QMC calculations of electroweak observables with local chiral interactions

Lepton Nucleus Interactions XVI – Marciana 2023

September 6th, 2023

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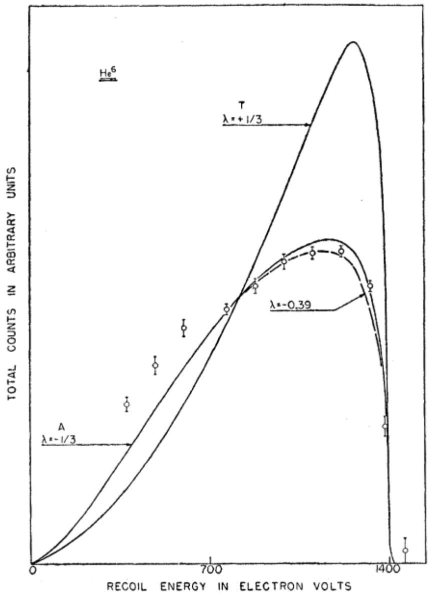
Motivation

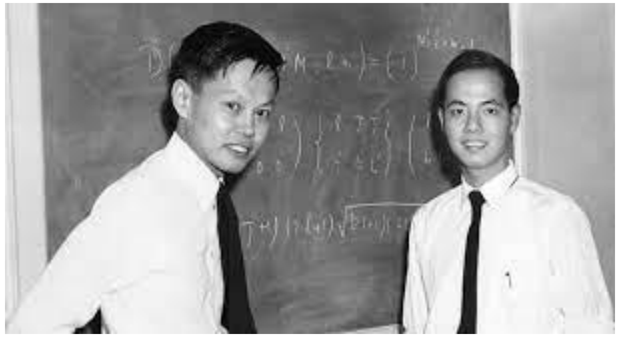
