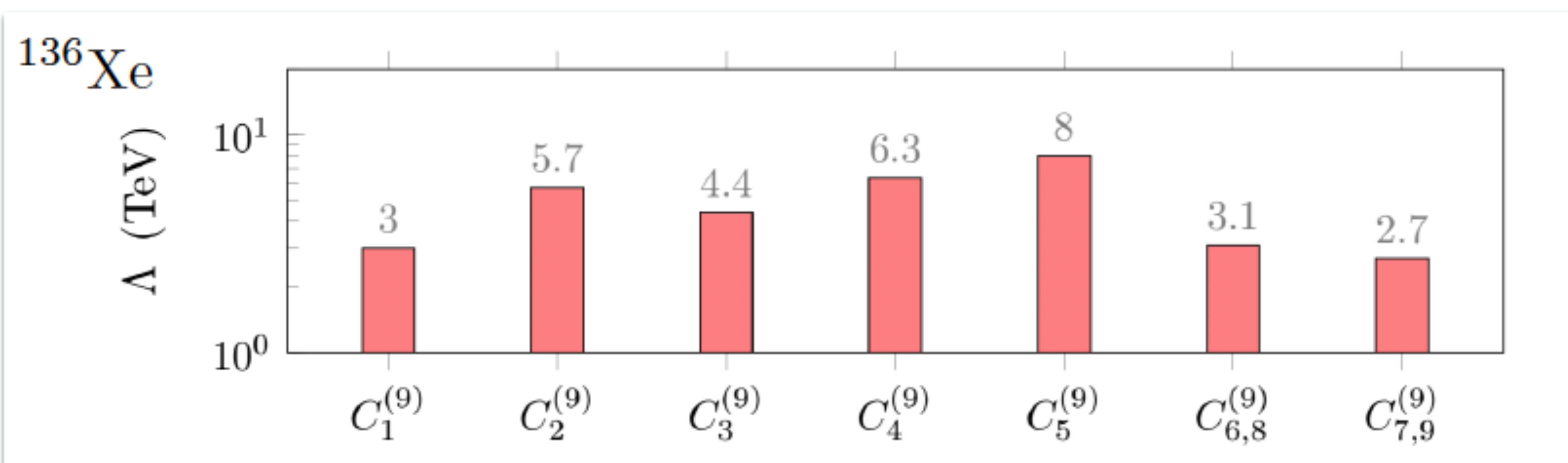
Dim 7 in SM-EFT

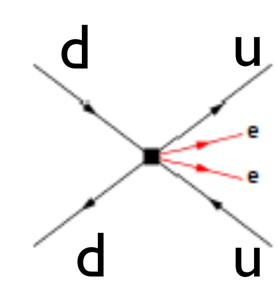
$(v/\Lambda)^3$



Dim 9 in SM-EFT

$(v/\Lambda)^5$





Bounds reflect dependence on Λ_X / Λ and Q/Λ_X

Conclusions & Outlook

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

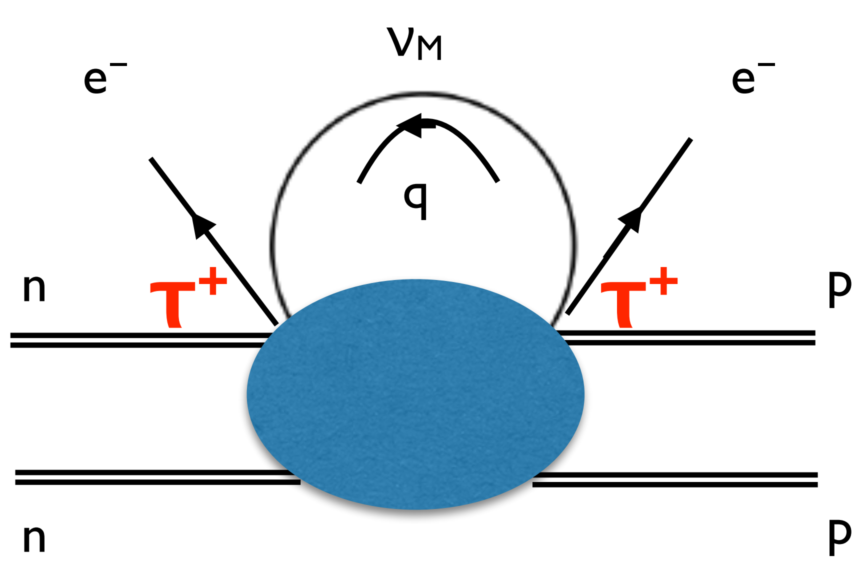
- EFT approach provides a general framework to:
  1. Relate $0\nu\beta\beta$ to underlying LNV dynamics (and collider & cosmology)
  2. Organize contributions to hadronic and nuclear matrix elements
     - Identified new leading order short-range contributions
     - Implications for $m_{\beta\beta}$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

