BNL-HET & RBRC Joint Workshop "DWQ@25"
December 13-17 2021

Hadronic inputs for neutrinoless double beta decay

Vincenzo Cirigliano
Los Alamos National Laboratory

LA-UR-21-25541

Outline

- Introduction: $0\nu\beta\beta$, Lepton Number Violation, and EFT framework

- Hadronic input needed to interpret $0\nu\beta\beta$
  - High scale seesaw: light Majorana ν exchange
  - (multi)TeV-scale Lepton Number Violation

- Conclusions

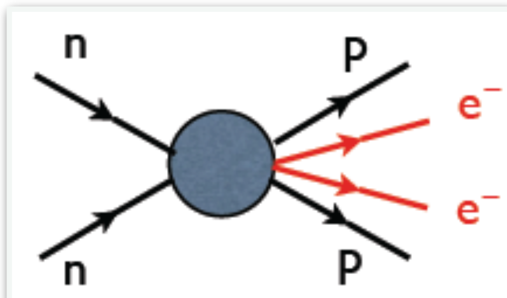
Special thanks to collaborators:
W. Dekens, J. de Vries, M. Graesser, M. Hoferichter, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, A. Walker-Loud, R. Wiringa

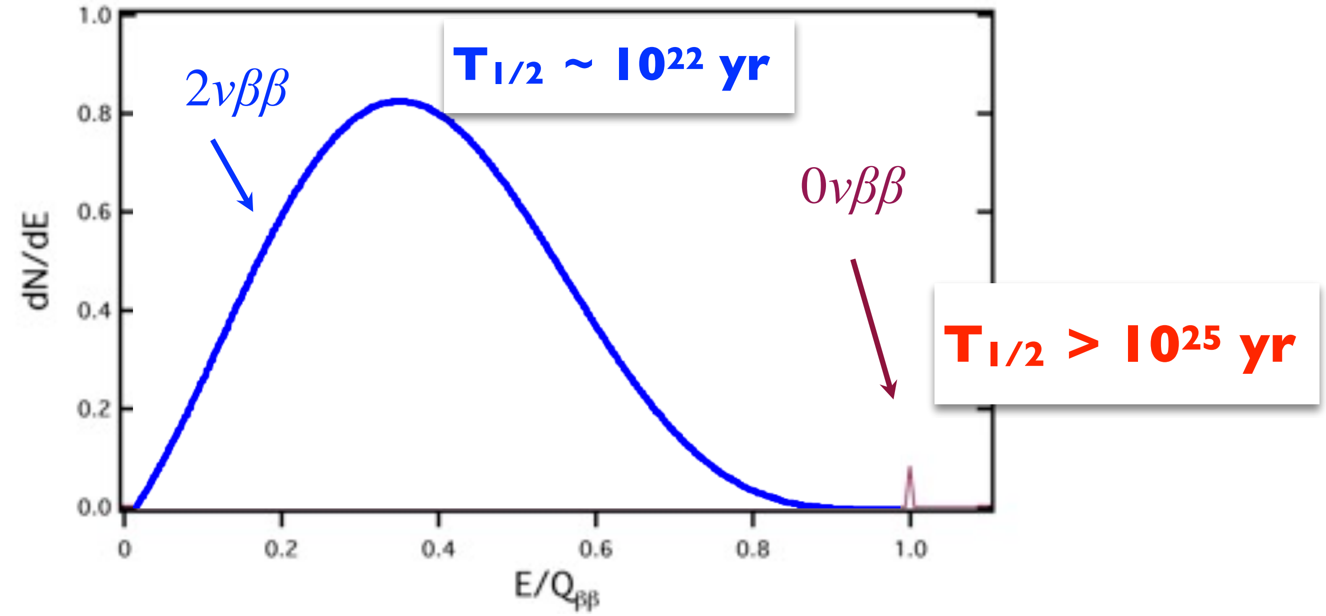
DBD Nuclear Theory Topical Collaboration (PI Jon Engel):
http://c51.lbl.gov/~0nubb/webhome/

Neutrinoless double beta decay (0νββ)

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

ΔL=2



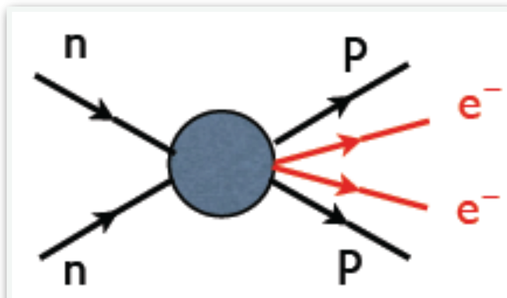


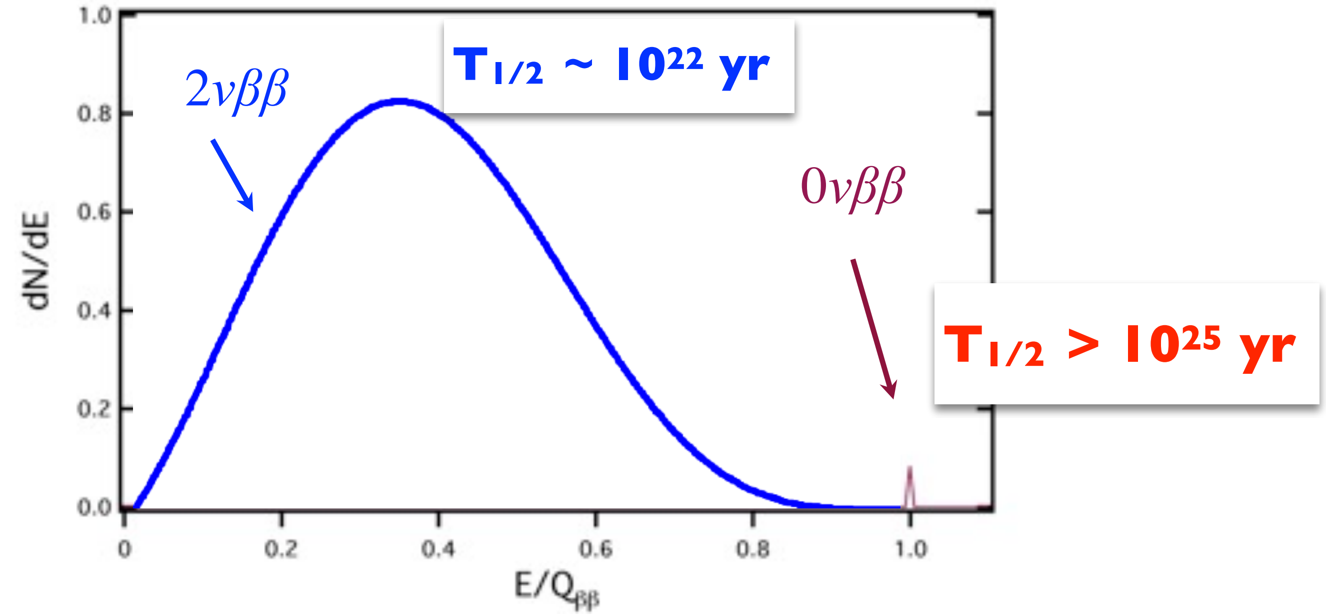
- Observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), for which single beta decay is energetically forbidden

Neutrinoless double beta decay (0νββ)

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

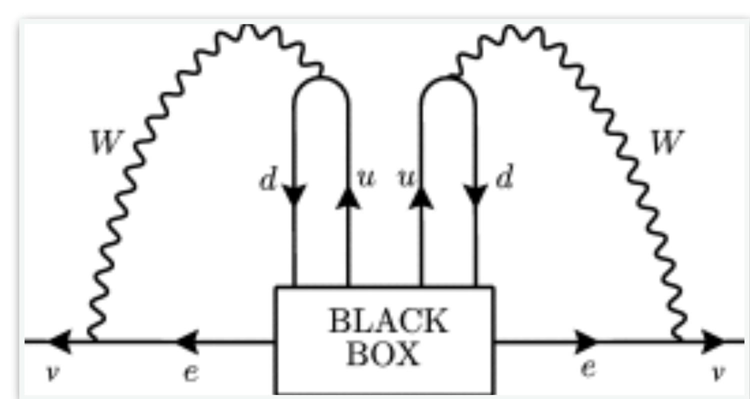
ΔL=2





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

- B-L conserved in the SM → new physics, with far-reaching implications
  - Demonstrate that neutrinos are Majorana fermions
  - Establish key ingredient for leptogenesis

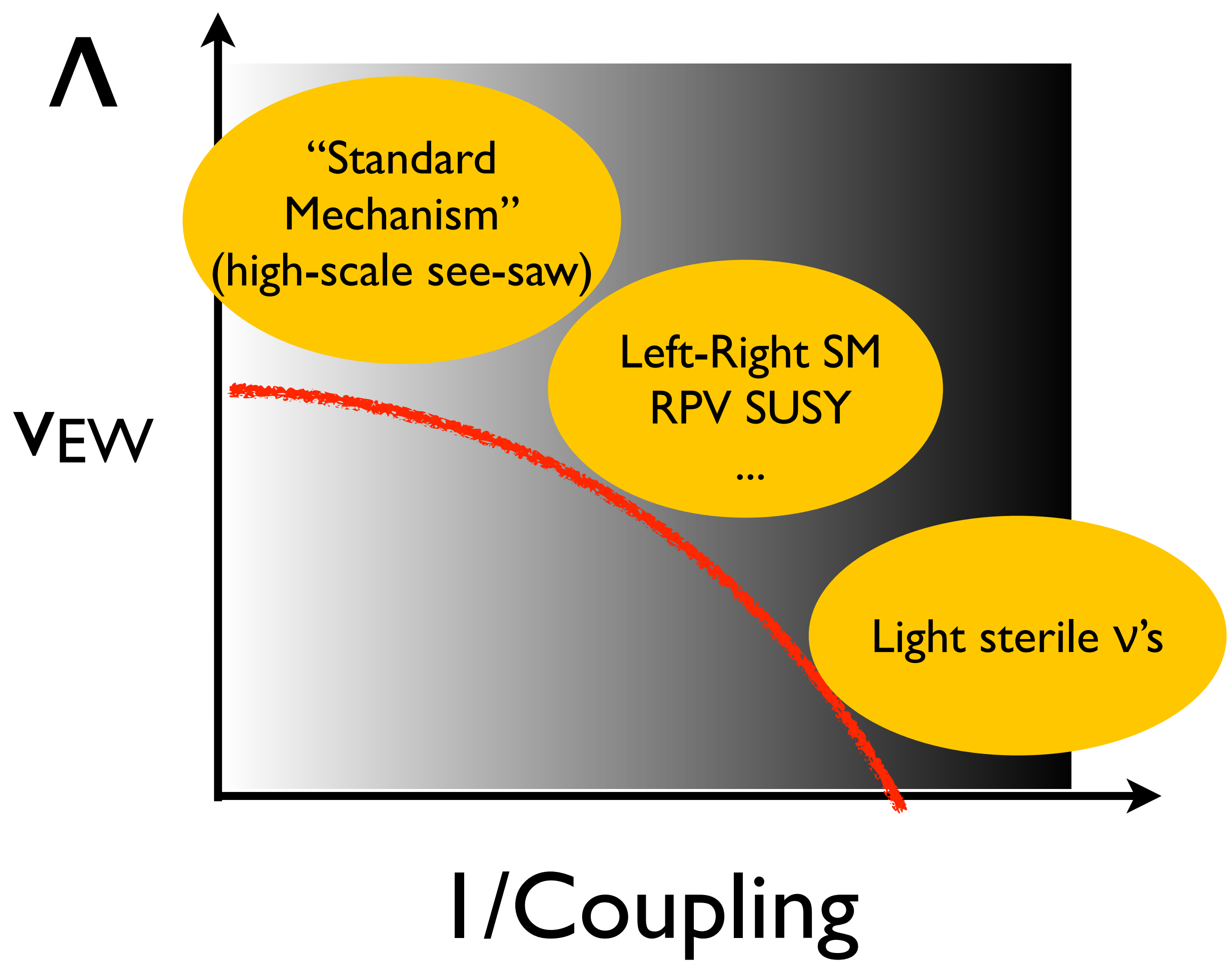


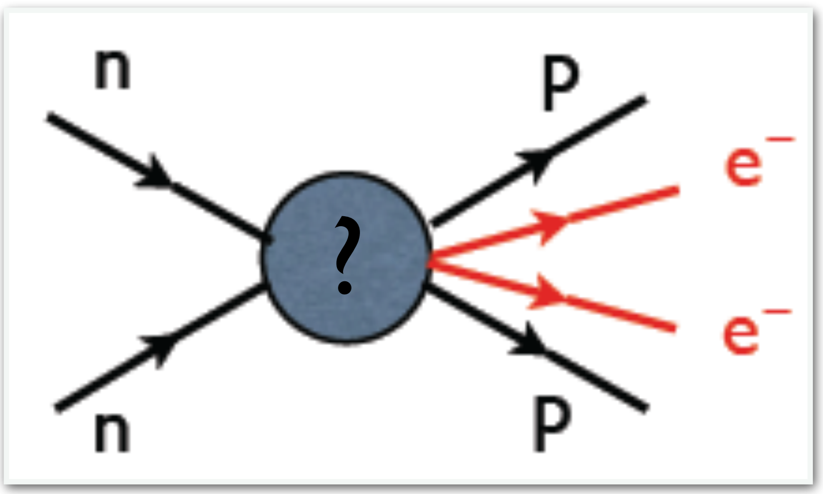
Fukugita-Yanagida 1987

Shechter-Valle 1982

0νββ physics reach

- 0νββ searches at the level of $T_{1/2} > 10^{27\text{-}28}$ yr (ton scale and beyond) probe ΔL=2 physics at unprecedented levels from a variety of mechanisms



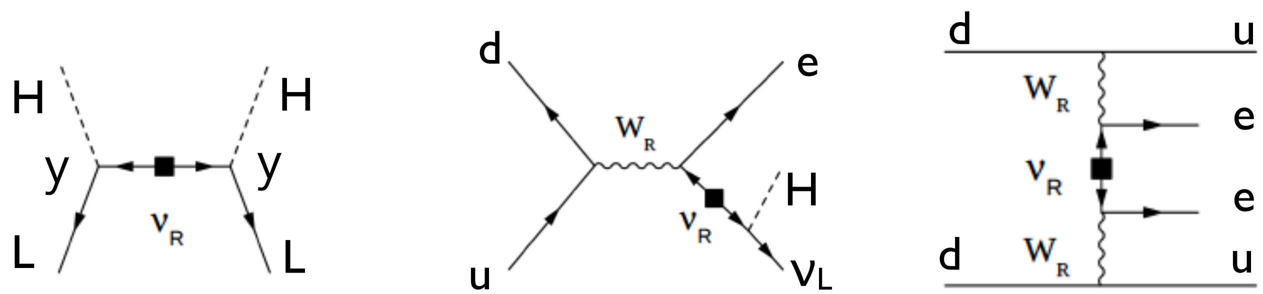


0νββ's impact and relation to other probes of LNV is best analyzed through a tower of EFTs that connect the LNV scale Λ to nuclear scales

EFT framework

E

Λ
(> TeV)



