Ab Initio Nuclear Theory for New Physics at the Electroweak Scale

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2026-02-25

Discovery, accelerated

Motivation

- The Standard Model (SM) successfully describes known particle interactions but fails to predict several observed phenomena [1].
- We want to perform a precision test on the SM’s electroweak sector to investigate whether this could be the source of discrepancies.

Background: The CKM Matrix

- The universality of the weak interaction is mathematically expressed by the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2].
- Elements represent transition probabilities between different quark flavours.

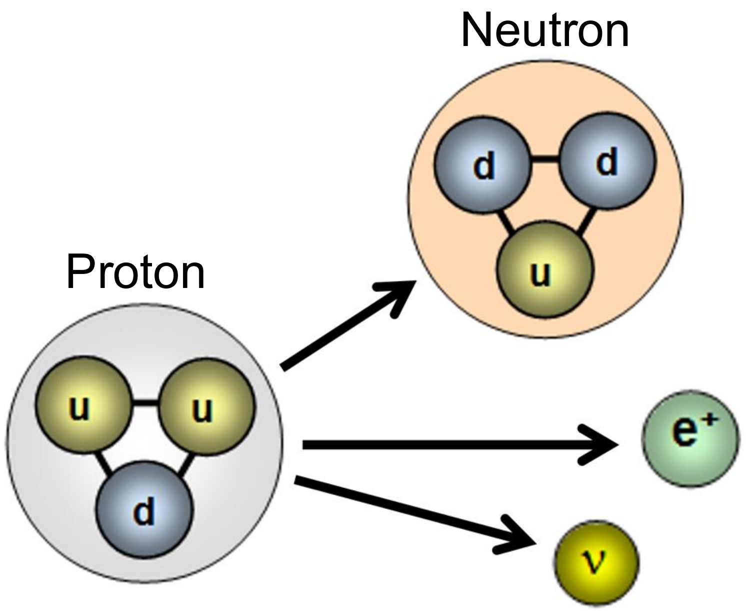
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A constraint imposed upon this matrix is unitarity among the top row [2]; non unitarity would indicate new physics!

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Background: Superallowed Beta Decay

- Analyze element V_{ud} through Superallowed Beta Decays!
- Superallowed Beta decays are a process in which a proton in an atomic nucleus turns into a neutron, or equivalently, an up quark turning into a down quark [1].



https://schoolphysics.co.uk/age16-19/Nuclear%20physics/Nuclear%20structure/text/Quarks_/index.html

$$|V_{ud}|^2 = \frac{K}{ft(1+\delta'_R)(1+\Delta^V_R)(1+\delta_{NS}-\delta_C)} \quad [3]$$

- Need to calculate two corrections from nuclear theory:
  1) **Isospin symmetry breaking correction (δ_C)**

$$M_F{}^2 = (M_F^0)^2(1-\delta_C) \quad \begin{cases} M_F = \langle 0_f^+ | \tau^- | 0_i^+ \rangle \\ M_F^0 = \sqrt{2} \end{cases} \quad [2]$$

  2) **Nuclear structure correction (δ_{NS})**
- Use ab initio methods to calculate these!

Ab Initio Method: the VS-IMSRG

- The Valence-Space formulation of the In-Medium Similarity Renormalization Group (VS-IMSRG) was largely developed here at TRIUMF!
- Decouples a core nucleus and associated valence-space Hamiltonian via flow equations such that the many-body physics is mapped into the smaller valence space, enabling easier diagonalization [4].