Nuclear weak processes have a rich history as a probe of the SM as the fundamental theory of the weak interaction and that continues to this day



Wu et al. Phys. Rev. 105, 1413 (1957)

Feynman and Gell-Mann
Phys. Rev. 109, 193 (1958)

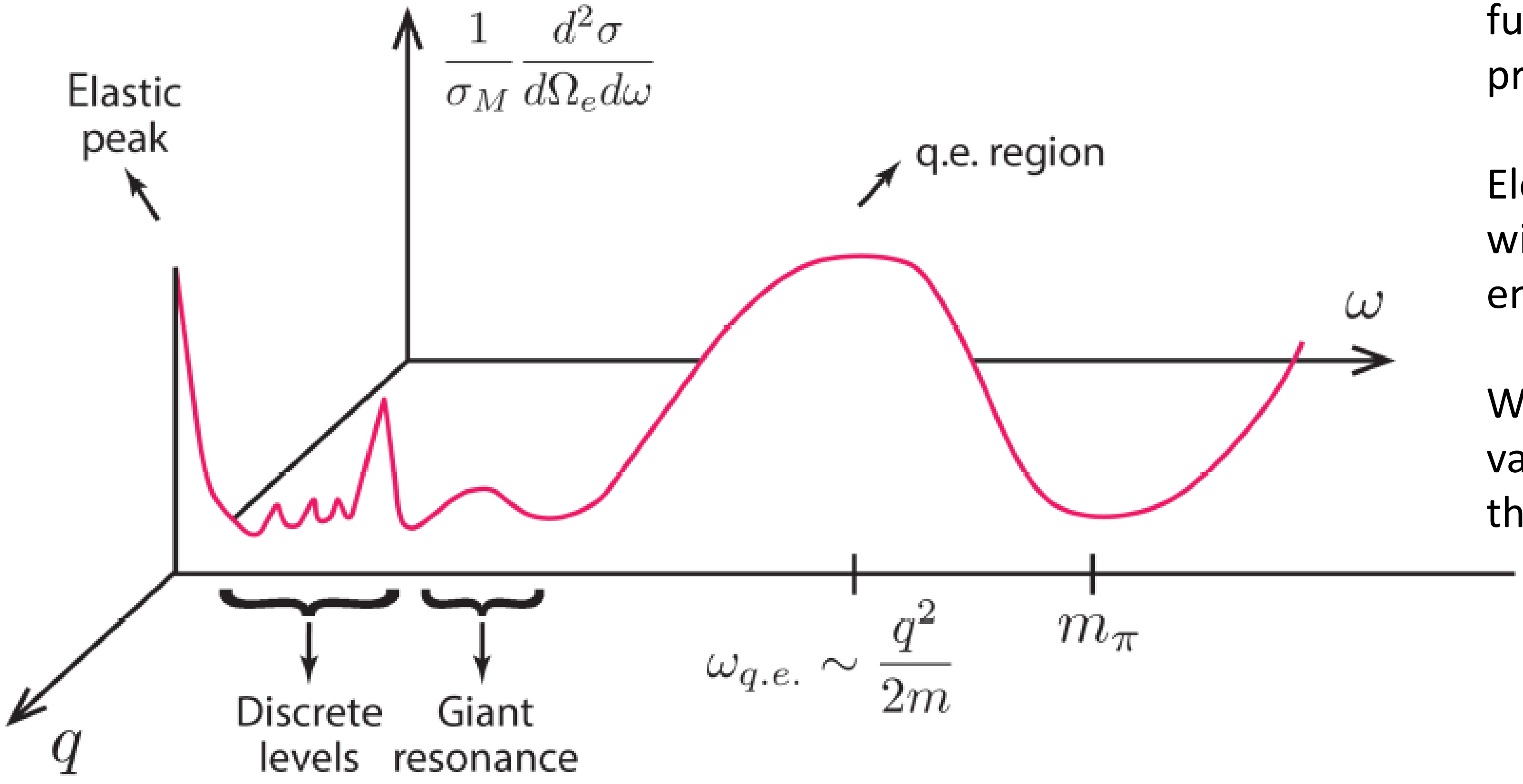
Allen et al.
Phys. Rev. 116, 134 (1959)