BSM dynamics

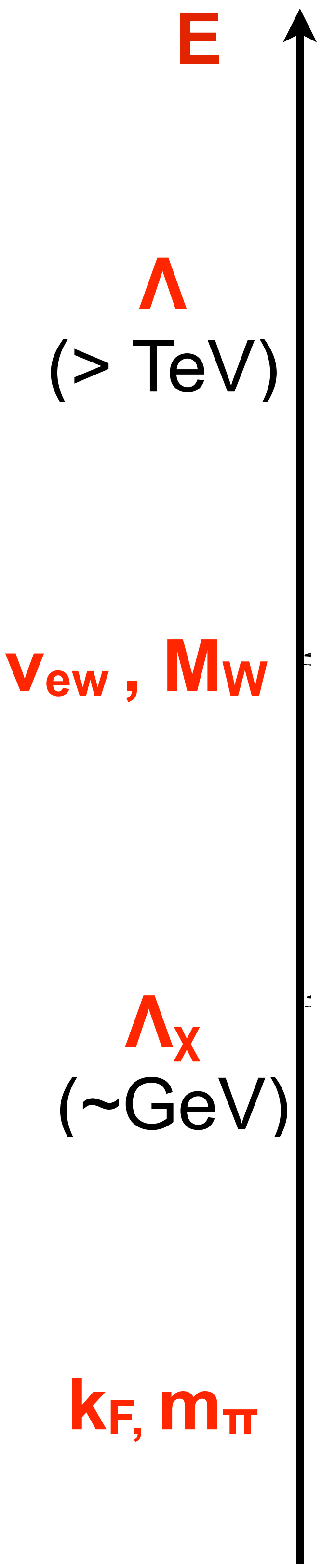
Example:
Left-Right Symmetric Model

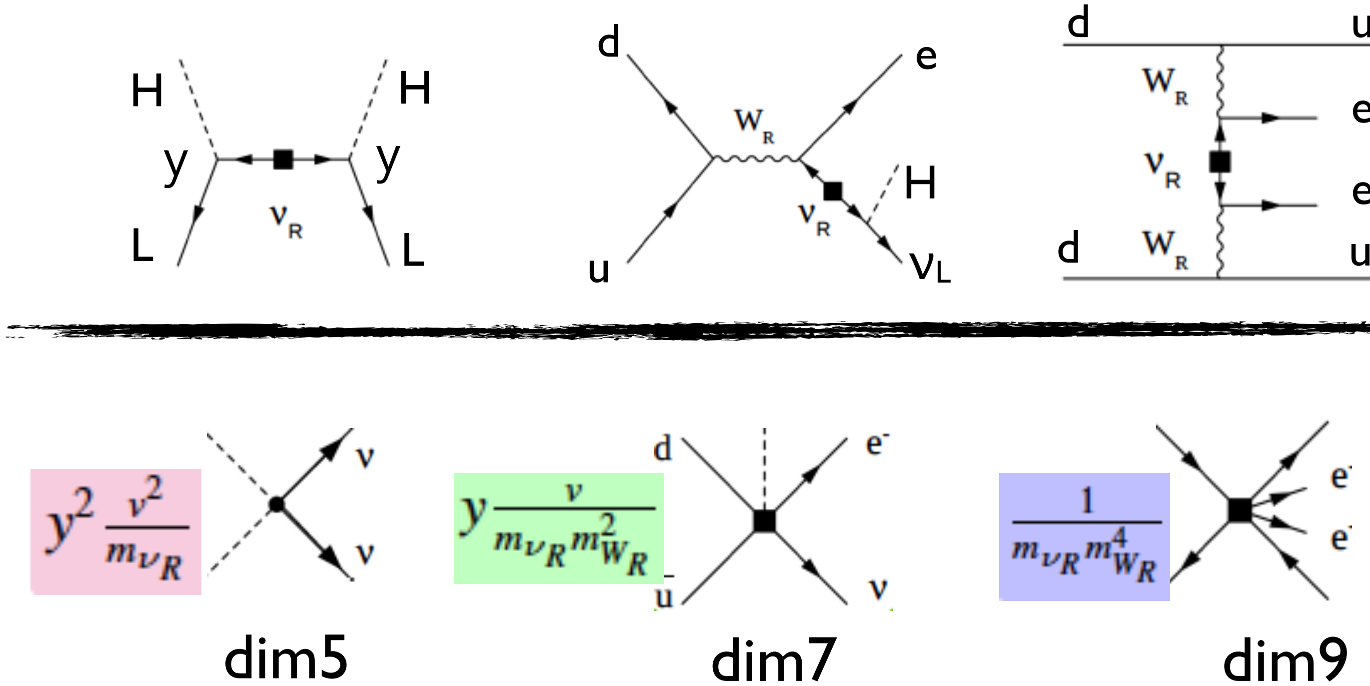
v_{ew} , M_W

Λ_χ
(~GeV)

k_F, m_π

EFT framework





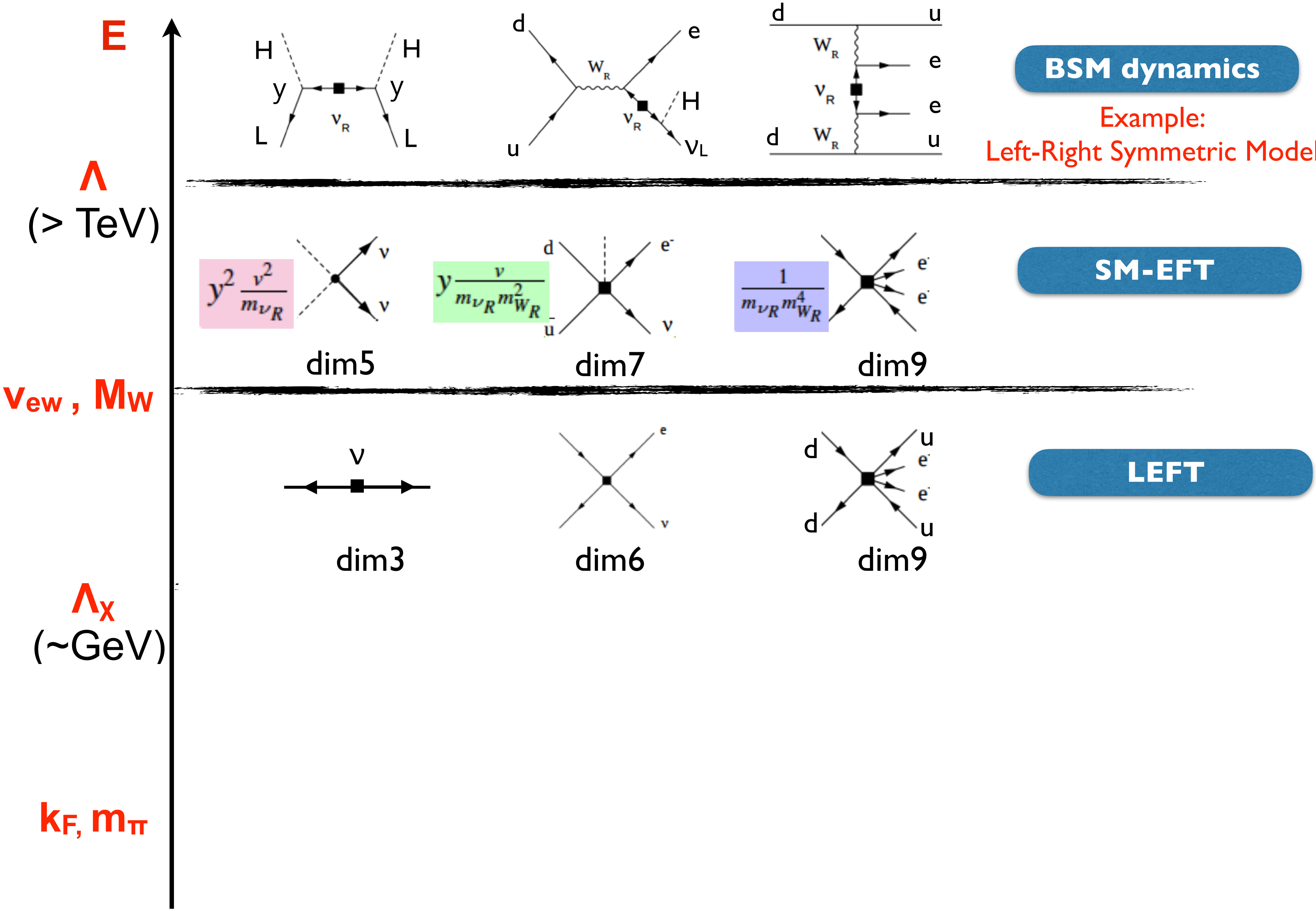
BSM dynamics

Example:
Left-Right Symmetric Model

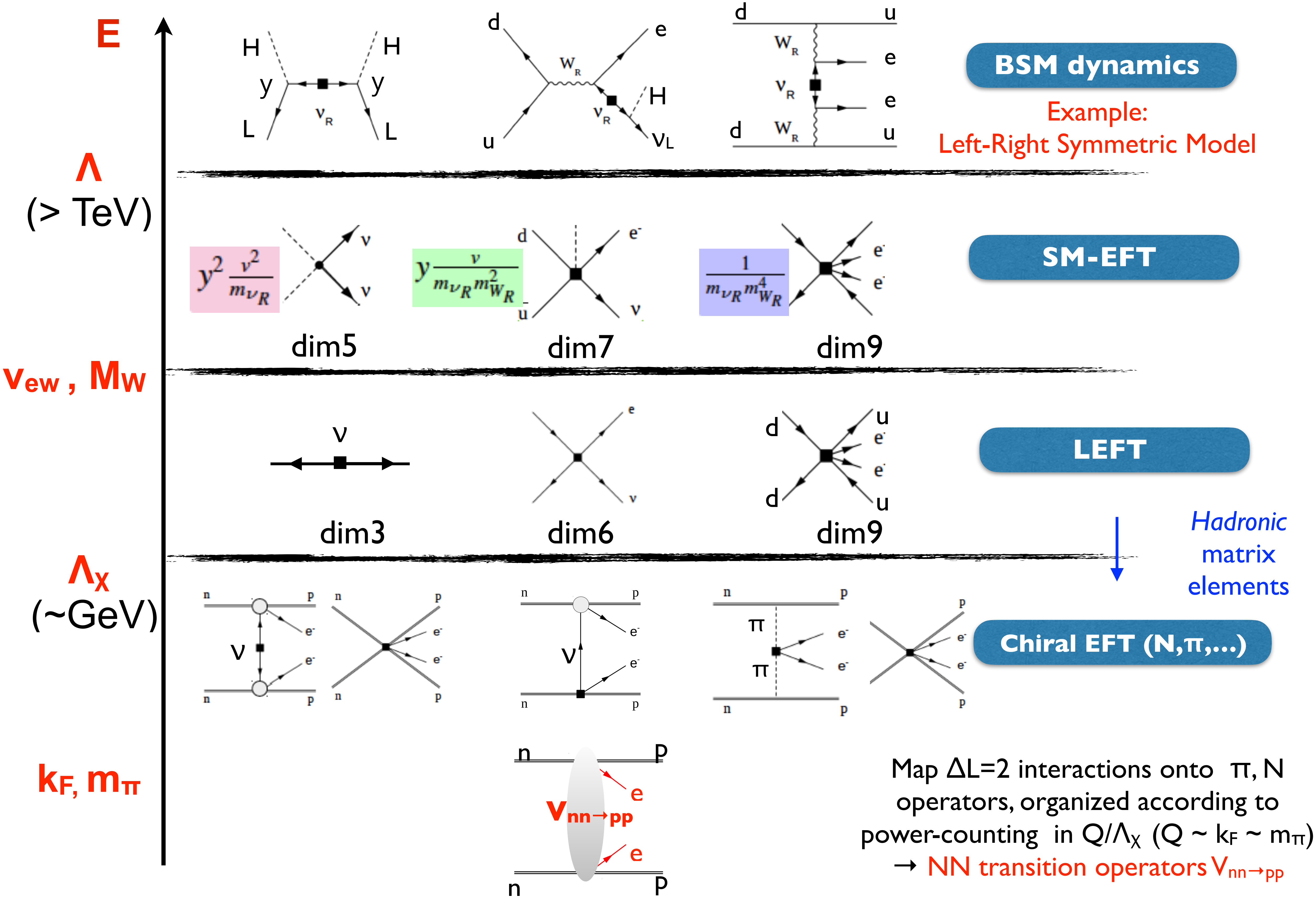
SM-EFT

- 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 — **Dekens et al. 2002.07182**