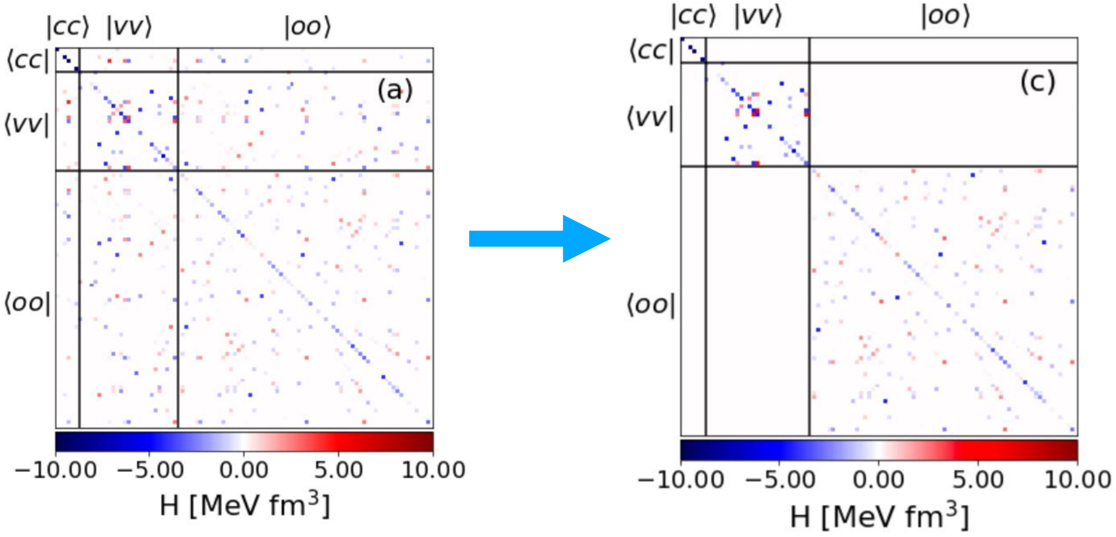


Figure 1: Visualization of the VS-IMSRG core-valence space decoupling for ^{6}He where $|cc\rangle$, $|vv\rangle$, and $|oo\rangle$ are the core, the valence, and the excluded space, respectively [5].

Application: Isospin Symmetry Breaking Correction (δ_C)