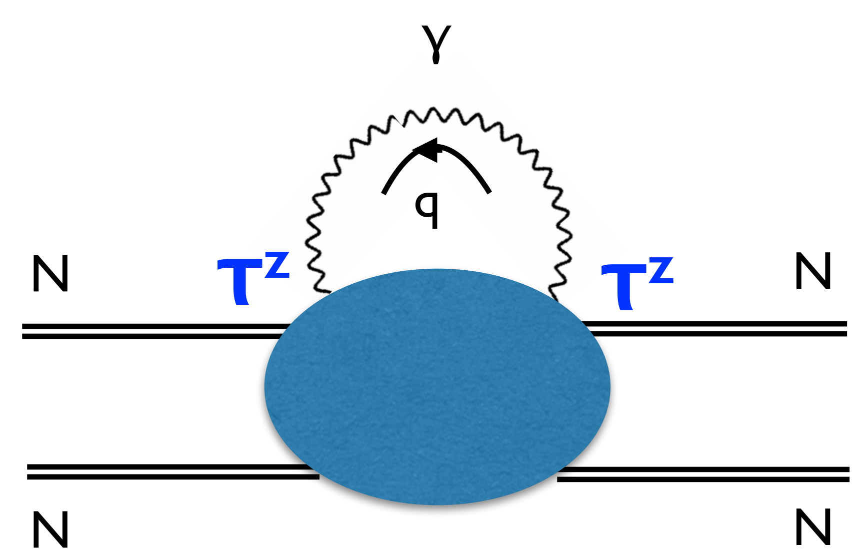
Improving the theory uncertainty is challenging, but there are exciting prospects thanks to advances in EFT, lattice QCD, and nuclear structure

Backup

Estimating finite part of g_ν (v2)

- Long term: compute nn→pp in lattice QCD and match to EFT
- Chiral symmetry relates g_ν to one of two I=2 EM LECs (hard γ's vs ν's)





