Improved Nuclear Matrix Elements for Neutrinoless Double-Beta Decay

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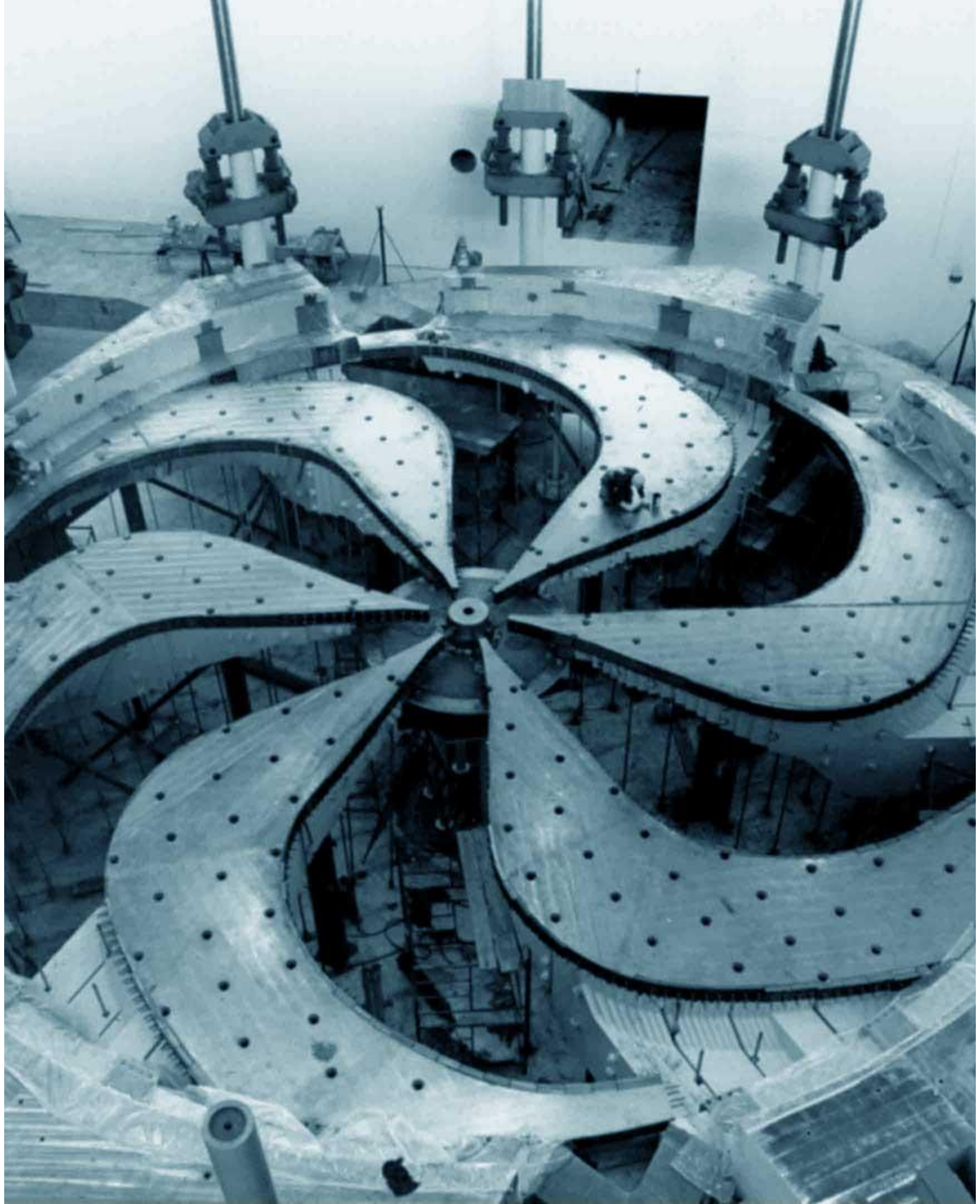
McDonald Institute Annual National Meeting,
Queen’s University, Kingston
08/08/2024

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute



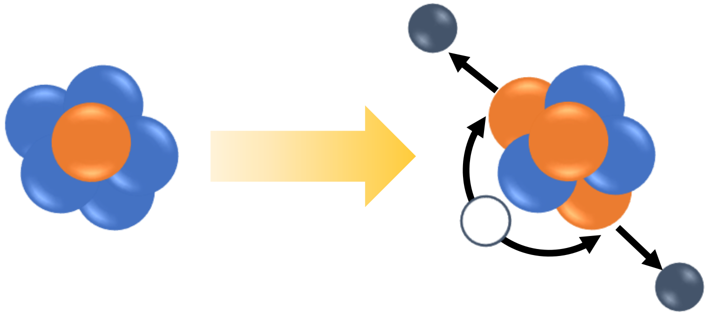
Discovery, accelerated

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

- Violates lepton-number conservation:

$$2p \rightarrow 2n + 2e^{-}$$

- Requires that neutrino is its own antiparticle (*Majorana particle*)
- If observed, $t_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ years ($t_{1/2}^{2\nu\beta\beta} \gtrsim 10^{20}$ years)



1935

M. Göppert Mayer

1937

E. Majorana

1939

W. Furry

Half-life of neutrinoless double-beta decay

$$\frac{1}{t_{1/2}^{0\nu\beta\beta}} = g_A^4 G^{0\nu\beta\beta} \left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life

Observable to be measured

Axial-vector coupling

Known from β-decay of neutrons; $g_A \approx 1.27$

Phase-space factor

Physics of the emitted electrons → solved from atomic physics

Nuclear matrix element (NME)

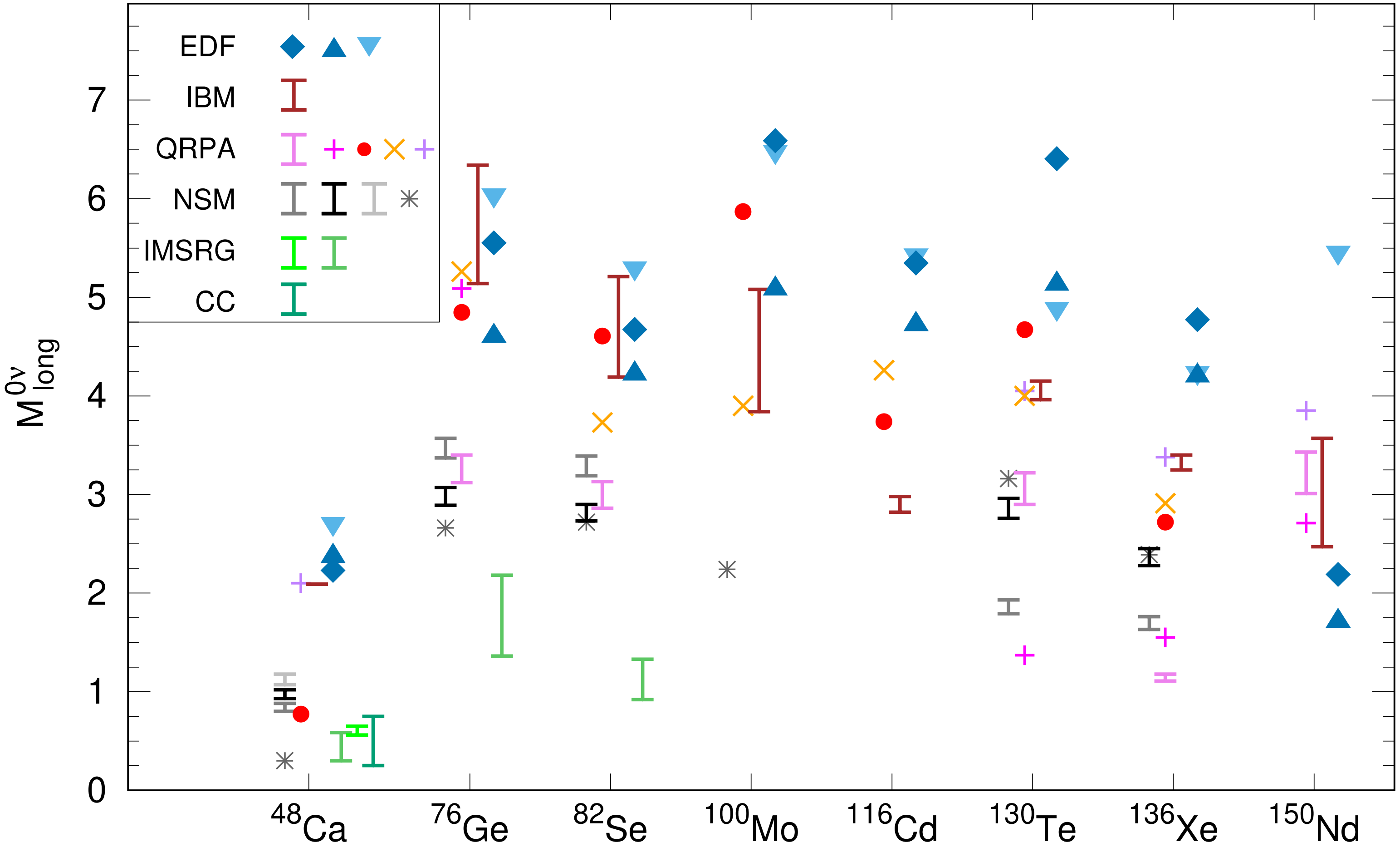
*From **nuclear theory***

Majorana mass

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

New physics we want to extract

Nuclear matrix elements currently poorly known



M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

Nuclear matrix element

Operator $(2n \rightarrow 2p + 2e^{-})$

$$M^{0\nu\beta\beta} = \langle 0_f^+ \| \mathcal{O}^{0\nu\beta\beta} \| 0_i^+ \rangle$$