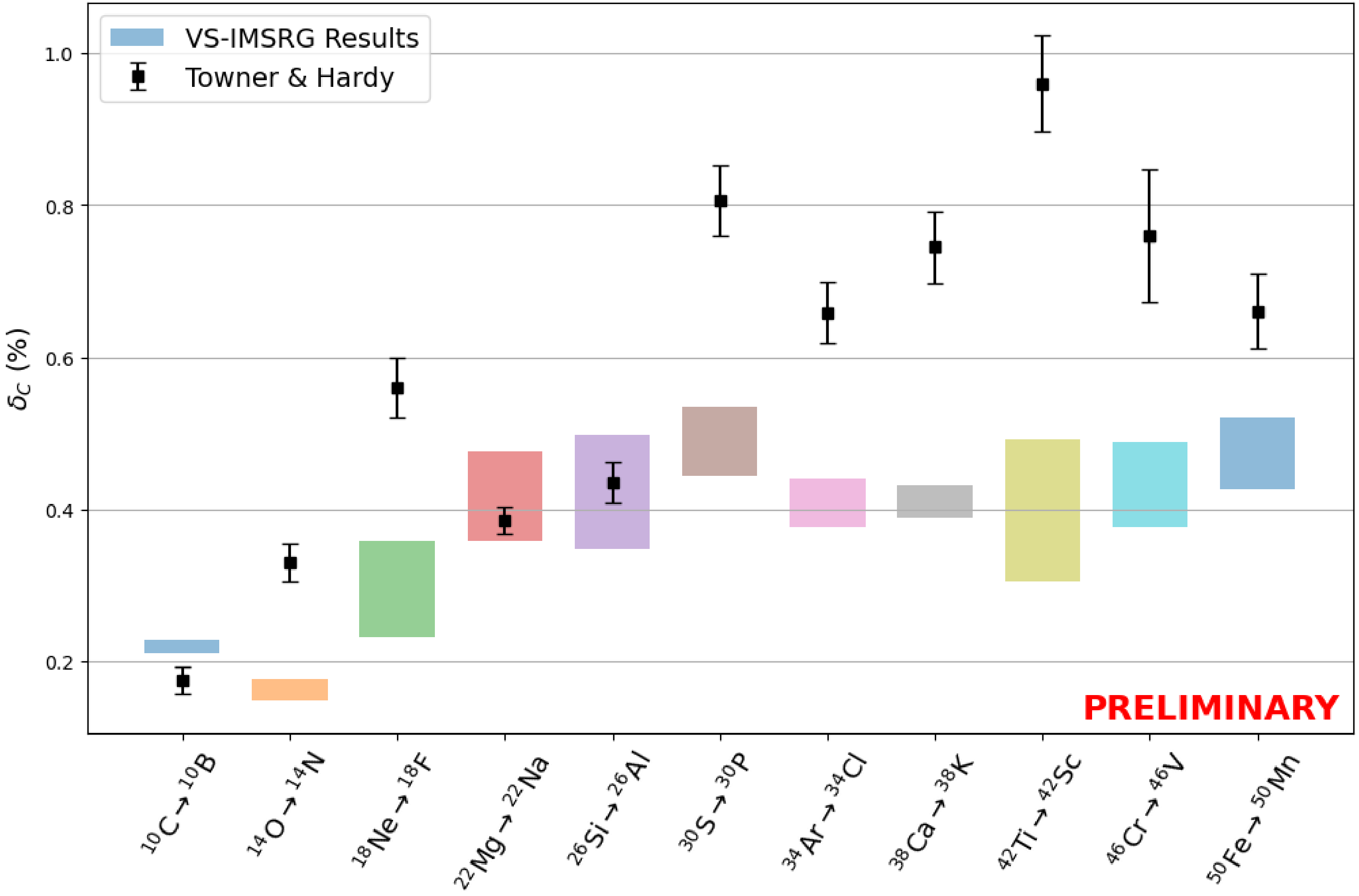


Figure 2: The coloured bands show the spread of δ_C across chiral effective field theory interactions from the VS-IMSRG at e_{max}=14. The black markers denote the δ_C values quoted by Towner & Hardy [6].

Application: Isospin Symmetry Breaking Correction (δ_C)

