Effective field theories for neutrinoless double-beta decay

Javier Menéndez

University of Barcelona
Institute of Cosmos Sciences

20th International Conference on
Hadron Spectroscopy and Structure (HADRON 2023)
9th June 2023

UNIVERSITAT DE BARCELONA
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA Fondo Social Europeo El FSE invierte en tu futuro
AGENCIA ESTATAL DE INVESTIGACIÓN
ICCUB

Creation of matter in nuclei: $0\nu\beta\beta$ decay

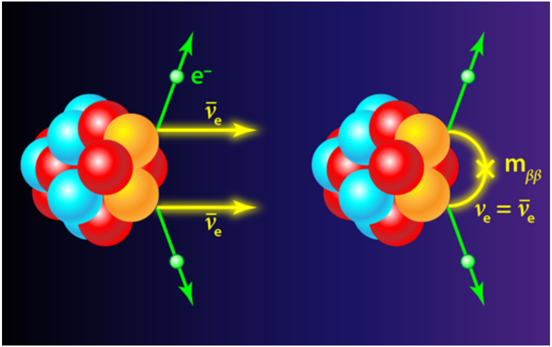
Lepton number is conserved in all processes observed:

single β decay,
$\beta\beta$ decay with ν emission...

Neutral massive particles (Majorana ν's) allow lepton number violation:

neutrinoless $\beta\beta$ decay
creates two matter particles (electrons)

Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)



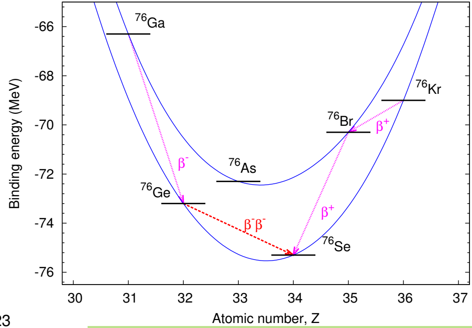
$\beta\beta$ decay

Second order process in the weak interaction

Only observable in nuclei where (much faster) β-decay is forbidden energetically due to nuclear pairing interaction

$$BE(A) = -a_v A + a_s A^{2/3} + a_c \frac{Z(Z-1)}{A^{1/3}} + \frac{(A-2Z)^2}{A} + \begin{cases} -\delta_{pairing} & \text{N,Z even} \\ 0 & \text{A odd} \\ \delta_{pairing} & \text{N,Z odd} \end{cases}$$

or where β-decay is very suppressed by ΔJ angular momentum change



$^{48}Ca \rightarrow {}^{48}Ti$
$^{76}Ge \rightarrow {}^{76}Se$
$^{82}Se \rightarrow {}^{82}Kr$
$^{96}Zr \rightarrow {}^{96}Mo$
$^{100}Mo \rightarrow {}^{100}Ru$
$^{110}Pd \rightarrow {}^{110}Cd$
$^{116}Cd \rightarrow {}^{116}Sn$
$^{124}Sn \rightarrow {}^{124}Te$
$^{130}Te \rightarrow {}^{130}Xe$
$^{136}Xe \rightarrow {}^{136}Ba$
$^{150}Nd \rightarrow {}^{150}Sm$

Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

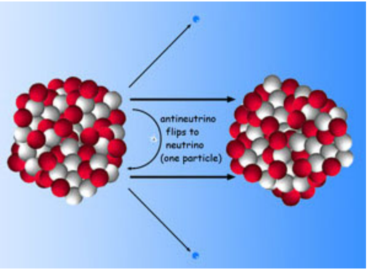
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

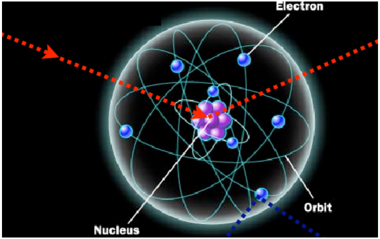
$$0\nu\beta\beta: \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

$$\text{Dark matter:} \quad \frac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i \, \zeta_i \, \mathcal{F}_i\right|^2$$

$$\text{CE}\nu\text{NS:} \quad \frac{d\sigma_{\nu\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i \, \zeta_i \, \mathcal{F}_i\right|^2$$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor





