Max Planck Institute for Nuclear Physics, Heidelberg
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Effective field theory approach to neutrino-less double beta decay

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Los Alamos National Laboratory

LA-UR-21-25541

Outline

- Introduction:
    - $0\nu\beta\beta$ and LNV
    - `End-to-end' EFT framework

- $0\nu\beta\beta$ from light Majorana ν exchange (high scale seesaw) in EFT

- Conclusion and outlook

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- Conclusion and outlook

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

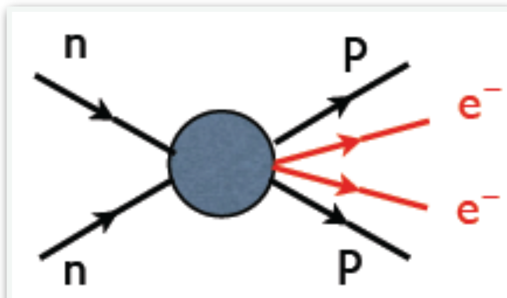
DBD Nuclear Theory Topical Collaboration (PI Jon Engel):
http://c51.lbl.gov/~0nubb/webhome/

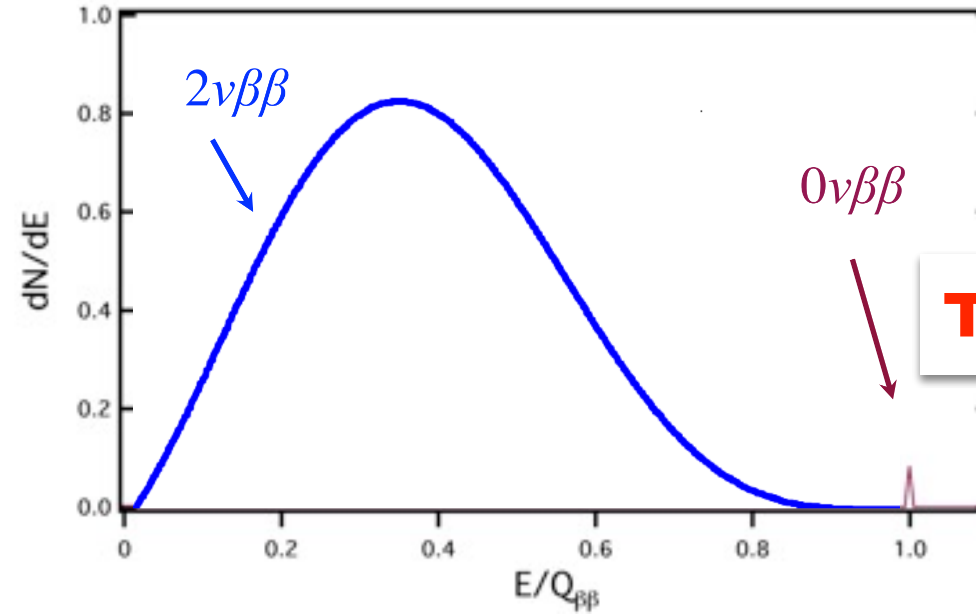
Introduction

Neutrinoless double beta decay (0νββ)

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

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

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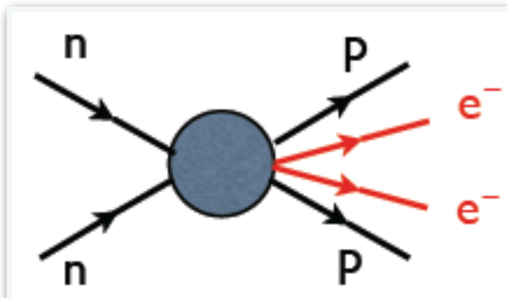
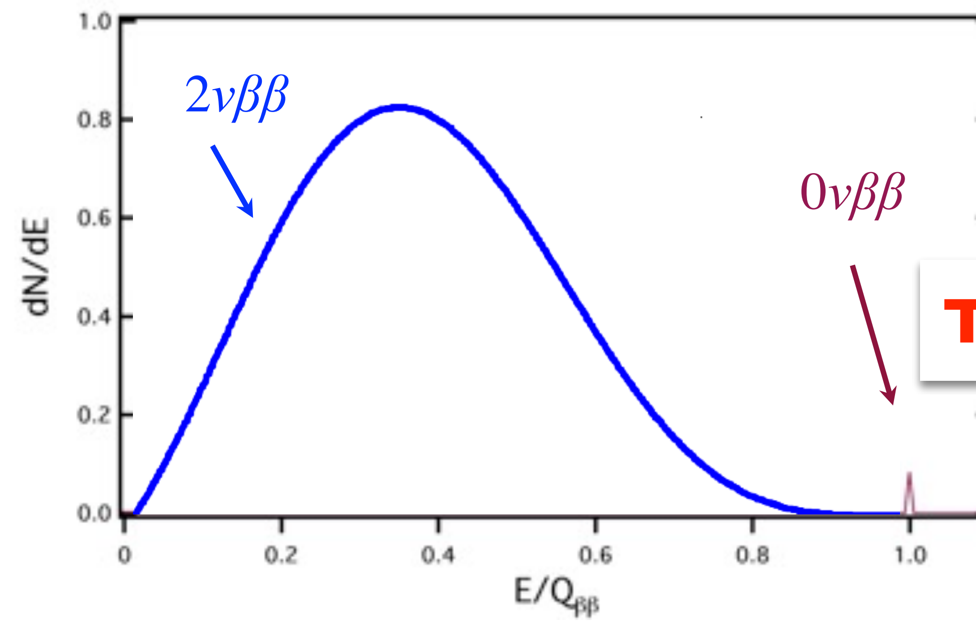




$T_{1/2} > 10^{25}$ yr

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

- B-L conserved in the SM → new physics, with far-reaching implications

  - Demonstrate that neutrinos are Majorana fermions

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

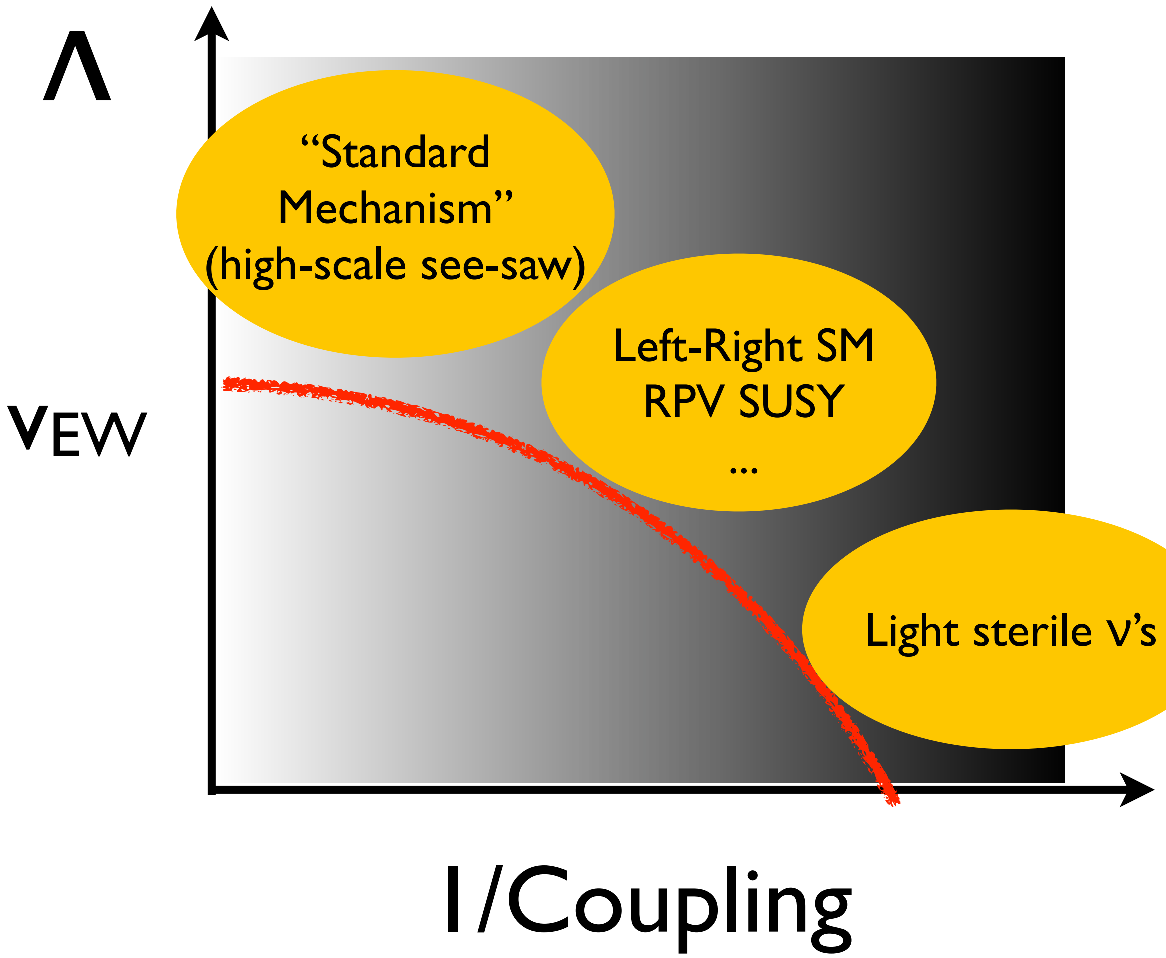
Majorana mass term: ΔL=2

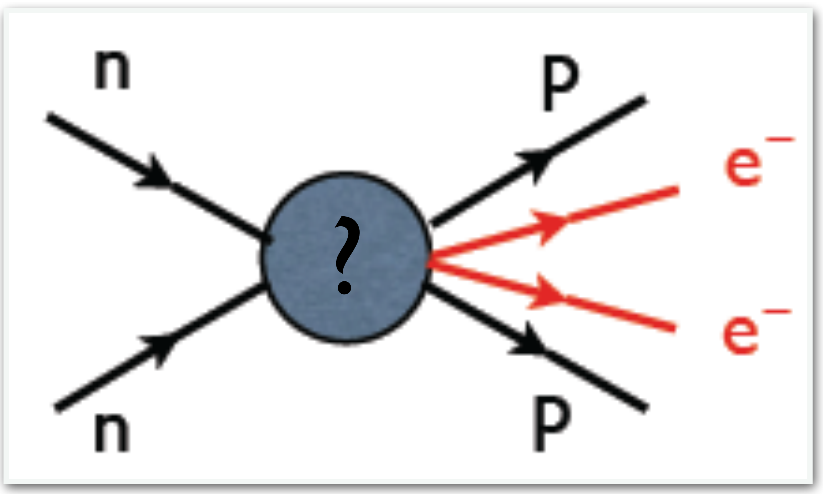
  - Establish key ingredient of leptogenesis

Fukugita-Yanagida 1987

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





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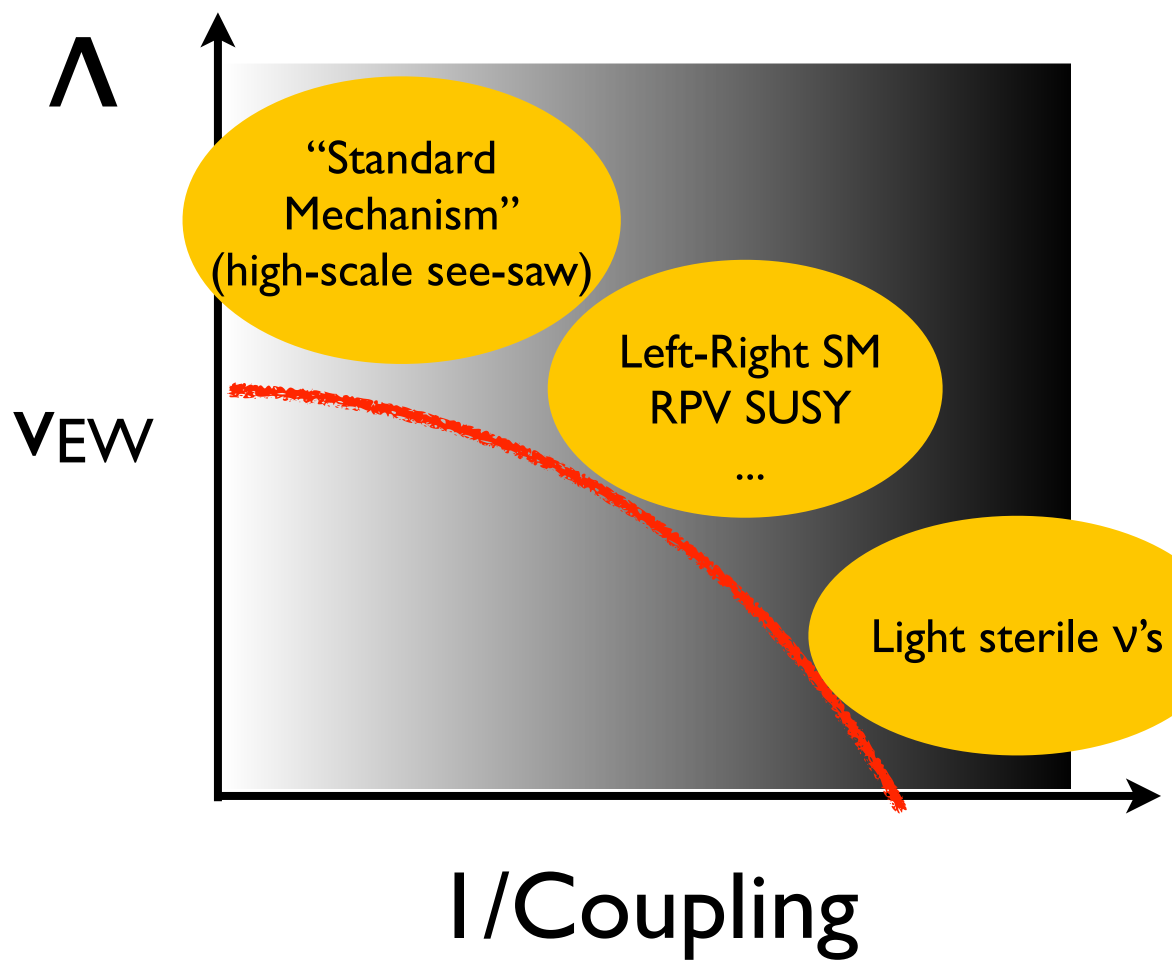
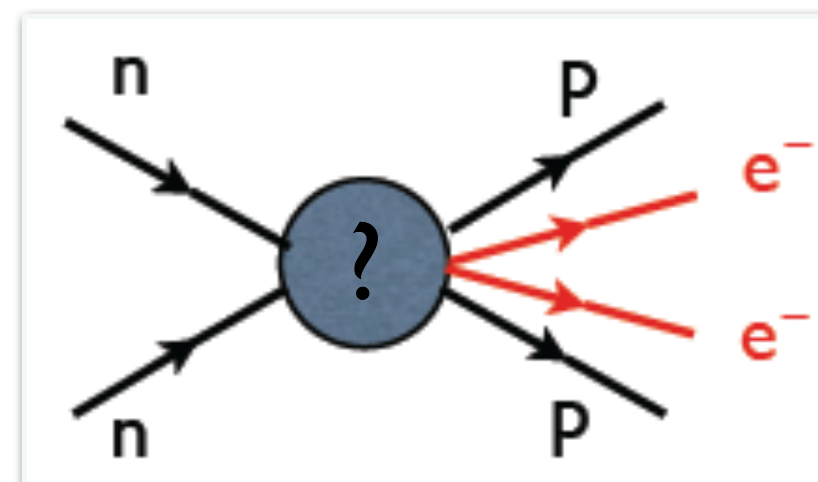


Some reviews:
Rodejohann 1106.1334,
Vergados-Eijiri-Simkovic 1205.0649
Deppisch-Hirsch-Pas 1208.0727
deGouvea-Vogel 1303.4097
...

