Towards Reliable Nuclear Matrix Elements for Neutrinoless Double Beta Decay with Ab initio Nuclear Theory

A. Belley, J. Pitcher and J. D. Holt
TRIUMF, University of Bristish Columbia, McGill University

Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical decay with profound implication on neutrino physics and physics beyond the standard model . To extract relevant information from experiments, theoretical inputs in the form of nuclear matrix elements are required. Previous nuclear models used to calculate this quantity show a large discrepancy with no way of assessing their uncertainty, calling for a more fundamental approach: ab initio nuclear theory.

Neutrinoless Double Beta Decay

- Weak process in which two neutrons decay into two protons by emitting two electrons.
- Violates lepton-number conservation.
- The half-life of the decay, $T_{0\nu}^{1/2}$, relates to the effective mass of the neutrino, $m_{\beta\beta}$, via

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

  where $G^{0\nu}$ is a phase-space factor and $M^{0\nu}$ is the nuclear matrix element (NME).
- The NME is composed of Gamow-Teller (GT), Fermi (F), Tensor (T) and a newly discovered contact (CT) parts as

$$M^{0\nu\beta\beta} = M^{0\nu\beta\beta}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu\beta\beta}_{F} + M^{0\nu\beta\beta}_{T} - 2g_{\nu\nu}M^{0\nu\beta\beta}_{CT}$$

Ab initio Nuclear Theory

Ab initio nuclear theory can be summarized in two steps:

Constructing the nuclear potential with chiral effective field theory (χEFT)

- Expansion of the nuclear Hamiltonian that can be systematically improved.
- Neglected orders are included via fitting of low-energy constants (LECs) to few-body observables.

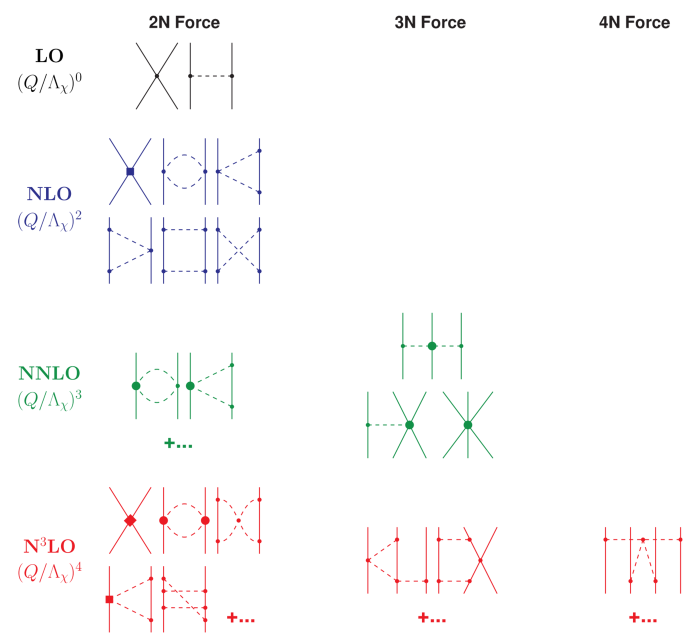

Figure 1: Hierarchy of diagrams involved in χEFT interactions adopted from Machleidt, R. & Entem, D. R. Phys. Rep. 503, 1–75 (2011).

Solving Schrödinger's equation:

- The valence-space formulation of the in-medium similarity renormalization group (VS-IMSRG) makes the many-body problem numerically tractable.