Different scales in $0\nu\beta\beta$ decay

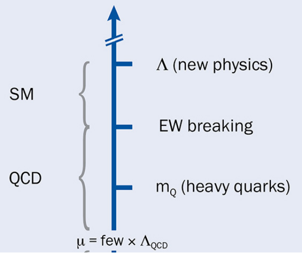
New physics scale: $\Lambda \gg 250$ GeV

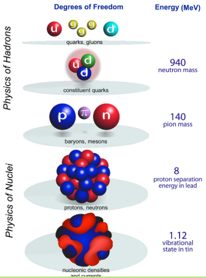
Electroweak scale:

$$v = \left(\sqrt{2}G_F\right)^{-1/2} \sim 250 \text{ GeV}$$

QCD (hadron) scale: $m_N \sim$ GeV

Nuclear scale: $k_F \sim m_\pi \sim 200$ MeV





$0\nu\beta\beta$ decay half-life

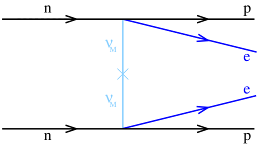
Half-life of $0\nu\beta\beta$ decay sensitive to
$m_{\beta\beta} \sim 1/\Lambda$ (dim-5 operator), new-physics scales $\widetilde{\Lambda}$ (dim-7) or $\widetilde{\Lambda}'$ (dim-9)

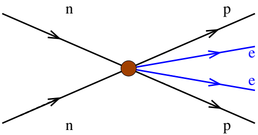
$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M^{0\nu}_{\rm light}\right)^2 m_{\beta\beta}^2 + m_N^2\, \tilde{G}\, \tilde{g}^4\, \tilde{M}^2 \left(\frac{v}{\widetilde{\Lambda}}\right)^6 + \frac{m_N^4}{v^2}\, \widetilde{G}'\, \widetilde{g}'^4\, \widetilde{M}'^2 \left(\frac{v}{\widetilde{\Lambda}'}\right)^{10}$$

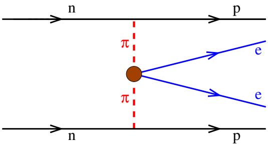
G_{01}, $\widetilde{G}$, $\widetilde{G}'$: phase-space factors (electrons), very well known

g_A, $g_\nu^{\rm NN}$, $\widetilde{g}$, $\widetilde{g}'$: coupling to hadron(s), experiment or calculate with QCD

$M^{0\nu}_{\rm long}$, $M^{0\nu}_{\rm short}$, $\widetilde{M}$, $\widetilde{M}'$: nuclear matrix elements, many-body challenge



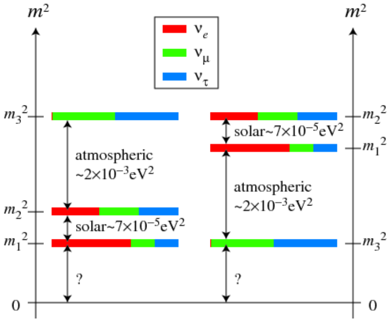


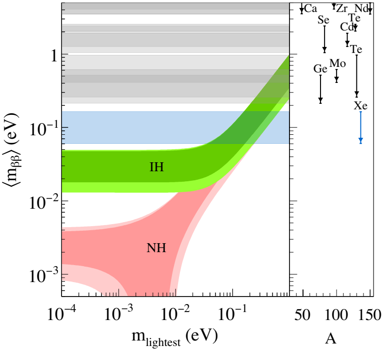


Next generation experiments: inverted hierarchy

Decay rate sensitive to neutrino masses, hierarchy
$m_{\beta\beta} = |\sum U_{ek}^2 m_k|$

$$T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)^{-1} = G_{0\nu}\, g_A^4 \left|M_{\rm light}^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