Lee and Yang, Phys. Rev. 104, 254 (1956)

Fermi, Z. Physik 88, 161 (1934)

Motivation



Nuclear electroweak interactions are crucial for future fundamental physics searches on the precision and high energy frontiers

Electroweak interactions take place over a wide range of momentum transfer q and energy transfer ω

Want a model and many-body methods that is valid for all relevant kinematics and processes that we intend to study

Strategy

Validate nuclear physics model on readily-available experimental data:

- Energy spectra, form factors, moments
- EM and beta decay rates
- Muon capture rates
- Electron-nucleus scattering cross sections

Predict experimentally relevant quantities with validated model:

- Beta decay spectra
- Neutrinoless double beta decay
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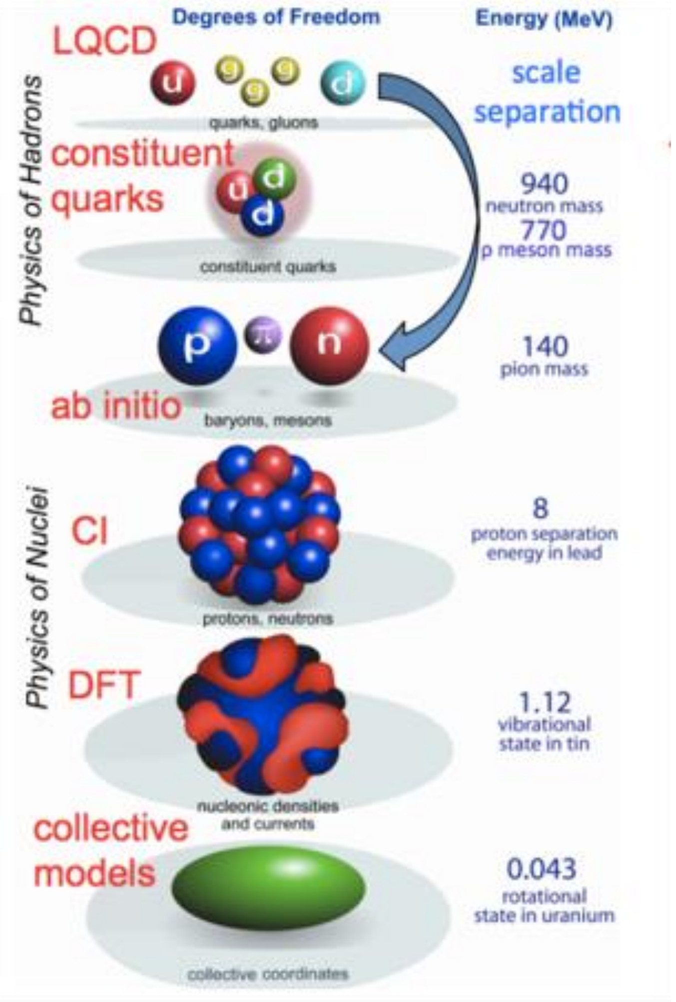
Microscopic (or *ab initio*) description of nuclei