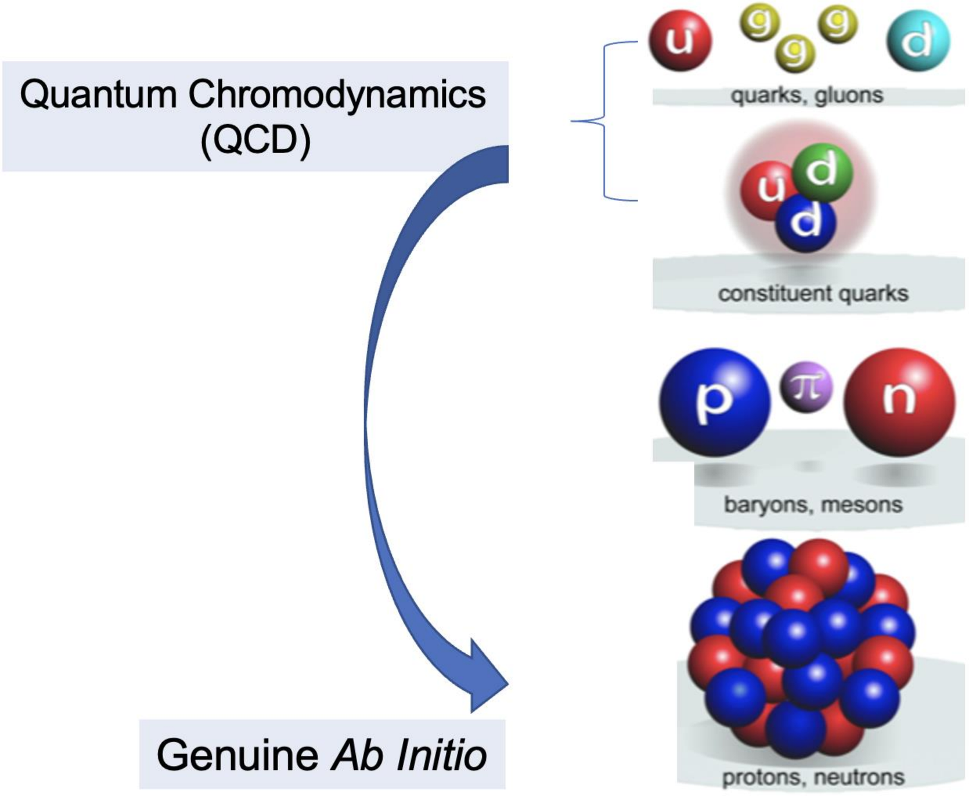
Final state nuclear wave function

Initial state nuclear wave function

$$H\Psi^{(A)} = E\Psi^{(A)} \leftarrow H = \sum_i \frac{p^2}{2m} + \sum_{i \neq j} V^{2N} + \sum_{i \neq j \neq k} V^{3N}$$

Ab initio vs. phenomenological nuclear methods

Ab initio (lat. 'from the beginning')



Phenomenological

Solve

$$H^{\text{eff}}\Psi^{(A)} = E\Psi^{(A)}$$

with H^{eff} adjusted to nuclear data (energies, decays, …)

- Different models (nuclear shell model, random-phase approximation, …)
- Not systematically improvable

What can we do with *ab initio* methods?

Exponentially scaling methods (NCSM, quantum Monte Carlo, …)

Polynomially scaling methods (coupled cluster, IM-SRG, IM-GCM)

Valence-space methods (VS-IMSRG)

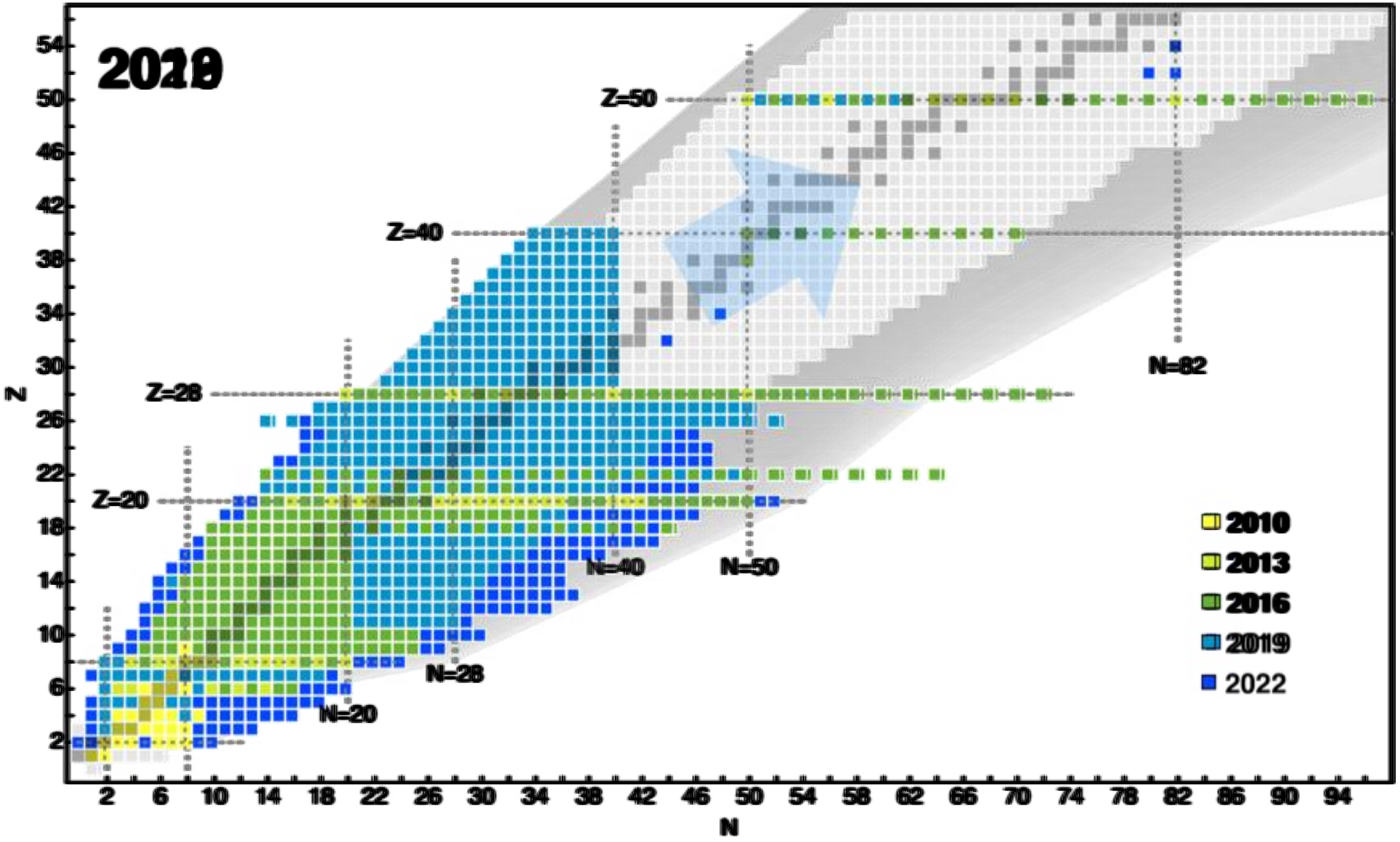
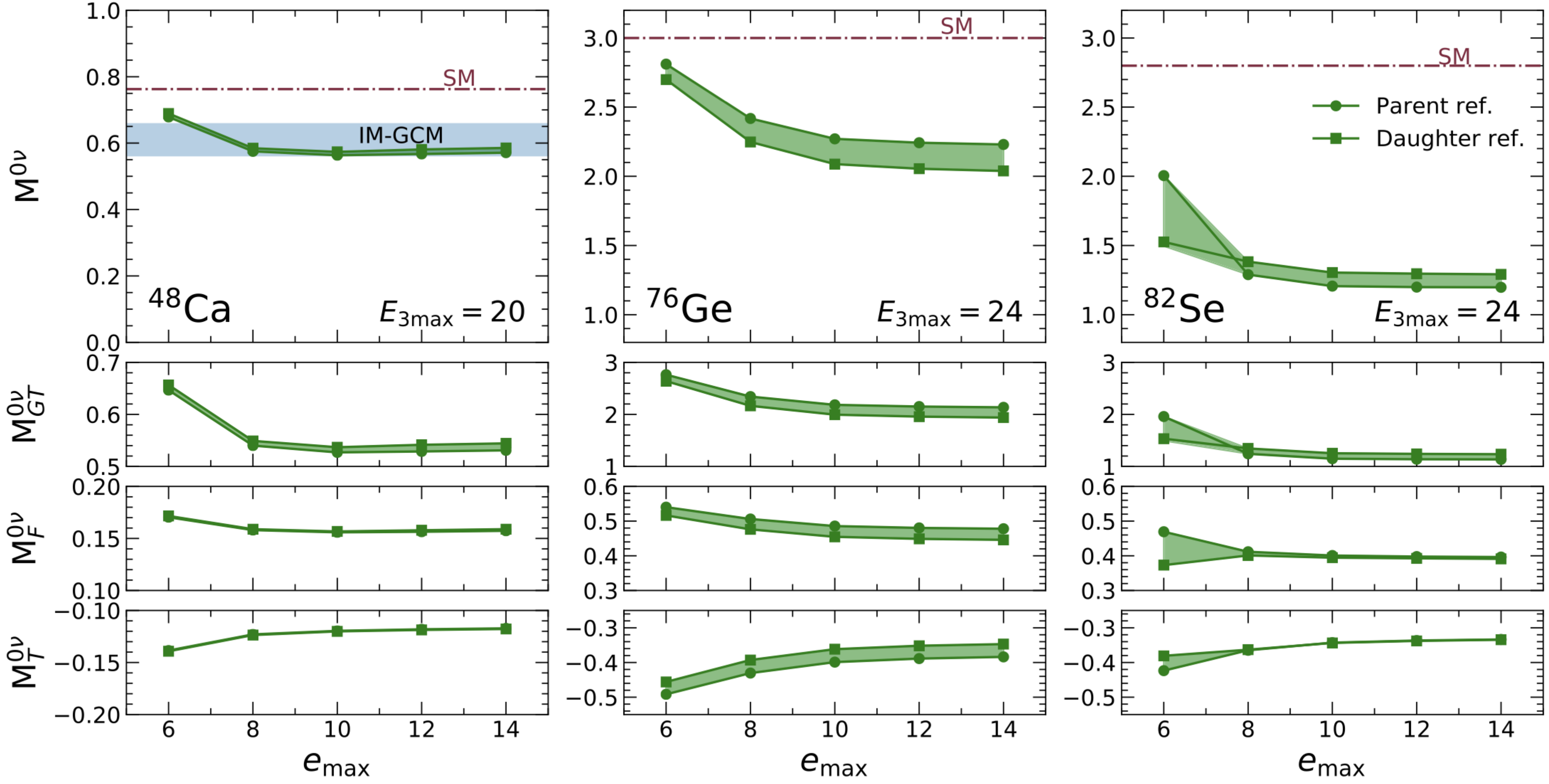