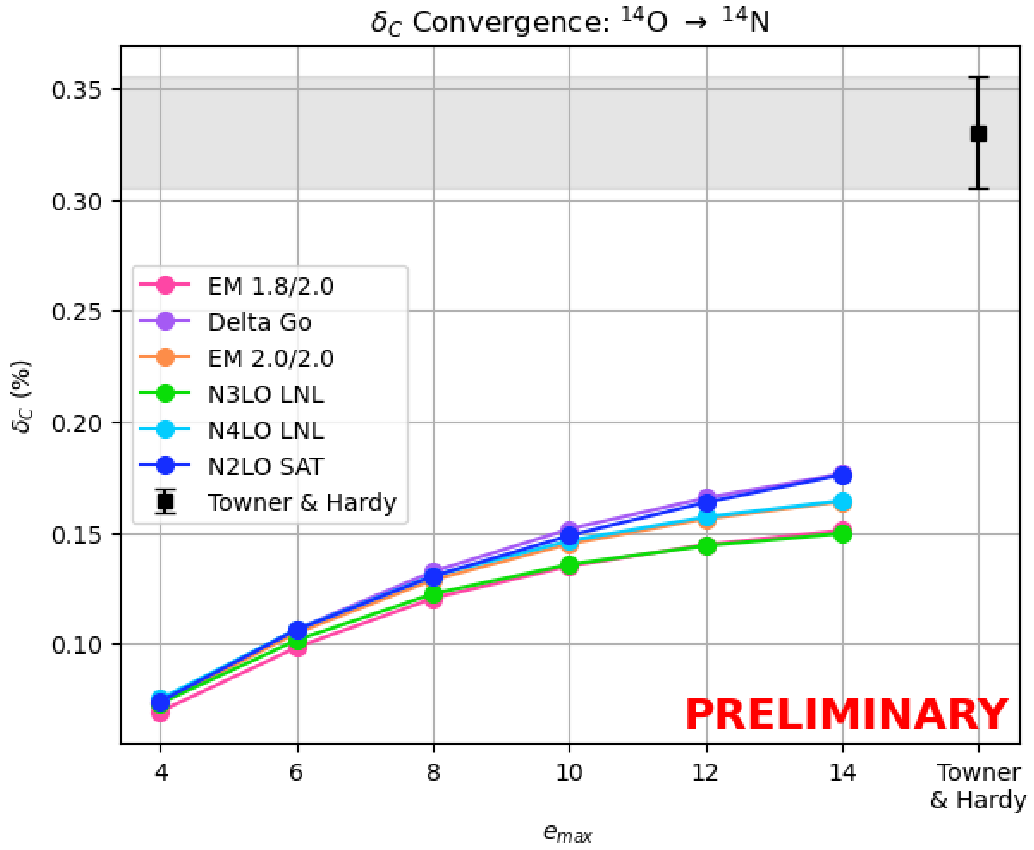


Figure 3: δ_C convergence for ^{14}O → ^{14}N, demonstrating clear convergence with increase in model space.

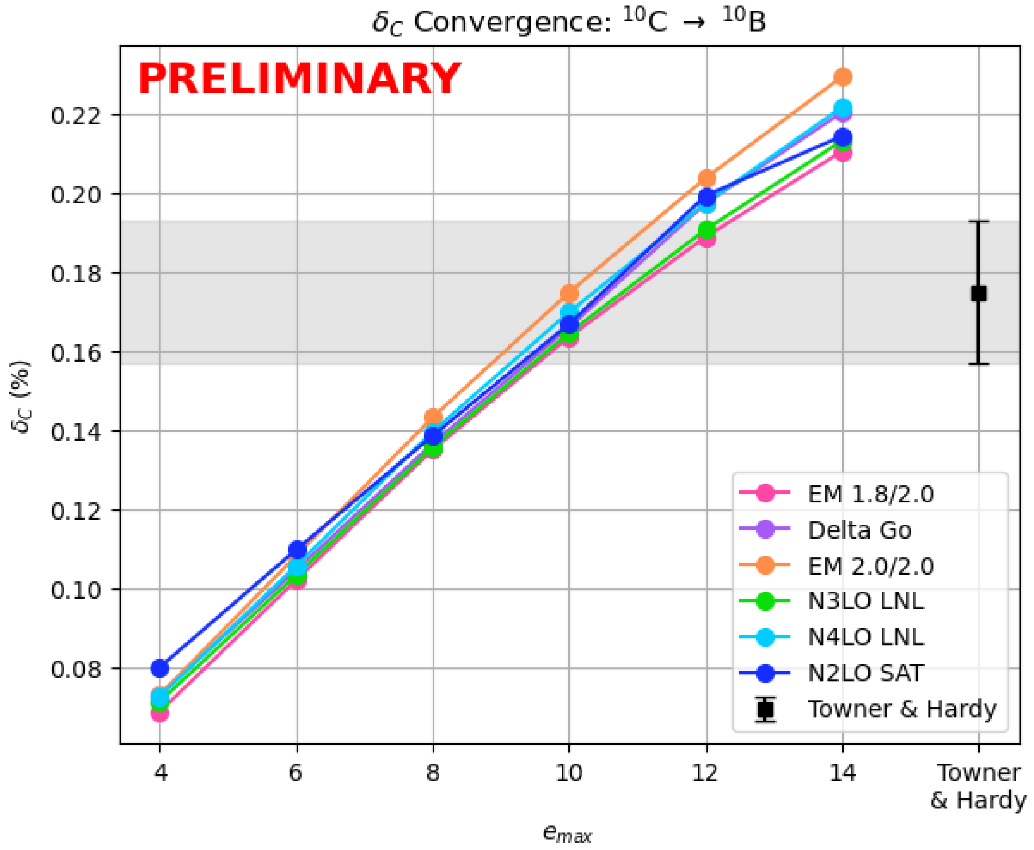


Figure 4: δ_C convergence for ^{10}C → ^{10}B, demonstrating poor convergence with increase in model space.

Application: δ_C in the Natural Orbital Basis

- When using the Hartree-Fock (HF) basis before VS-IMSRG evolution, convergence for δ_C is not always promising…
- Move to the Natural Orbital (NAT) basis where convergence is expected to improve[7].