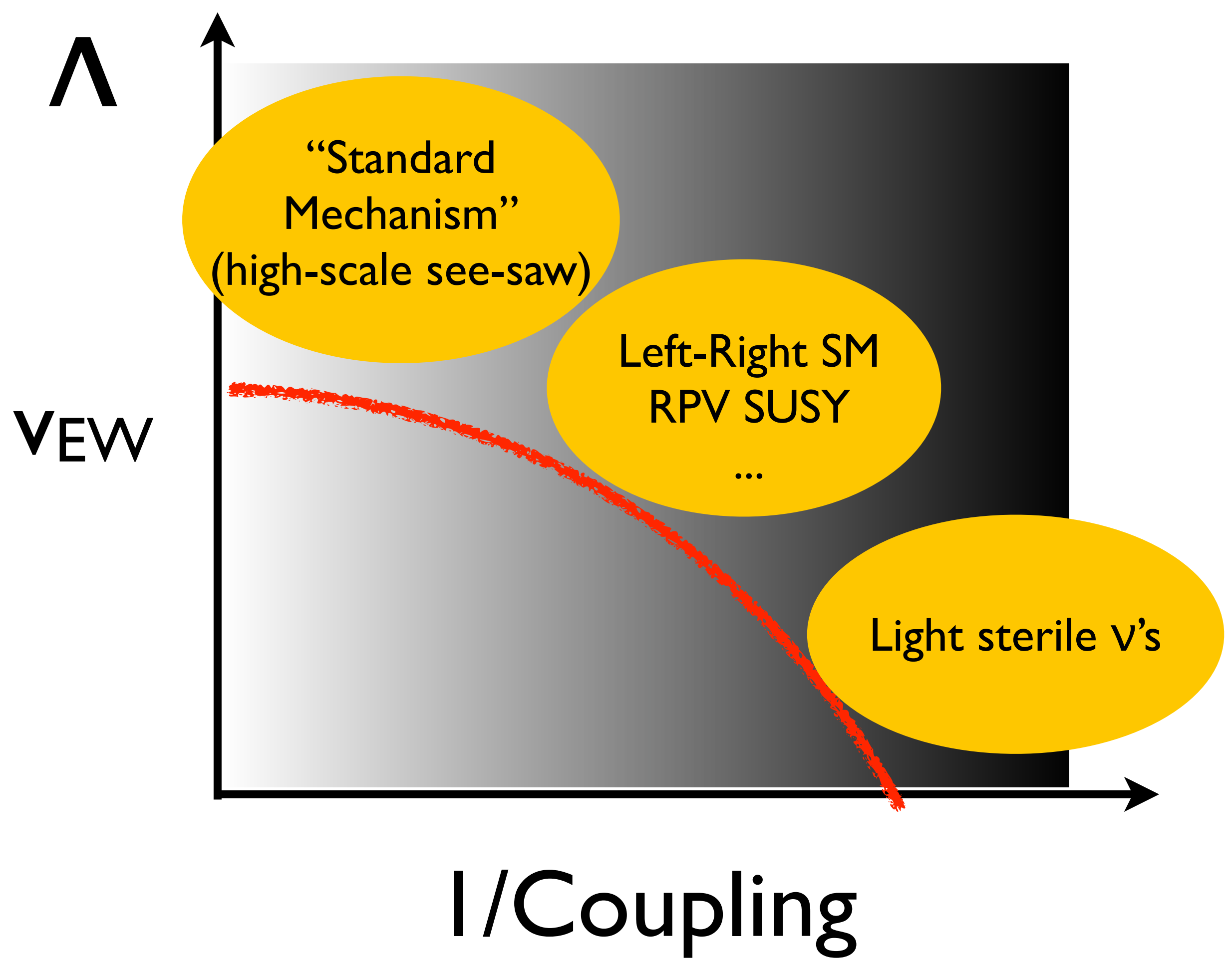


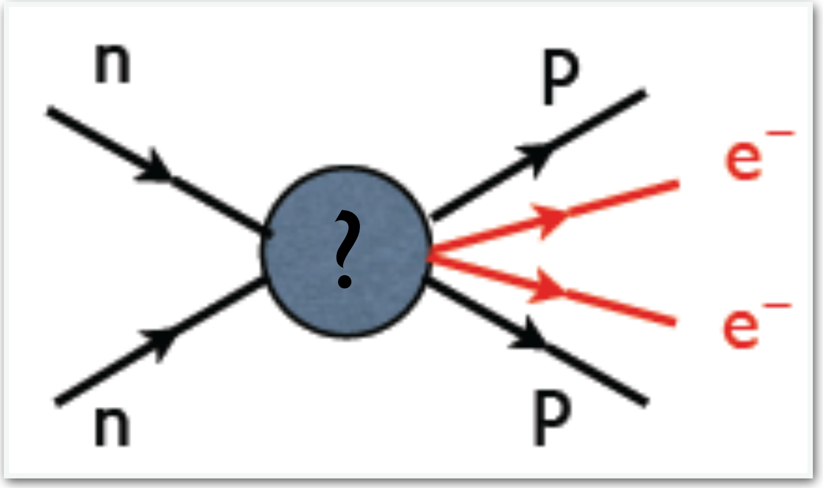
Vast literature, with varying degree of enthusiasm for EFT tools

Some papers:
VC-Dekens-deVries-Graesser-Mereghetti,1806.02780
Neacsu-Horoi 1801.04496.
Graf-Deppisch-Iachello-Kotila, 1806.06058
...
Prezeau, Ramsey-Musolf, Vogel, hep-ph/0303205
Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko, hep-ph/0008182
...

0νββ physics reach

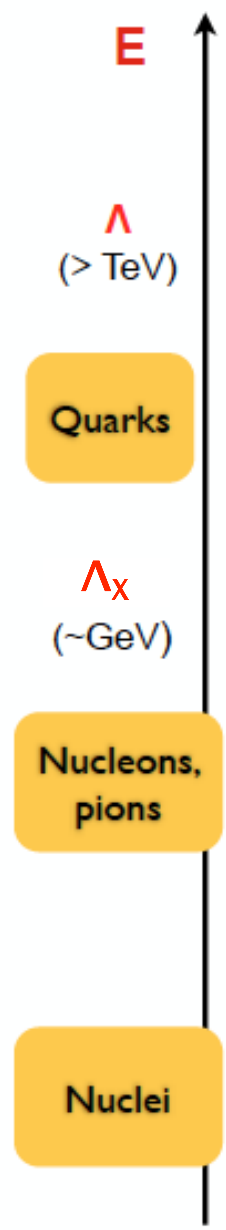
- 0νββ searches at the level of $T_{1/2} > 10^{27\text{-}28}$ yr (ton scale and beyond) probe ΔL=2 physics at unprecedented levels from a variety of mechanisms





0νββ's impact and relation to other probes of LNV is best analyzed via EFT, that connects LNV scale Λ to nuclear scales

`End-to-end' EFT framework for 0νββ



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

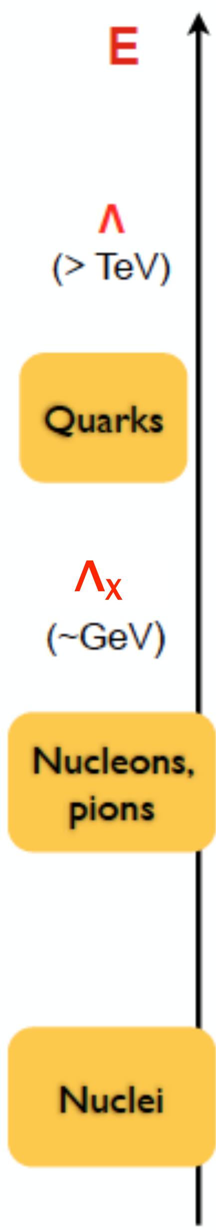
Integrate out heavy particles

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

ΔL=2 in the "Standard Model EFT": only dim=5,7,9,…

Addition of light ν_R systematically studied in Dekens et al. 2002.07182

`End-to-end' EFT framework for 0νββ



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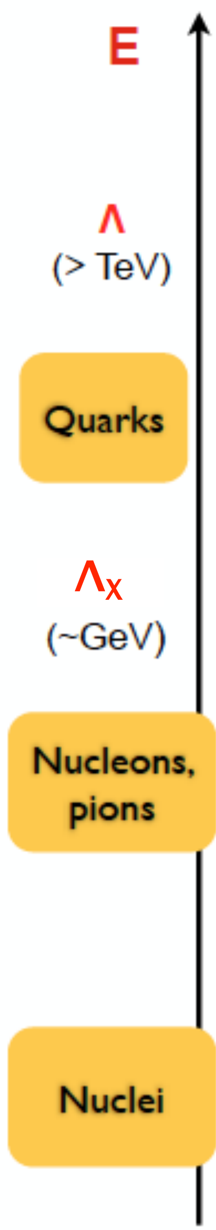
Hadronic matrix elements

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

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

Derive two-nucleon `potentials'

`End-to-end' EFT framework for 0νββ



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↓ *Hadronic* matrix elements

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↓ *Nuclear* matrix elements

$T_{1/2}[\,\tilde{C}_i\,[C_j]]$

Connect LNV sources to nuclear scale with controllable uncertainty

Chain of EFTs +

Hadronic matrix elements (LQCD,…)

& many-body methods

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

`End-to-end' EFT framework for 0νββ

E

Λ
(> TeV)

Quarks

Λ_χ
(~GeV)

Nucleons, pions

Nuclei

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

Integrate out heavy particles

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

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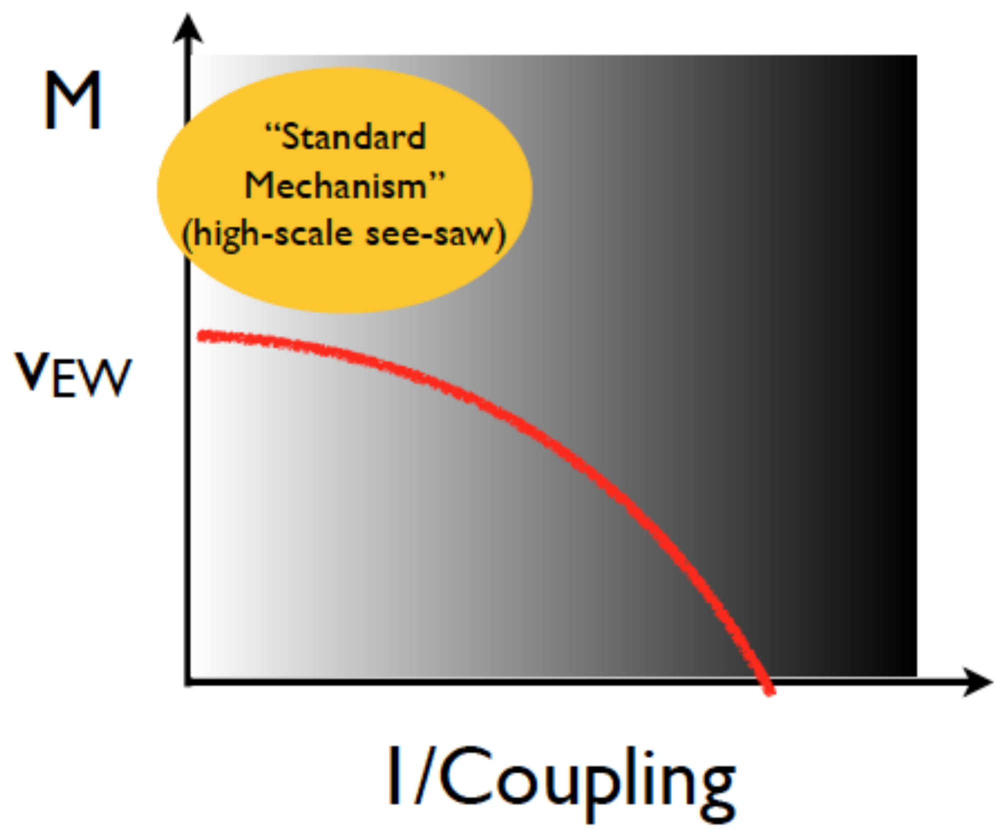
$0\nu\beta\beta$ from light Majorana ν (dim-5 operator)



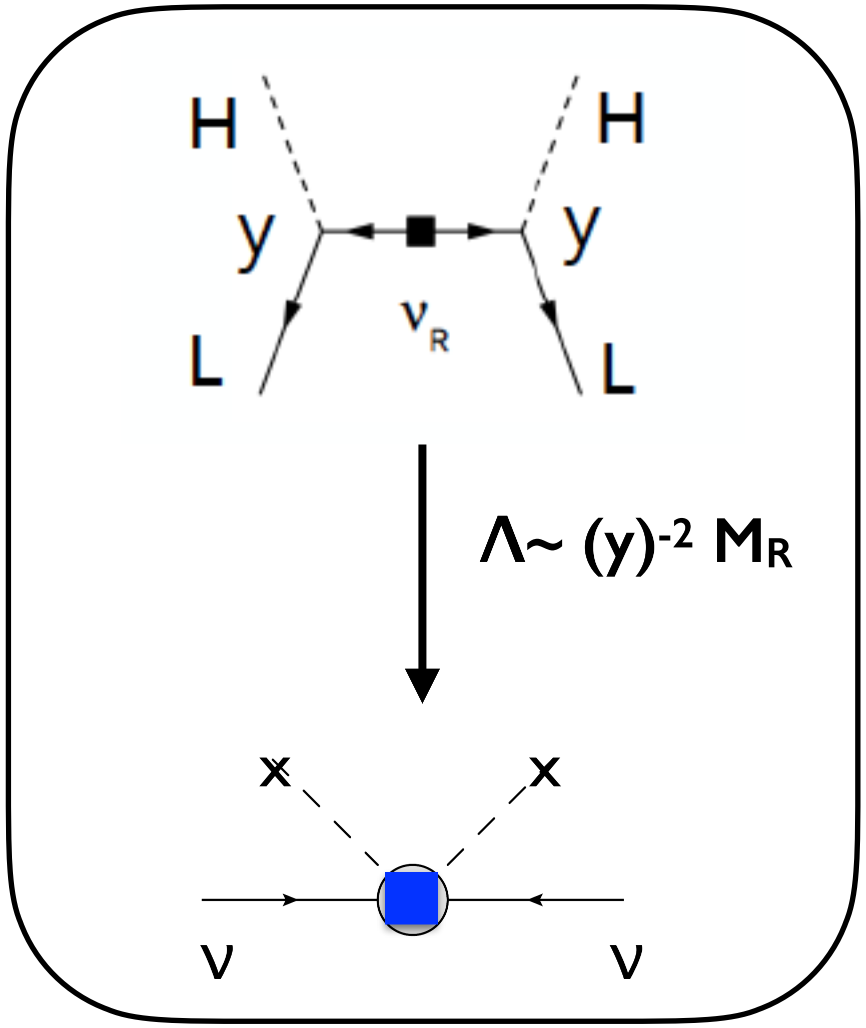
The 'standard mechanism'

- LNV originates at very high scale ($\Lambda >> v$) → dominant low-energy remnant is Weinberg's dim-5 operator:

$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L_\alpha^T C \epsilon H \, H^T \epsilon L_{\alpha'}$$

- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee} v^2/\Lambda$)

Ex: Type I see-saw with heavy ν_R



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- $0\nu\beta\beta$ mediated by *active* ν_M with amplitude proportional to $m_{\beta\beta}$