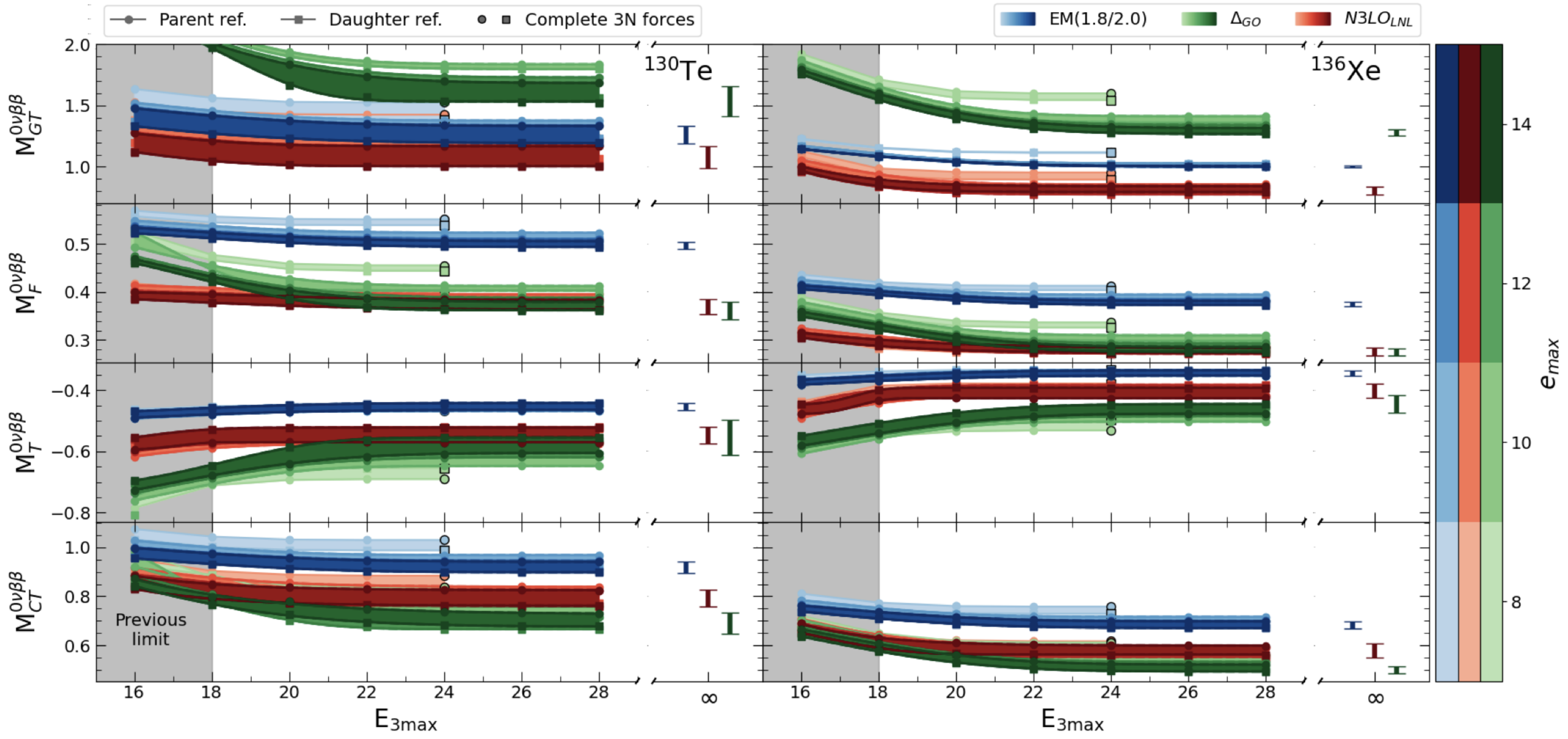
Figure courtesy of A. Belley, (adapted from H. Hergert, Front. Phys. 8 (2020))

Ab initio $0\nu\beta\beta$-decay NMEs for ^{48}Ca, ^{76}Ge and ^{82}Se



A. Belley et al., Phys. Rev. Lett. 126, 042502 (2021)

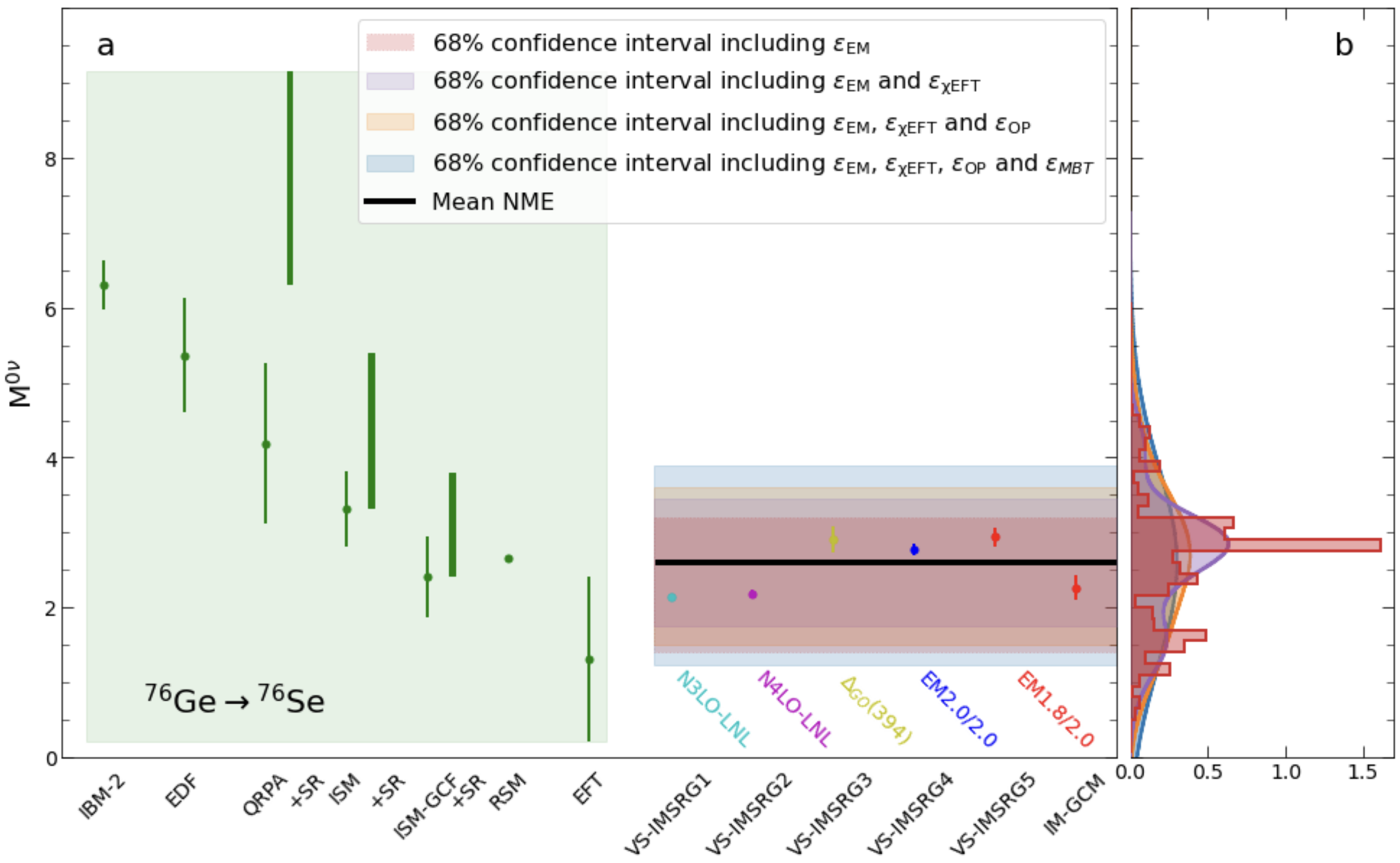
Ab initio $0\nu\beta\beta$-decay NMEs for ^{130}Te and ^{136}Xe