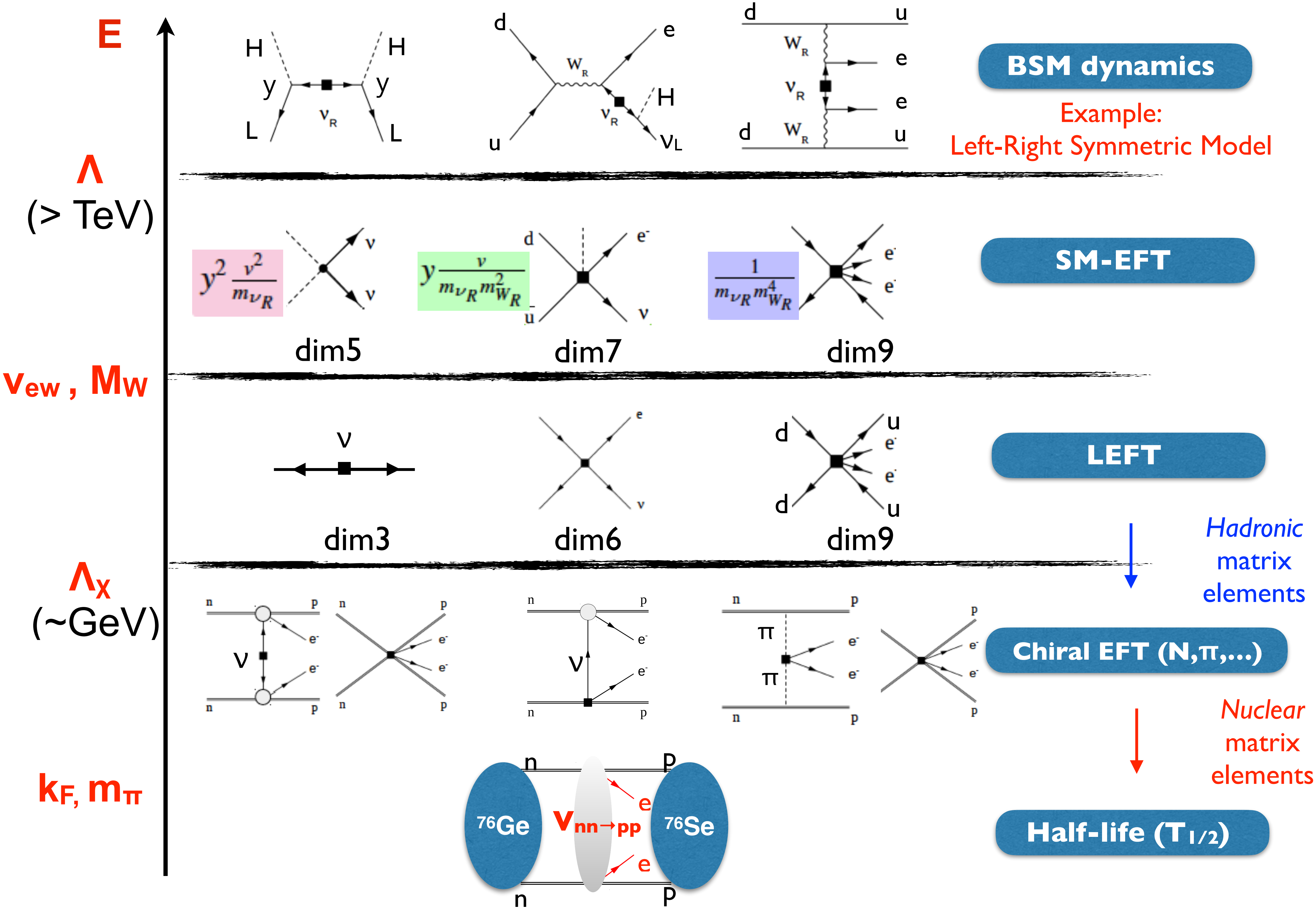
EFT framework



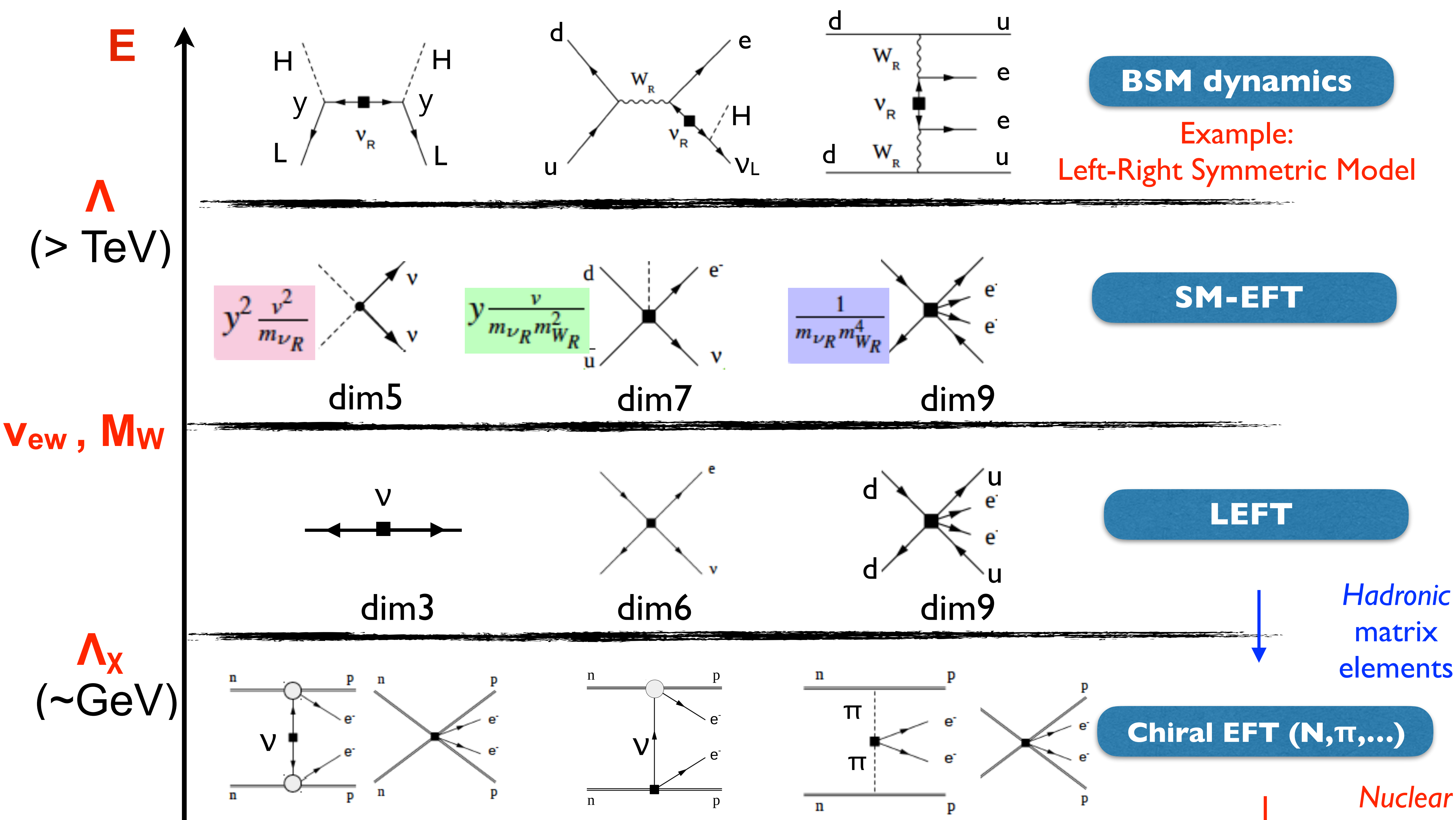
EFT framework



EFT framework



EFT framework



Chain of EFTs +

hadronic & nuclear matrix elements

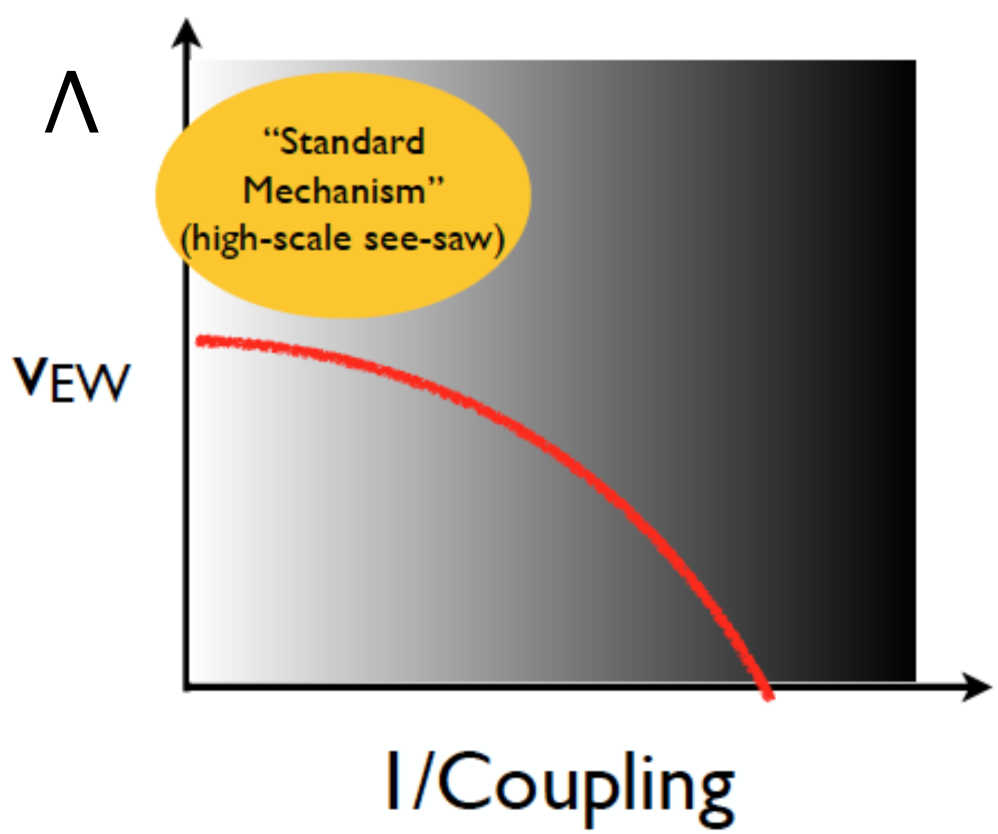
Controllable uncertainties:

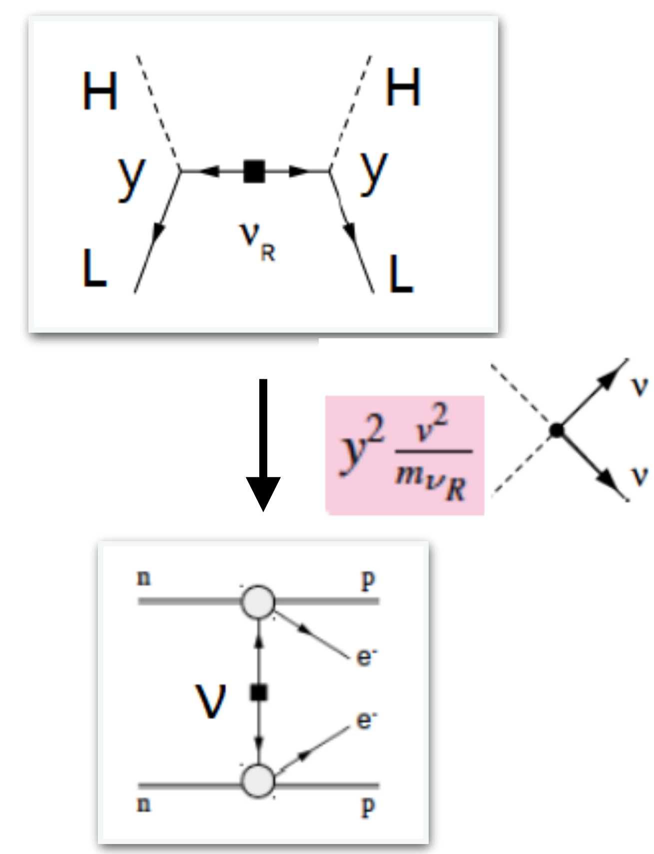
$T_{1/2} \sim (m_W/\Lambda)^A \; (\Lambda_\chi/m_W)^B \; (k_F/\Lambda_\chi)^C$

LNV @ dim-5

$0\nu\beta\beta$ mediated by the exchange of light Majorana ν

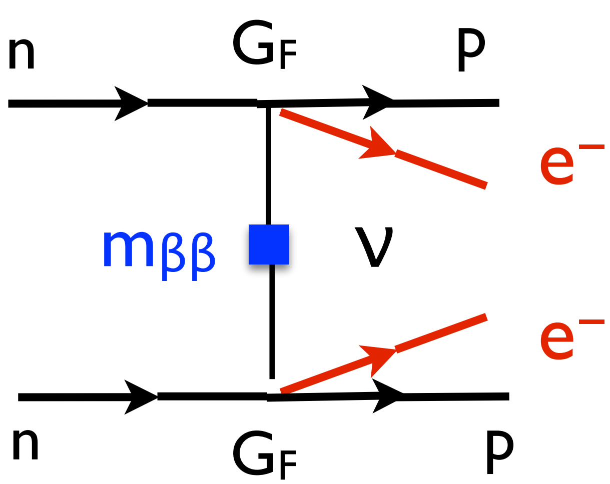
Dominant mechanism if LNV originates at very high scale ($\Lambda >> v_{EW}$)





Phenomenological interest

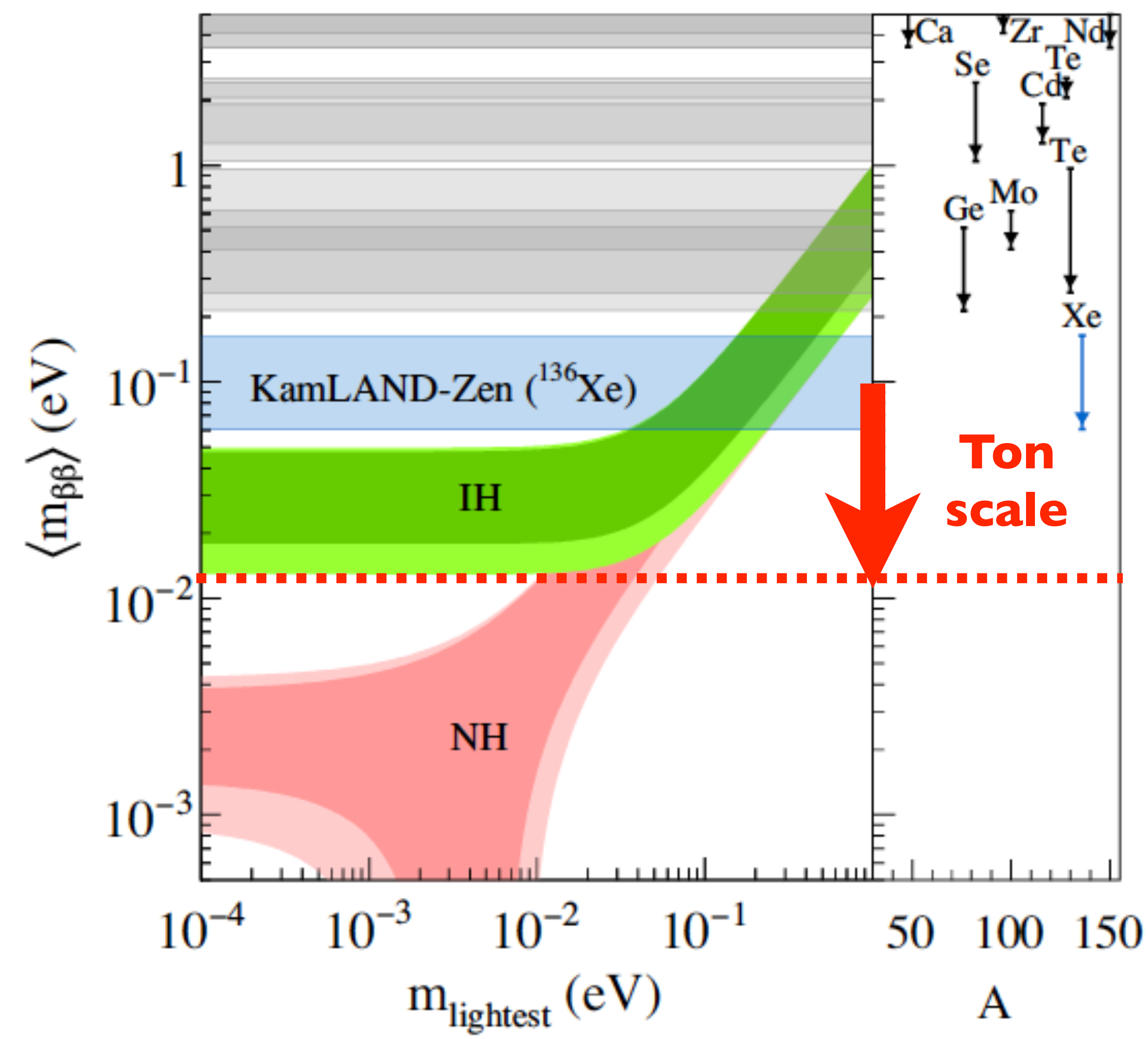
- In this case $0\nu\beta\beta$ is a *direct* probe of Majorana mass: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$



$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

Strong correlation with ν oscillation parameters

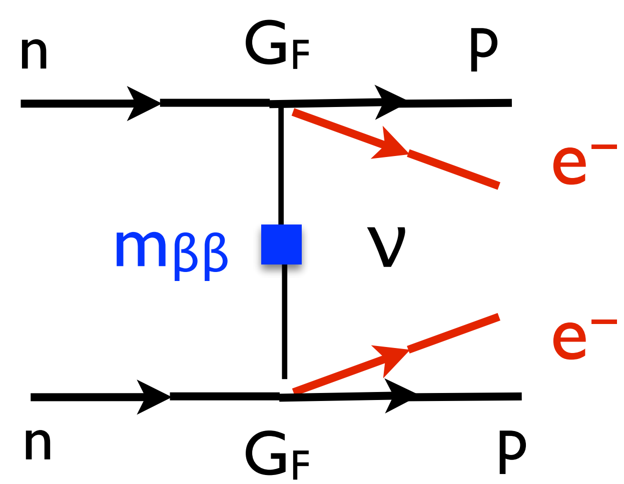
KamLAND-Zen 1605.02889



Discovery *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

Phenomenological interest

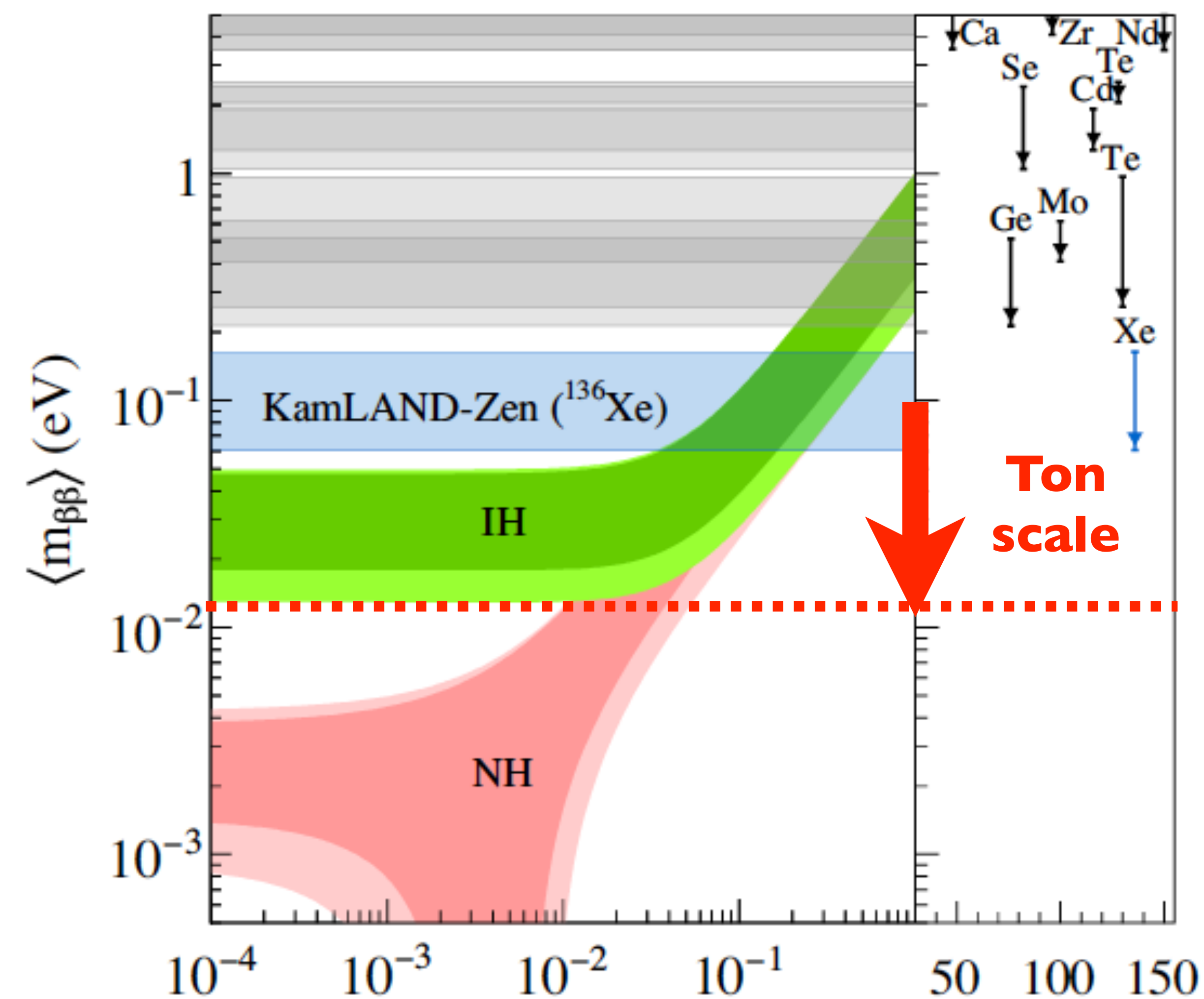
- In this case 0νββ is a *direct* probe of Majorana mass: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$