Comprehensive theory that describes quantitatively and predictably nuclear structure and reactions

Requirements:

- An accurate understanding of the interactions/correlations between nucleons in pairs, triplets, … **(two- and three-nucleon forces)**
- An accurate understanding of the electroweak interactions of external probes (electrons, neutrinos, photons) with nucleons, correlated pairs of nucleons, … **(one- and two-body electroweak currents)**
- **Computational Methods** to solve the nuclear many-body problem

Chiral Effective Field Theory (χEFT)



Procedure to derive the nuclear interaction containing all low-energy symmetries of QCD

Provides a hierarchy of two- and many-nucleon forces and electroweak currents

Pions, Nucleons, possibly Δ(1232), and external fields may be retained as the relevant degrees of freedom

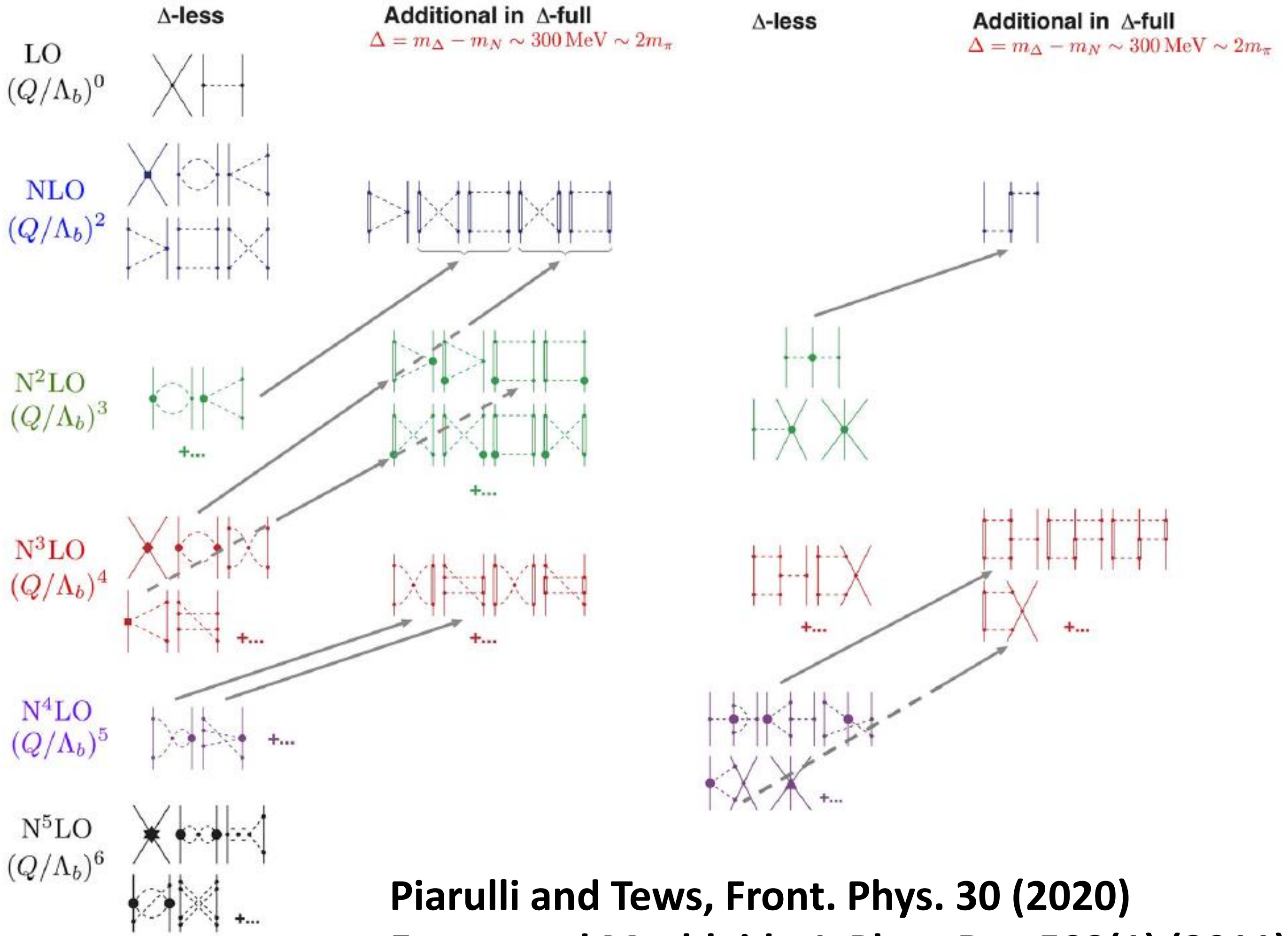
Weinberg, van Kolck, Ordóñez, Epelbaum, Hammer, Meißner, Entem, Machleidt, …