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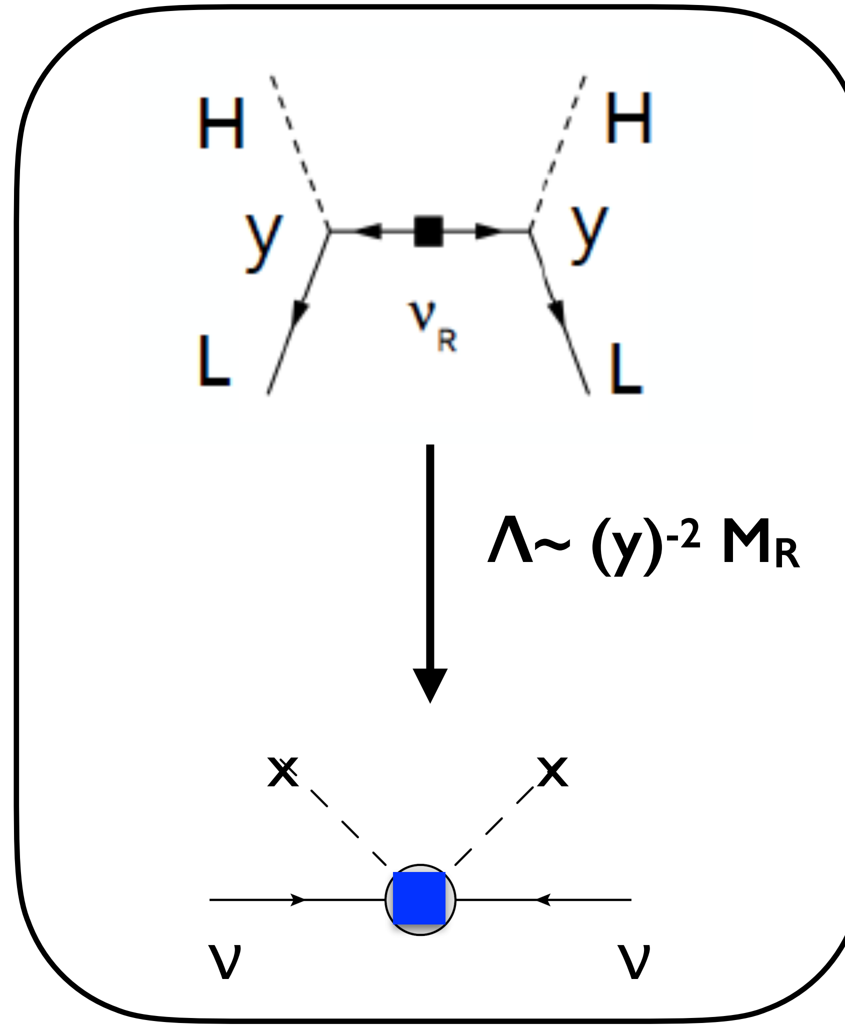
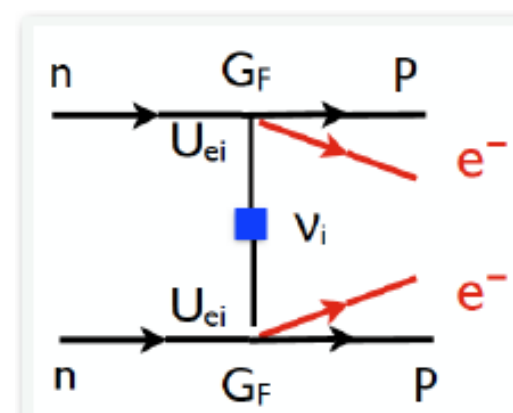




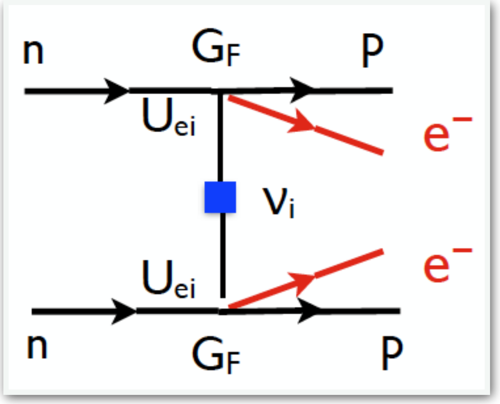
$\propto m_{\beta\beta}$

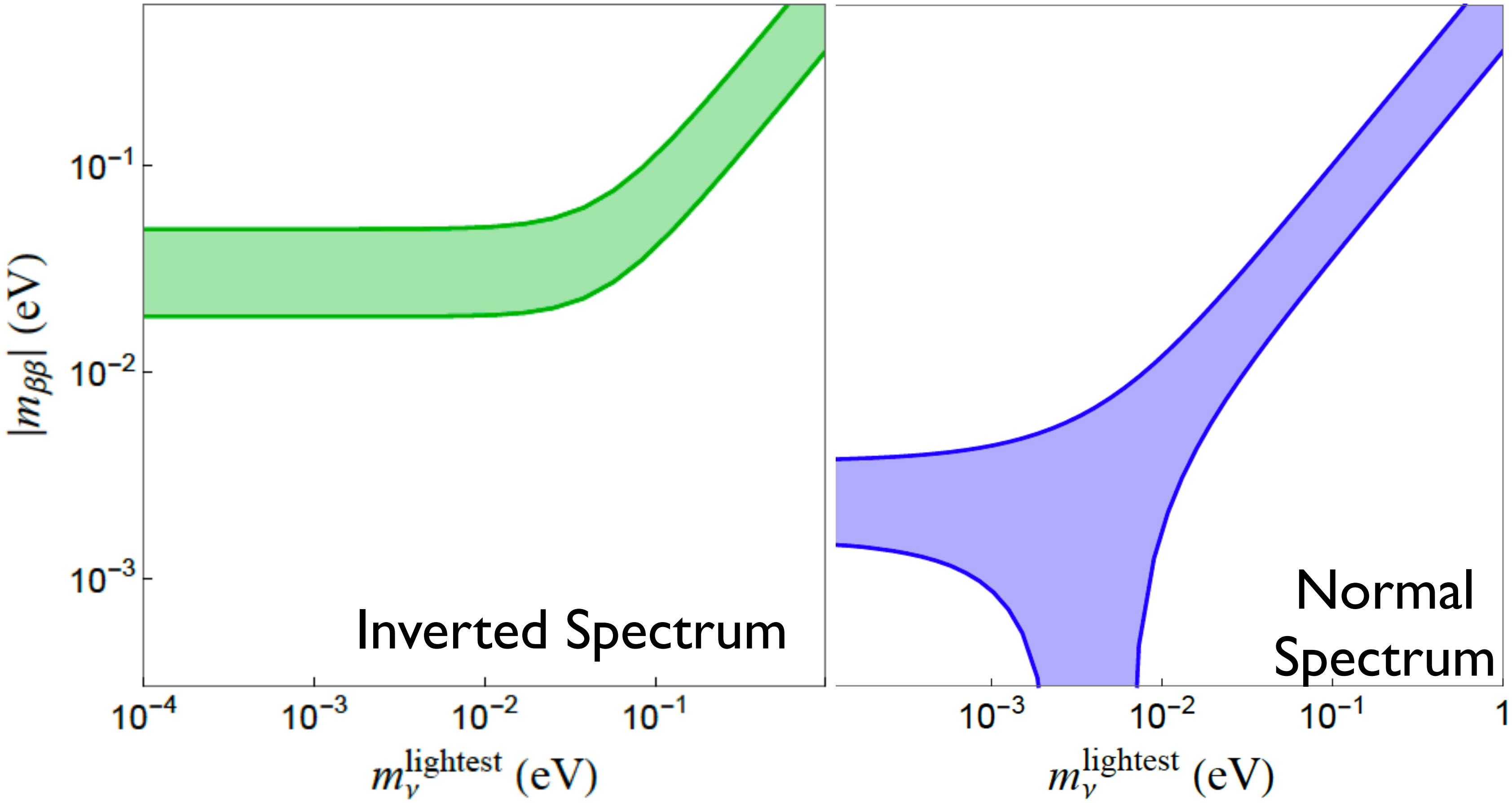
Discovery potential / target

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

Strong correlation with oscillation parameters

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$





Discovery potential / target

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

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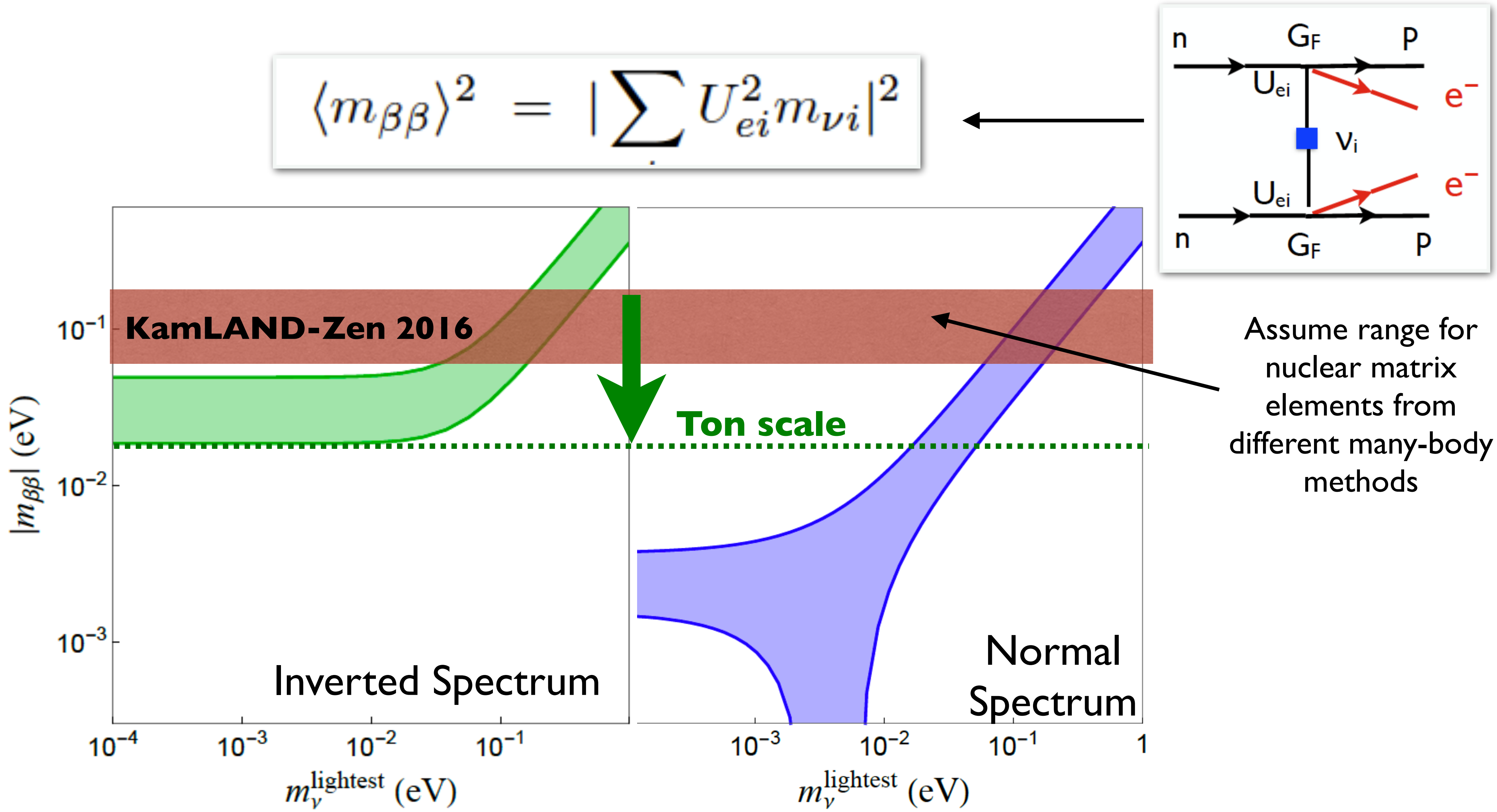


Assuming current range for matrix elements,
discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes.

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

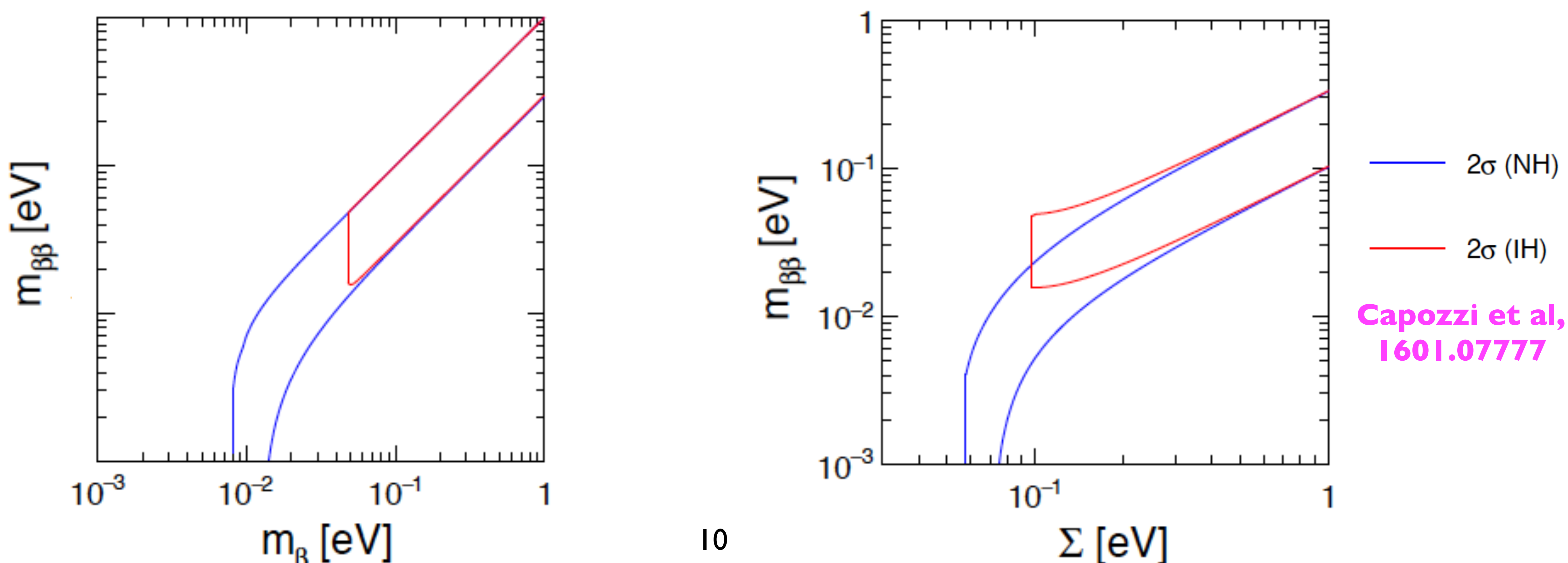
0νββ decay

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology



Capozzi et al, 1601.07777

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes. Future data can unravel new LNV sources or physics beyond "ΛCDM + m_ν"