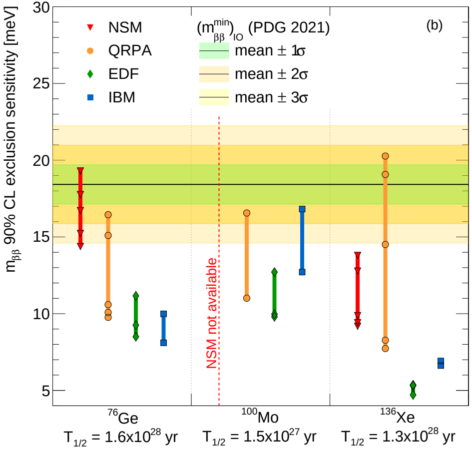




KamLAND-Zen, PRL117 082503(2016)

Matrix elements assess if next generation experiments fully explore "inverted hierarchy"

Uncertainty in physics reach of $0\nu\beta\beta$ experiments



Agostini, Benato, Detwiler, JM, Vissani

Phys. Rev. C 104 L042501 (2021)

Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

Current uncertainty in $m_{\beta\beta}$ prevents to foresee if next-generation experiments will fully cover parameter space of "inverted" neutrino mass hierarchy

Uncertainty needs to be reduced!

$0\nu\beta\beta$ mediated by new-physics heavy particles

Stantard Model extensions
trigger $0\nu\beta\beta$ decay (heavy ν, M_R...)

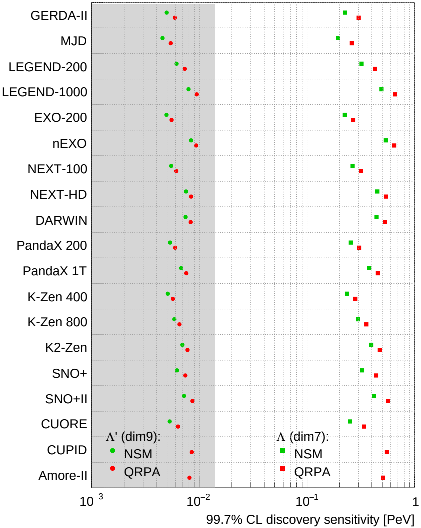
Phase-space,
hadronic/nuclear matrix elements,
known or calculated

Effective field theory

Cirigliano et al JHEP 12 097 (2018)

dimension-7 ($\sim 1/\Lambda^3$),
dimension-9 ($\sim 1/\Lambda^5$) operators

constrained by current searches
$\Lambda \gtrsim 250$ TeV (dim-7)
$\Lambda \gtrsim 5$ TeV (dim-9)

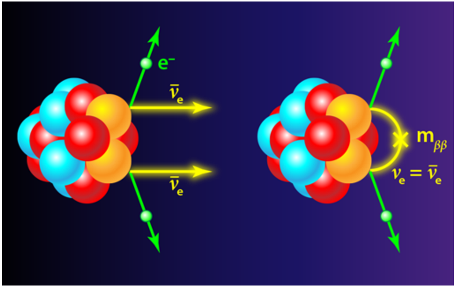


Nuclear matrix elements

Nuclear matrix elements needed in low-energy new-physics searches

$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \rangle = \langle \text{Final} \,|\int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD

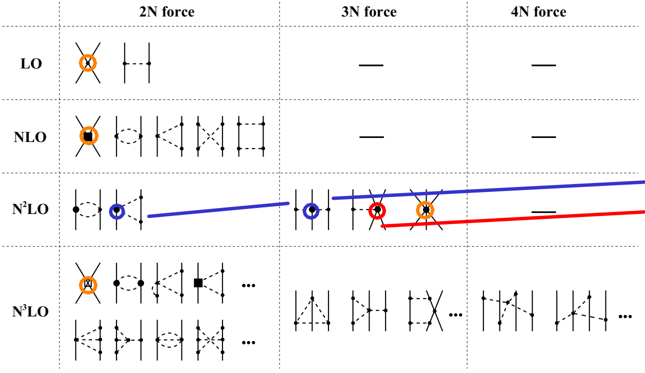


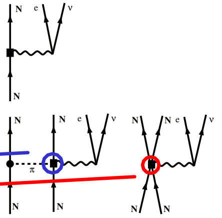
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





Park, Gazit, Klos, Hoferichter...