$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

Strong correlation with ν oscillation parameters

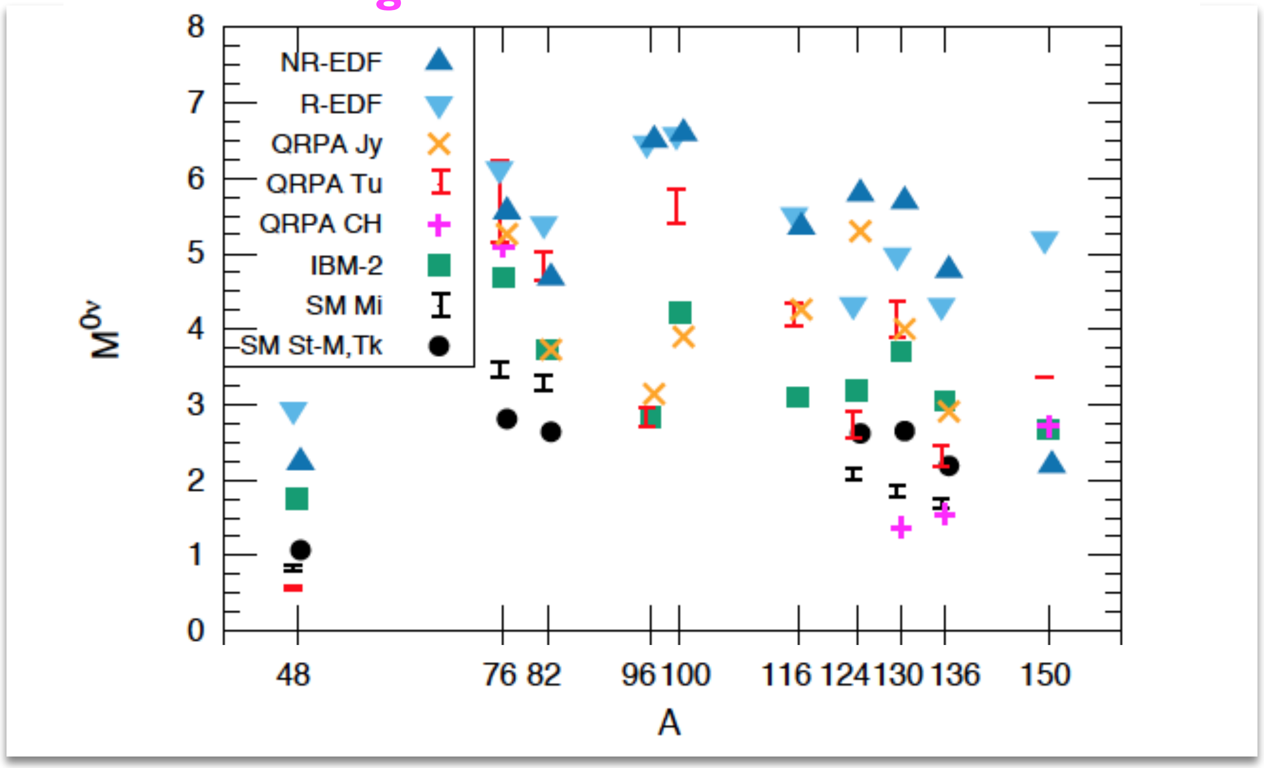
KamLAND-Zen 1605.02889



Correlation with other ν mass probes can test high-scale seesaw and possibly unravel new sources of LNV or physics beyond "ΛCDM + m_ν". But these interesting connections require robust matrix elements!

Theoretical developments

Engel-Menendez 1610.06548



- Snapshot as of a few years ago [recall $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$]

- Steps towards controlled uncertainties in matrix elements:
    - Use chiral EFT as guiding principle
    - Compute hadronic matrix elements: lattice QCD, dispersive, …
    - First-principles nuclear structure calculations: light nuclei, ^{48}Ca , ^{76}Ge, …

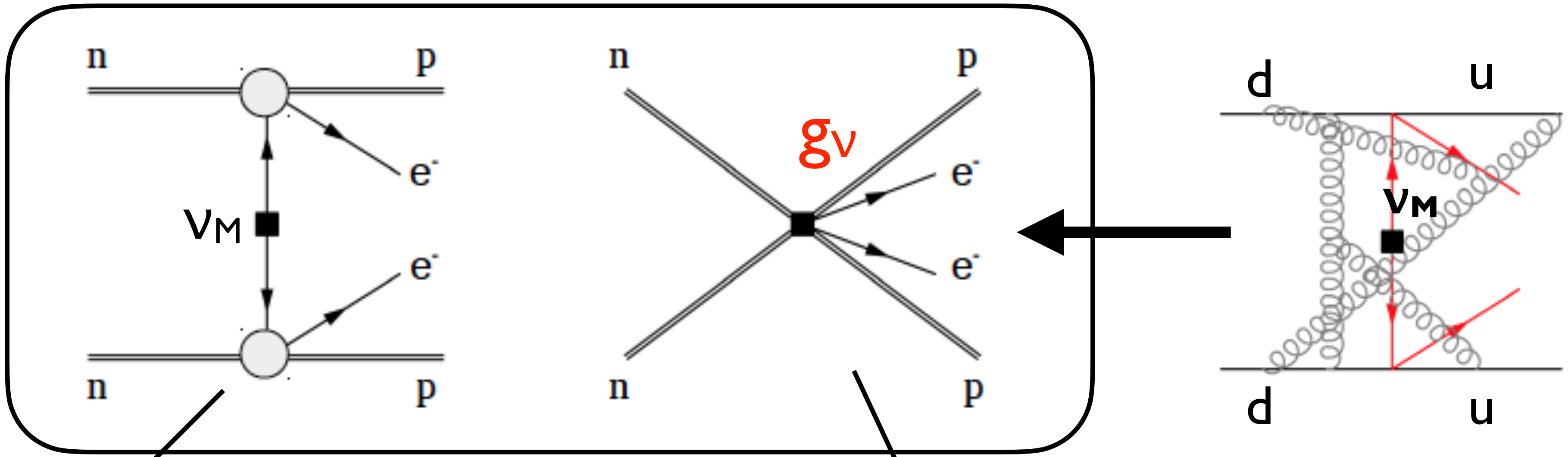
Pastore et al., 1710.05026; Yao et al., 1908.05424;
Belley et al.; 2008.06588; Novario et al., 2008.09696

New insights from EFT

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

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Transition operator to leading order in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)



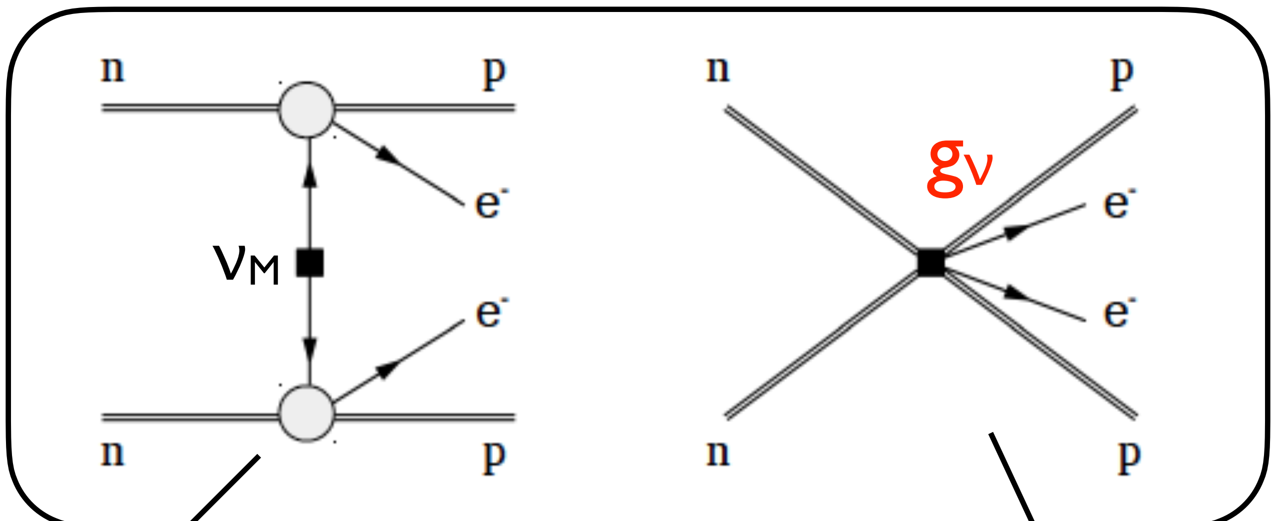
'Usual' ν_M exchange $\sim 1/Q^2$
Coulomb-like potential

'New': short-range coupling $g_\nu \sim 1/Q^2$

New insights from EFT

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Transition operator to leading order in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)



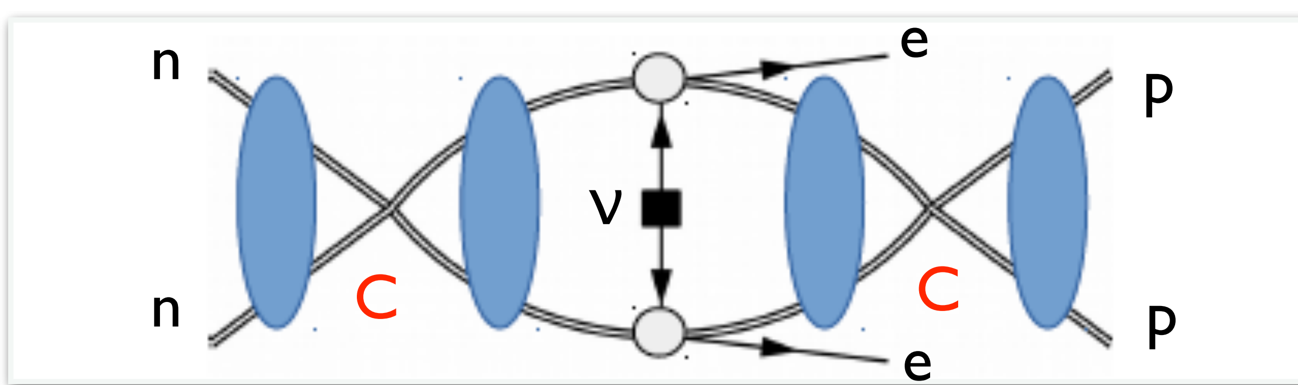
'Usual' ν_M exchange $\sim 1/Q^2$
Coulomb-like potential

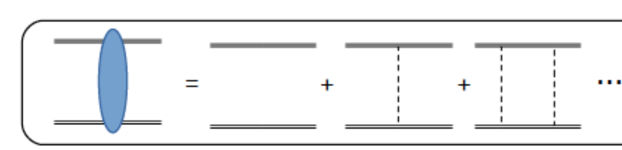
'New': short-range coupling $g_\nu \sim 1/Q^2$
Required by renormalization of $nn \to ppee$ amplitude in presence of strong interactions

UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$

$C \sim 4\pi/(m_N Q)$

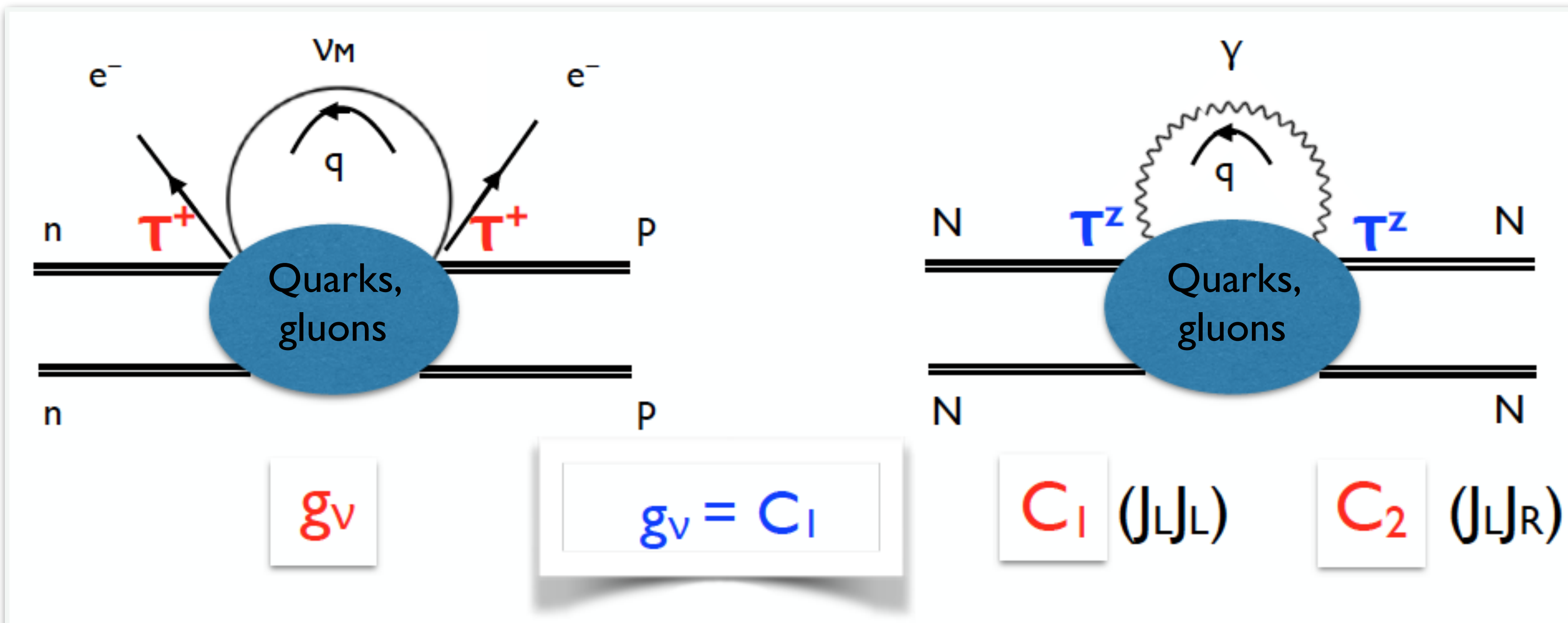
Strong $^1S_0$ short-range interaction





Connection with data?