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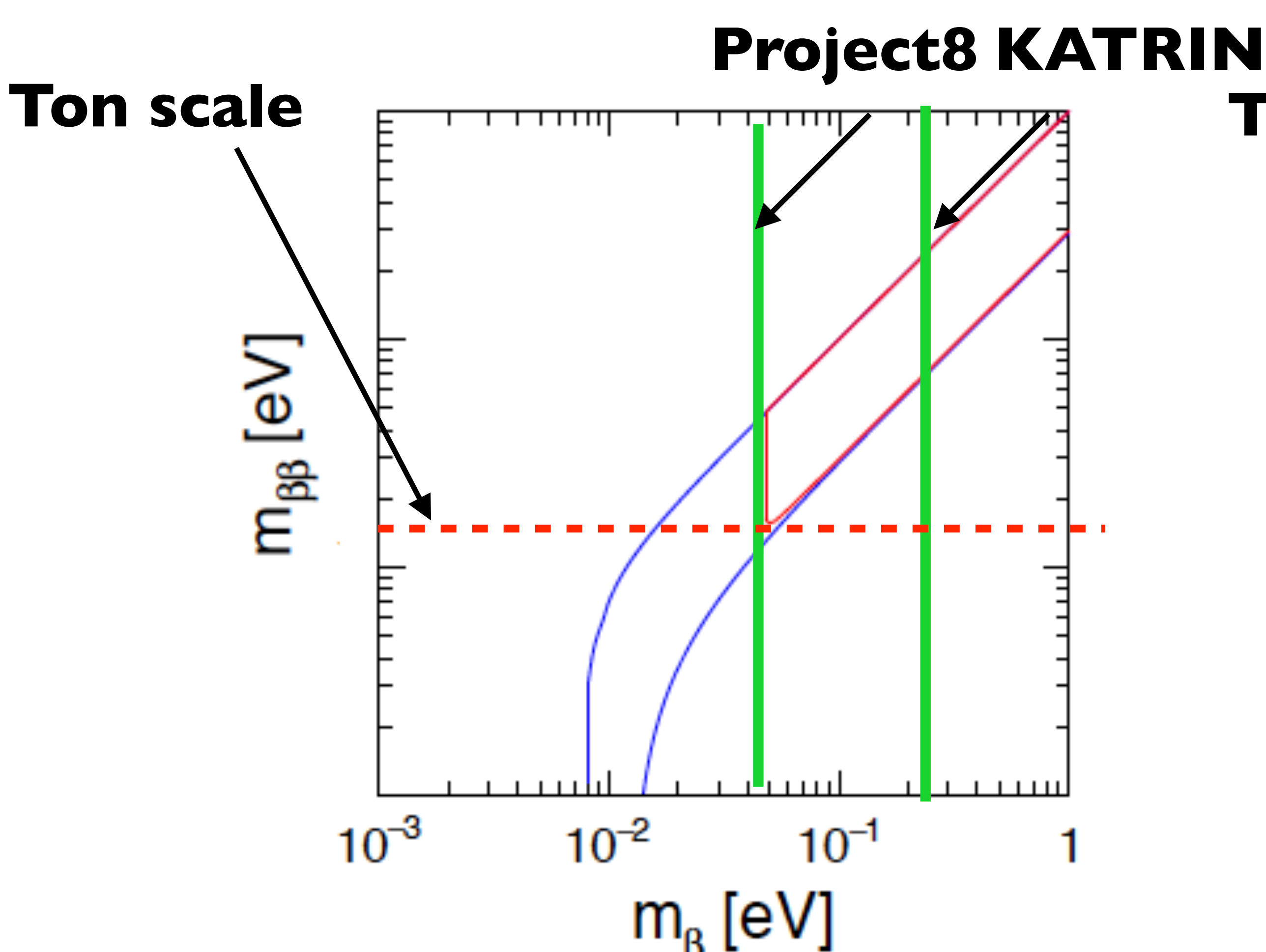
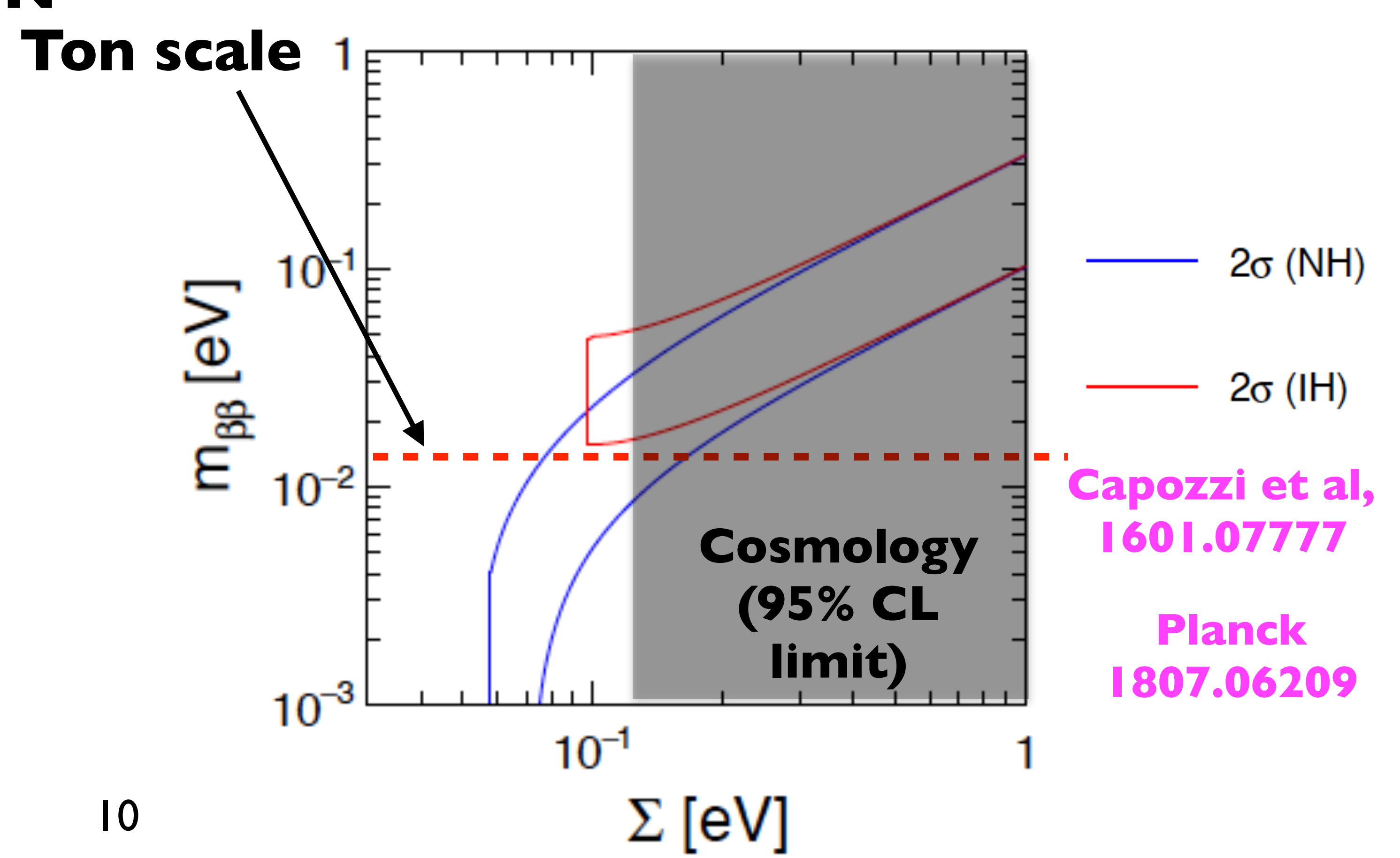
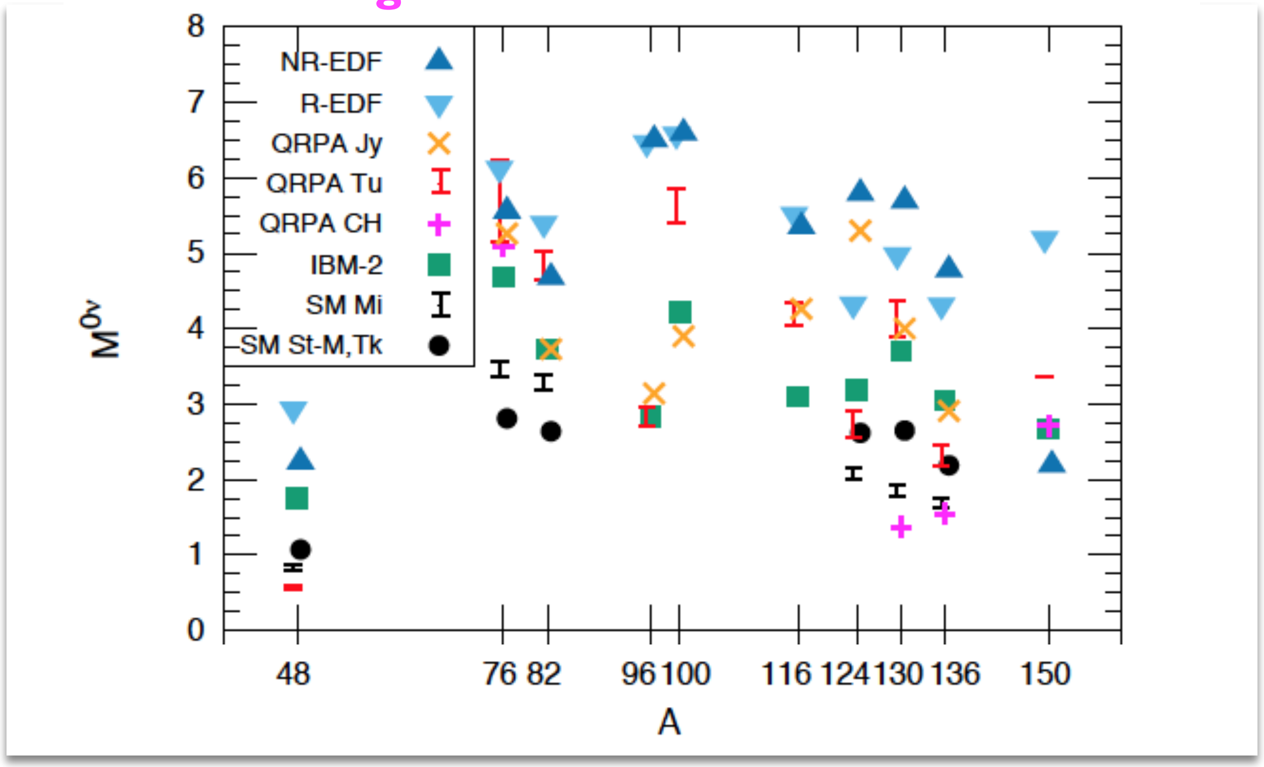




Theory status / developments

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 with QCD-based methods
  - Ab initio 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

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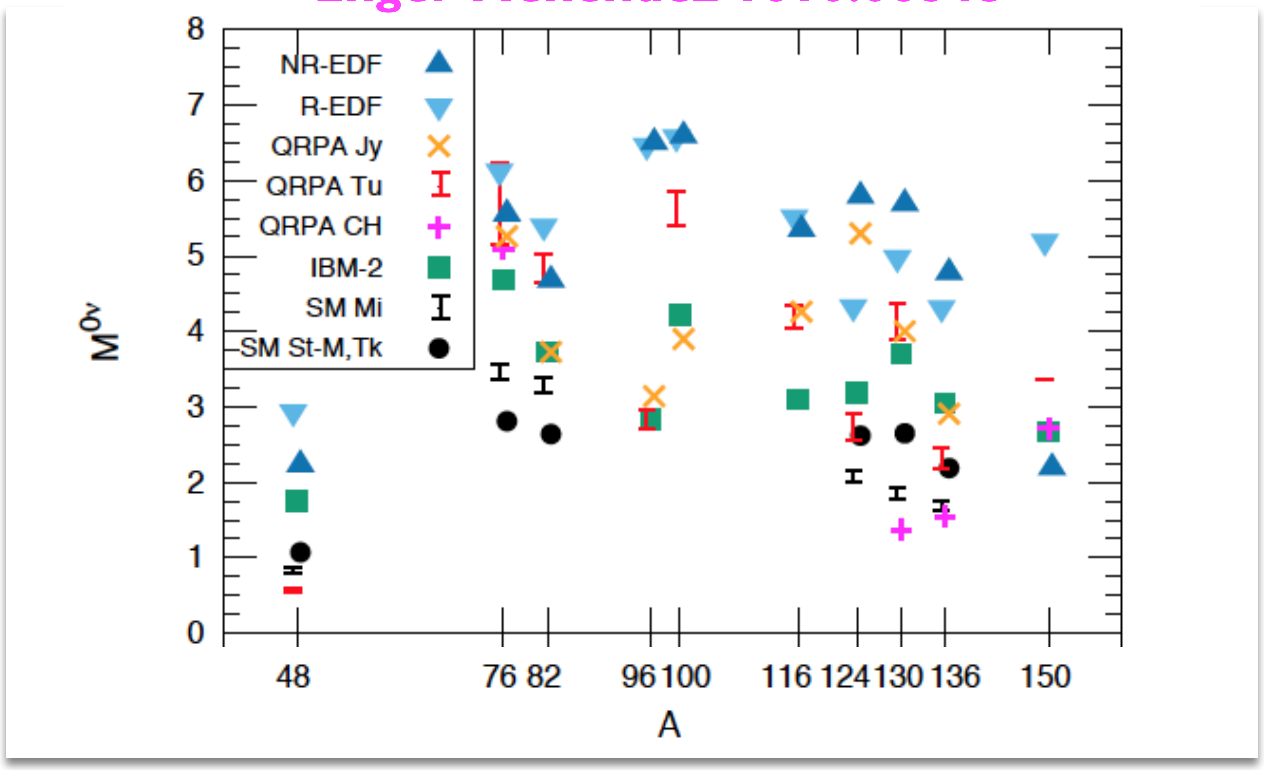

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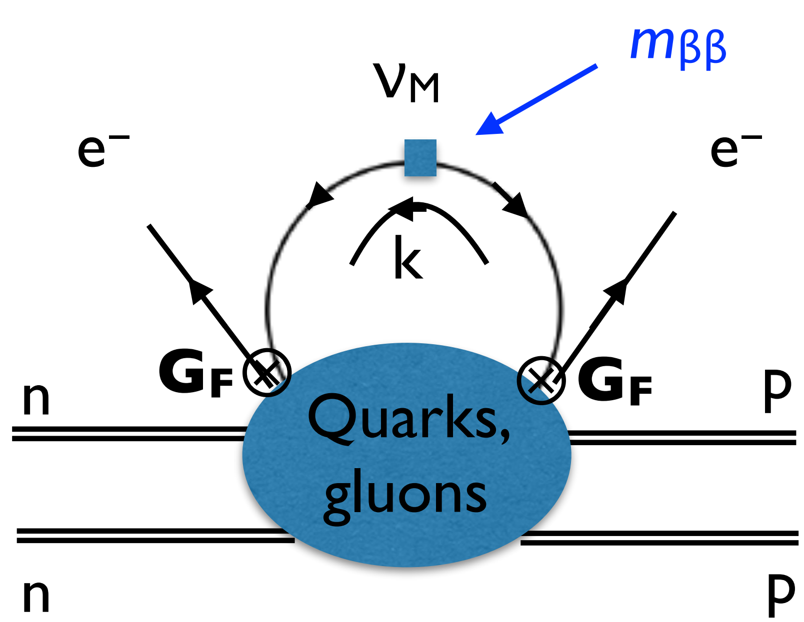
From quarks to nuclei using EFT

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

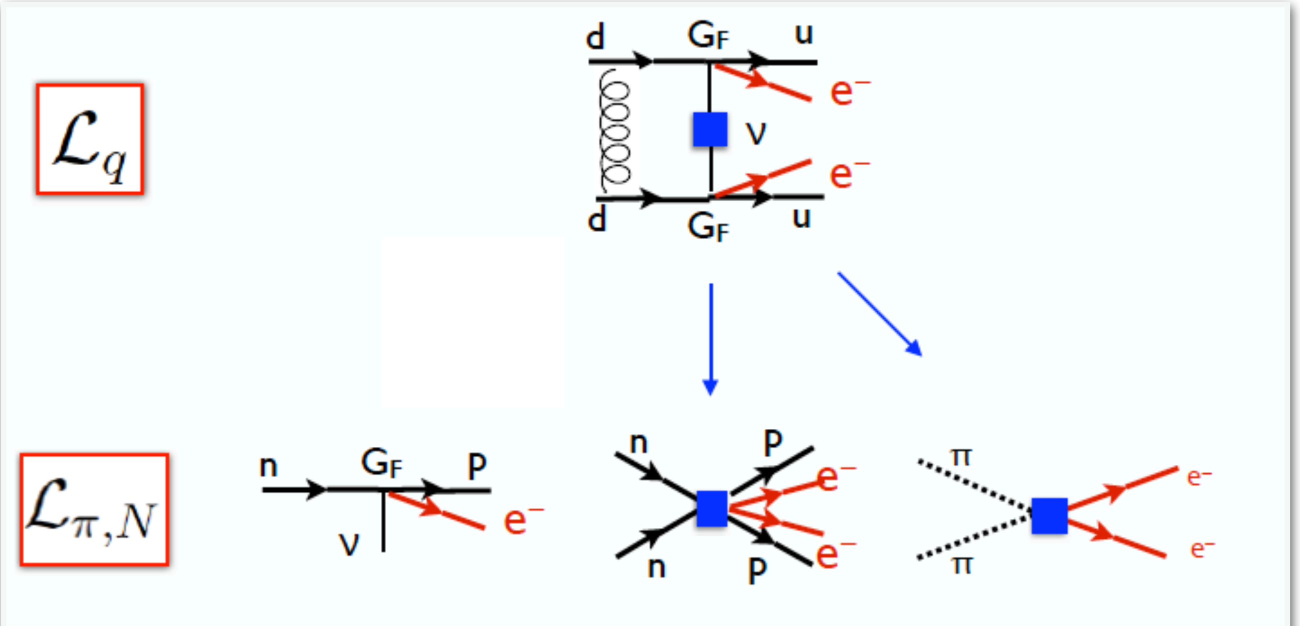


Chiral EFT captures contributions from all relevant momentum regions

From quarks to nuclei using EFT

- At $E \sim \Lambda_\chi \sim m_N \sim$ GeV integrate out hard ν's and gluons ($E, |\mathbf{k}| > \Lambda_\chi$)