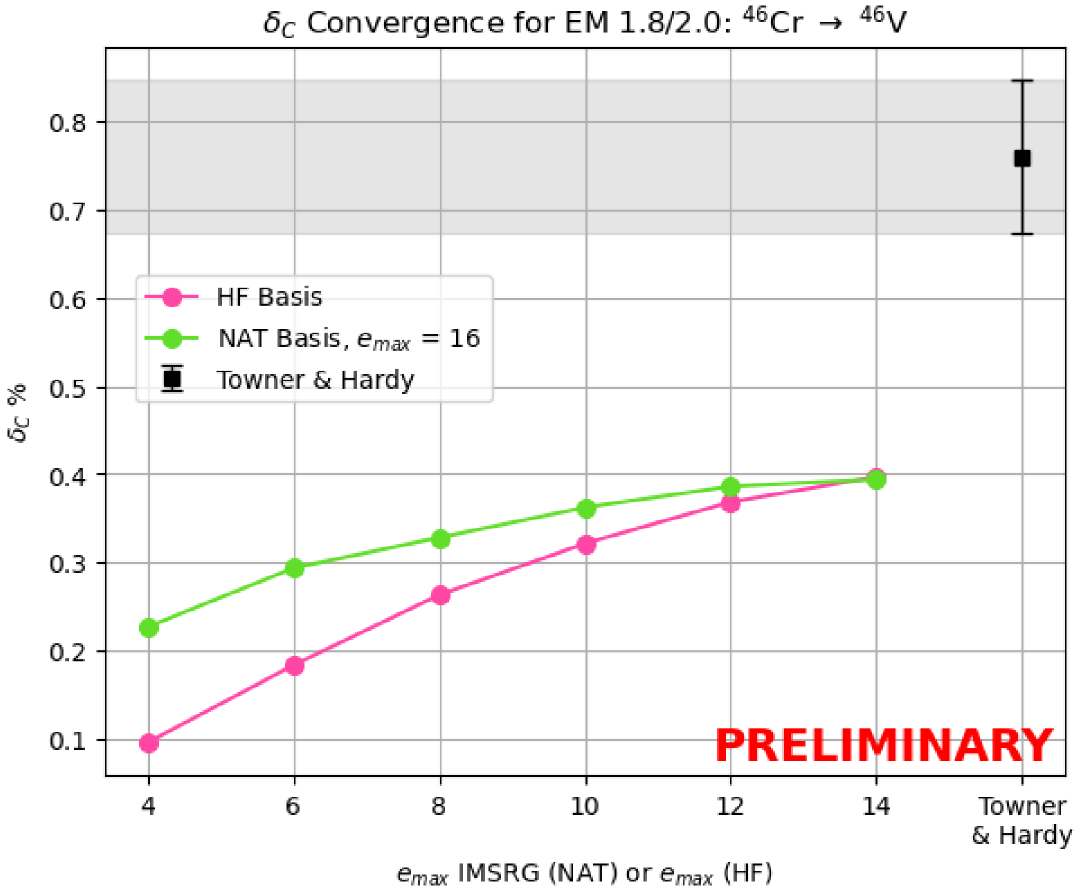


Figure 5: Comparing δ_C convergence between the HF basis and the NAT basis for ^{46}Cr → ^{46}V. The NAT basis was constructed from the HF basis truncated at e_{max}=16.

Summary

- **Goal:** Conduct precision test on SM's electroweak sector with Superallowed Beta Decays where the VS-IMSRG is used to calculate δ_C and δ_{NS}.
- **Results:** The results for δ_C show convergence among some transitions but not all… move to the NAT basis instead!
- **Next steps:**
  - Conduct an uncertainty analysis for δ_C.
  - Use the VS-IMSRG to calculate δ_{NS}.

References

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[3] MacLean, A. D., et al. (2020). High-precision branching ratio measurement and spin assignment implications for ^{62}Ga superallowed β decay. Physical Review C, 102, 054325. https://doi.org/10.1103/PhysRevC.102.054325

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