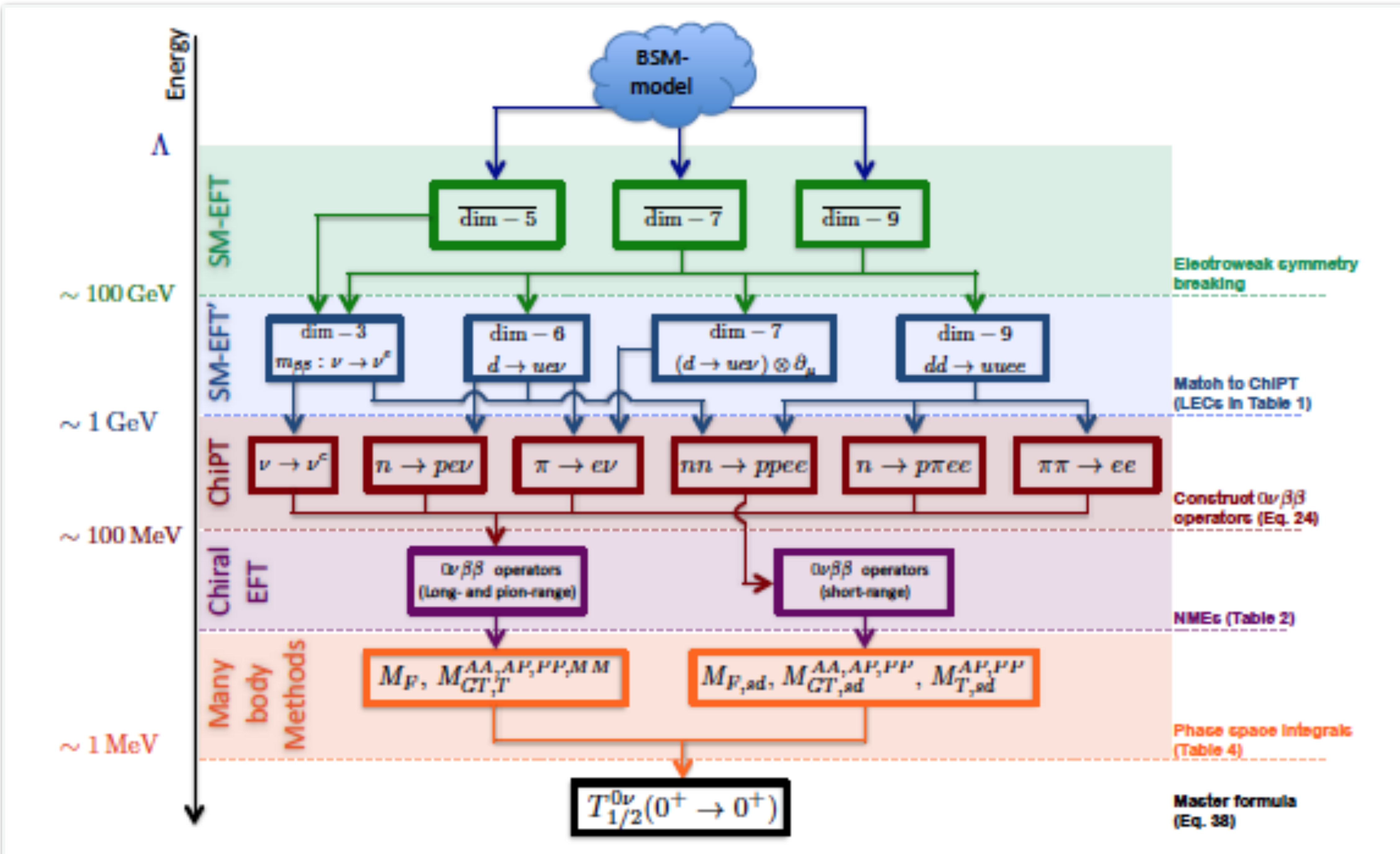
$$S_{\rm eff}^{\Delta L=2} = i4G_F^2 V_{ud}^2 m_{\beta\beta} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, g^{\mu\nu}\, T\Big(\bar{u}_L\gamma_\mu d_L(x)\, \bar{u}_L\gamma_\nu d_L(y)\Big)$$

Massless propagator
(remnant of ν propagator)