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



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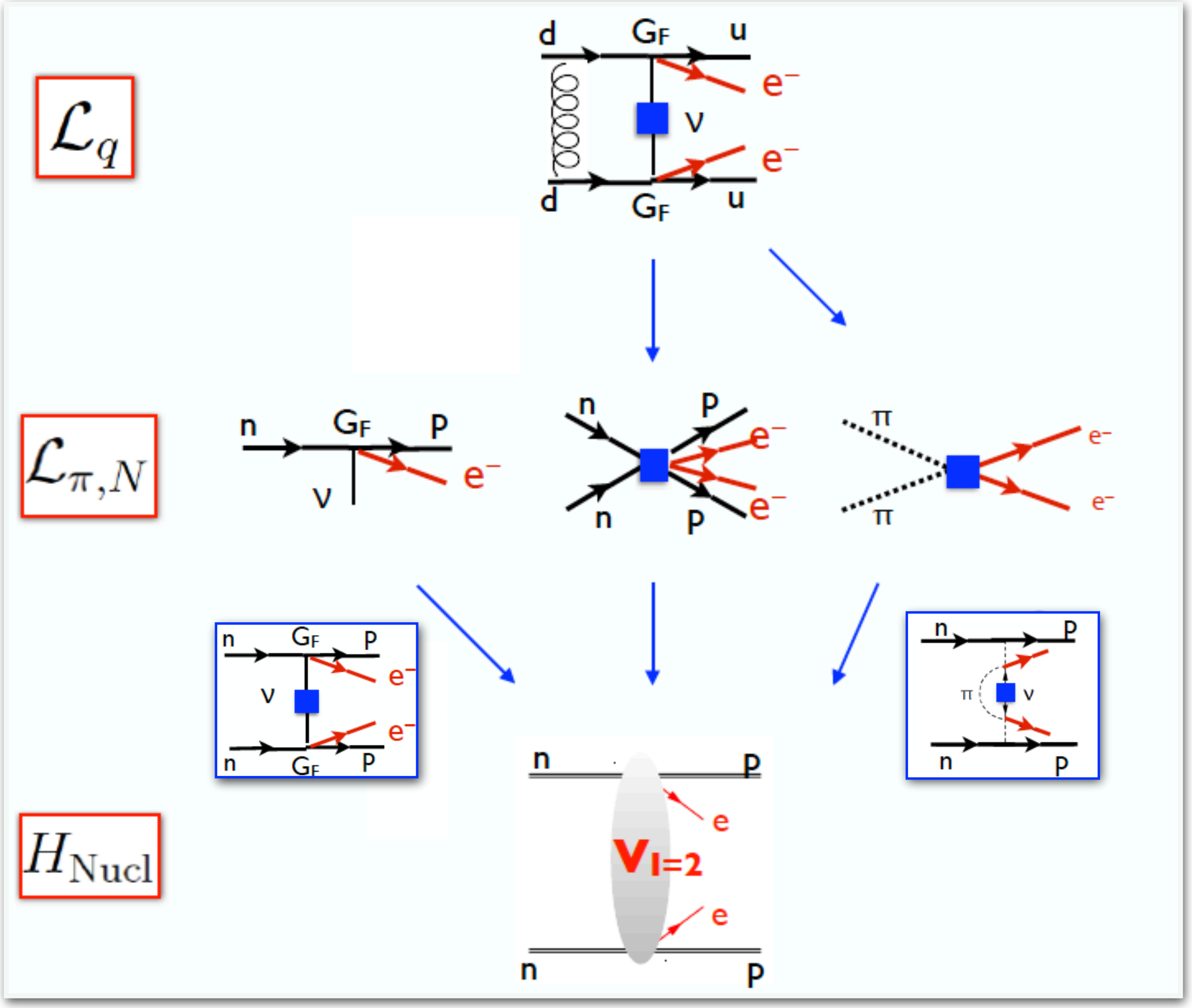
- Integrate out soft and potential ν's and π's with (E,|**k**|)~Q and (E,|**k**|)~(Q^2/m_N, Q) → obtain 2-body transition operator ('potential')



From quarks to nuclei using EFT

- At $E \sim \Lambda_\chi \sim m_N \sim$ GeV integrate out hard ν's and gluons (E, $|\mathbf{k}| > \Lambda_\chi$)

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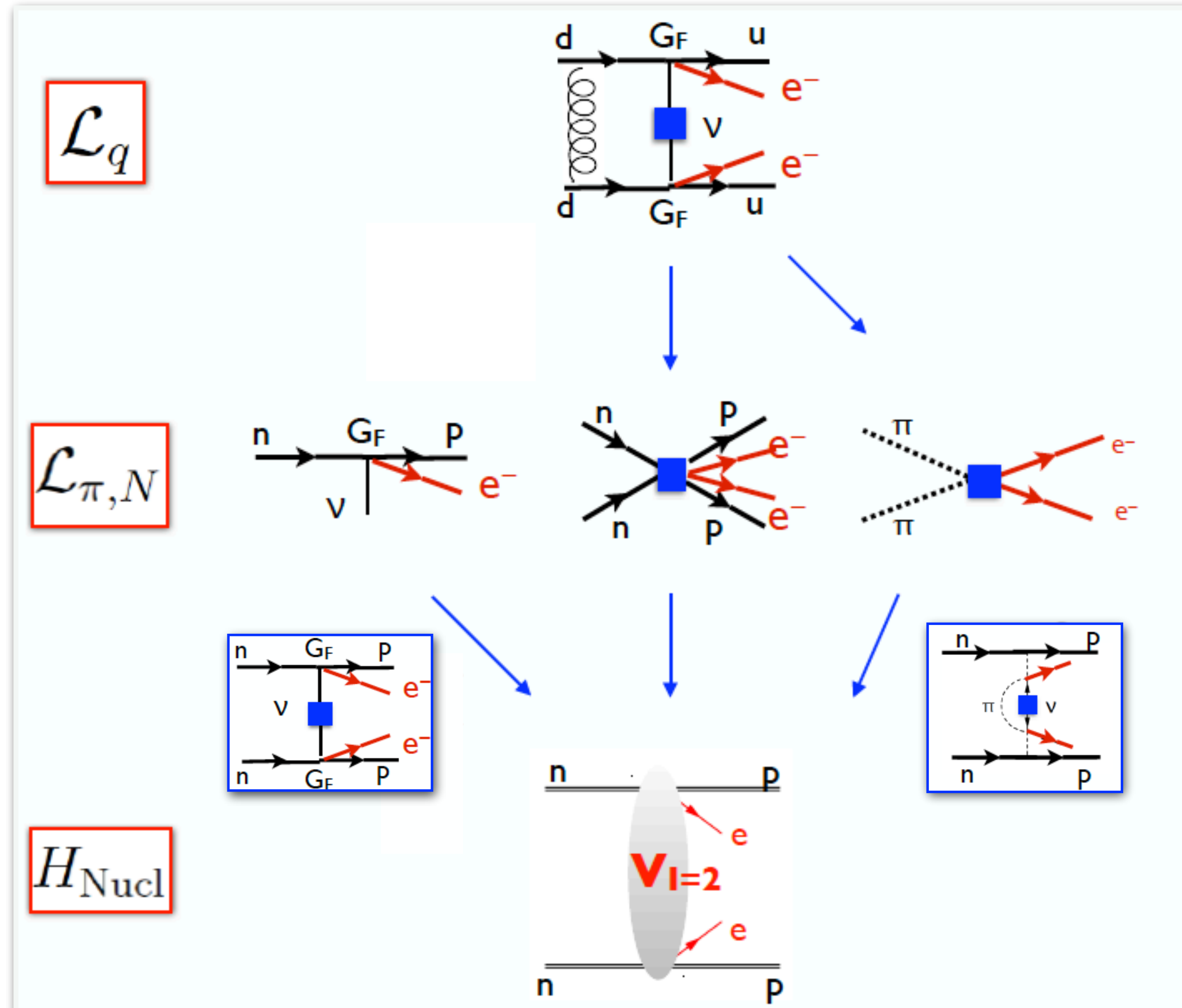
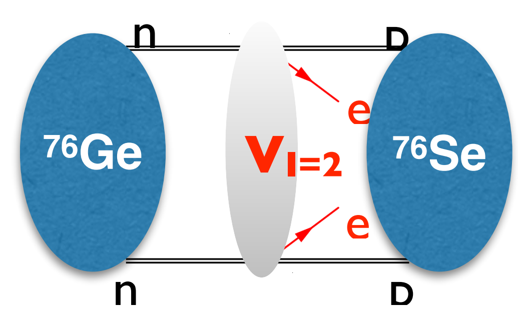


- Final step: take matrix element of $V_{I=2}$ in nuclear states



Next discuss LO terms in the expansion in Q/Λ_χ

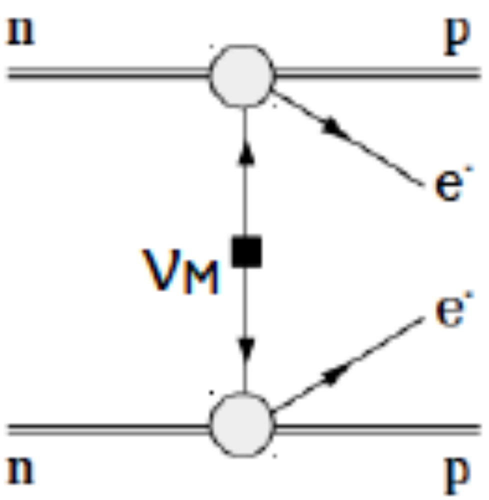
Details & beyond LO: 1710.01729, 1802.10097, 1907.11254

New insights from EFT

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

- Transition operator to leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)
  - 'Usual' ν_M exchange $\sim 1/Q^2$

$$\boxed{V_\nu^{(a,b)} = \frac{J^{(a)}(\mathbf{q}) J^{(b)}(-\mathbf{q})}{\mathbf{q}^2} \tau^{(a)+} \tau^{(b)+}}$$



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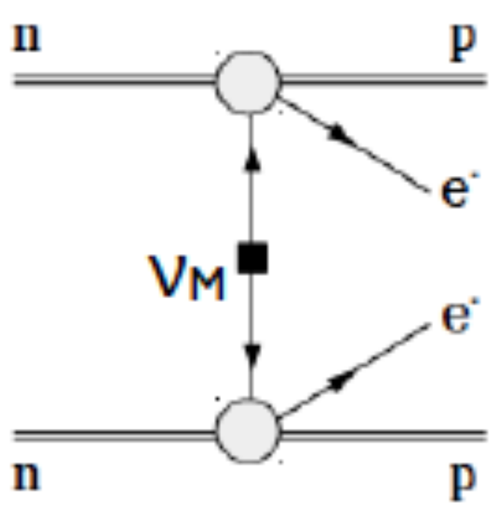
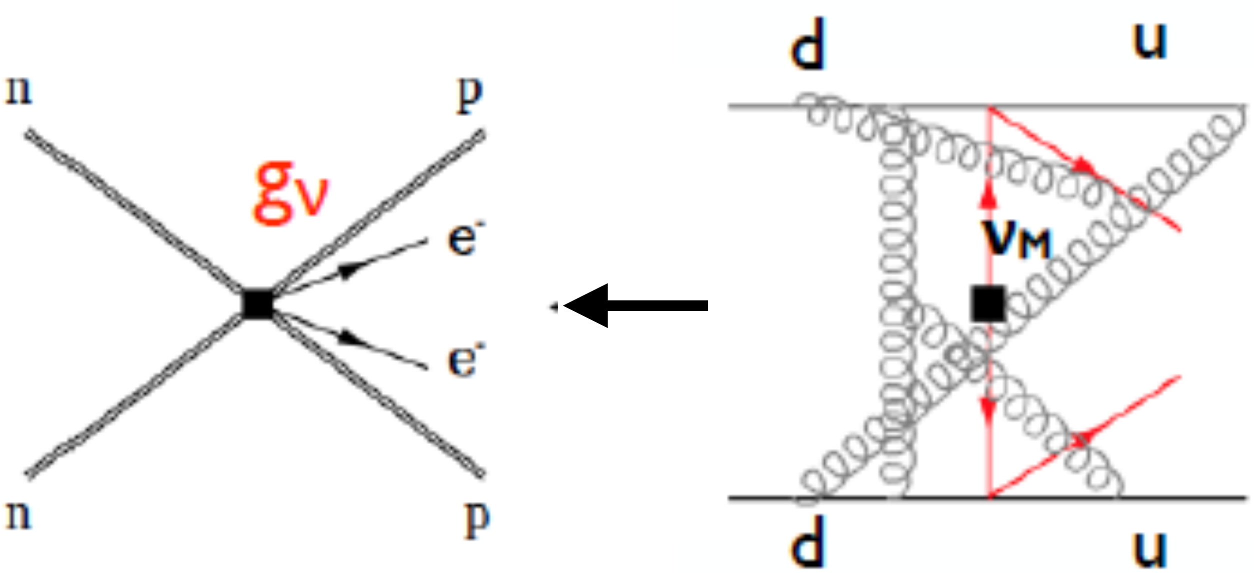


  - 'New': short-range coupling $g_\nu \sim 1/F_\pi^2 \sim 1/k_F^2$, required by renormalization of $nn \to ppee$ amplitude

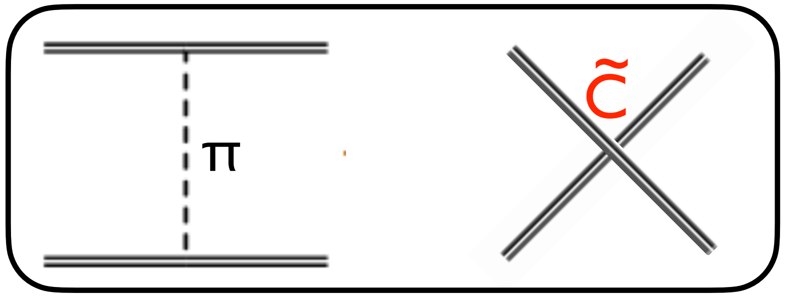


g_ν encodes the physics of high- and intermediate-momentum ν_M

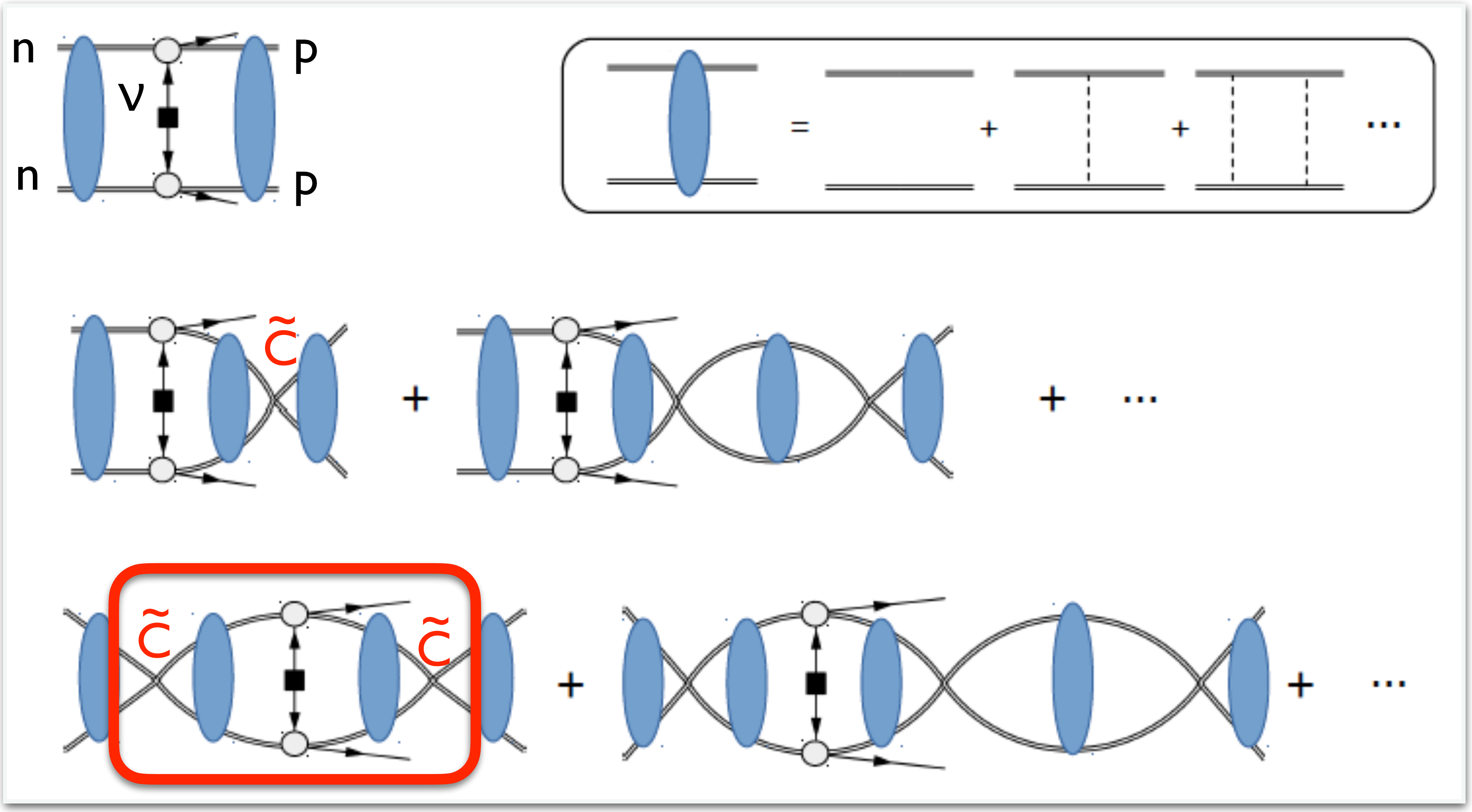
Why is the contact term LO?