Chiral Effective Field Theory (χEFT)

Pions are the pseudo-Goldstone boson of spontaneously broken chiral symmetry

Low-energy constants (LECs) subsume the underlying QCD

Power expansion in the typical nucleon momentum *Q* ~ pion mass insertions ~ N-to-Δ mass splittings over the QCD scale (Λ ~ 1 GeV)



Piarulli and Tews, Front. Phys. 30 (2020)
Entem and Machleidt, J. Phys. Rep 503(1) (2011)

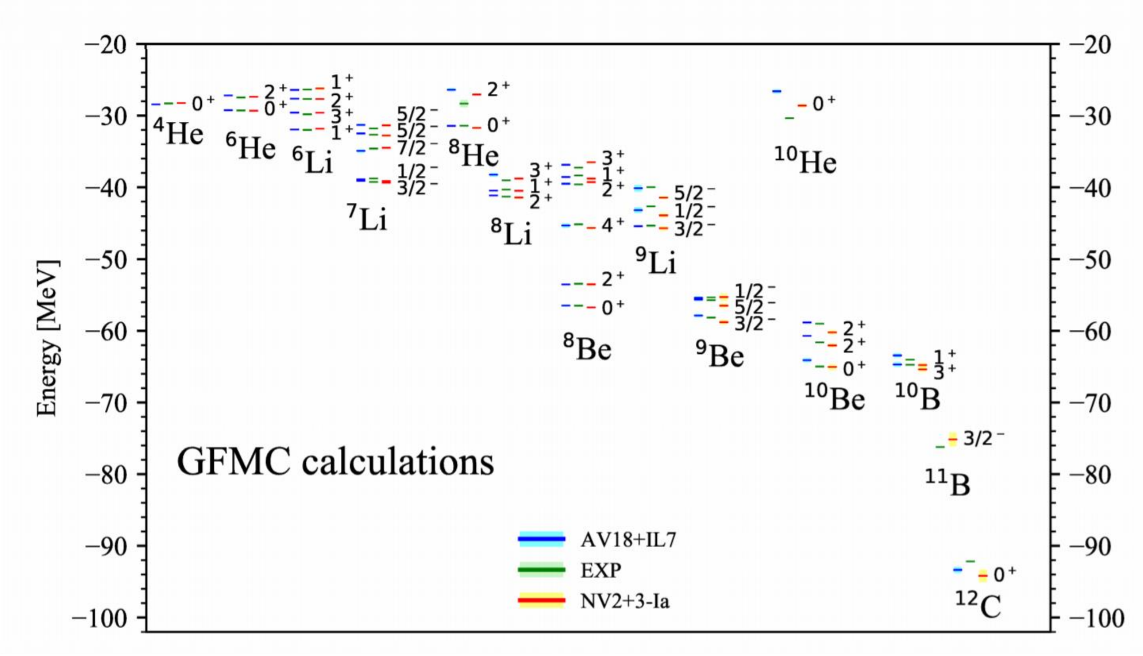
The Norfolk (NV2+3) Interaction

$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

Derived in χEFT with pion, nucleon, and delta degrees of freedom

NV2 is fully local chiral interaction to N2LO (including some N3LO contributions) containing 26 unknown contact LECs

NV3 includes two long-range interactions and two contact interactions introducing two new unknown LECs, form as derived by **van Kolck PRC 49, 2932 (1994)** and **Epelbaum et al PRC 66, 064001 (2002)**



Piarulli et al. PRL 120, 052503 (2018)

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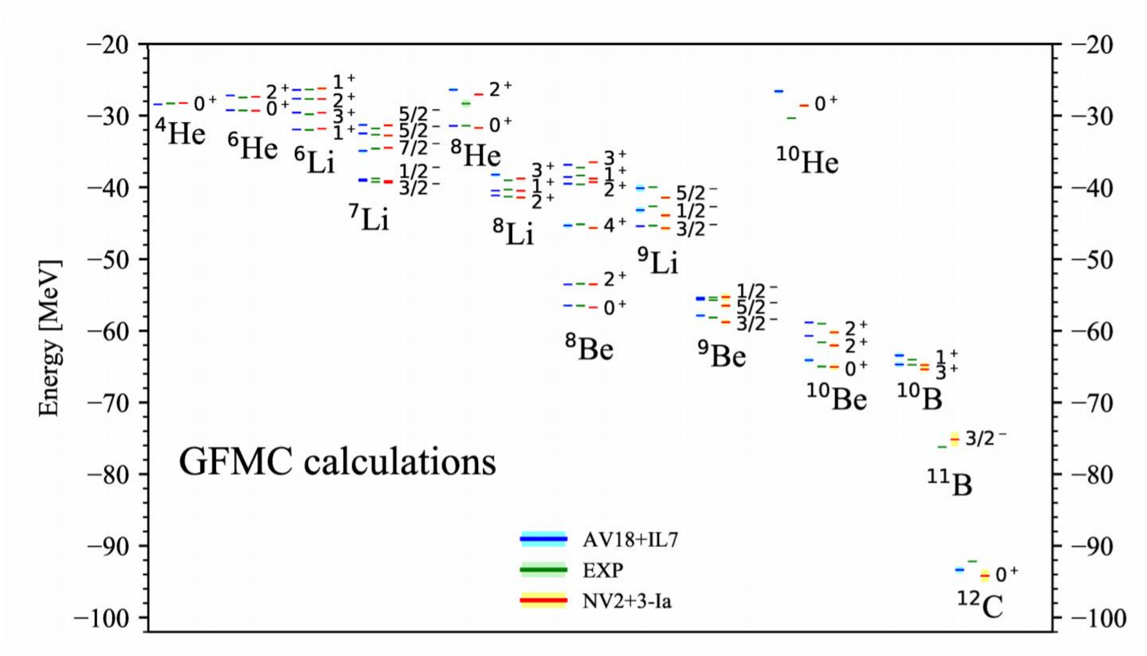
Eight different Model classes:



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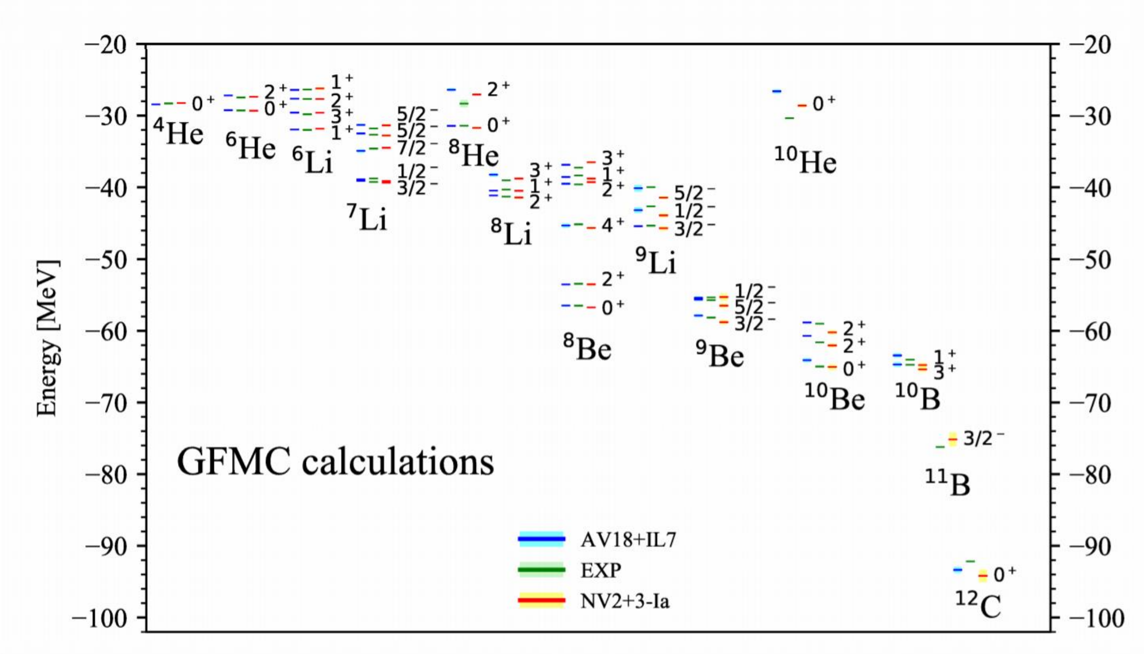

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Eight different Model classes:

- I [II]: NN scattering to fit two-body interaction from 0 to 125 [200] MeV

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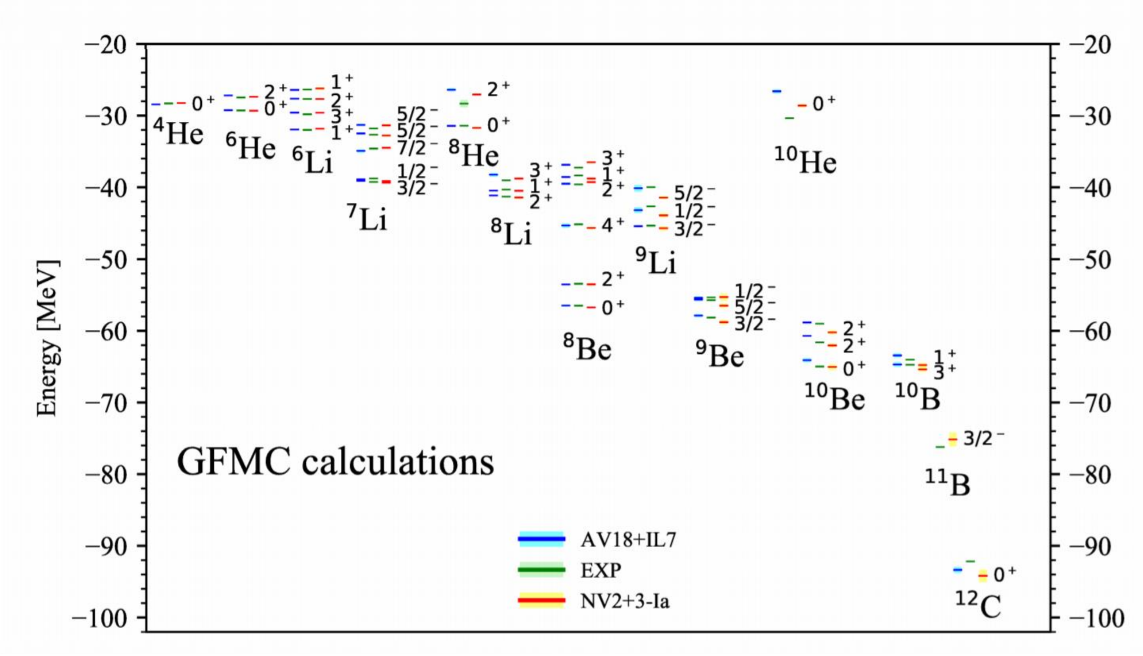