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

EFT-based master formula

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



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

EFT-based master formula

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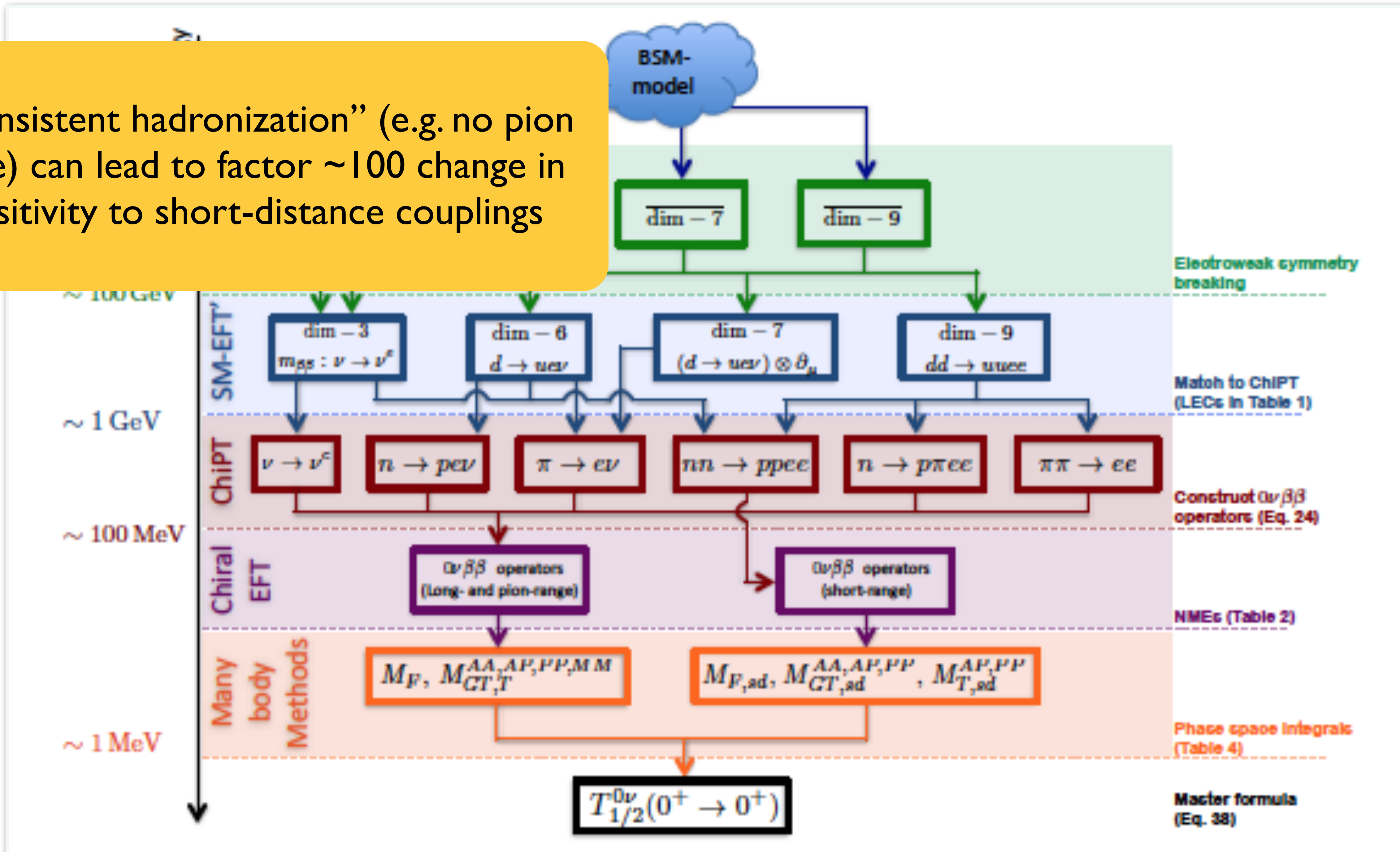
“Inconsistent hadronization” (e.g. no pion range) can lead to factor ~100 change in sensitivity to short-distance couplings