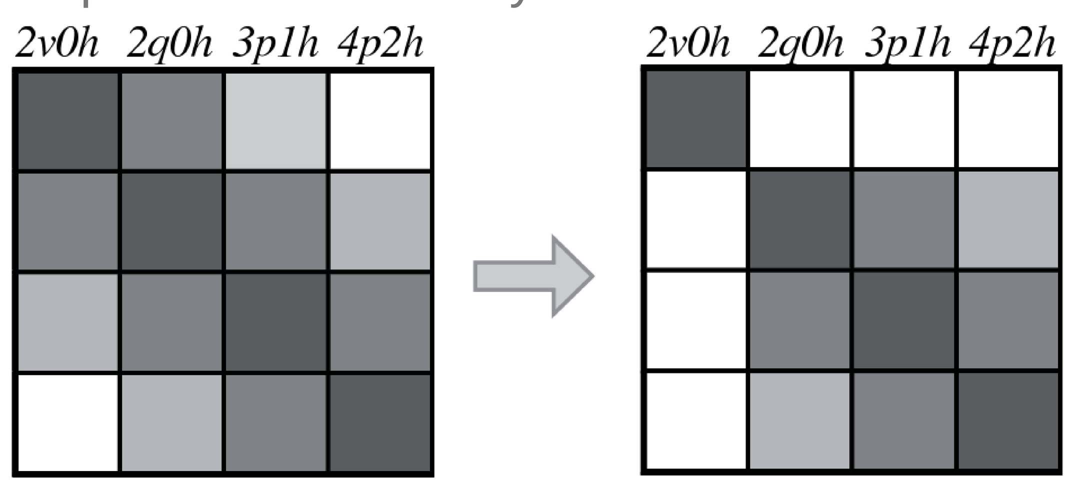

Figure 2: Decoupling by the VS-IMSRG for two valence nucleons. Figure adopted from K. Tsukiyama, et al. Phys. Rev. C 85, 061304(R) (2012).

Current Status

- Ab initio methods agree on the NMEs of the lightest double-beta decay candidates, while the experimentally relevant cases have been computationally inaccessible.
- New improvements now allow to compute all isotopes of experimental relevance!

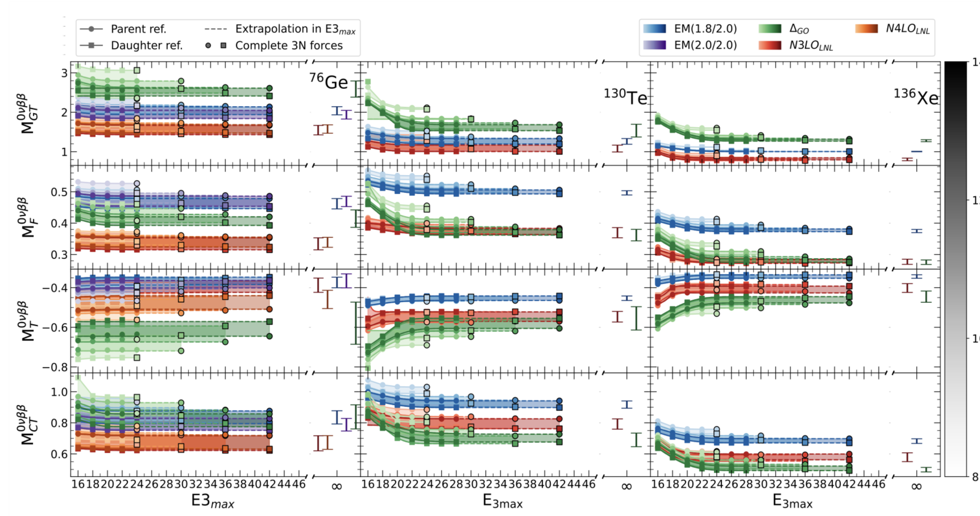

Figure 3: Convergence of the NMEs.