- Chiral+isospin symmetry relates g_ν to I=2 e.m. couplings (hard γ's & ν's)

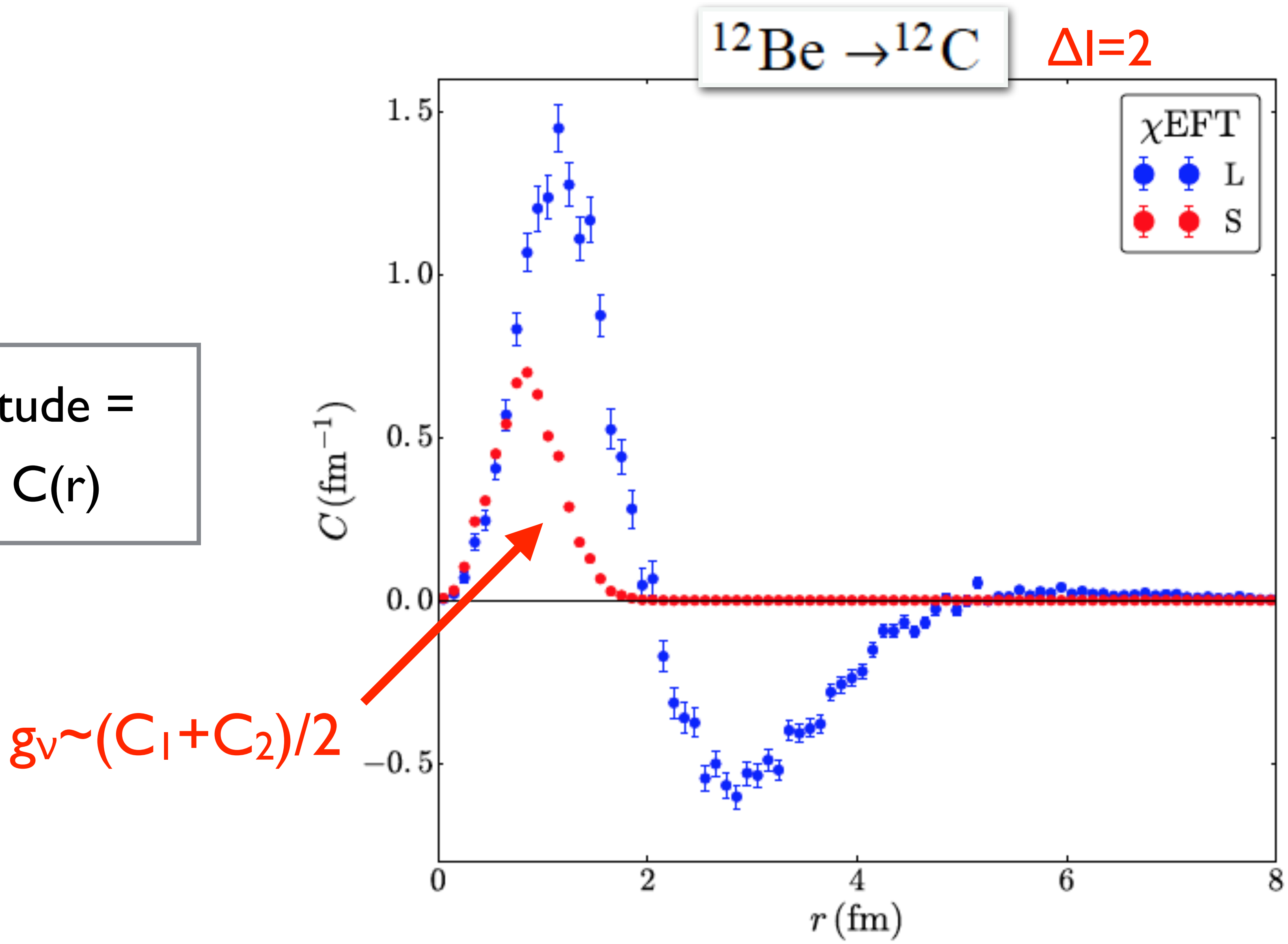


- NN data ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling!
- Assuming $g_\nu \sim (C_1+C_2)/2$, what is the impact on $m_{\beta\beta}$ extraction?

Impact on nuclear matrix elements (I)

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

Amplitude = $\int dr\, C(r)$



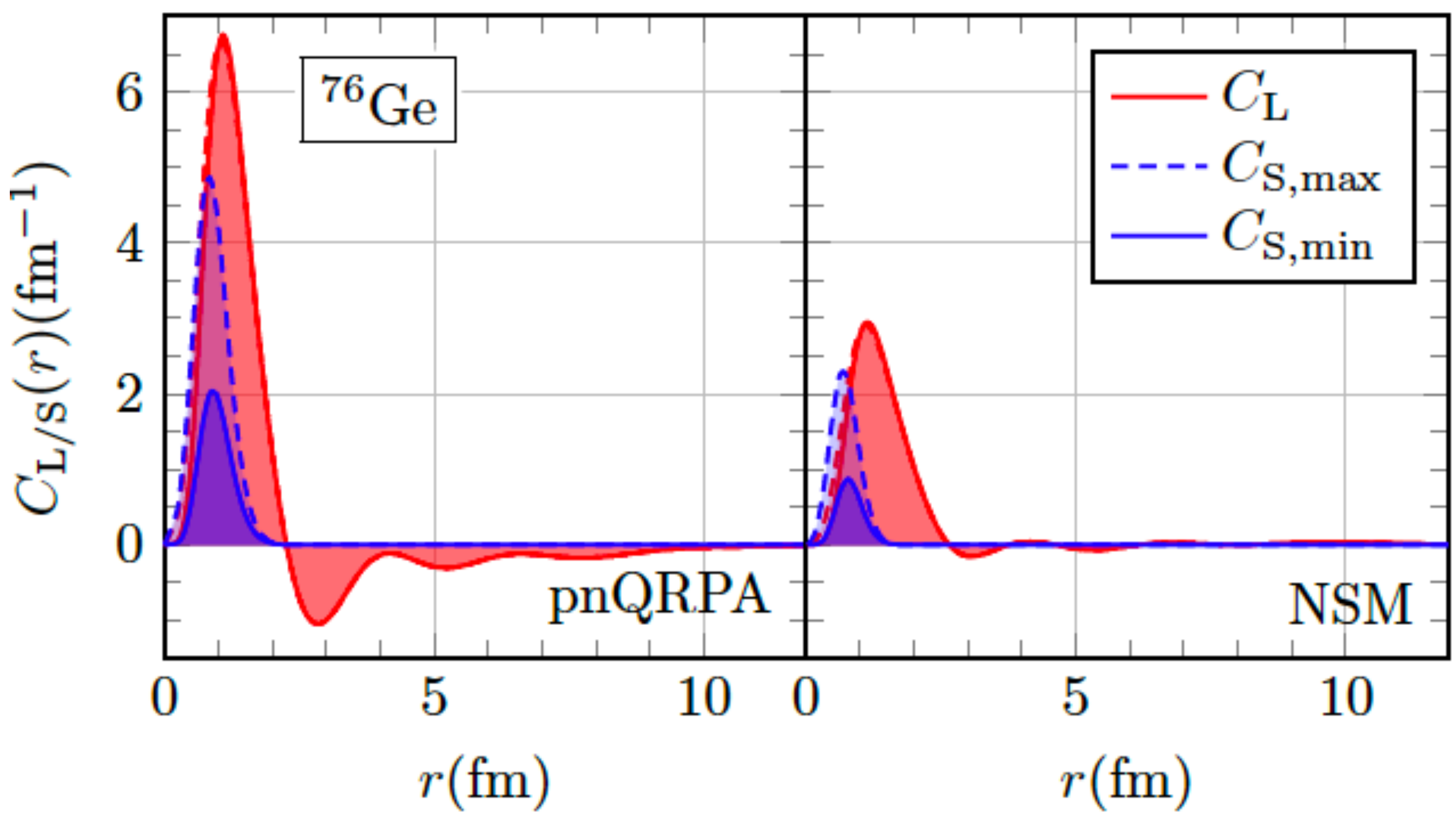
Light nuclei with Norfolk chiral potential [1606.06335]

g_V contribution large in ΔI=2 transition: for A=12, A_S/A_L = 0.75

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

Impact on nuclear matrix elements (2)

- Similar large effects for nuclei of experimental interests are found with other methods as well (QRPA, nuclear shell model), taking $g_V \sim (C_1+C_2)/2$



30-70% effect in QRPA and 15-45% in NSM. Similar or larger in other isotopes

Jokiniemi-Soriano-Menendez, 2107.13354

Approaches to g_ν

- Large-N_C arguments point to $g_\nu \sim (C_1+C_2)/2 + O(1/N_C)$

  Richardson, Shindler, Pastore, Springer, 2102.02814

- Lattice QCD
  - $\pi^- \to \pi^+ e^- e^-$ precisely known
  - Formalism for NN developed

  Tuo et al. 1909.13525; Detmold, Murphy 2004.07404

  Davoudi, Kadam, 2012.02083, 2111.11599

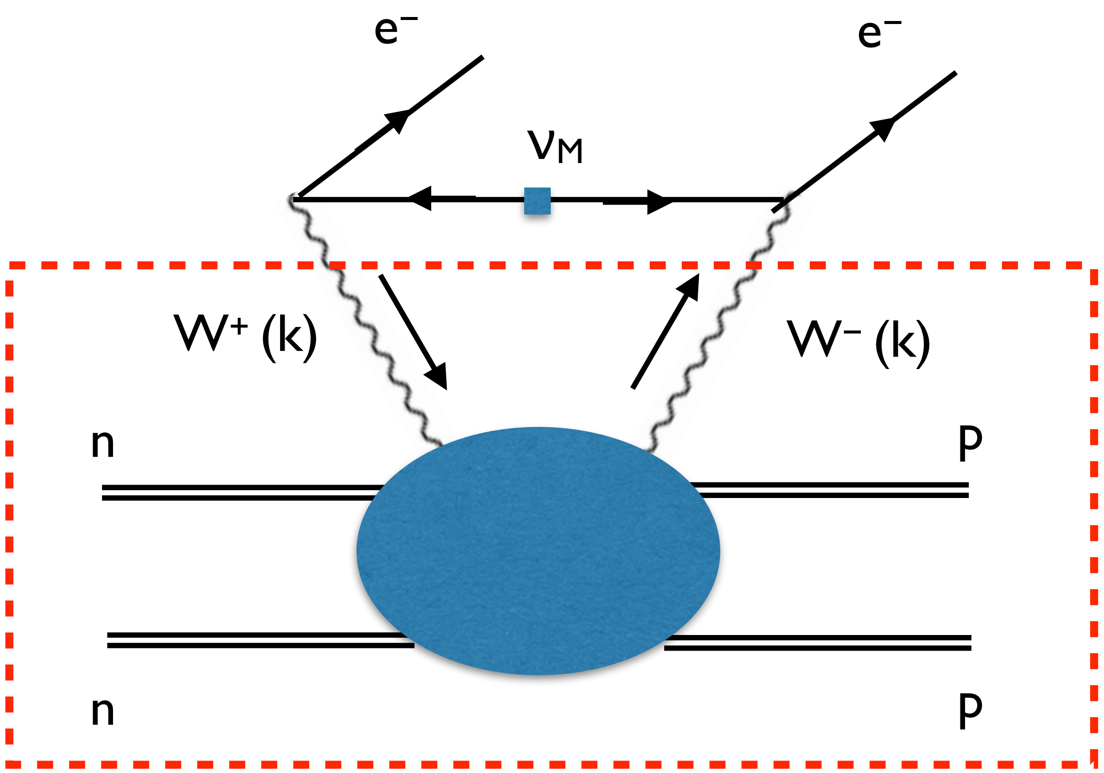
- Analytic method inspired by Cottingham formula for $\delta m_{p,n}$ (EM)

  VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Estimating the contact term (1)

- Integral representation of the amplitude

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\rm w}^{\alpha}(x) j_{\rm w}^{\beta}(0) \} | nn \rangle$$



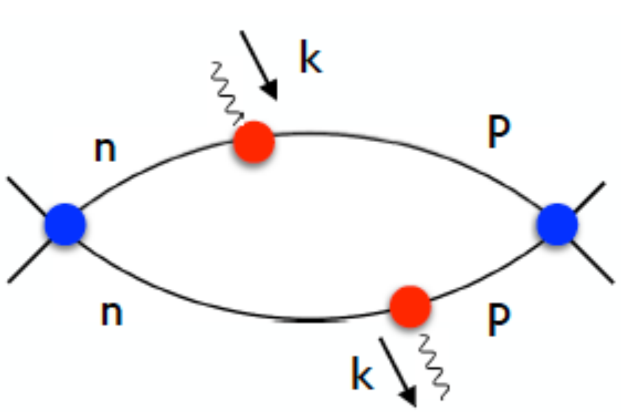
Forward "Compton" amplitude

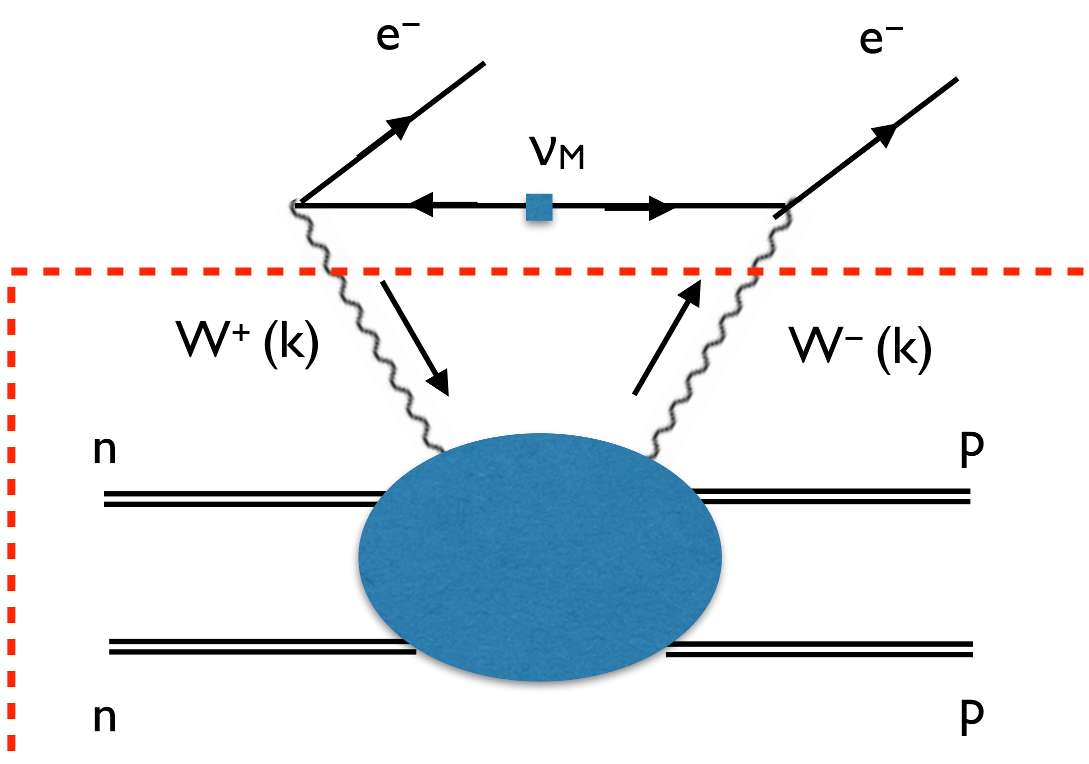
Estimating the contact term (1)

- Integral representation of the amplitude

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\rm w}^{\alpha}(x) j_{\rm w}^{\beta}(0) \} | nn \rangle$$

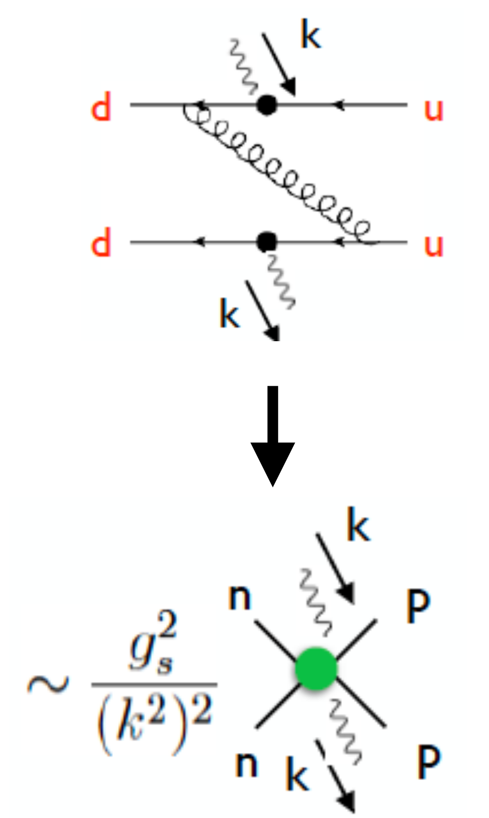
Low k: chiral EFT to NLO





Forward "Compton" amplitude

High k: QCD OPE

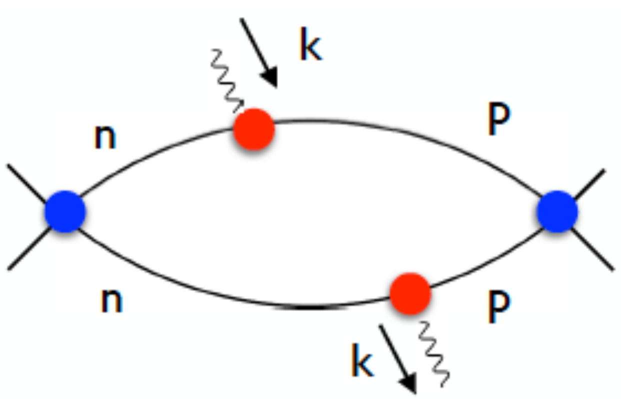


Estimating the contact term (I)