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!

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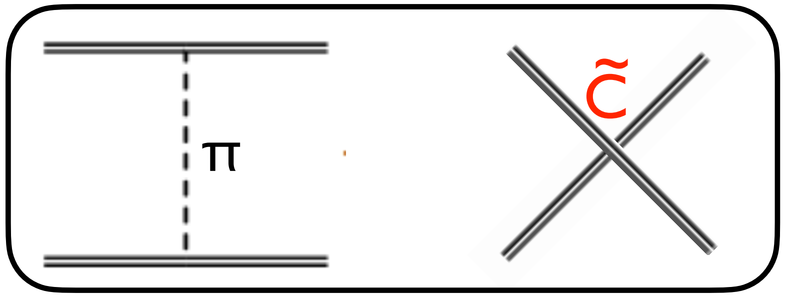

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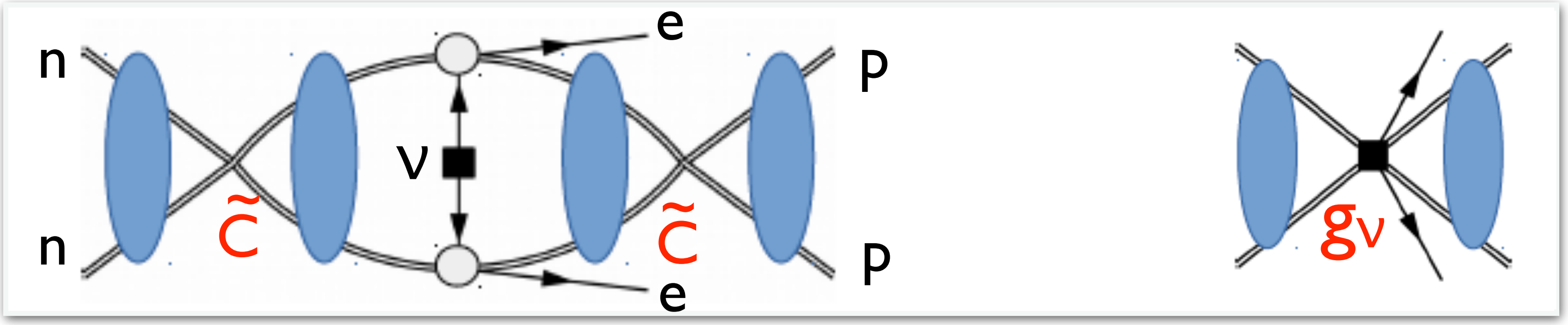
- Renormalization requires contact operator at LO

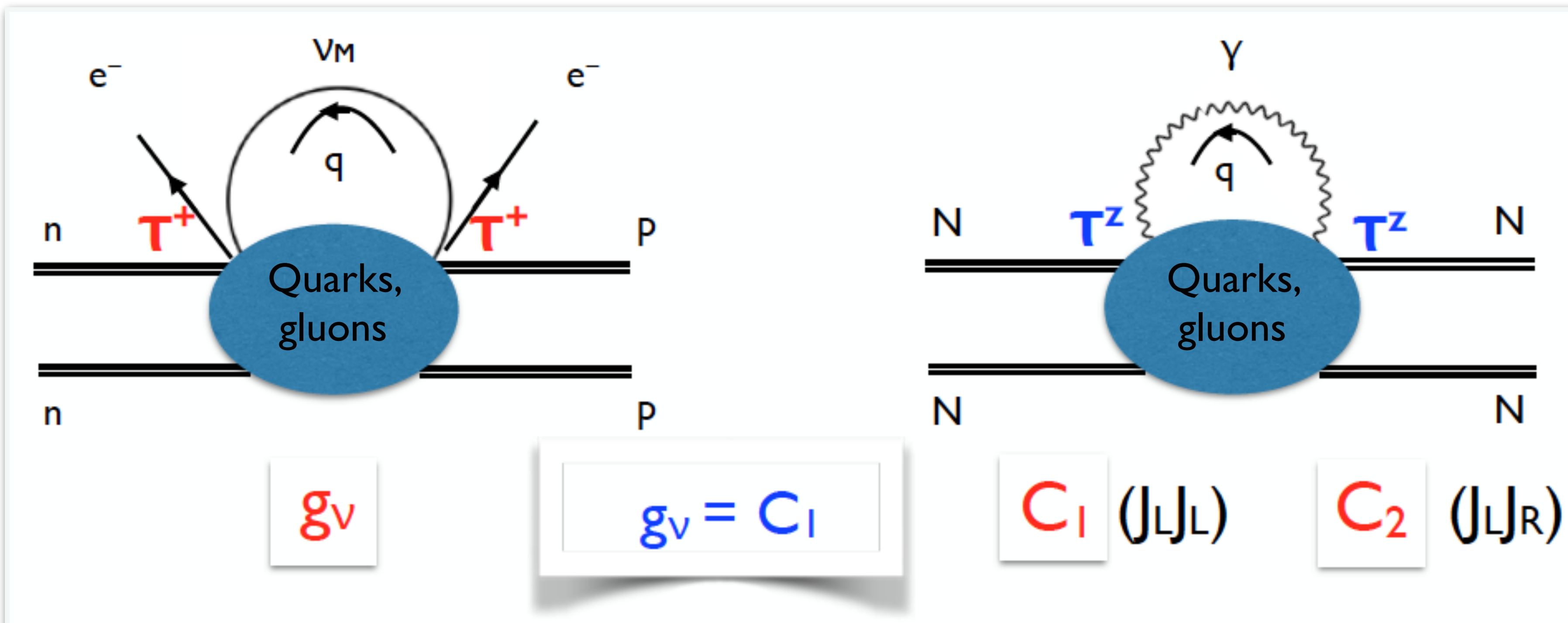


UV divergence $\quad \boxed{\sim \frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2\left(\frac{1}{4-d}+\log\mu^2\right)} \quad \sim 1/(Q^2)\log\mu$

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

Connection with data?

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

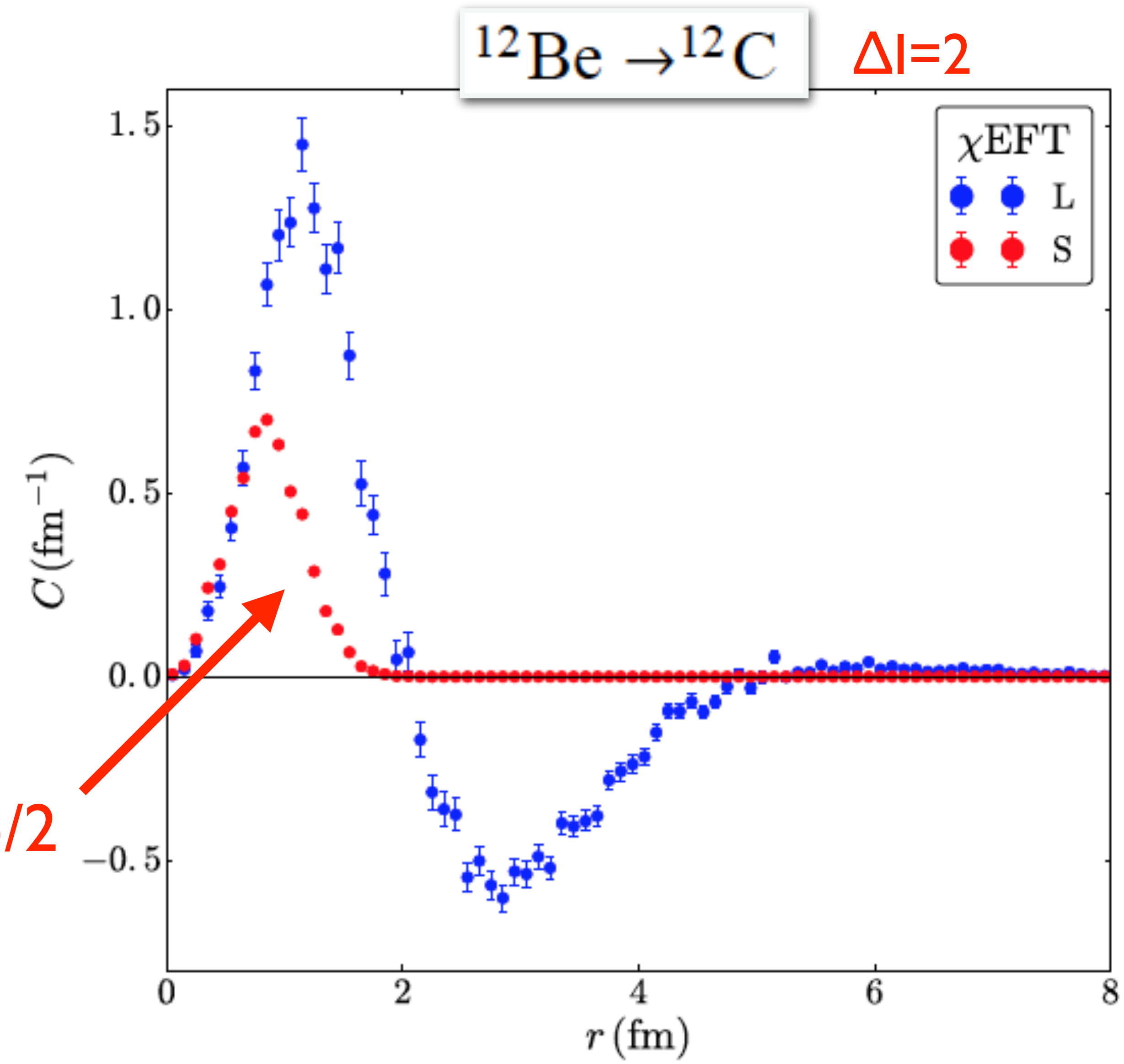


- NN data ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling!
- Assuming $g_\nu \sim (C_1+C_2)/2$, what is the impact on $m_{\beta\beta}$ extraction?

Impact on nuclear matrix elements

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

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



$g_\nu \sim (C_1+C_2)/2$

Light nuclei with Norfolk chiral potential [1606.06335]

g_ν 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!

Challenge: determination of g_ν

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

Richardson, Shindler, Pastore, Springer, 2102.02814

- Compute nn→ppee in full theory and match to EFT expression

Lattice QCD

- $\pi^- \to \pi^+ e^- e^-$ precisely known

Tuo et al. 1909.13525; Detmold, Murphy 2004.07404

- Formalism for NN developed

Davoudi, Kadam, 2012.02083

Analytic approach

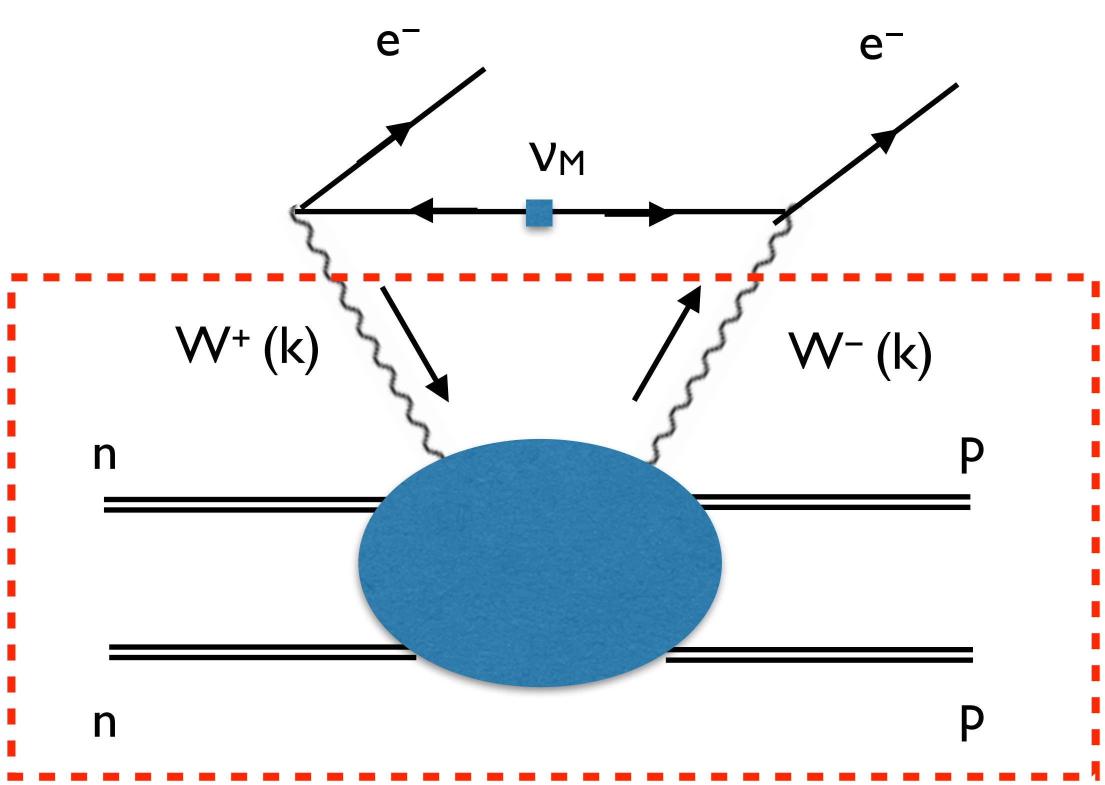
Inspired by the Cottingham approach to electromagnetic nucleon mass splitting

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602 (PRL), 2102.03371 (JHEP)

Estimating the contact term

- Integral representation of the amplitude

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



Forward
"Compton" amplitude

Estimating the contact term

- Integral representation of the amplitude

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

- Introduce separation scale Λ ~ 1-2 GeV, corresponding to onset of QCD asymptotic behavior
- Split `full theory' amplitude into "<" and ">" components, corresponding to |**k**| < Λ and |**k**| > Λ
- Use appropriate degrees of freedom in each region

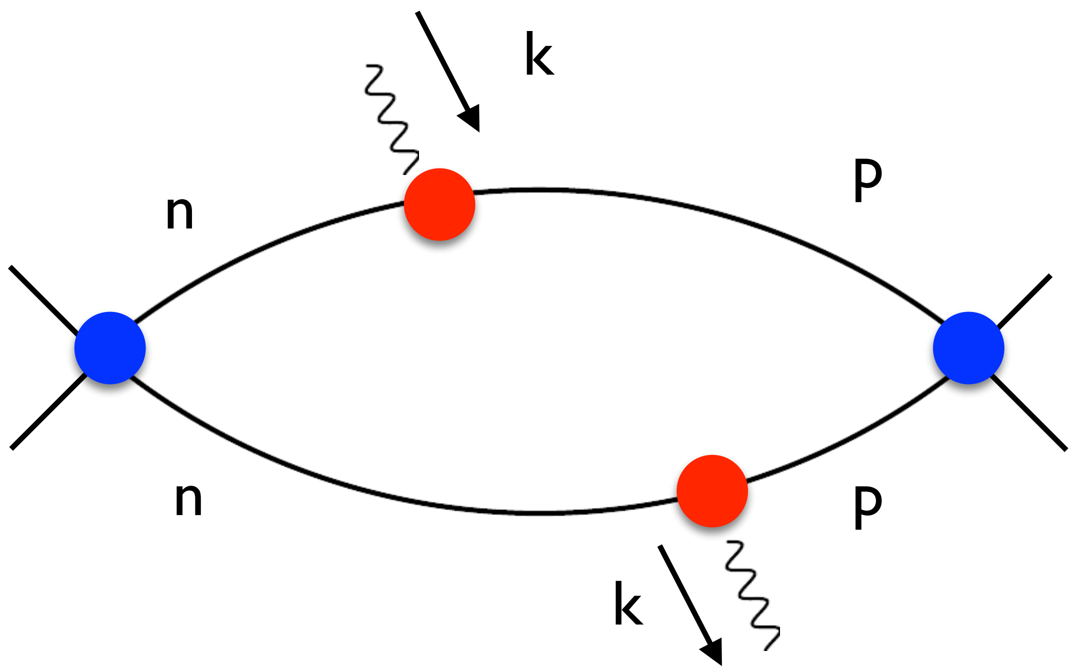
Estimating the contact term

- Integral representation of the amplitude

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

- Low momentum: chiral EFT up to NLO

- Extend to intermediate momentum $|\mathbf{k}| \sim \Lambda$: resonance contributions to nucleon weak form factors and $^1S_0$ NN vertex