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EFT-based master formula

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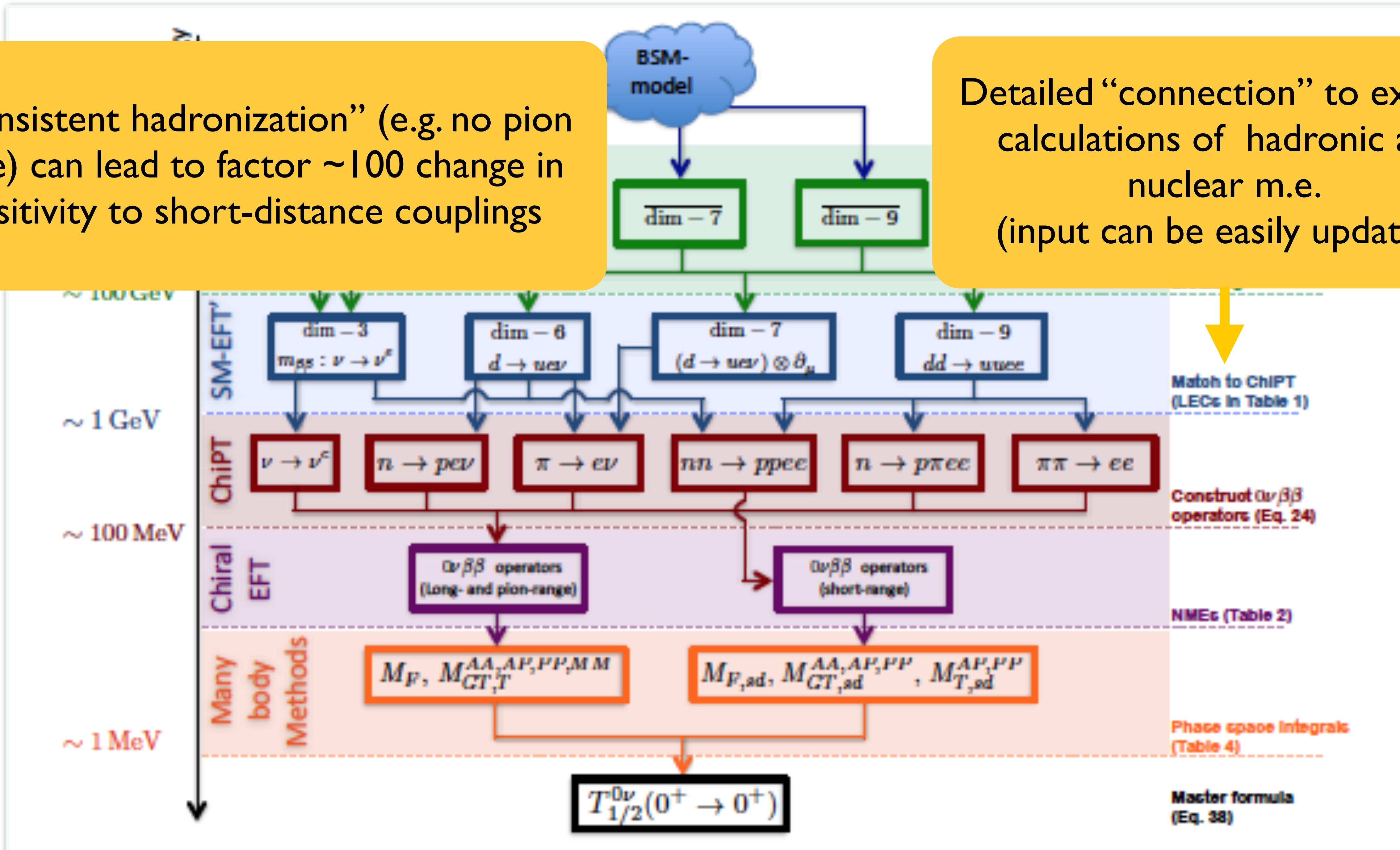
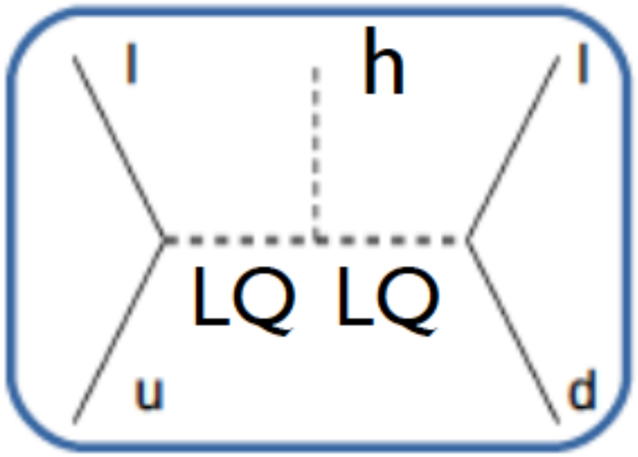
Detailed “connection” to existing calculations of hadronic and nuclear m.e.
(input can be easily updated)