2b currents applied to νd scattering (SNO), ^{3}H β-decay, μ moment...

Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

Ab initio many-body methods

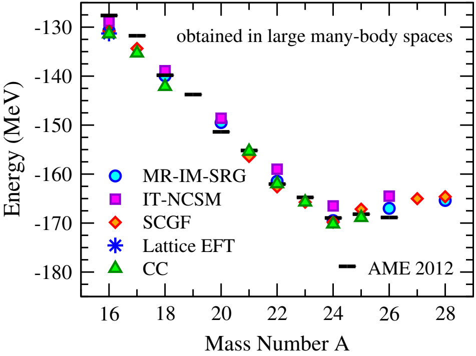
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

In-medium SRG
Hergert et al. PRL110 242501(2013)

Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

Coupled-clusters
Jansen et al. PRL113 142502(2014)



Recent application to ^{208}Pb
Hu, Jiang, Miyagi et al. Nature Phys. 18, 1196 (2022)

Ab initio many-body methods

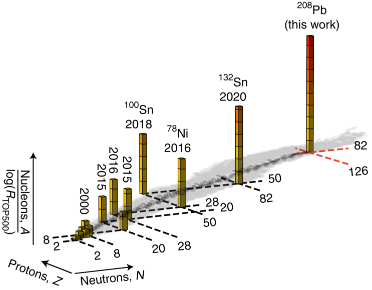
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

In-medium SRG
Hergert et al. PRL110 242501(2013)

Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

Coupled-clusters
Jansen et al. PRL113 142502(2014)

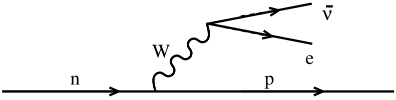


Recent application to ^{208}Pb

Hu, Jiang, Miyagi et al. Nature Phys. 18, 1196 (2022)

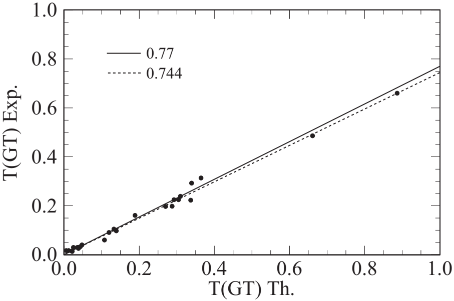
Gamow-Teller transitions: quenching

Single β decays well described by nuclear structure (shell model)



$$\langle F | \sum_i g_A^{\text{eff}} \boldsymbol{\sigma}_i \tau_i^- | I \rangle$$

$$g_A^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8.$$



Martínez-Pinedo et al. PRC53 2602 (1996)

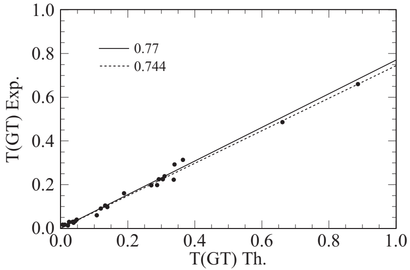
Theory needs to “quench“ Gamow-Teller operator to reproduce Gamow-Teller lifetimes: problem in nuclear many-body wf or operator?