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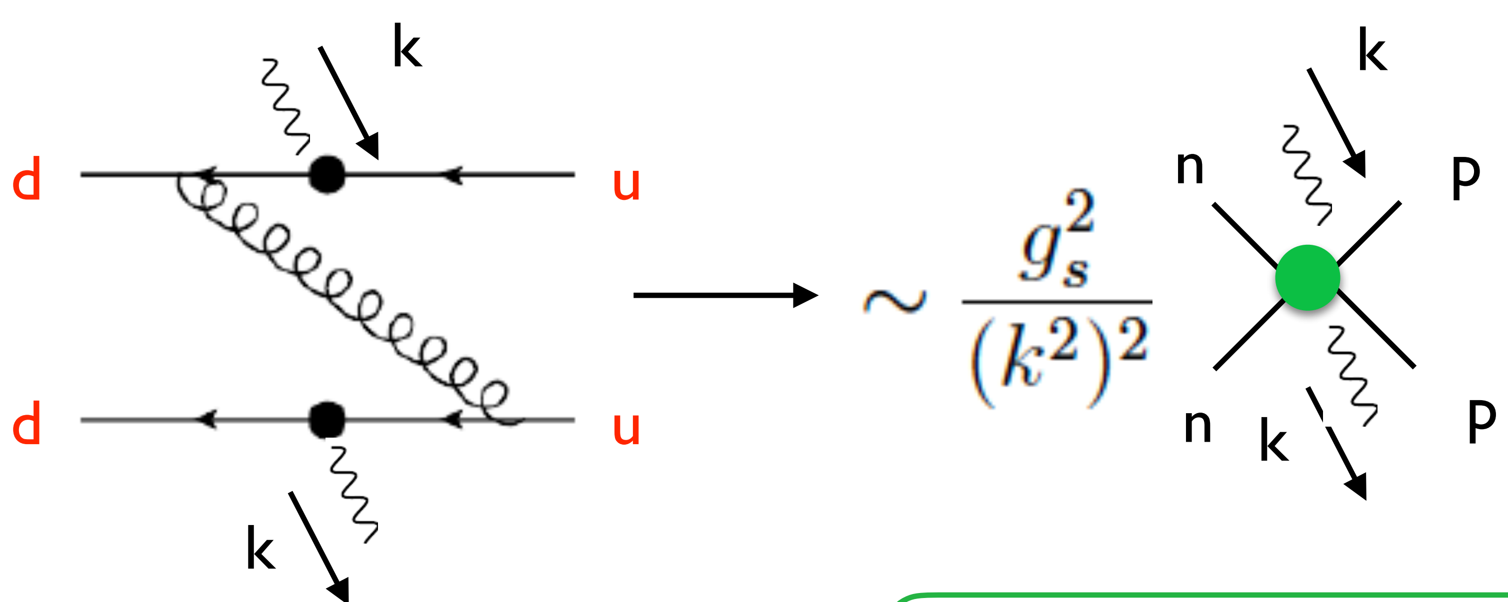
- High momentum (|**k**| > Λ): QCD operator product expansion



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

$$O_1 \;\rightarrow\; g_1^{\rm NN} \, \bar{p} n \bar{p} n \;+\; \ldots$$

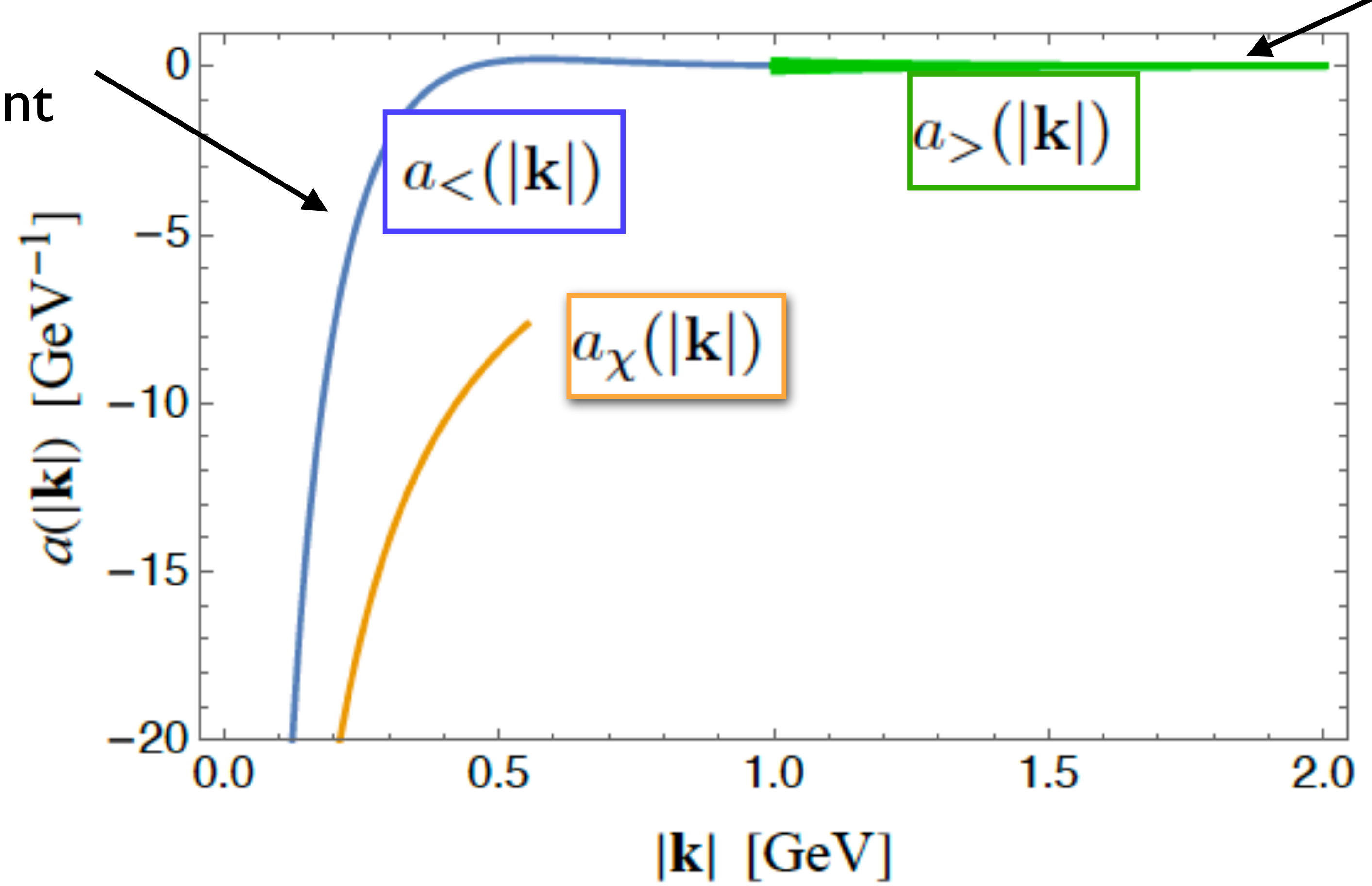
Estimating the contact term

- Integral representation of the amplitude

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

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

Uncertainty due to unknown local operator matrix element is negligible



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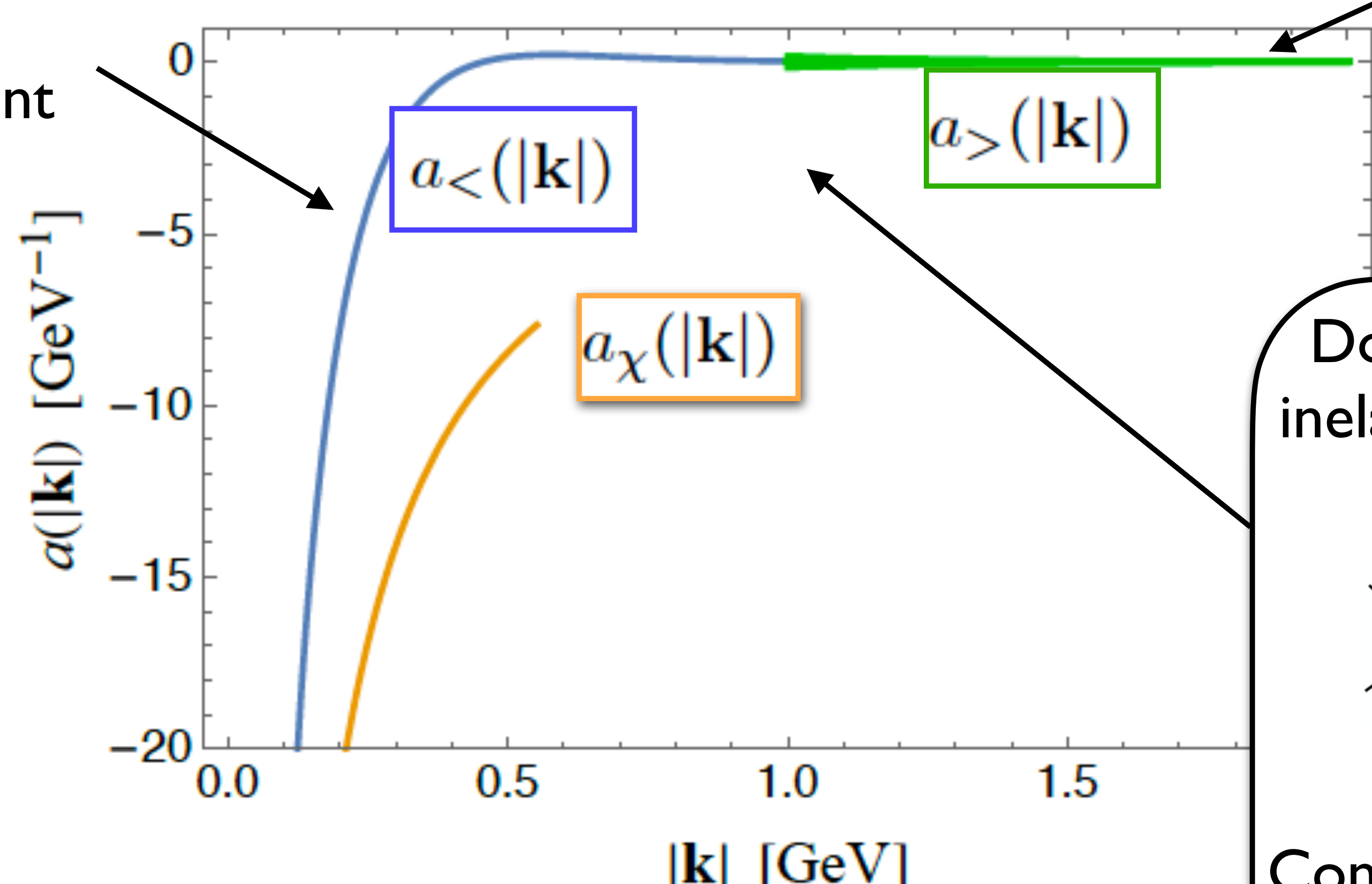
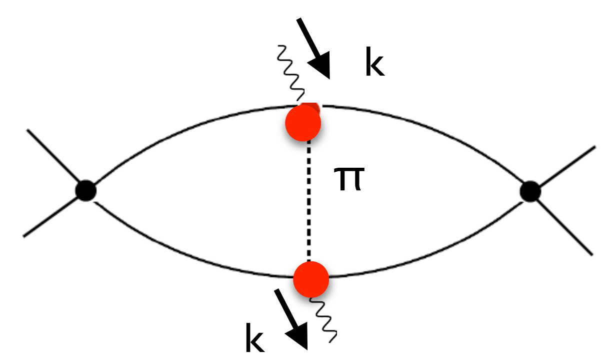


Dominant uncertainty from inelastic channels (NNπ , …):



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

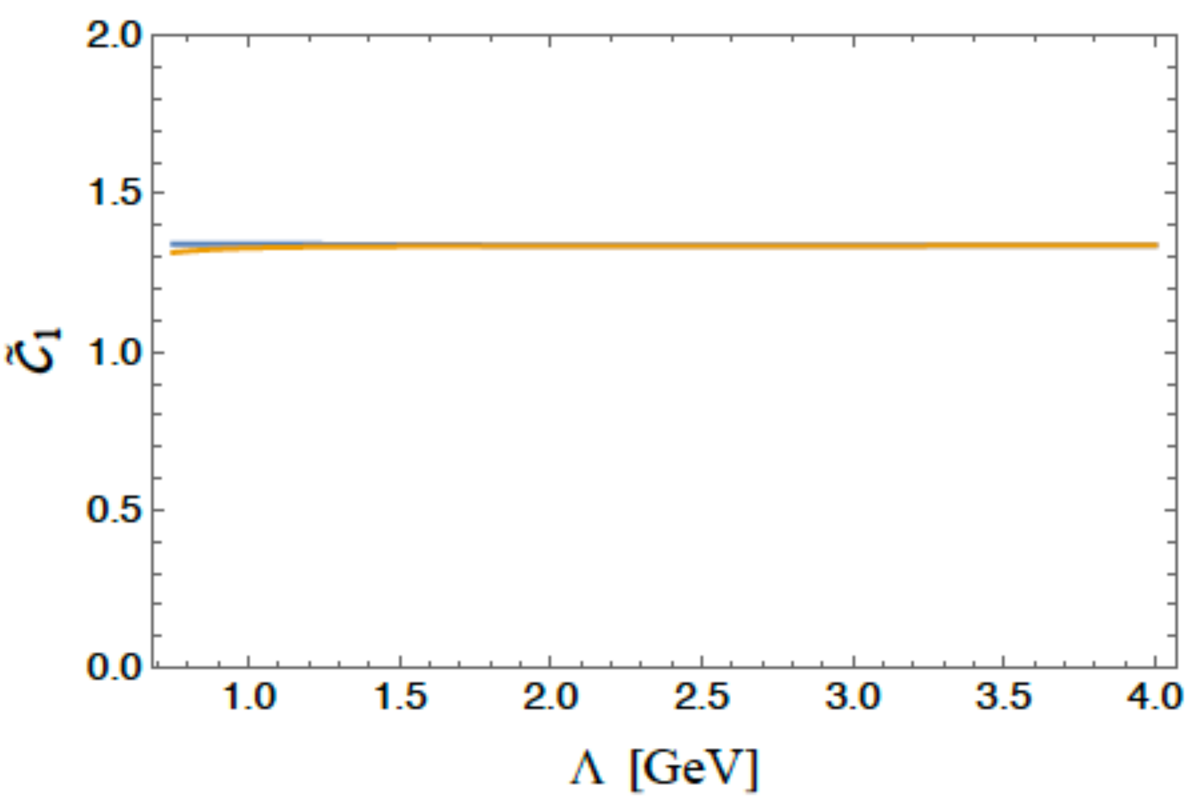
Results & validation

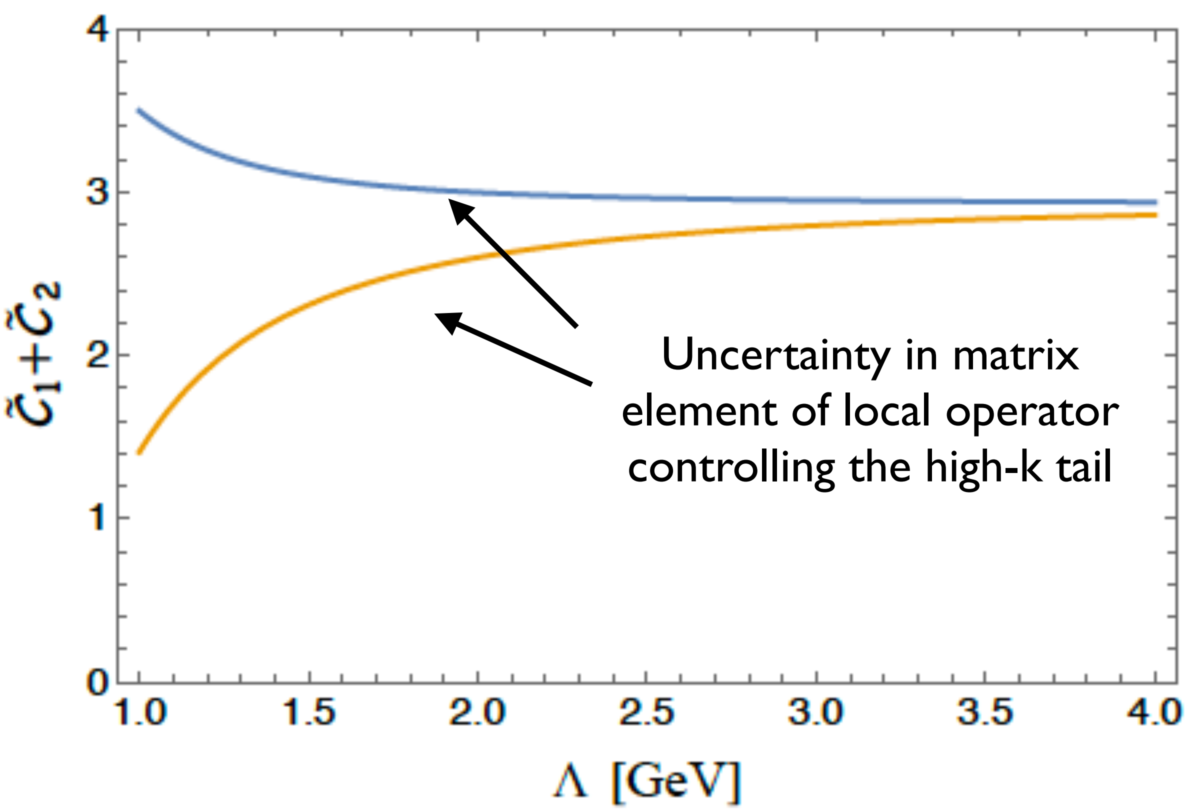
- LECs in dim. reg. with modified minimal subtraction

$$\boxed{\begin{aligned}\tilde{\mathcal{C}}_1(\mu_\chi = M_\pi) &= 1.3(6)\\ (\tilde{\mathcal{C}}_1 + \tilde{\mathcal{C}}_2)(\mu_\chi = M_\pi) &= 2.9(1.2)\end{aligned}}$$

$$C_{1,2} = \left(\frac{m_N C_{^1S_0}}{4\pi}\right)^2 \tilde{\mathcal{C}}_{1,2}$$

$$g_\nu = C_1$$





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- Validation: use C_1+C_2 to predict CIB scattering lengths to LO in χEFT

$$a_{\rm CIB} = \frac{a_{nn} + a^C_{pp}}{2} - a_{np} = 15.5^{+4.5}_{-4.0}\ \mathrm{fm} \quad \text{vs} \quad 10.4(2)\ \mathrm{fm,\ from\ data}$$

Fairly good agreement.