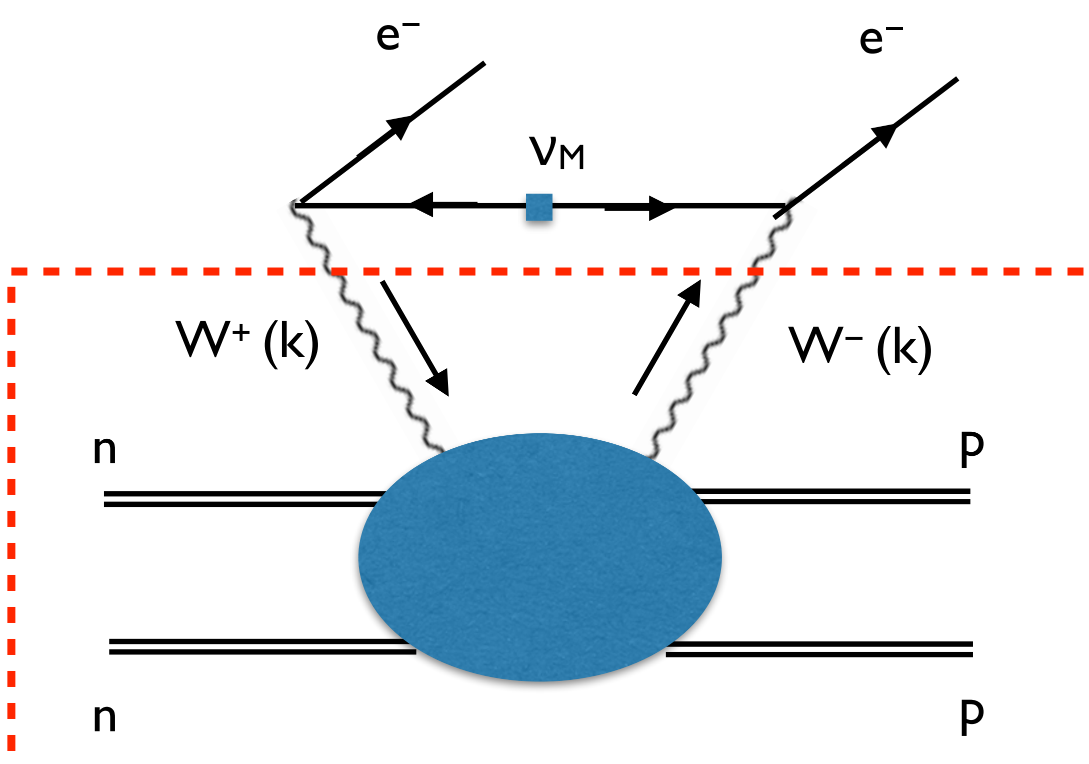
- Integral representation of the amplitude

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\rm W}^{\alpha}(x) j_{\rm W}^{\beta}(0) \} | nn \rangle$$

Low k: chiral EFT to NLO

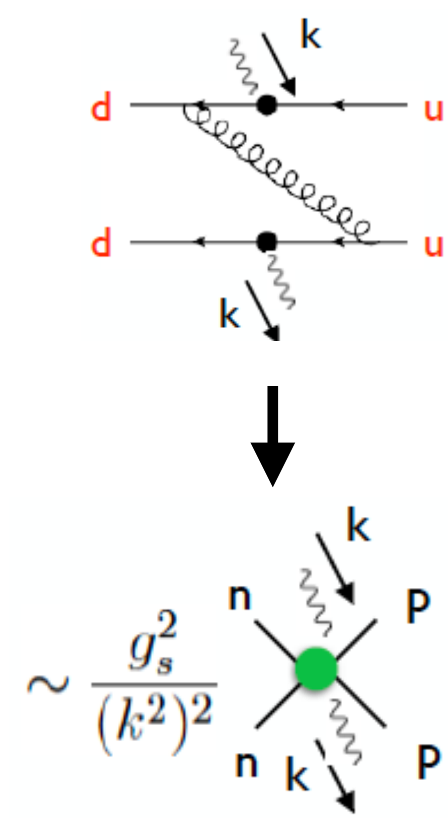


Intermediate k: resonance contributions in (blue) and (red), πNN intermediate state, …



Forward "Compton" amplitude

High k: QCD OPE

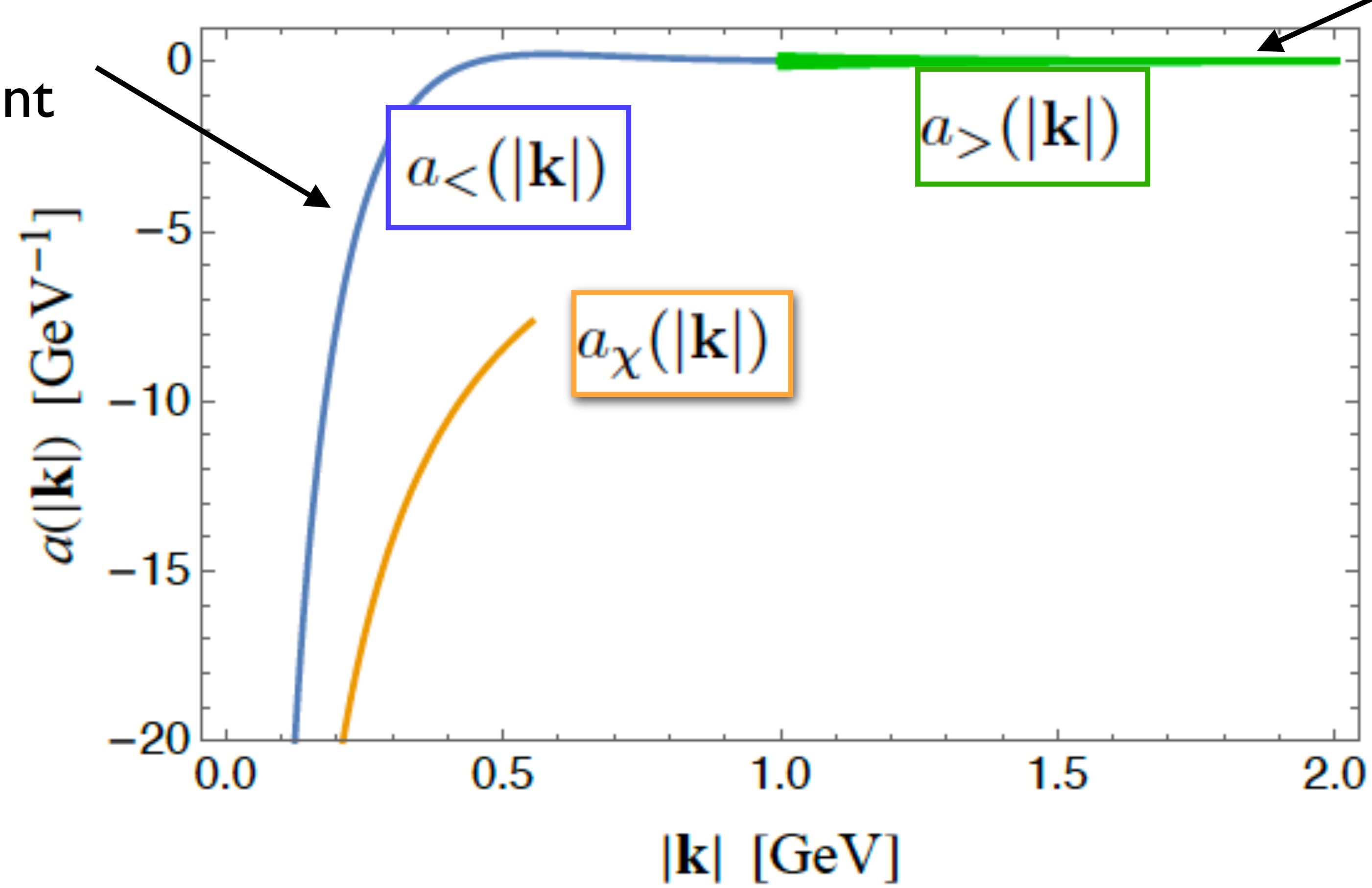


Estimating the contact term (2)

- Integral representation of the amplitude

$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\ a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\ a_>(|\mathbf{k}|)$$

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



Uncertainty due to unknown local operator matrix element is negligible

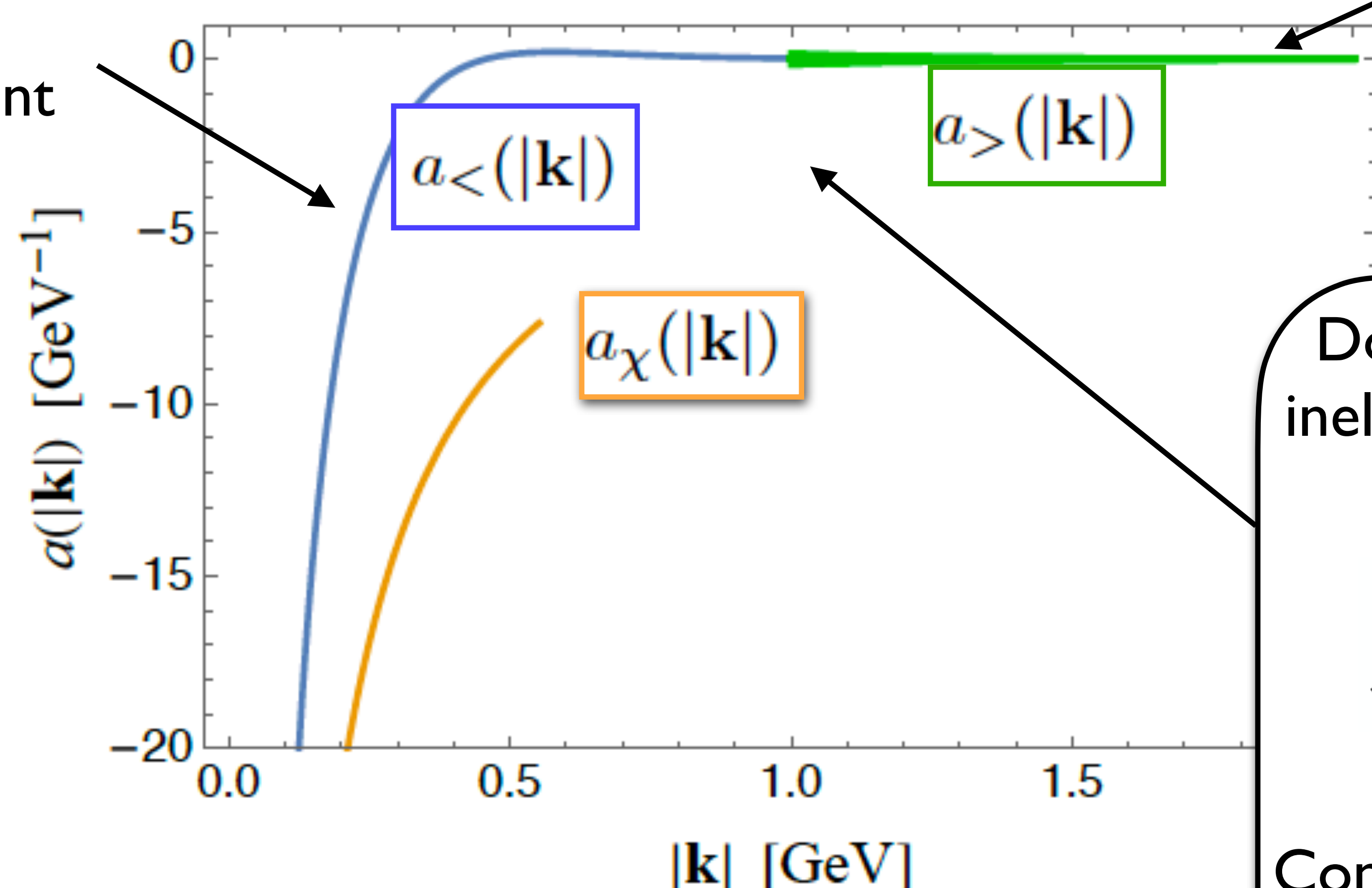
Estimating the contact term (2)

- Integral representation of the amplitude

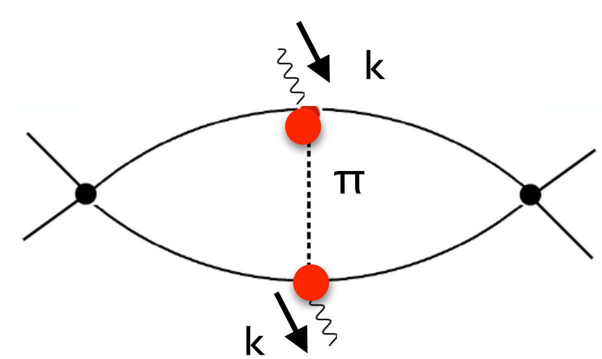
$$\mathcal{A}_\nu \propto \int_0^{\Lambda} d|\mathbf{k}|\ a_<(|\mathbf{k}|) + \int_{\Lambda}^{\infty} d|\mathbf{k}|\ a_>(|\mathbf{k}|)$$

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

Uncertainty due to unknown local operator matrix element is negligible



Dominant uncertainty from inelastic channels (NNπ , …):



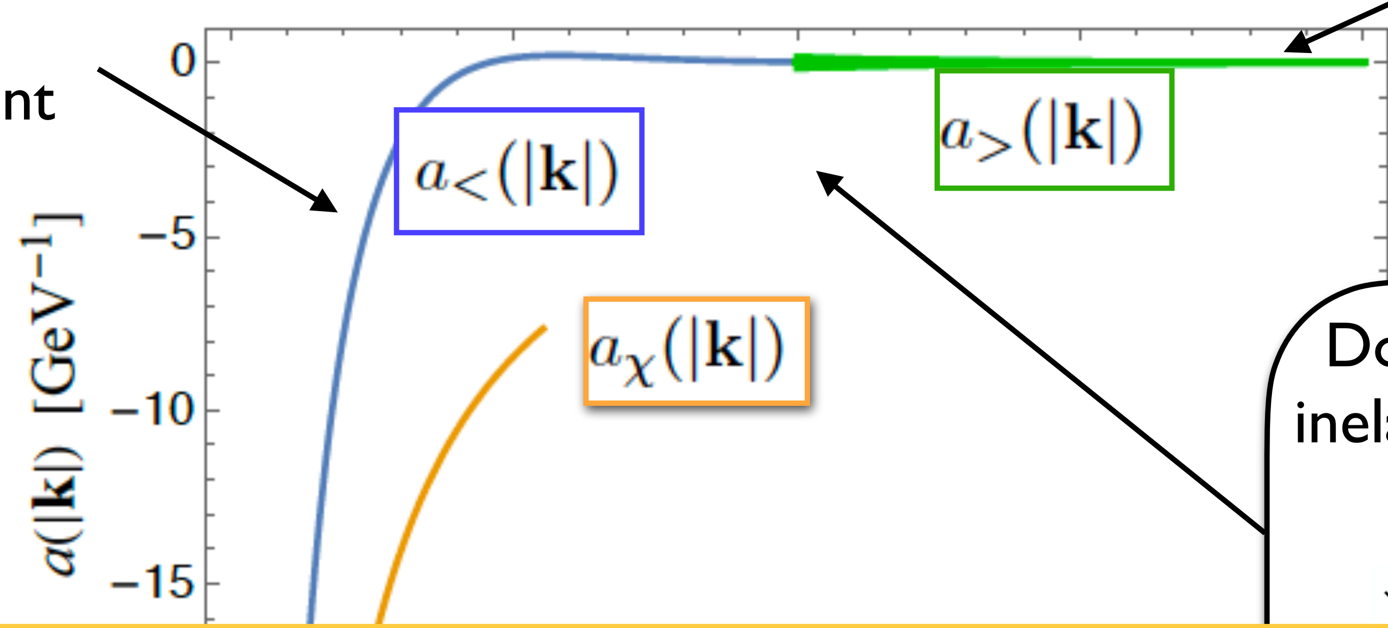
Consistent with <30% effect in Cottingham approach to π,N EM mass splittings

Estimating the contact term (2)

- Integral representation of the amplitude

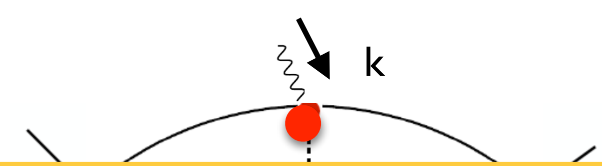
$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$

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



Uncertainty due to unknown local operator matrix element is negligible

Dominant uncertainty from inelastic channels (NNπ , ...):



- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)
- Validation: $C_1+C_2 \Rightarrow (a_{nn}+a_{pp})/2 - a_{np}$ = 15.5(4.5)*fm* versus 10.4(2)*fm* (exp)

Connecting to nuclear structure

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_ν with regulators suitable for many-body nuclear calculations