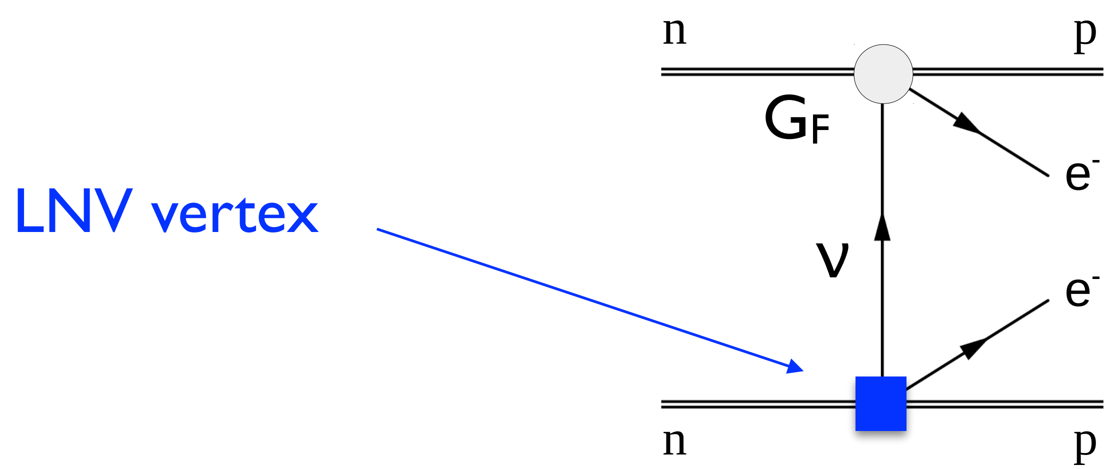
V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

A leptoquark example

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (leptoquark-induced)



$$C_{LL\bar{Q}uH}\, \epsilon_{ij}\, (\bar{Q}_m u)\, (L_m^T C L_i)\, H_j$$



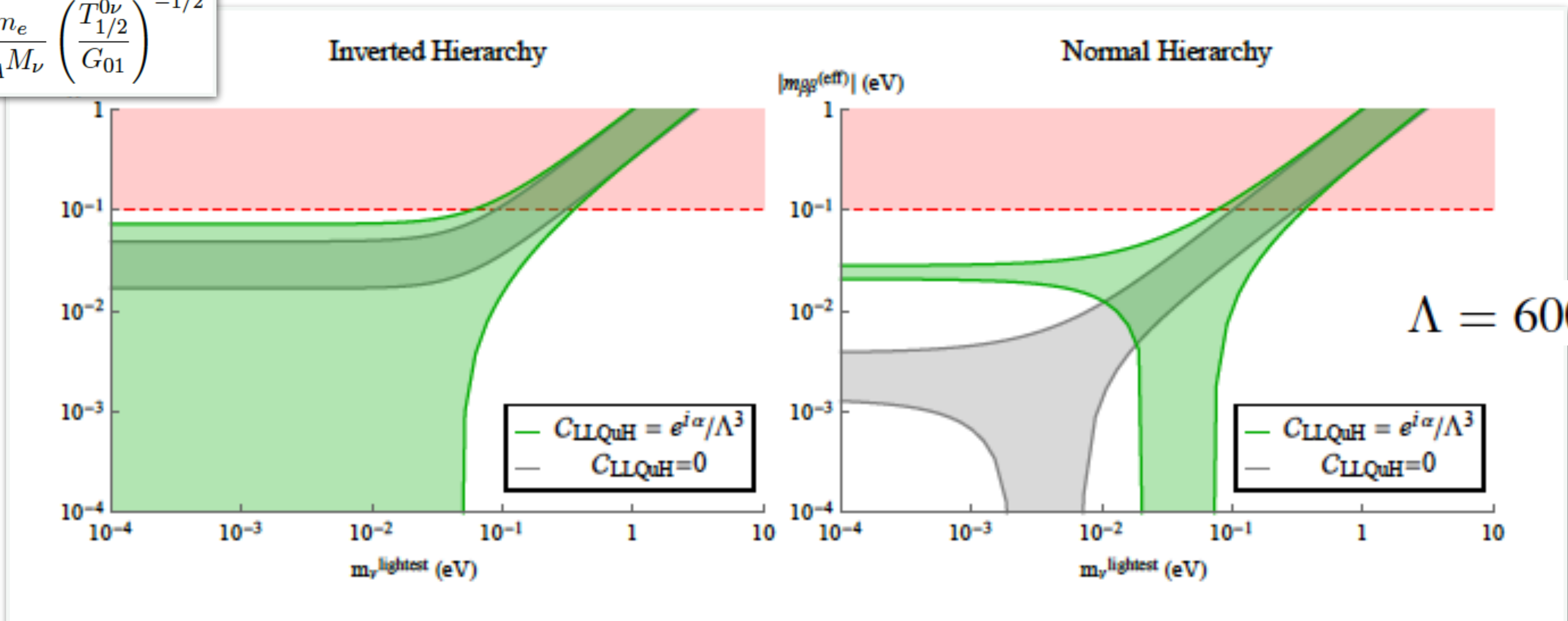
- Same leptonic structure as in ν_M exchange: can cancel $m_{\beta\beta}$!!