Note: $(C_1+C_2)(M_\pi)=0$ → a_{CIB} ~ 30 fm: contact term pushes result in the right direction.

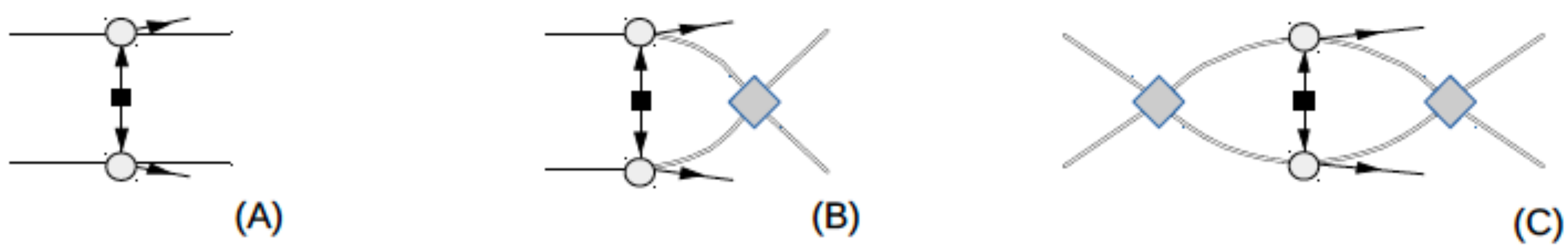
Uncertainty estimate is realistic

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

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

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



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

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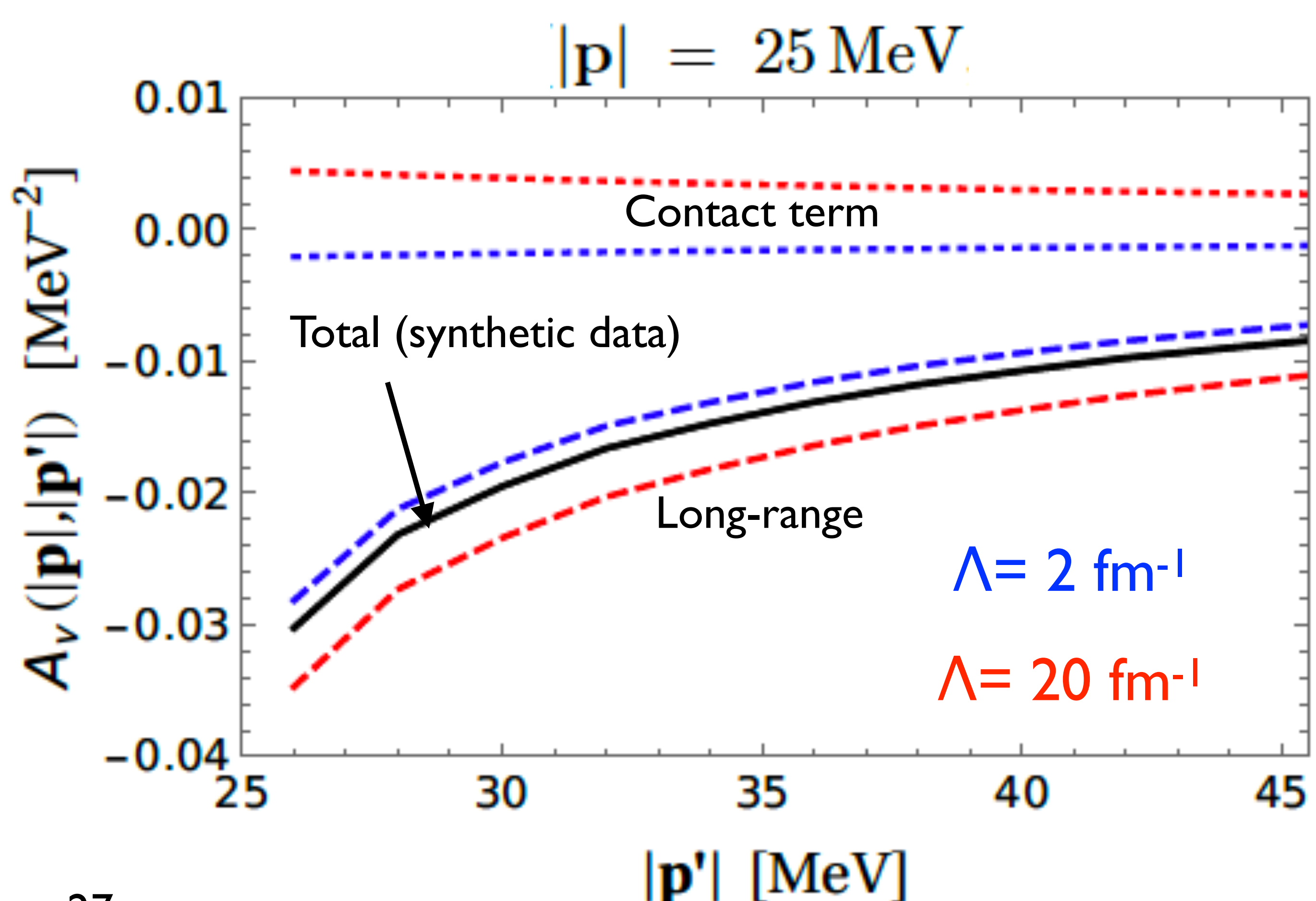
- Illustrated fitting procedure with various cutoffs

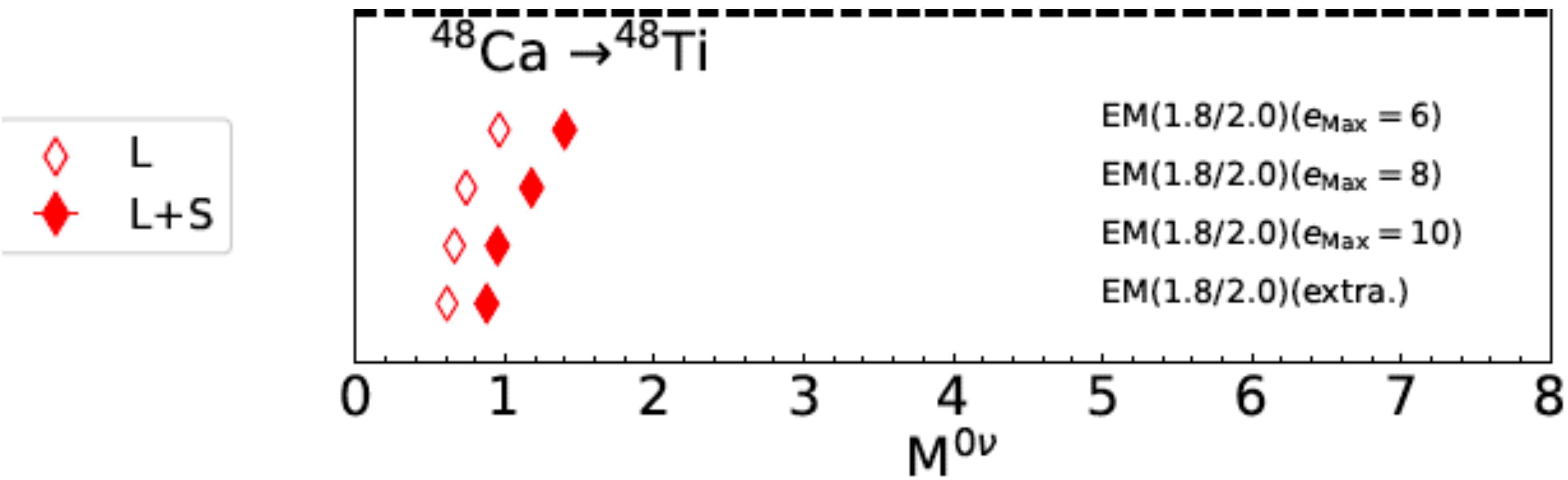
- Constructive or destructive? The sign of the interference is regulator dependent!



Many body calculation

Wirth, Yao, Hergert, 2105.05415

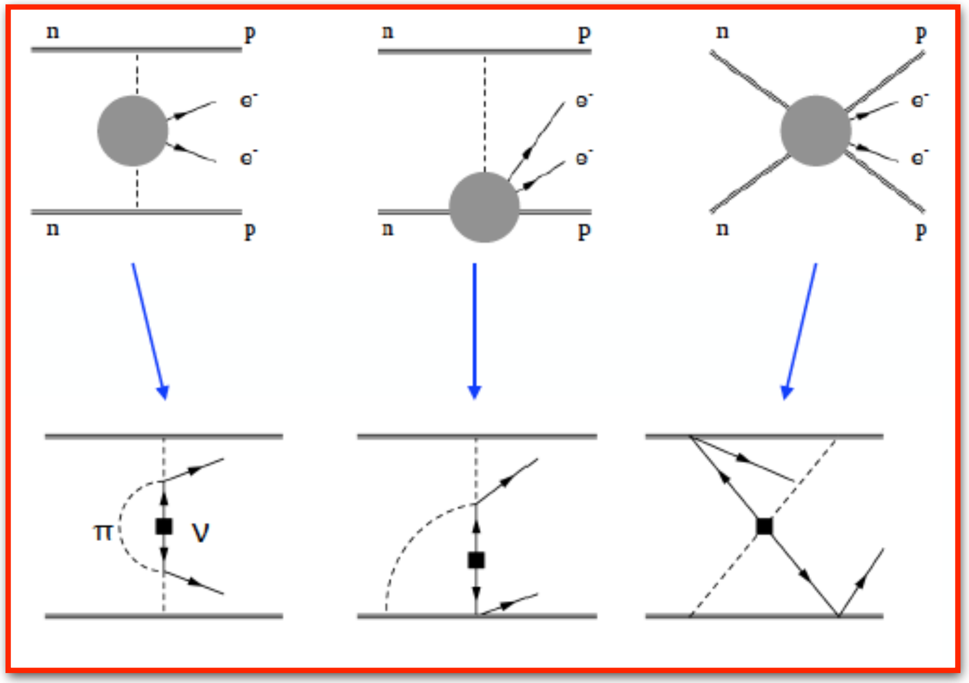
- First calculation of $^{48}Ca \rightarrow ^{48}Ti$ with contact fitted to synthetic datum
- Use Entem-Machleidt class of chiral potentials



- Contact term *enhances* nuclear matrix element by (43±7)%

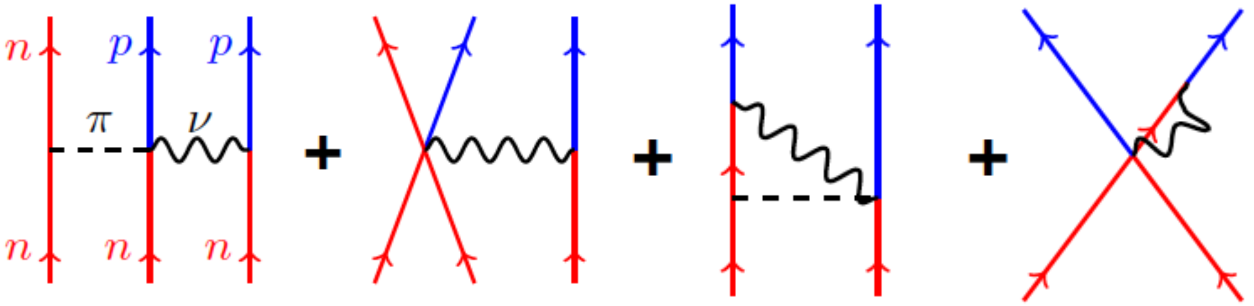
What about higher orders?

- 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]



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

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



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, X. Menendez, E. Mereghetti, in preparation

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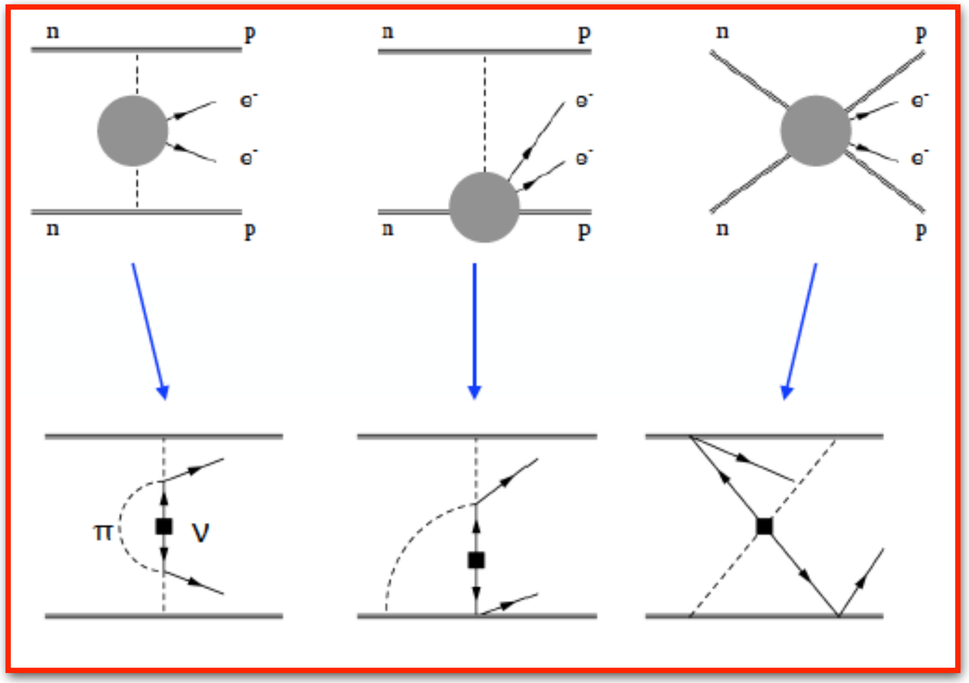

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Chiral EFT + estimate of contact term + many-body →

Significant step towards reduction of matrix element uncertainty & robust interpretation of a positive or null result in terms of $m_{\beta\beta}$

Wang-Engel-Yao 1805.10276

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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 chiral power counting: controllable errors

- Identified new leading order NN contact couplings in light ν exchange (discussed today) 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