$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\mathcal{A}_\nu(|\mathbf{p}|, |\mathbf{p}'|)e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}$$

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Connecting to nuclear structure

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_ν with regulators suitable for many-body nuclear calculations

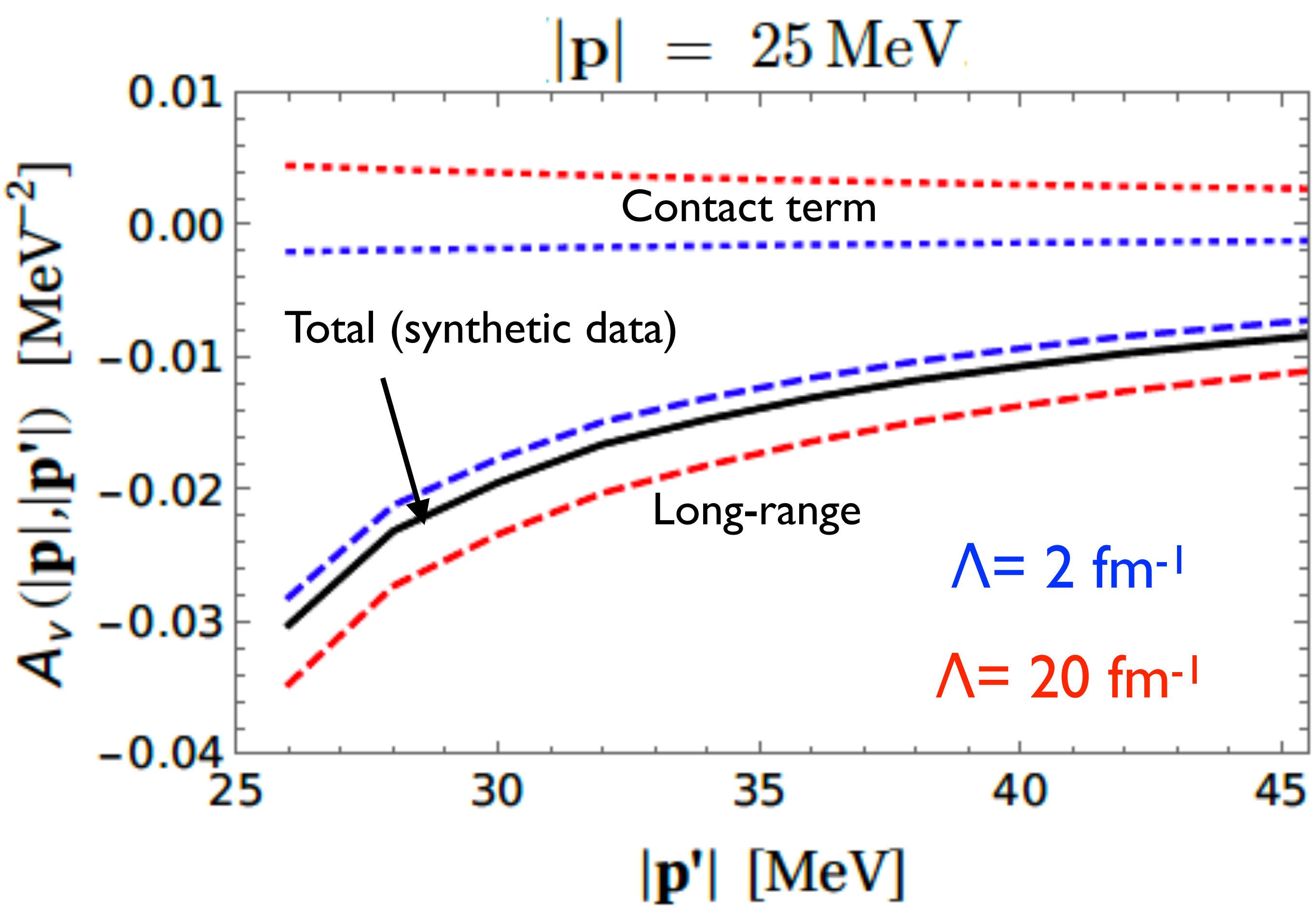
$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|)e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}$$

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Illustrated fitting procedure with various cutoffs

- Constructive or destructive? The sign of the interference depends on the regulator!



Connecting to nuclear structure

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_ν with regulators suitable for many-body nuclear calculations

$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\mathcal{A}_\nu(|\mathbf{p}|, |\mathbf{p}'|) e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}$$

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Wirth, Yao, Hergert, 2105.05415

- First calculation of $^{48}Ca \rightarrow {}^{48}Ti$ with contact fitted to synthetic data
- Use Entem-Machleidt class of chiral potentials
- Contact term *enhances* nuclear matrix element by (43±7)%

Connecting to nuclear structure

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_ν with regulators suitable for many-body nuclear calculations

$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\mathcal{A}_\nu(|\mathbf{p}|, |\mathbf{p}'|) e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}$$

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Wirth, Yao, Hergert, 2105.05415

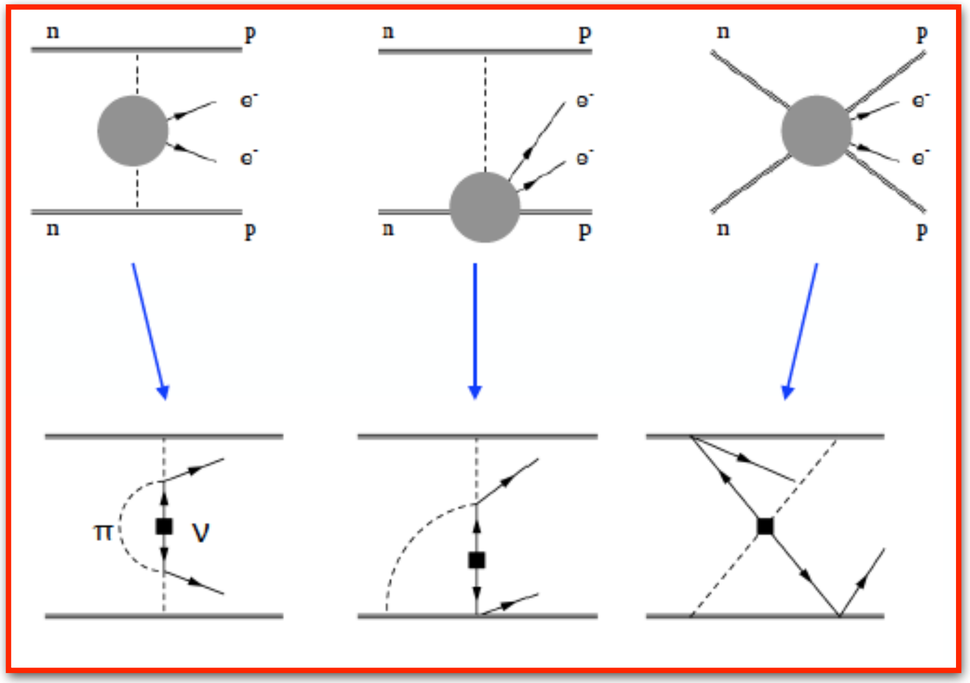
- First calculation of $^{48}Ca \rightarrow ^{48}Ti$ with contact fitted to synthetic data
- Use Entem-Machleidt class of chiral potentials
- Contact term *enhances* nuclear matrix element by (43±7)%

Good news, while we wait for lattice results

What about higher orders?

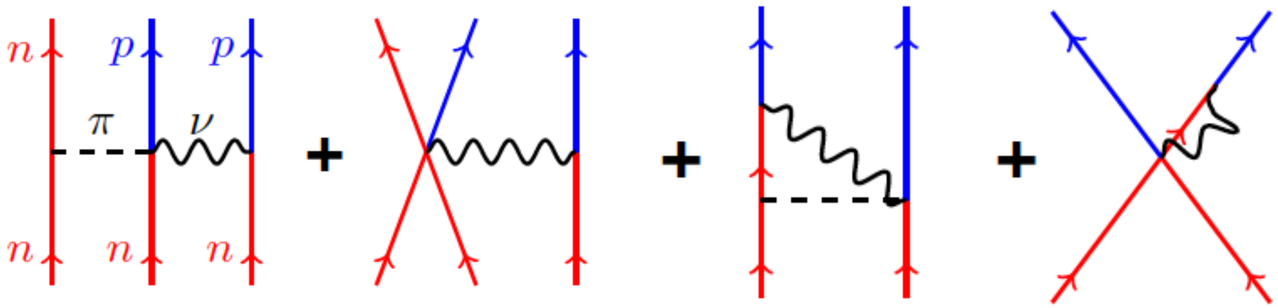
- N2LO

  - πN loops + new contact



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

  - 2-body **x** 1-body current



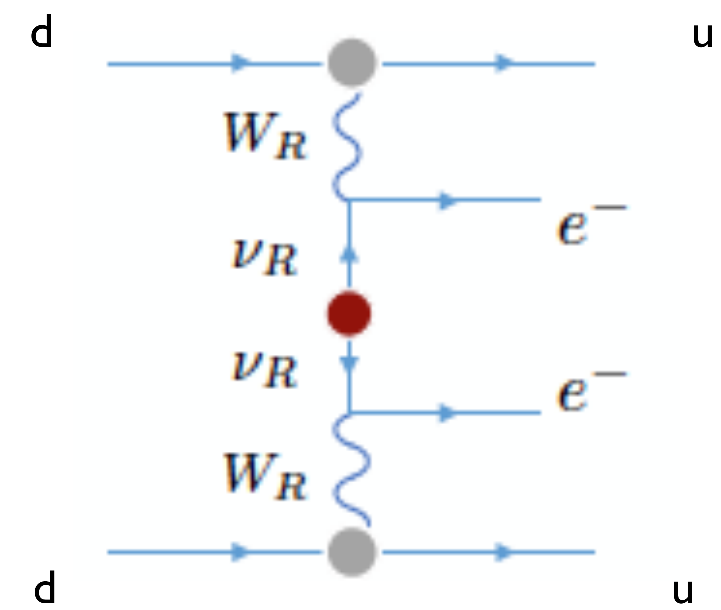
Wang-Engel-Yao 1805.10276

Calculations 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, j. Menendez, E. Mereghetti, in preparation

LNV from multi-TeV scale physics

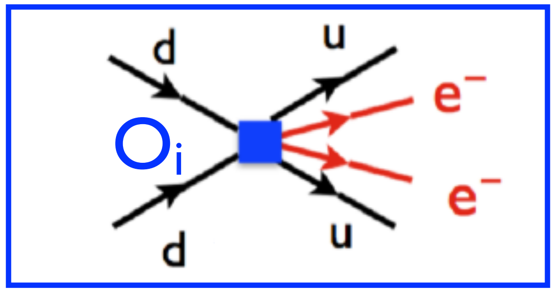
- Induce contributions to 0νββ *not directly related to the exchange of light neutrinos,* within reach of current experiments



- May lead to correlated (or precursor!) signal at LHC: pp → ee jj

- Chiral EFT: several unknown leading-order NN contact interactions. They are needed to probe physics beyond high-scale seesaw and assess the complementarity of 0νββ to collider searches. Another great opportunity for lattice QCD!

Hadronic realization of dim-9 operators



Scalar operators (arising in most models)

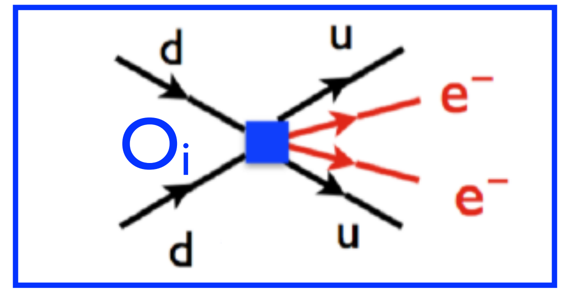
$$\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \, \gamma_\mu d_L$$

$$\mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R, \qquad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha$$

$$\mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \, \gamma_\mu d_R, \qquad \mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta \, \bar{u}_R^\beta \, \gamma_\mu d_R^\alpha$$

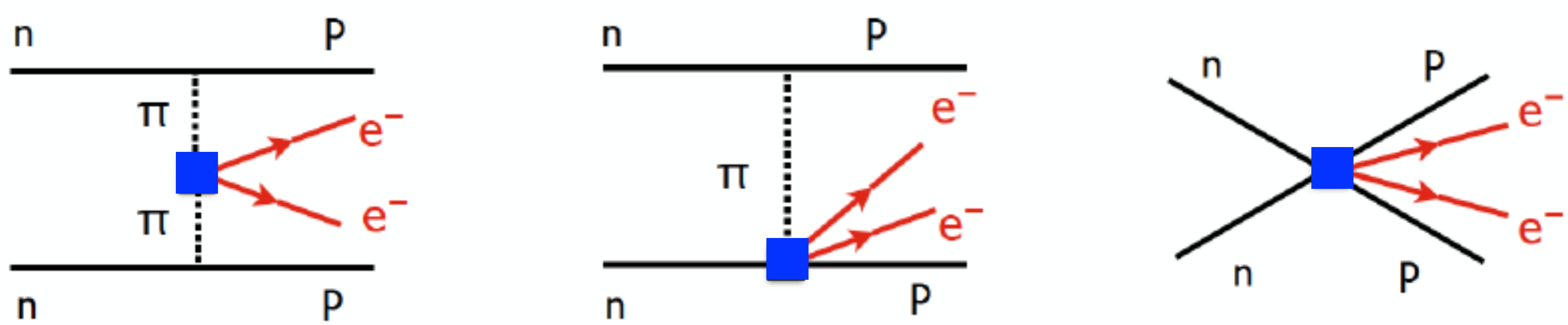
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205
M. Graesser 1606.04549

Hadronic realization of dim-9 operators



Pion-range effects

Short-range effects

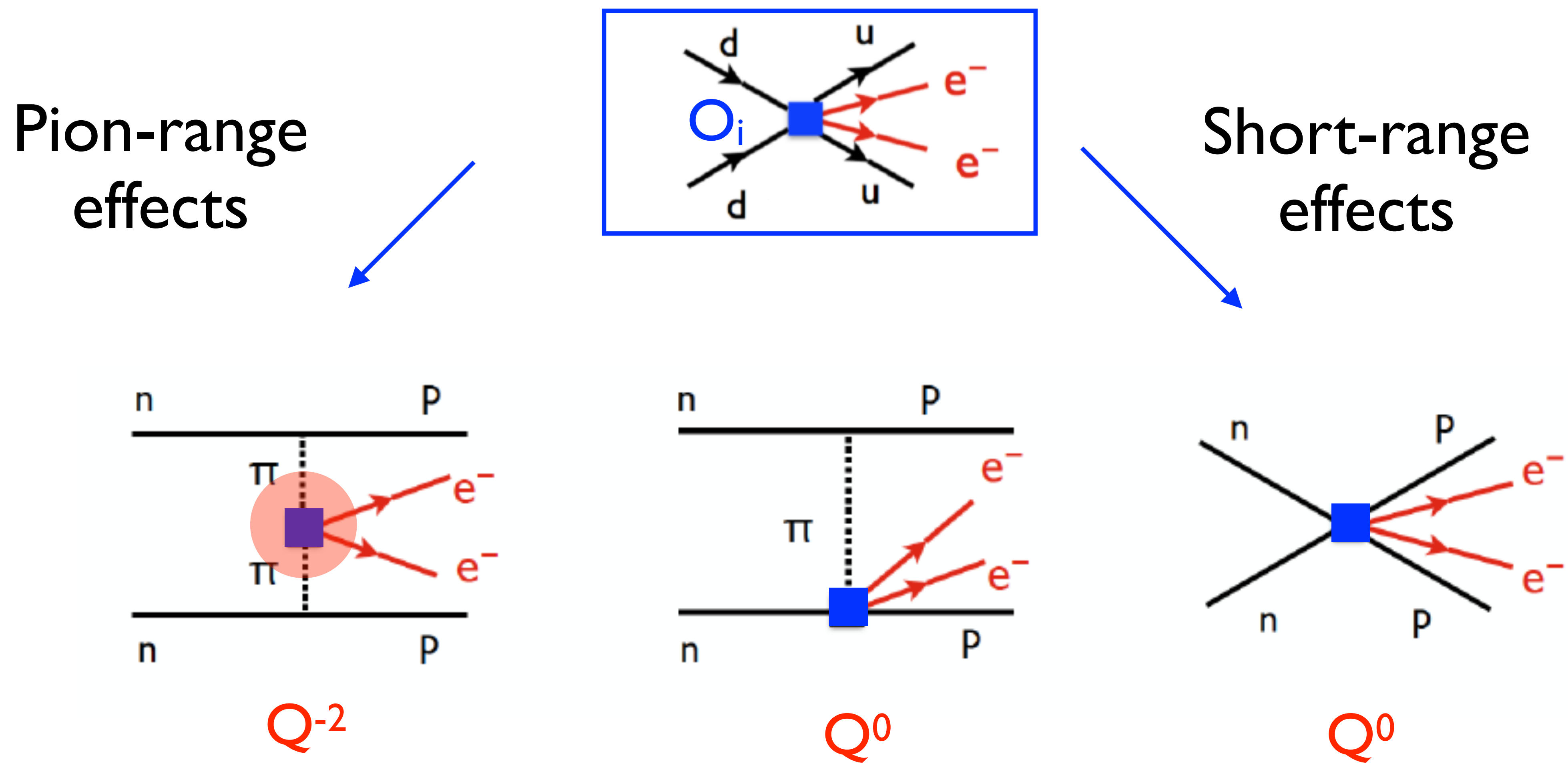


Q^{-2} Q^{0} Q^{0}

Naive dimensional analysis → $V_{\pi\pi}$ dominates (except for O_1)