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

A leptoquark example

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (leptoquark-induced)

$$m_{\beta\beta}^{(\text{eff})} = \frac{m_e}{g_A^2 M_\nu} \left(\frac{T_{1/2}^{0\nu}}{G_{01}} \right)^{-1/2}$$



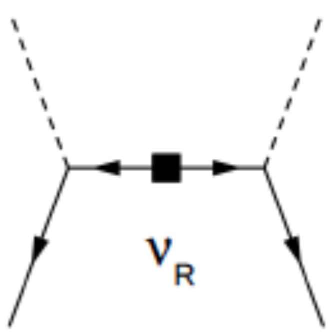
$\Lambda = 600$ TeV

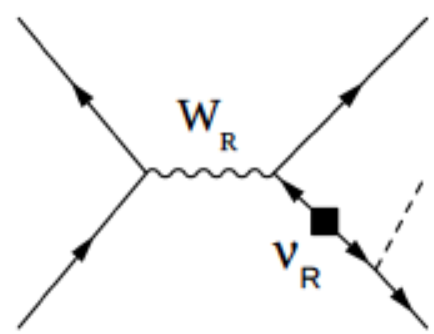
- Same leptonic structure as in ν_M exchange: can cancel $m_{\beta\beta}$!!

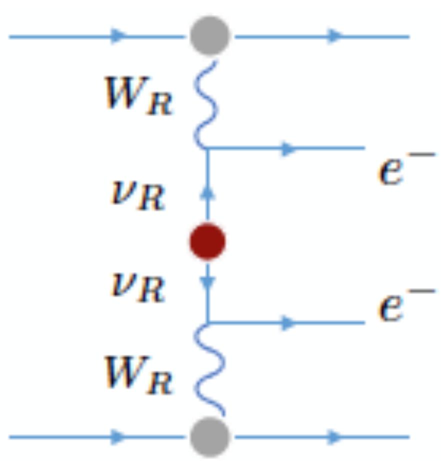
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