A. Belley, T. Miyagi, S.R. Stroberg, and J. D. Holt, arXiv:2307.15156

Uncertainty quantification of $0\nu\beta\beta$ decay of ^{76}Ge

Ab initio + machine learning + Bayesian statistics



A. Belley et al., Phys. Rev. Lett. 132, 182502 (2024)

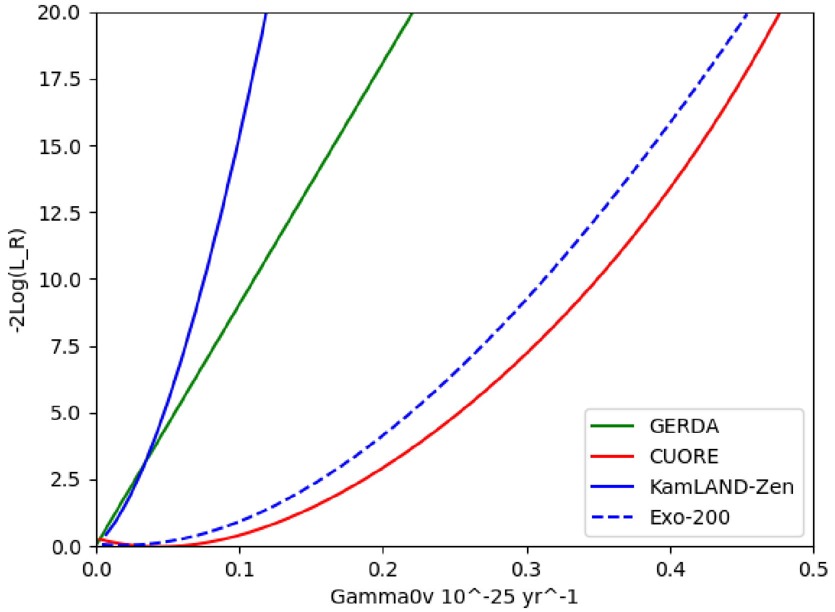
Combined constraints for Majorana masses

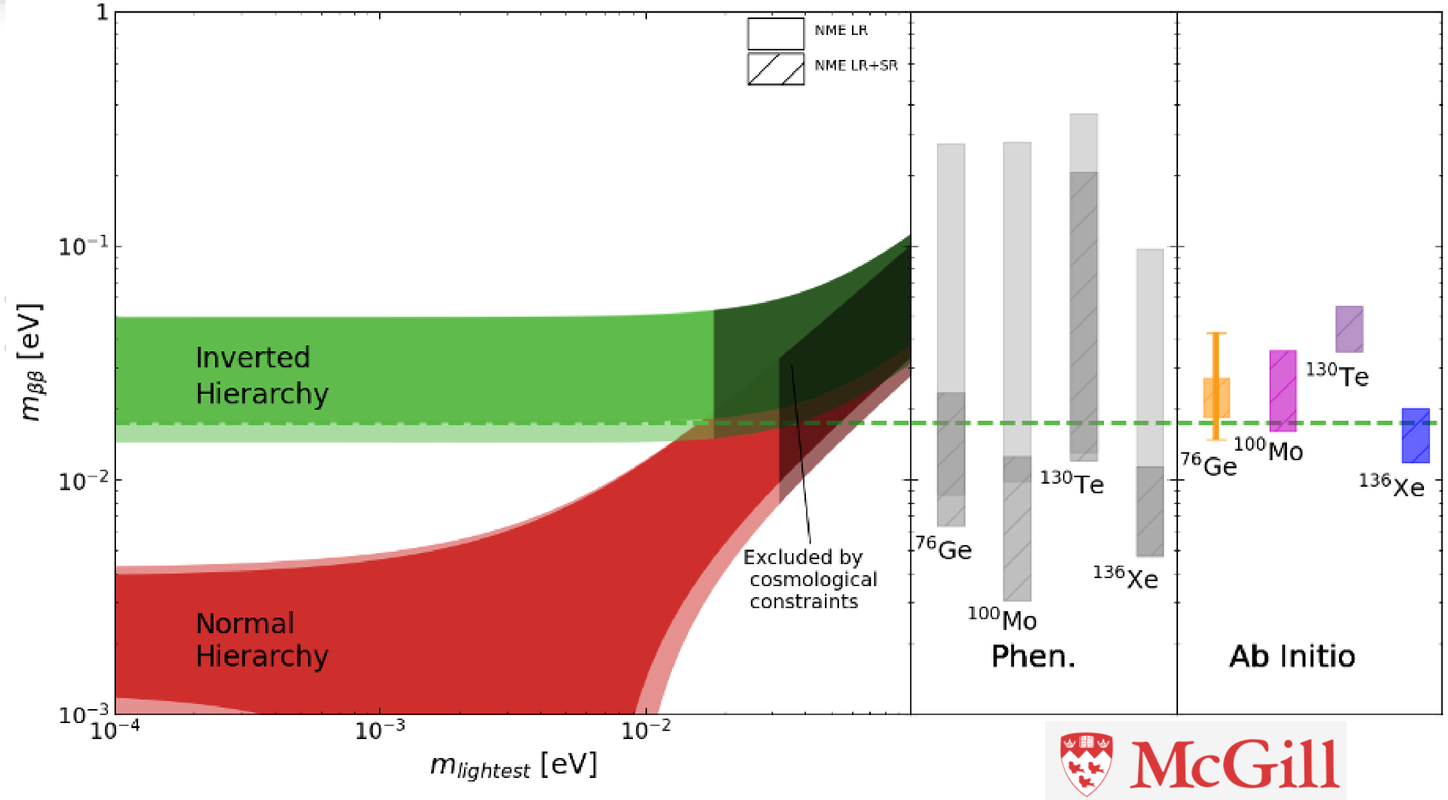
Combined constraints on Majorana masses from neutrinoless double beta decay experiments

Steven D. Biller
Phys. Rev. D **104**, 012002 – Published 6 July 2021

THE UNIVERSITY OF BRITISH COLUMBIA

***T. Shickele**, LJ, A. Belley, et al., in progress.*





GERDA: *PRL 125, 252502 (2020)*
CUORE: *arXiv:2404.04453*
KamLAND-Zen: *arXiv:2406.11438*
EXO-200: *PRL 123, 161802 (2019)*

McGill

→Constraints for heavy neutrinos (A. Todd)
→Constraints for next-generation experiments

Improvements to the operator of $0\nu\beta\beta$ decay

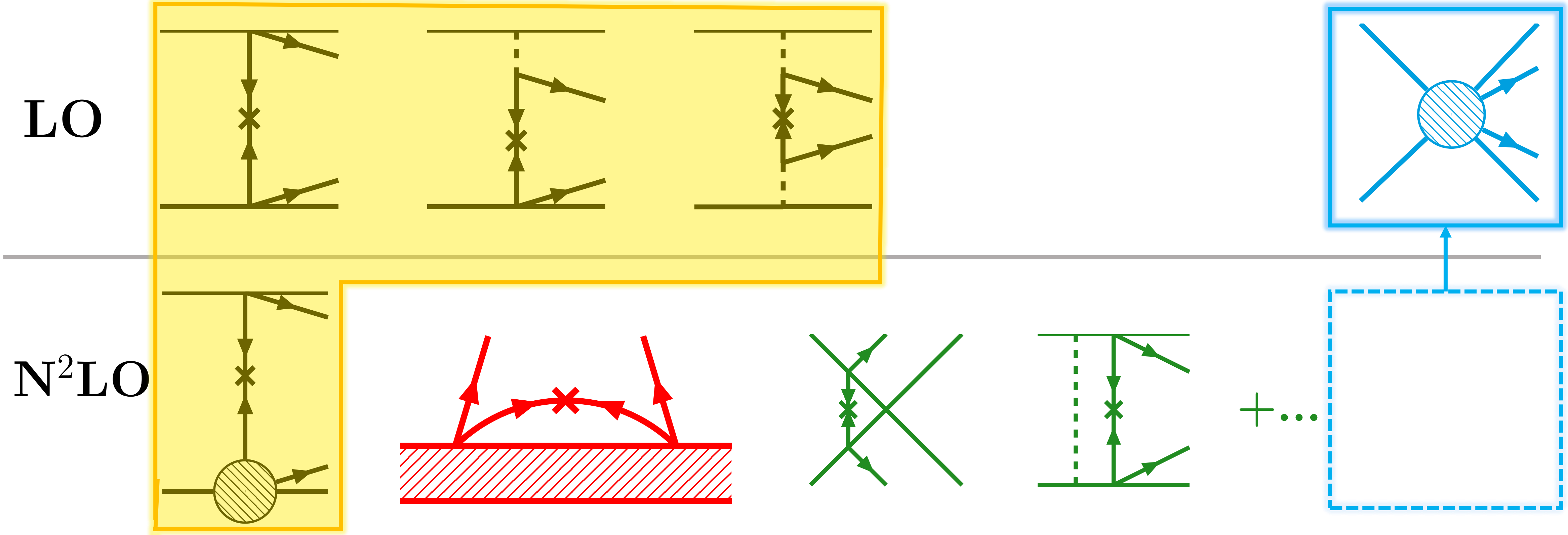
$$\mathcal{O}^{0\nu} = \mathcal{O}^{0\nu}_{\mathrm{LO}} + \mathcal{O}^{0\nu}_{\mathrm{N^2LO}} + \cdots$$