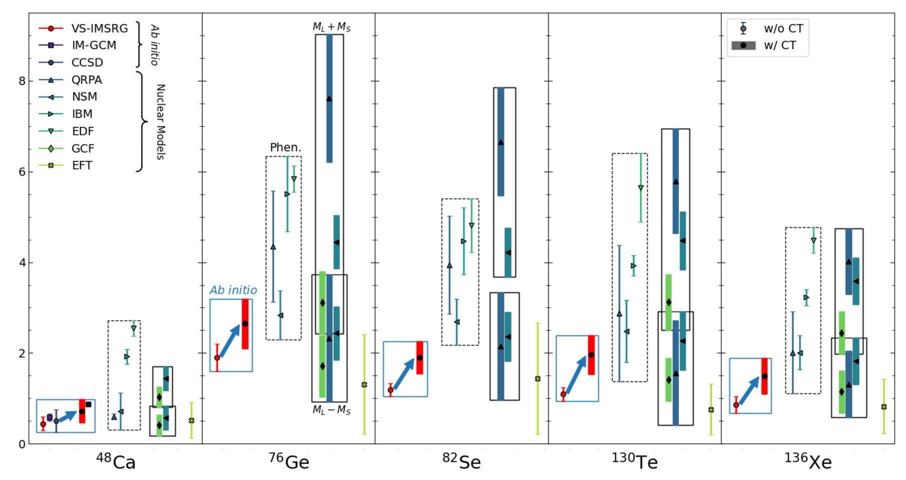

Figure 4: NMEs obtained from different methods.

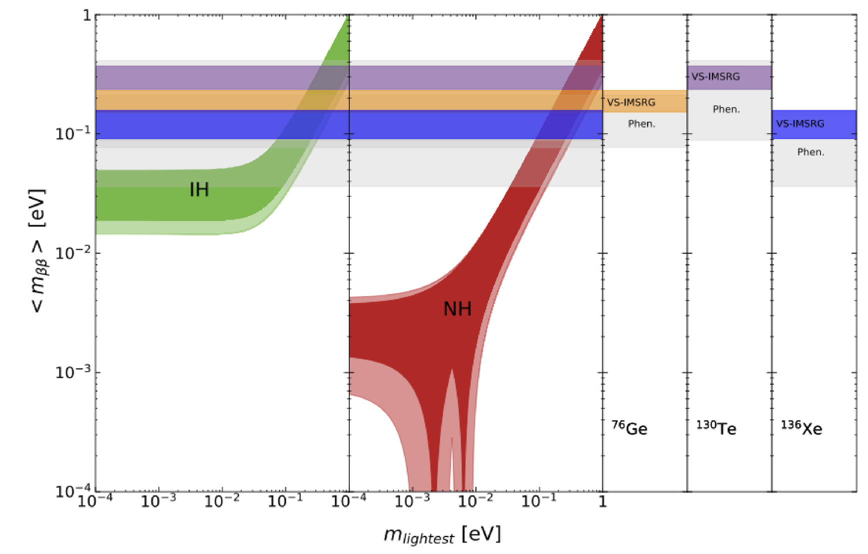

Figure 5: Updated limits on $m_{\beta\beta}$.

Uncertainty quantification with MM-DGP algorithm

- Sensitivity of the NMEs to the LECs is required to assess their uncertainty.
- Performing a sensitivity analysis the conventional way is too computationally expensive.
- Machine learning can be used to generate enough samples.

MM-DGP:

- Based on the Deep Gaussian Processes model which connects data of multiple fidelities using neural networks inside Gaussian Processes.
- Models a complex process using mostly low-fidelity (i.e. faster approximation) results and a few high-fidelity results (full calculations).
- Considers correlation between outputs to reduce inputs required for training, making a Multi-output Multi-fidelity Deep Gaussian Processes (MM-DGP) model.