This puzzle has been the target of many theoretical efforts:

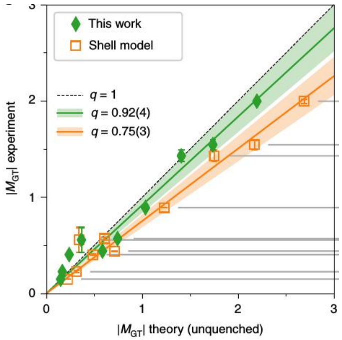
Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

No β-decay "quenching" with 2b currents

β decays (e^- capture): phenomenology vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

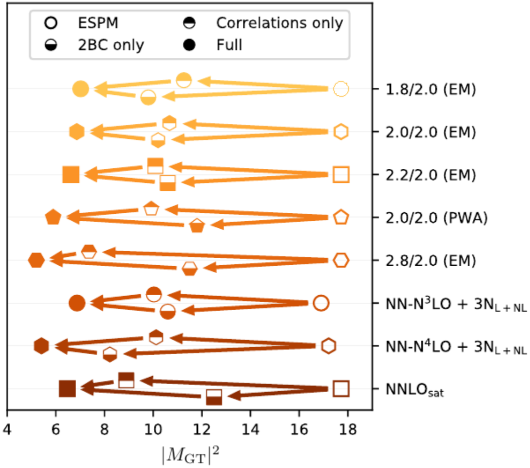
$$\langle F|\sum_i [g_A\,\boldsymbol{\sigma}_i\tau_i^-]^{\text{eff}}\,|I\rangle\,,\quad [\boldsymbol{\sigma}_i\tau]^{\text{eff}} \approx 0.7\boldsymbol{\sigma}_i\tau$$

Shell model need $\boldsymbol{\sigma}_i\tau$ "quenching"

Ab initio calculations including meson-exchange currents and additional nuclear correlations do not need any "quenching"

Origin of β decay "quenching"

Which are main effects missing in conventional β-decay calculations?

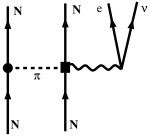


Relatively similar and complementary impact of

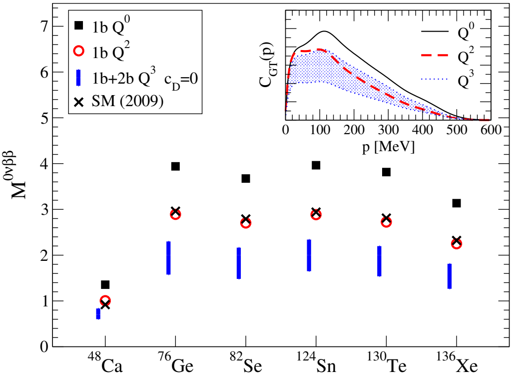
- nuclear correlations
- meson-exchange currents

Gysbers et al.

Nature Phys. 15 428 (2019)

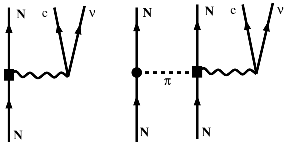


Nuclear matrix elements with 1b+2b currents

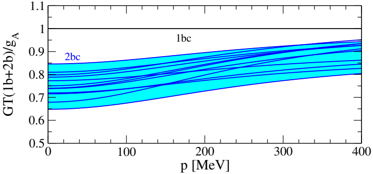


JM, Gazit, Schwenk PRL107 062501 (2011)

2b currents
reduce matrix elements
$\sim 20\% - 50\%$



Momentum transfer $p \sim m_\pi$, reduces quenching $\Downarrow$



Improved by recent calculation:
Jokiniemi, Romeo, Soriano, JM
PRC 107 044305 (2023)

UNIVERSITAT DE BARCELONA

Light-neutrino exchange: contact operator

Short-range operator contributes to light-neutrino exchange
for RG invariance of two-nucleon decay amplitude: high-energy ν's

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M_{\rm long}^{0\nu} + M_{\rm short}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2},$$

Cirigliano et al. PRL120 202001(2018)

$$M_{\rm short}^{0\nu} \equiv \frac{1.2A^{1/3}\,{\rm fm}}{g_A^2} \langle 0_f^+|\sum_{n.m} \tau_m^- \tau_n^- \,\mathbb{1}\, [\frac{2}{\pi}\int j_0(qr)\, 2g_\nu^{\rm NN}\, g(p/\Lambda)\, p^2 dp]\, |0_i^+\rangle,$$

$$M_{\rm GT}^{0\nu} \simeq \frac{1.2A^{1/3}\,{\rm fm}}{g_A^2} \langle 0_f^+|\sum_{n.m} \tau_m^- \tau_n^- \,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\, [\frac{2}{\pi}\int j_0(qr)\, \frac{1}{p^2}\, g_A^2\, f^2(p/\Lambda_A)\, p^2 dp]\, |0_i^+\rangle$$

Unknown value (and sign) of the hadronic coupling $g_\nu^{\rm NN}$!