What is normally included

Leading order

Next-to-next-to-leading order

What needs to be included



V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

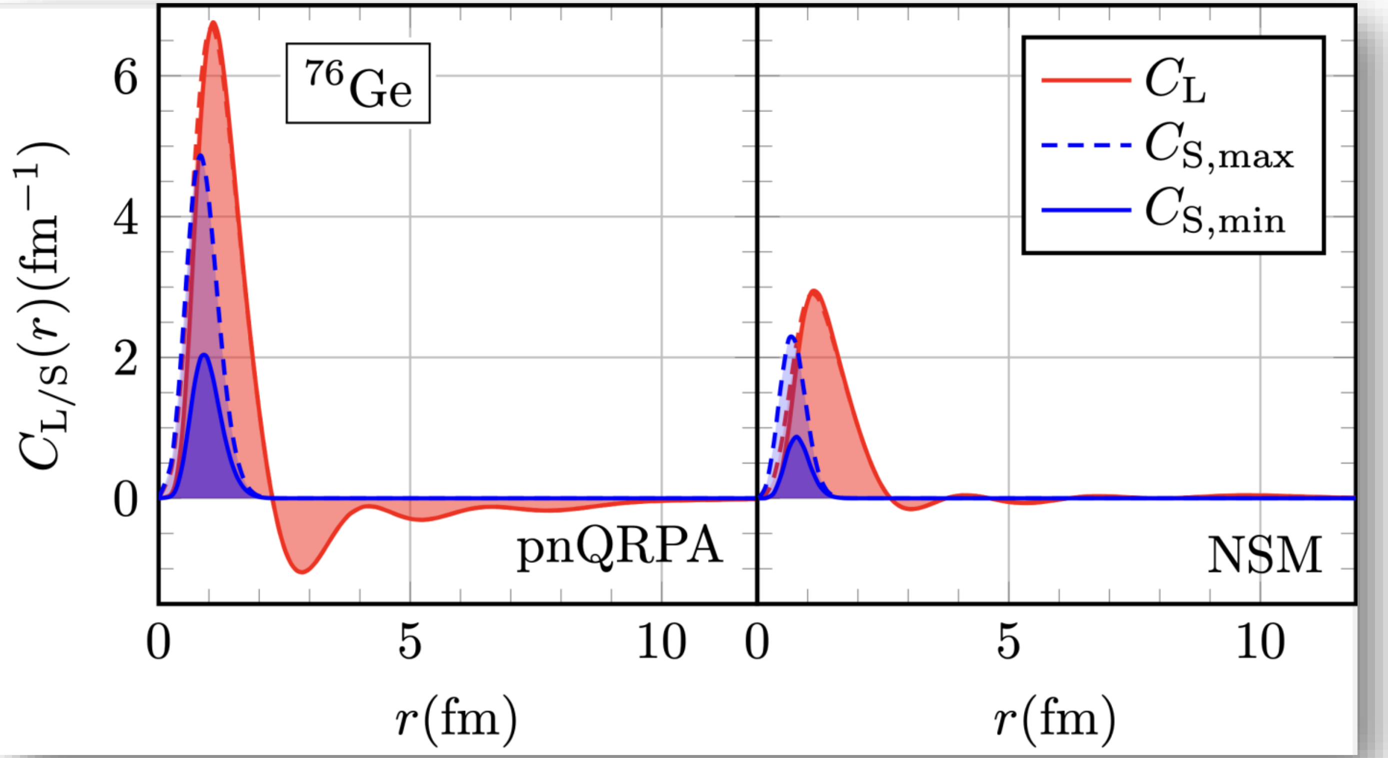
Contact term in pnQRPA and nuclear shell model (NSM)

$$\mathcal{O}_S^{0\nu} = 2g_\nu^{NN}\tau_a^-\tau_b^-$$

$$\int C_{L/S}(r)dr = M_{L/S}^{0\nu}$$

- $\frac{M_S^{0\nu}}{M_L^{0\nu}} \approx$ **30% – 80%**(pnQRPA)
- $\frac{M_S^{0\nu}}{M_L^{0\nu}} \approx$ **15% – 50%** (NSM)
- $\frac{M_S^{0\nu}}{M_L^{0\nu}} \approx$ **30% – 90%** (*ab initio*)

R. Wirth et al., PRL 127, 242502 (2021)
A. Belley et al., PRL 132, 182502 (2024)
A. Belley et al., arXiv:2307.15156



LJ, P. Soriano, J. Menéndez, Phys. Lett. B 823, 136720 (2021)

Effective-field theory corrections to the operator

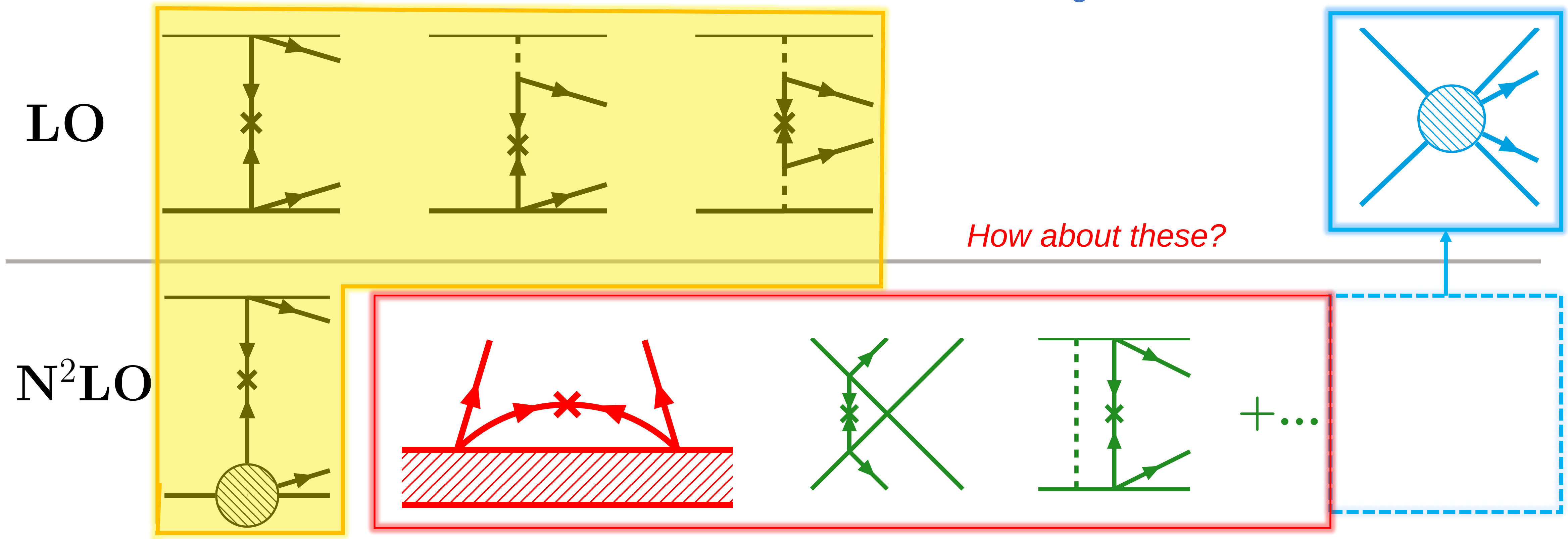
$$\mathcal{O}^{0\nu} = \mathcal{O}^{0\nu}_{\mathrm{LO}} + \mathcal{O}^{0\nu}_{\mathrm{N^2LO}} + \cdots$$

What is normally included

Leading order

Next-to-next-to-leading order

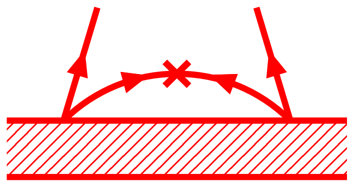
What needs to be included



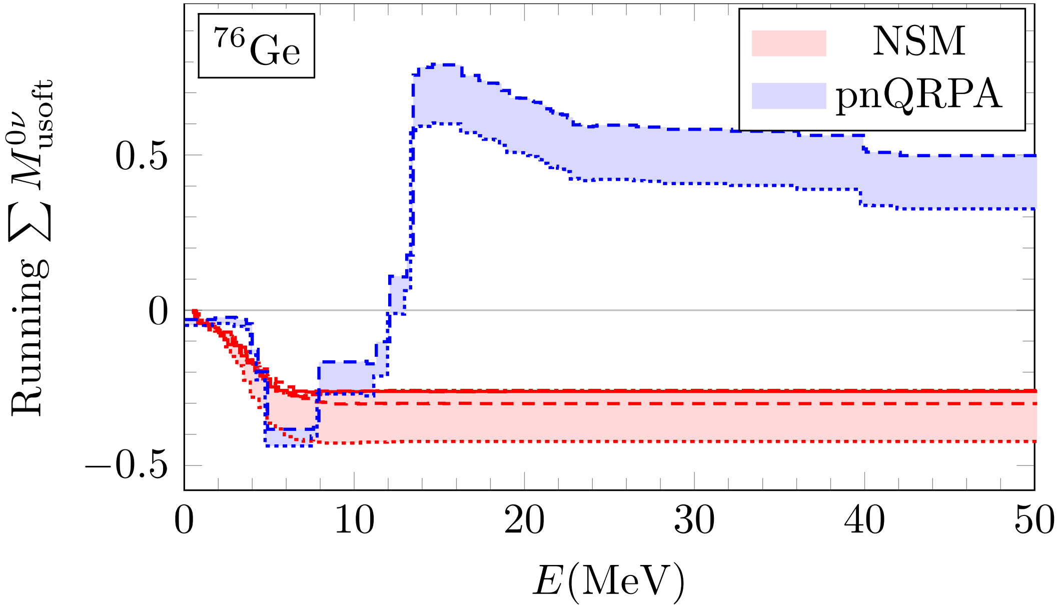
V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