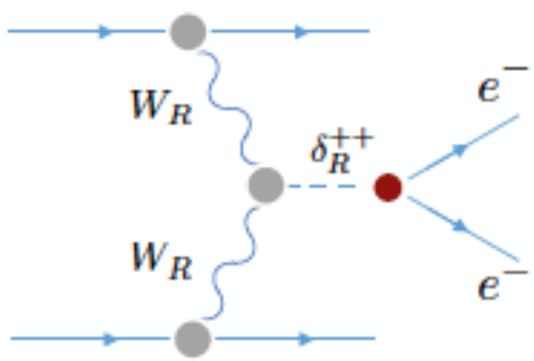
Left-Right symmetric model example

- Generates ops. at dim-5 ($m_{\beta\beta}$) + dim-7 & dim-9

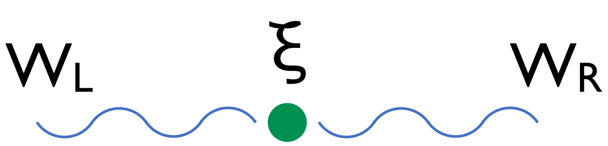








Chirally enhanced for ($\xi \neq 0$)



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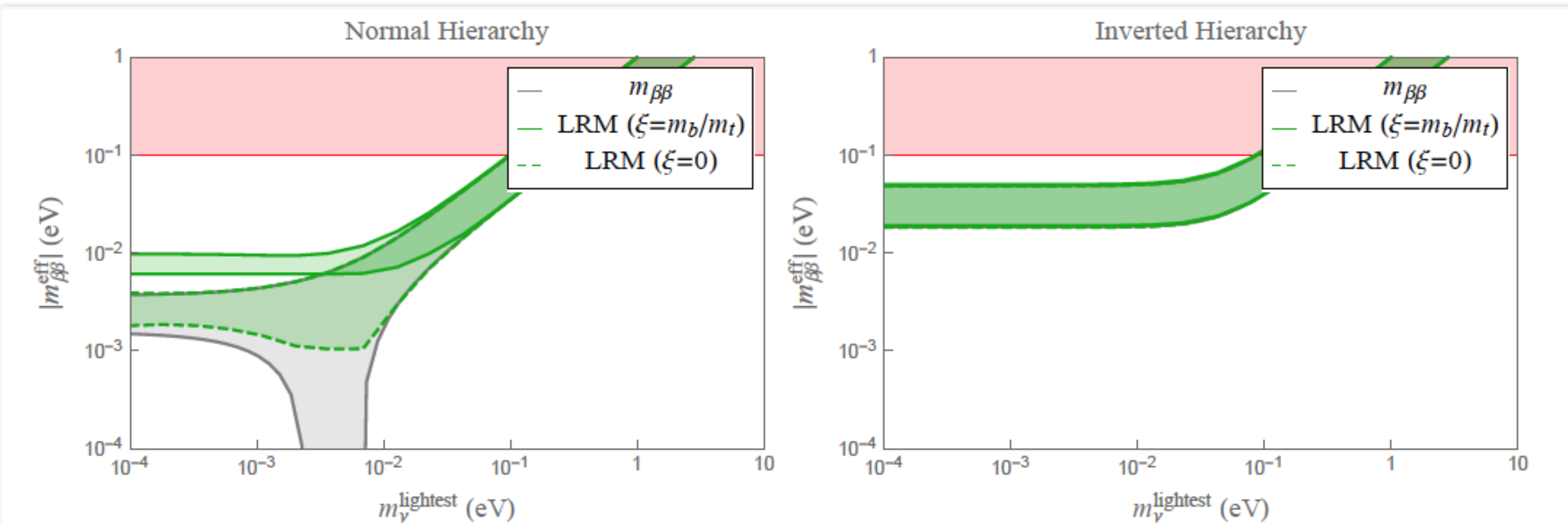
Left-Right symmetric model example

- Generates ops. at dim-5 ($m_{\beta\beta}$) + dim-7 & dim-9
- Dim-9 contribution can be dominant in NH

Illustrative LHC-safe parameters

$$m_{W_R} = 4.5\ \text{TeV} \quad m_{\Delta_R} = 10\ \text{TeV} \quad m_{\nu_R} = O(10\ \text{TeV}) \quad U_R = U_{\text{PMNS}}$$



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