Lattice QCD calculations can obtain value of $g_\nu^{\rm NN}$

Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)

match $nn \to pp + ee$ amplitude calculated with dispersion QCD methods

Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)

charge-independence breaking of nuclear Hamiltonians

Cirigliano et al. PRC100, 055504 (2019)

Contact matrix element: relative impact

Modified decay rate: $T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$

Assume

$g_\nu^{NN} \sim 1\text{fm}^2$

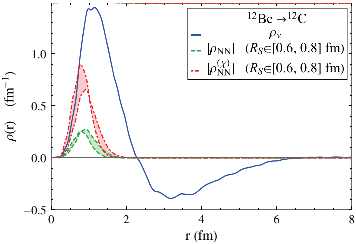
Cirigliano et al.
PRC100 055504 (2019)

TABLE II. Values of $\mathcal{C}_1 + \mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials.

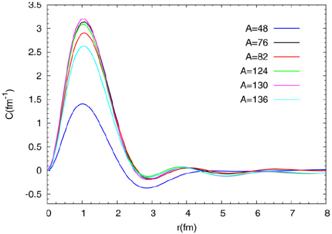
Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[38]	0.8	0.0158	−1.03	Entem-Machleidt	[34]	500	−0.47
NV-IIa*	[38]	0.8	0.0219	−1.44	Entem-Machleidt	[34]	600	−0.14
NV-Ic	[38]	0.6	0.0219	−1.44	Reinert *et al.*	[39]	450	−0.67
NV-IIc	[38]	0.6	0.0139	−0.91	Reinert *et al.*	[39]	550	−1.01
					NNLO_{sat}	[37]	450	−0.39

$\sim$ 75% correction for QMC ^{12}Be NME

What about heavy nuclei?



Cirigliano et al. PRL120 202001(2018)



JM et al. NPA818 139 (2009)

Short-range NME calculations in heavy nuclei

Calculate $M^{0\nu}_{\text{short}}$ in heavy nuclei to see impact in $0\nu\beta\beta$ searches

Use g_ν^{NN} and Λ values from
charge independence breaking (CIB) contact term, chiral EFT potentials
assume same value for two CIB couplings $\mathcal{C}_1 = \mathcal{C}_2$

$g_\nu^{\text{NN}}(\text{fm}^2)$	Λ (MeV)	
-0.67	450	Reiner et al. Eur. Phys. J. A 54 86 (2018)
-1.01	550	"
-1.44	465	Piarulli et al. Phys. Rev. C 94 054007 (2016)
-0.91	465	"
-1.44	349	"
-1.03	349	"

Consider Gaussian regulators: $h_s = 2g_\nu^{\text{NN}} g(p/\Lambda)$

Perform calculations with the nuclear shell model:
^{48}Ca, ^{76}Ge, ^{82}Se, ^{124}Sn, ^{128}Te, ^{130}Te and ^{136}Xe

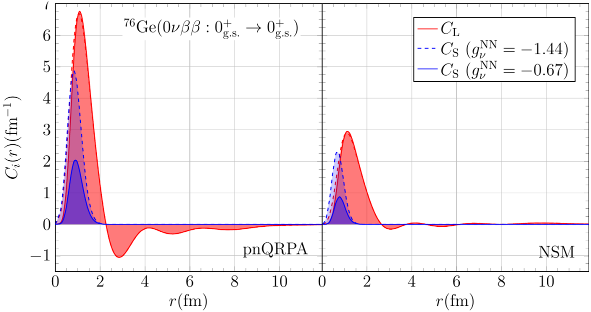
and the quasiparticle random-phase approximation method (QRPA):
^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{128}Te, ^{130}Te and ^{136}Xe