The ultrasoft-neutrino term

$$M^{0\nu}_{\rm usoft} = \sum_n f(E_n) \left\langle 0_f^+ \left\| \sum_a \boldsymbol{\sigma}_a \tau_a^- \right\| 1_n^+ \right\rangle \left\langle 1_n^+ \left\| \sum_b \boldsymbol{\sigma}_b \tau_b^- \right\| 0_i^+ \right\rangle$$

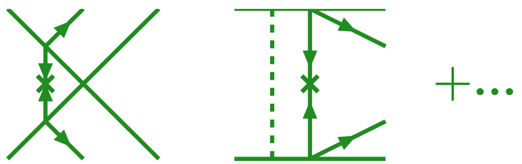


- Contribution from “Ultrasoft” neutrinos ($|\boldsymbol{k}| \ll k_F \sim 100$ MeV)
- $\dfrac{M^{0\nu}_{\rm usoft}}{M^{0\nu}_{\rm L}} \simeq$ **5% – 10%** (pnQRPA)
- $\dfrac{M^{0\nu}_{\rm usoft}}{M^{0\nu}_{\rm L}} \approx$ **−5%** (NSM)

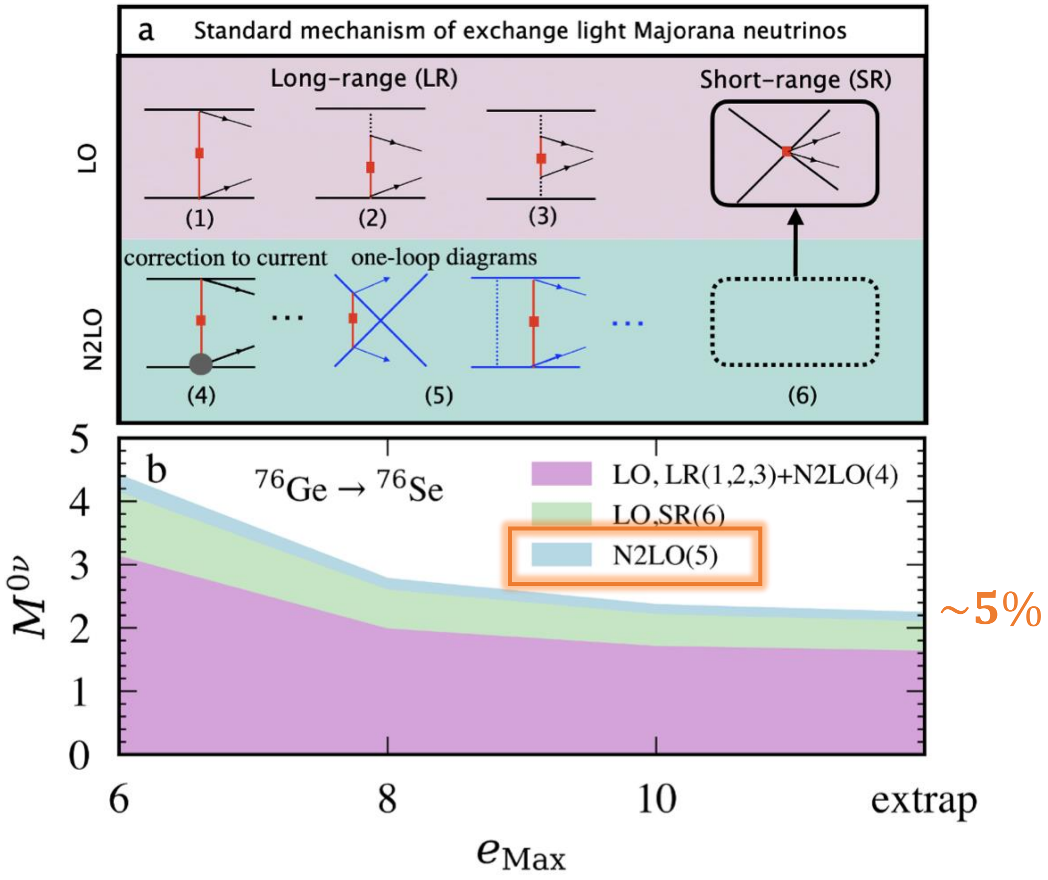


D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

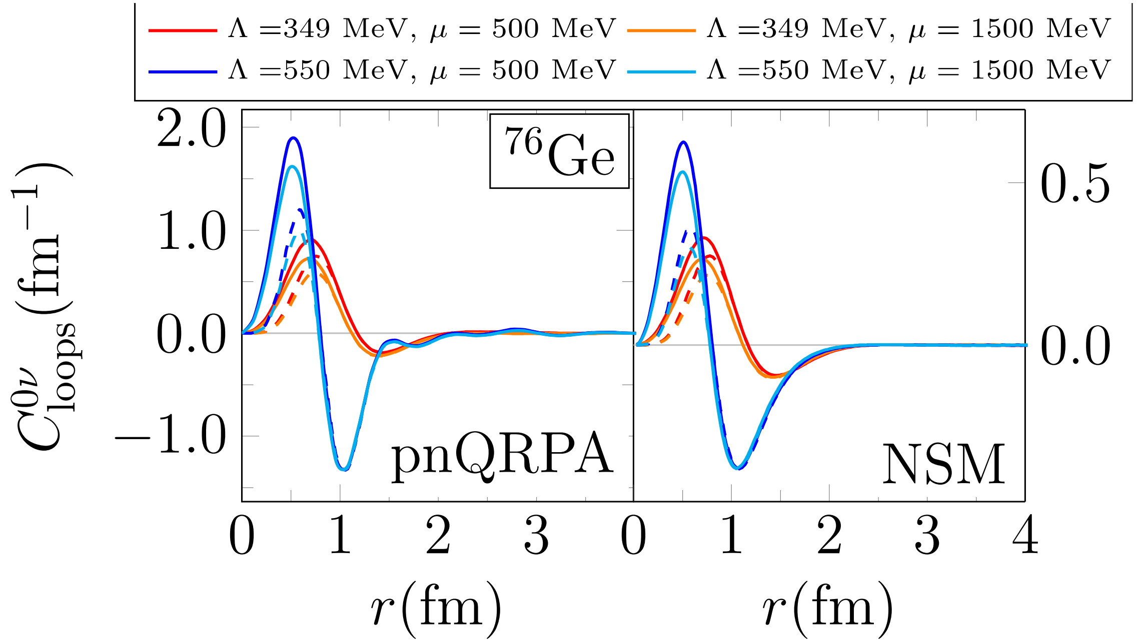
$\mathrm{N^2LO}$ loop corrections



$$\mathcal{O}^{0\nu}_{\mathrm{loops}} = e^{-q^2/(2\Lambda^2)}\left(\mathcal{O}^{(m,n)}_{\mathrm{VV}} + \mathcal{O}^{(m,n)}_{\mathrm{AA}} + \mathcal{O}^{(m,n)}_{\mathrm{US}} + \mathcal{O}^{(m,n)}_{\mathrm{CT}}\right)$$



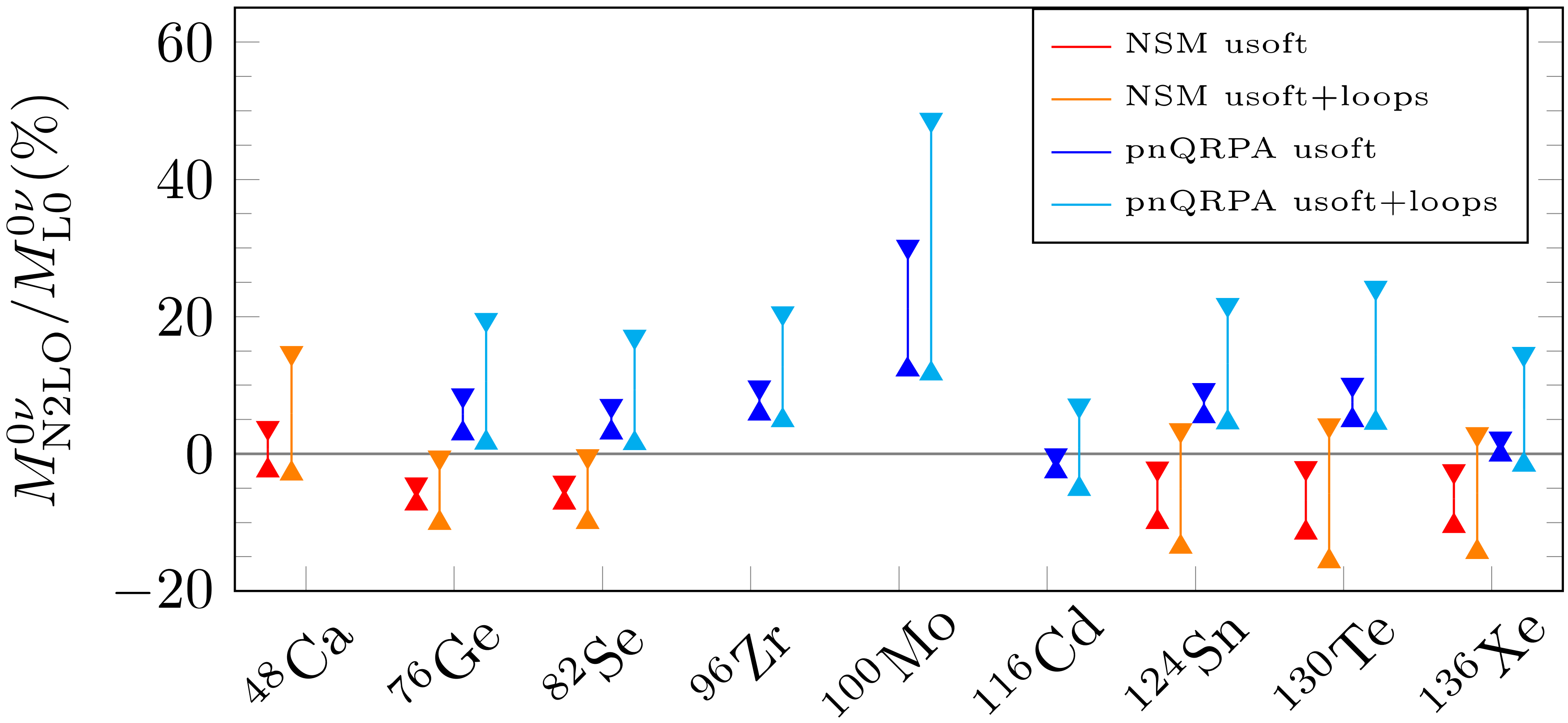
A Belley et al., Phys. Rev. Lett. 132, 182502 (2024)