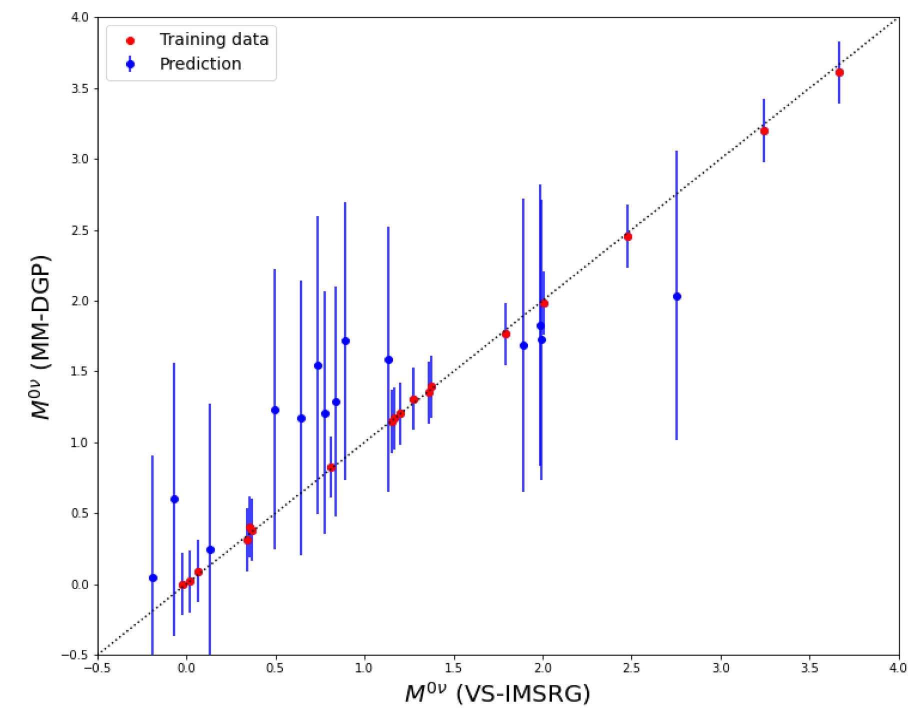

Figure 6: NME obtained from the MM-DGP compared to VS-IMSRG calculations.

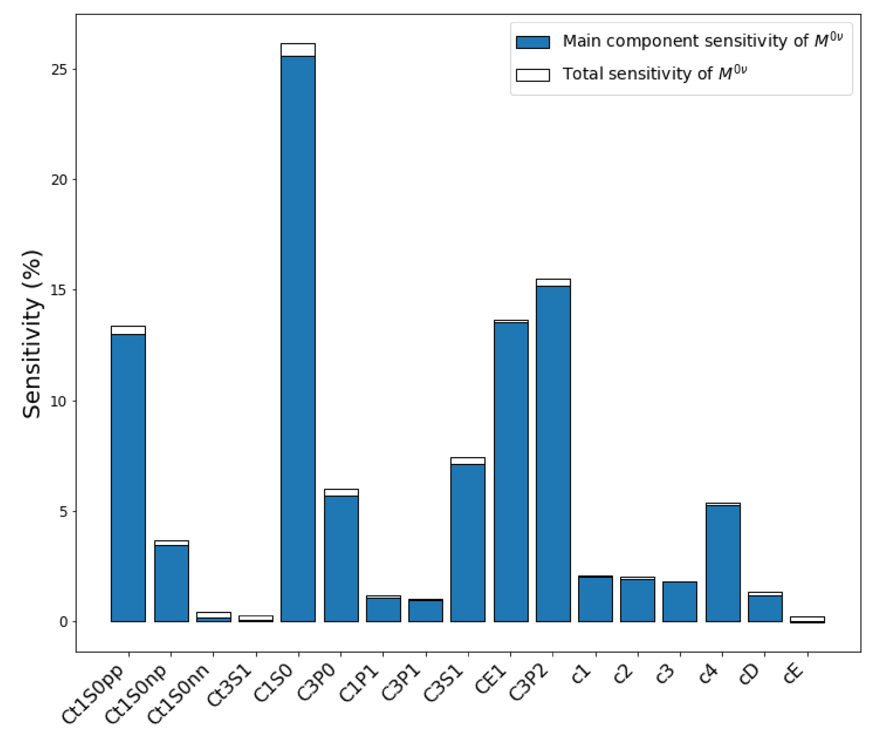

Figure 7: Preliminary sensitivity analysis with the MM-DGP samples.

Discovery, accelerated