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L:

20% – 50% impact of short-range NME in shell model
30% – 70% impact of short-range NME in QRPA

consistent with 43% effect in IM-GCM for ^{48}Ca
using result from $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)



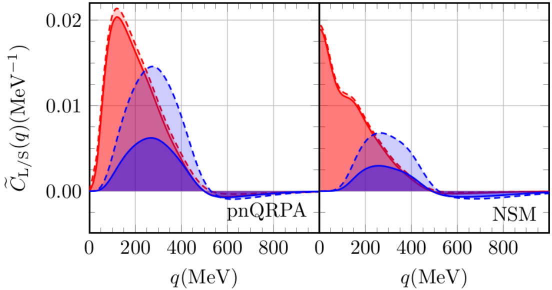
Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L:

20% – 50% impact of short-range NME in shell model
30% – 70% impact of short-range NME in QRPA

consistent with 43% effect in IM-GCM for ^{48}Ca
using result from $nn \rightarrow pp + ee$ decay Wirth et al. PRL127 242502 (2021)



Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

Relative impact of new short-range contribution

In transitions with larger cancellation from tail in NME distribution new short-range term becomes relatively more important

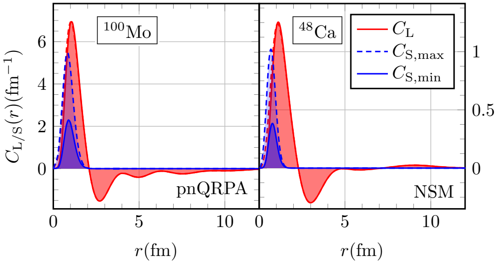
Nuclear shell model: ^{48}Ca with 25% – 65% contribution

consistent with Wirth et al. PRL127 242502 (2021)

QRPA: ^{100}Mo with 50% – 100% contribution

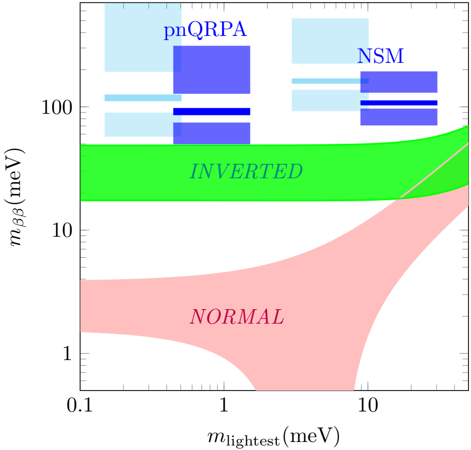
due to negative contributions of 1^+ intermediate states

explains larger QRPA than shell model impact, but less than QMC



Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

Impact on tests of inverted hierarchy of ν mass



Jokiniemi, Soriano, JM

Phys. Lett. B 823 136720 (2021)

With these g_ν^{NN} values significant impact on current $0\nu\beta\beta$ limits on neutrino mass, $m_{\beta\beta}$

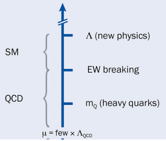
Ab initio determination based on $nn \to pp + ee$ result suggests constructive sign between M_L and M_S

Wirth et al. PRL127 242502 (2021)

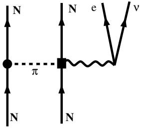
Short-range matrix element may roughly compensate effect of missing correlations meson-exchange currents in shell model, QRPA NME calculations

Summary

$0\nu\beta\beta$ involves new-physics,
hadron-physics, nuclear-physics scales:
ideal playground
for effective field theories



Chiral EFT
very successful in nuclear structure
predicts meson-exchange currents
which decrease $0\nu\beta\beta$ rate



EFT analysis of $0\nu\beta\beta$ decay
requires new short-range term:
enchances $0\nu\beta\beta$ rate
(better constrain two-nucleon coupling)