$$\frac{M^{0\nu}_{\mathrm{loops}}}{M^{0\nu}_{\mathrm{L}}} \lesssim 10\% \qquad \frac{M^{0\nu}_{\mathrm{loops}}}{M^{0\nu}_{\mathrm{L}}} \lesssim 5\%$$

D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

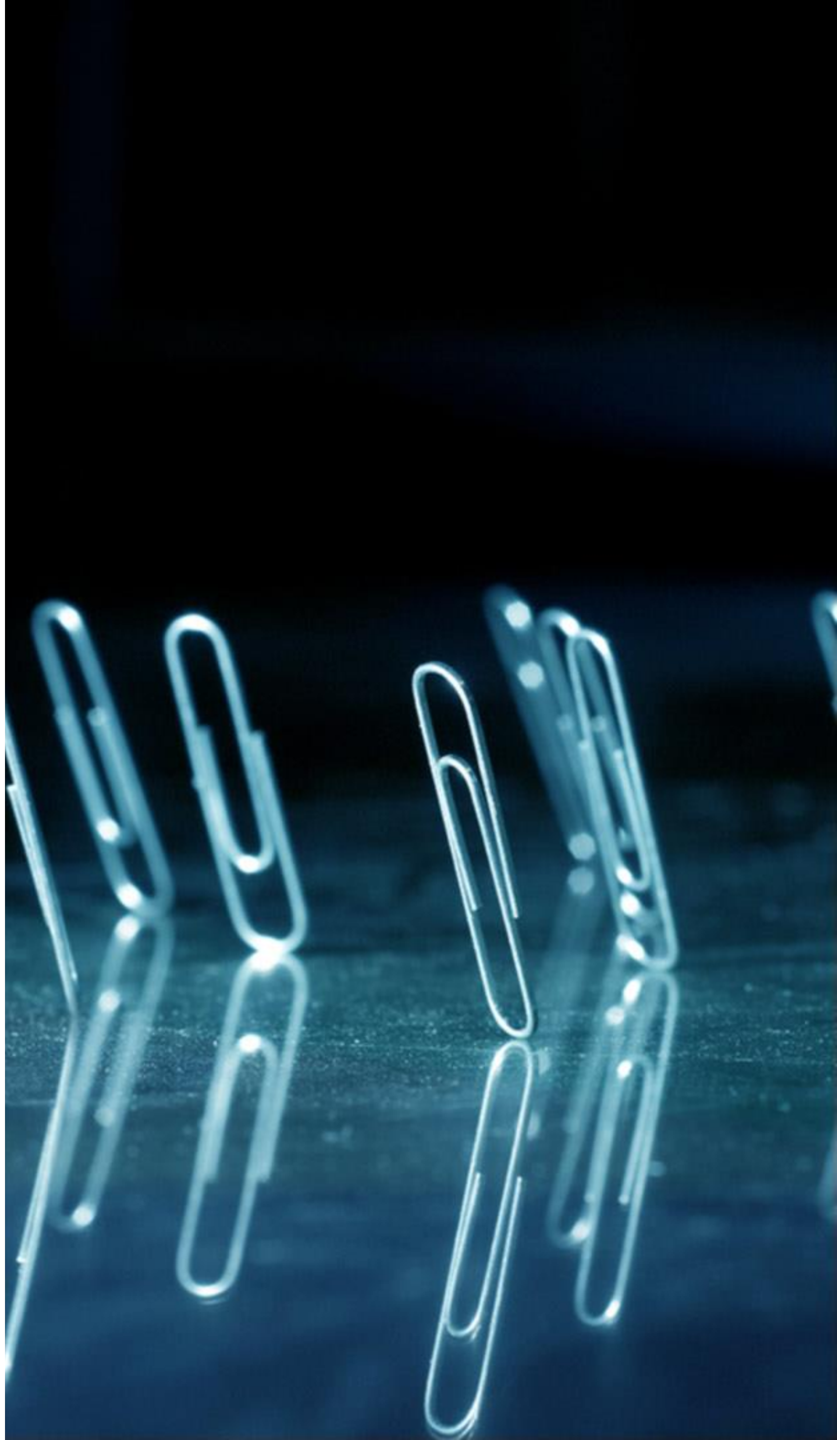
Combined N^2LO corrections



D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

→The N2LO corrections should be included in any $0\nu\beta\beta$ calculations

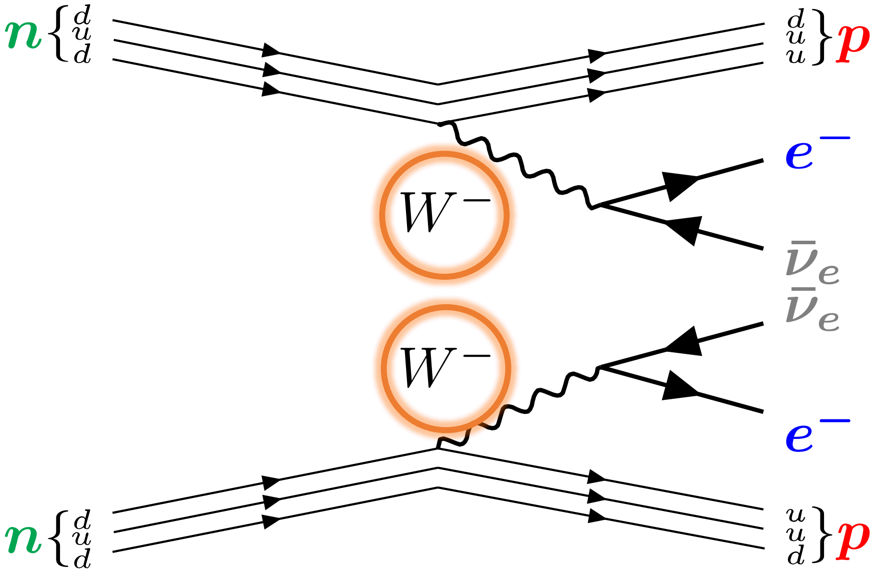
Could We Learn from Other Nuclear Processes?



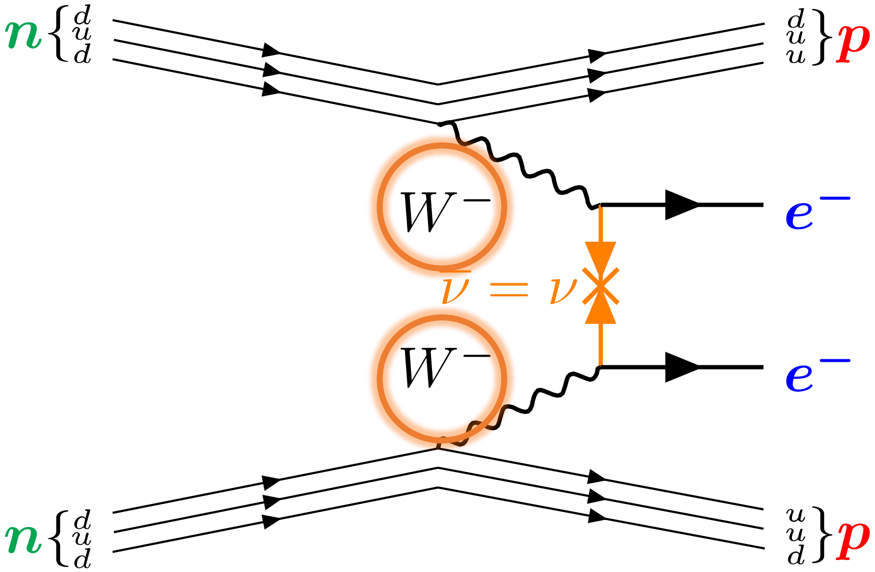
Probing $0\nu\beta\beta$ decay by $2\nu\beta\beta$ decay

Similarities:
- ❑ Same initial and final nuclei
- ❑ Weak-interaction processes

Differences:
- ❑ Different momentum exchange
- ❑ **$2\nu\beta\beta$ decay measured, $0\nu\beta\beta$ not**