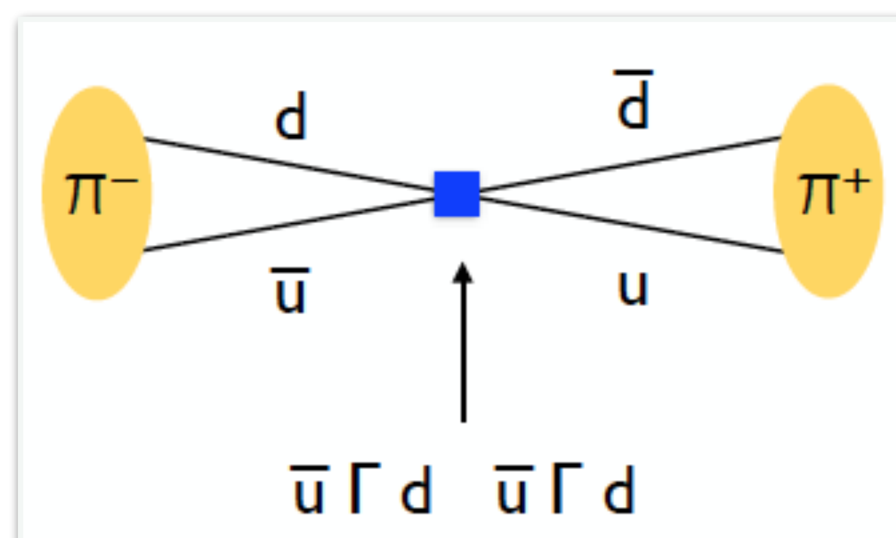
Vergados 1982, Faessler, Kovalenko, Simkovic, Schweiger 1996
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Hadronic realization of dim-9 operators



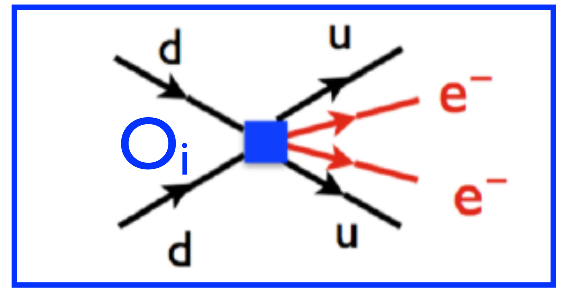
- Two recent developments:

  1. ππ matrix elements now precisely calculated in lattice QCD



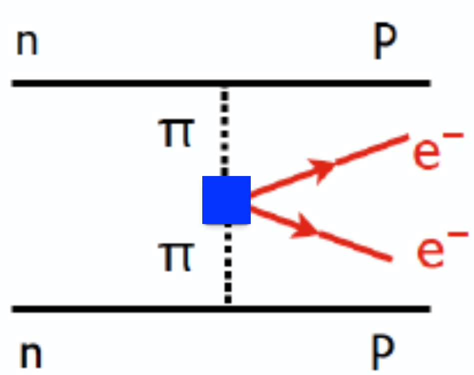
Nicholson et al (CalLat), 1805.02634

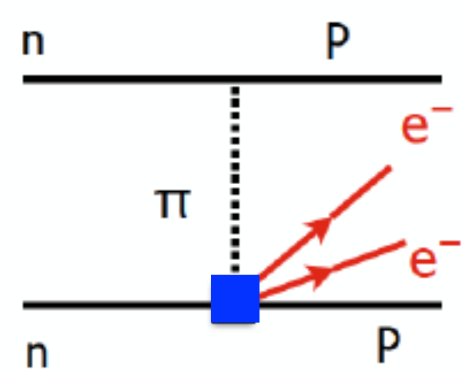
Hadronic realization of dim-9 operators

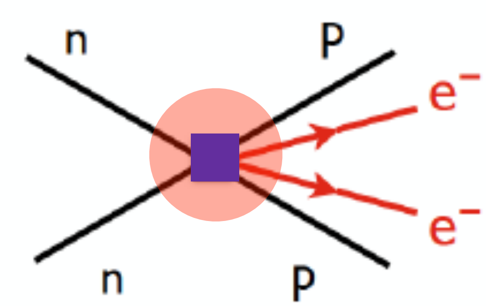


Pion-range effects

Short-range effects



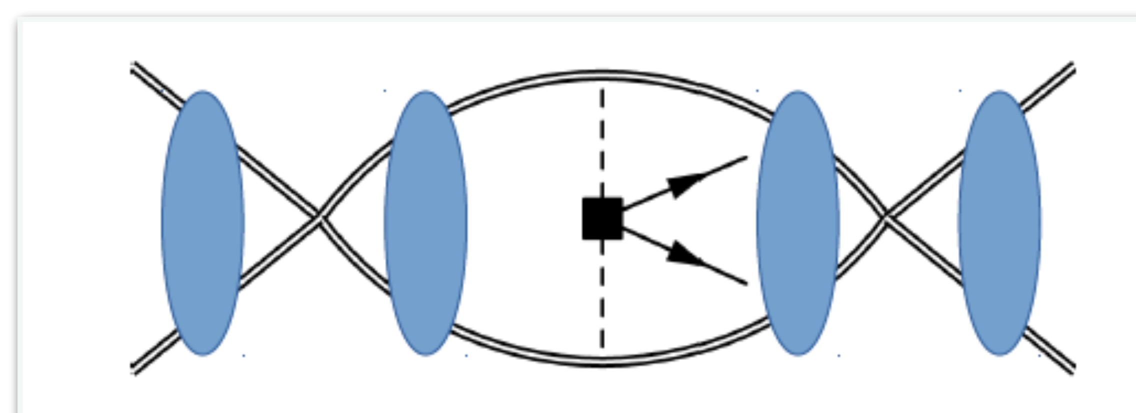




Q^{-2} Q^{0} Q^{-2}

- Two recent developments:

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



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

Conclusions

- 'End-to-end' EFT framework for $0\nu\beta\beta$: (1) connect to underlying sources of LNV; (2) organize contributions to nuclear matrix elements according to power counting: controllable errors

- Identified new leading order NN contact couplings in light ν exchange (dim-5 op.) and TeV-scale mechanisms (dim-9 ops)

- Estimated the 'dim-5' contact with Cottingham-inspired techniques

- First many-body analysis fitted to our synthetic data shows (43±7)% increase in the nuclear matrix element for $^{48}Ca \to ^{48}Ti$

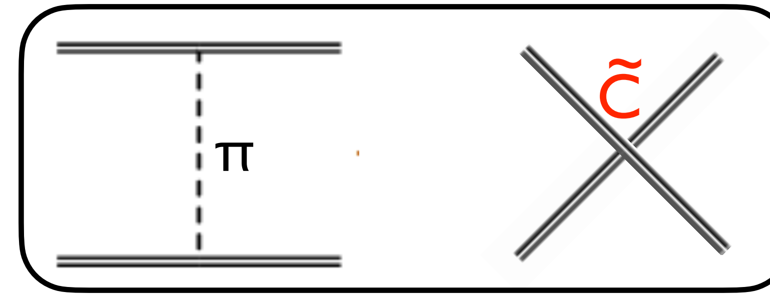
- Good prospects to control theory uncertainties thanks to synergy of EFT, lattice QCD, and nuclear structure

Backup

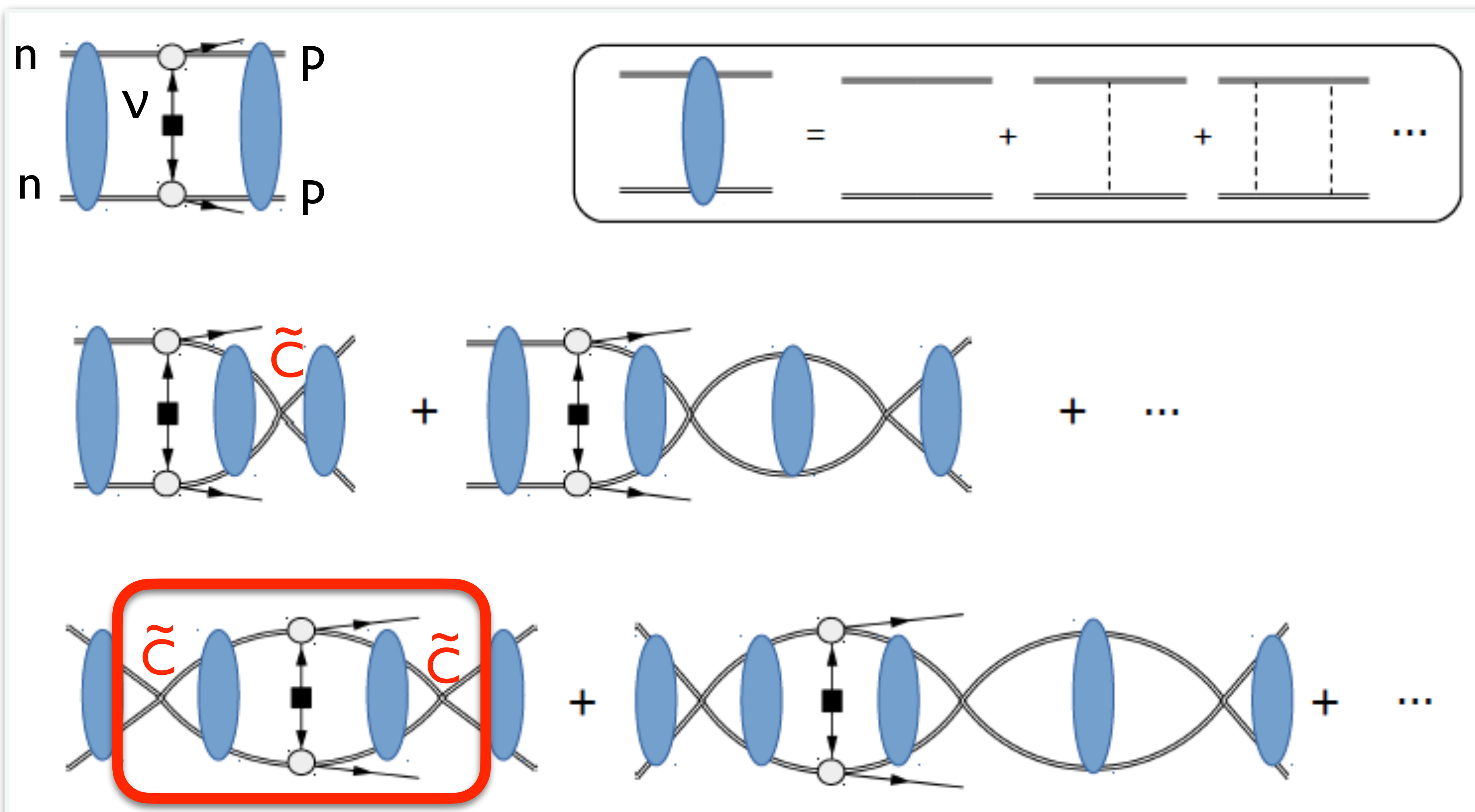
Why is the contact term LO?

Weinberg 1991, Kaplan-Savage-Wise 1996

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



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



UV finite

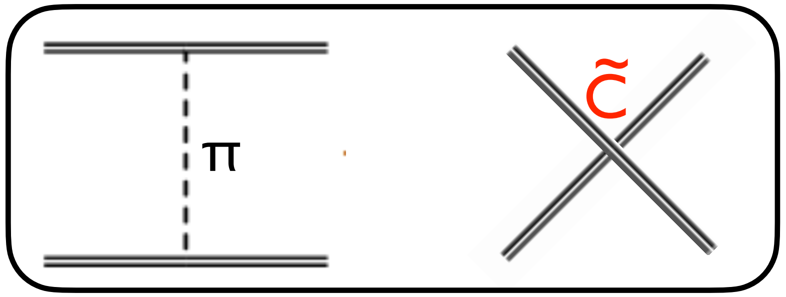
UV finite

2-loop diagram is UV divergent!

Why is the contact term LO?

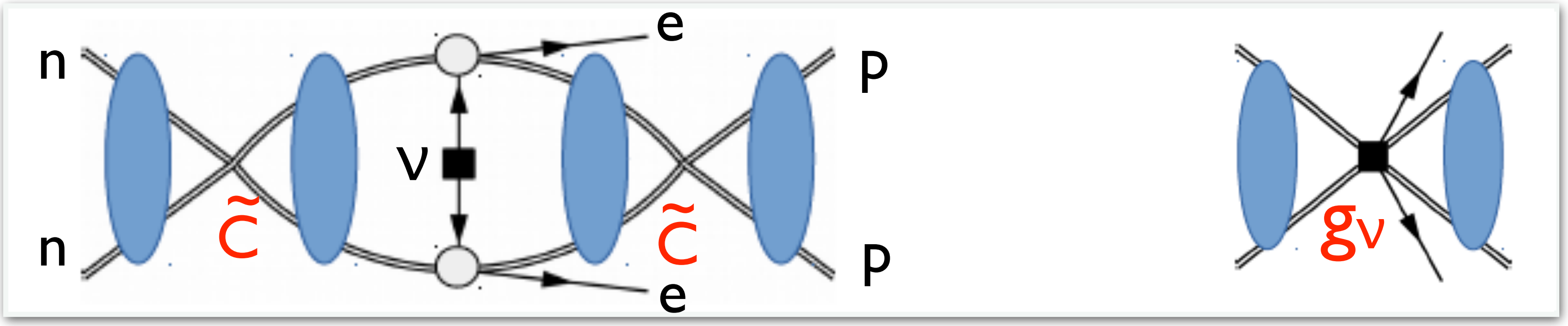
Weinberg 1991, Kaplan-Savage-Wise 1996

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



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

- Renormalization requires contact operator at LO



UV divergence

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

~ $1/(Q^2) \log \mu$

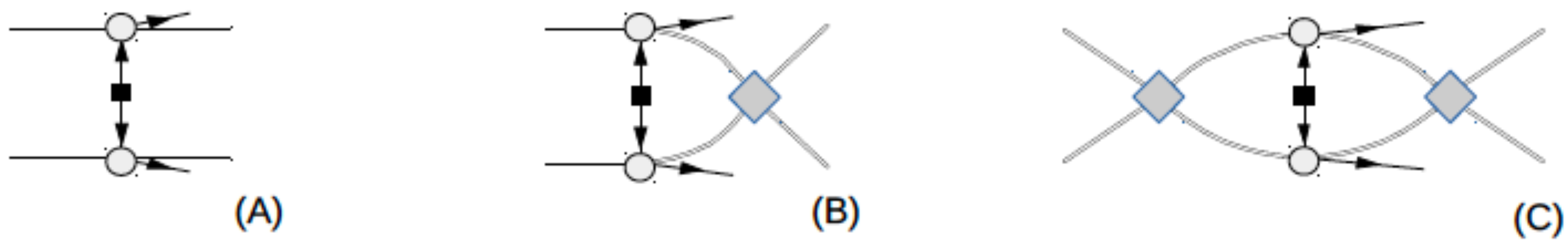
- Coupling flows to $g_\nu \sim 1/Q^2 \sim 1/F_\pi^2$, same order as ν_M exchange!

Connecting to nuclear structure

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_ν with regulators suitable for many-body nuclear calculations

$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|)e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}$$



Uncertainty dominated by topology C (fractional error of ~30-40%),
but A and B give large contribution to the amplitude at this kinematic point