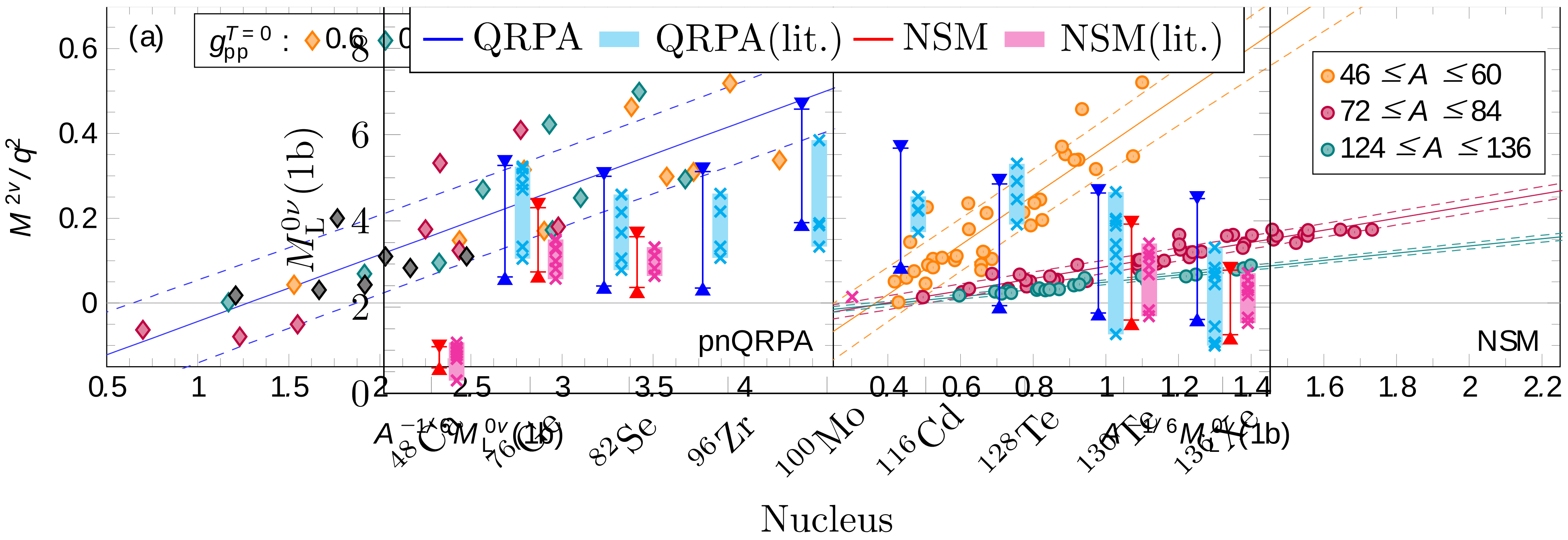
$q_{2\nu\beta\beta} \approx 2$ MeV



$q_{0\nu\beta\beta} \approx 100$ MeV

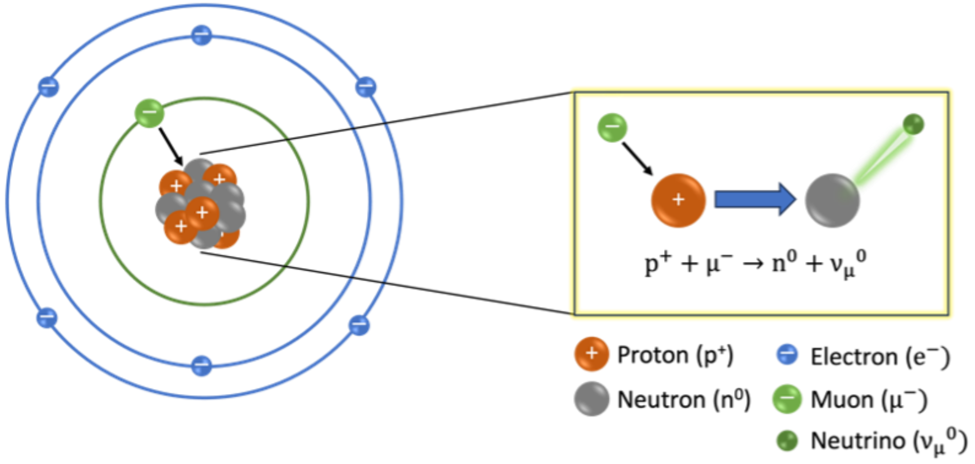
Probing $0\nu\beta\beta$ decay by $2\nu\beta\beta$ decay

- Nuclear matrix elements of $0\nu\beta\beta$ and $2\nu\beta\beta$ decays correlated
- We can derive $M^{0\nu}$ from the correlations and measured $2\nu\beta\beta$-decay half-lives
  - → ***Theoretical uncertainties based on systematics***
- Will *ab initio* methods find similar correlations? (D. Sedghi)



LJ, B. Romeo, P. Soriano, J. Menéndez, Phys. Rev. C 107, 044305 (2023)

Muon capture on ^{6}Li, ^{12}C, ^{16}N from *ab initio* nuclear theory



- Momentum exchange $q = m_{\mu} + E_i - E_f \approx 100$ MeV
- Involves vector, axial-vector, magnetic and pseudoscalar nuclear-weak currents
  - → **Can be used as a probe of $0\nu\beta\beta$ decay**

PHYSICAL REVIEW C **109**, 065501 (2024)

Muon capture on ^{6}Li, ^{12}C, and ^{16}O from *ab initio* nuclear theory

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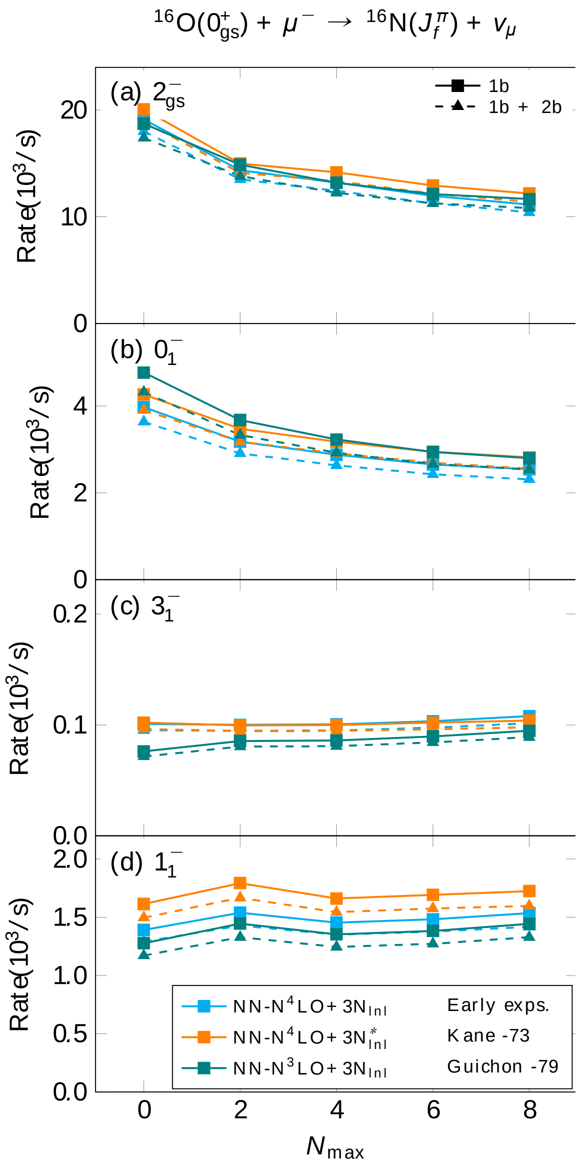
(Received 14 March 2024; accepted 21 May 2024; published 10 June 2024)



- ***Ab initio no-core*** **shell-model calculations in good agreement with experiments**

Summary and Outlook

- *Ab initio* methods now capable of computing $0\nu\beta\beta$-decay nuclear matrix elements
- Corrections to the $0\nu\beta\beta$-decay operators evaluated up to N^2LO
- Related processes, such as $2\nu\beta\beta$ decay and muon capture can help further constrain $0\nu\beta\beta$ decay

Outlook

- $0\nu\beta\beta$ decay can be mediated by **other mechanisms** (ongoing *ab initio* studies by A. Todd et al.)
- *Ab initio* studies for $\boldsymbol{2\nu\beta\beta}$ **decay** (D. Sedghi)
- **Two-body currents** would enter at N^3LO, but effects may be larger (TODO to the community)
- How does nuclear deformation affect the *ab initio* predictions? (TODO to the community)

Thank you
Merci

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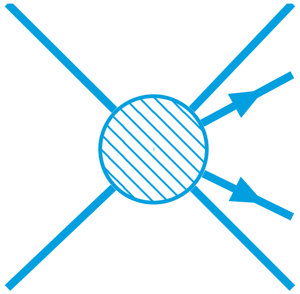
Thanks to Arthur B. McDonald Canadian Astroparticle Physics Research Institute from:

Jason D. Holt (PI)
Lotta Jokiniemi ($0\nu\beta\beta$ decay)
Baishan Hu (dark matter)
Antoine Belley ($0\nu\beta\beta$ decay)
Mathieu Bruneault (dark matter)
Taiki Shickele ($0\nu\beta\beta$ decay)
Alexander Todd ($0\nu\beta\beta$ decay)
Didar Sedghi ($2\nu\beta\beta$ decay)

Oak Ridge National Laboratory
The University of British Columbia
McGill

New leading order short-range nuclear matrix element

$$\frac{1}{t_{1/2}^{0\nu\beta\beta}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$



- The contact term was missing from all calculations

V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

- The operator connects directly initial and final nuclei

$$M_S^{0\nu} = \frac{2R}{\pi g_A^2} (0_f^+ || \sum_{a,b} \tau_a^- \tau_b^- \int j_0(qr) h_S(q^2) q^2 dq || 0_i^+),$$

$$h_S(q^2) = 2 g_\nu^{NN} e^{-q^2/(2\Lambda^2)}$$

Unknown