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Eight different Model classes:

- I [II]: NN scattering to fit two-body interaction from 0 to 125 [200] MeV
- a [b]: Long- and short-range regulators (R_L,R_S) = (1.2 fm, 0.8 fm) [(1.0 fm, 0.7 fm)]

$$C_{R_L}(r) = 1 - \frac{1}{(r/R_L)^6 e^{(r-R_L)/a_L} + 1}$$

$$C_{R_S}(r) = \frac{1}{\pi^{3/2} R_S^3} e^{-(r/R_S)^2}$$

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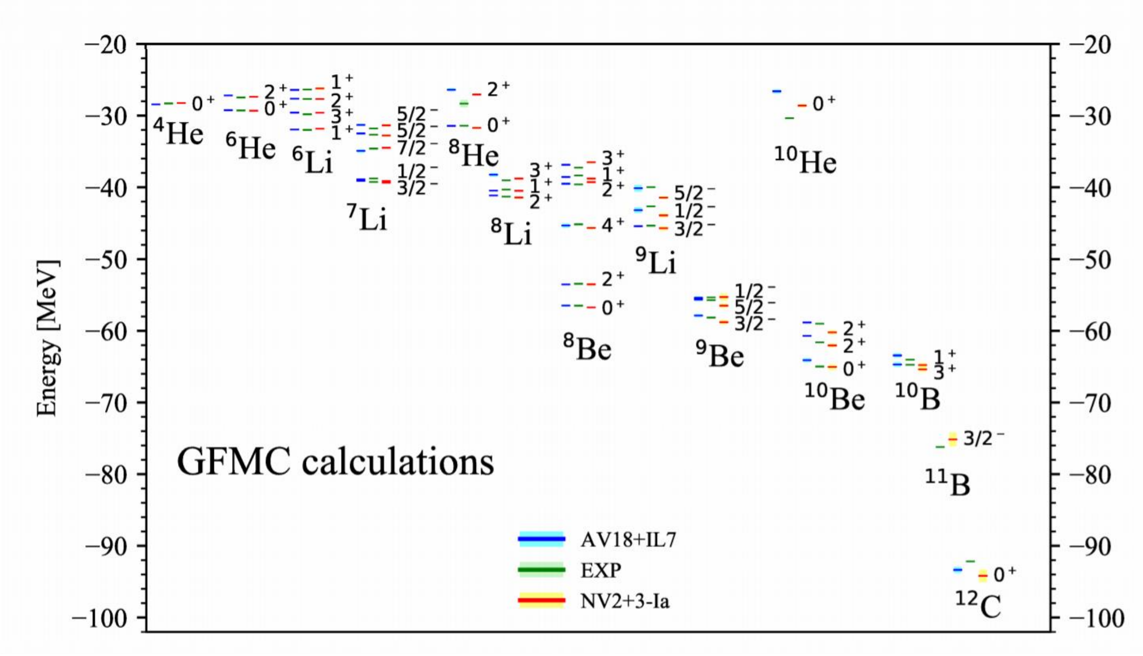

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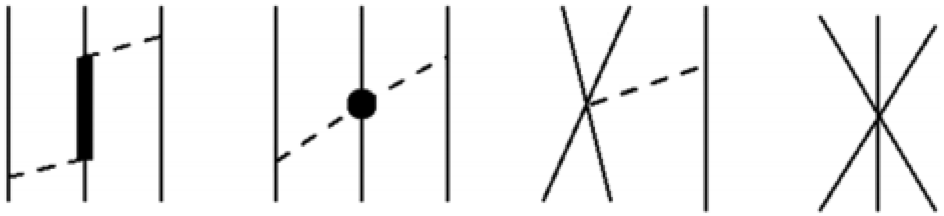
- Unstarred: Three-body term constrained with strong data only
- Star: Three-body term constrained with strong and weak data



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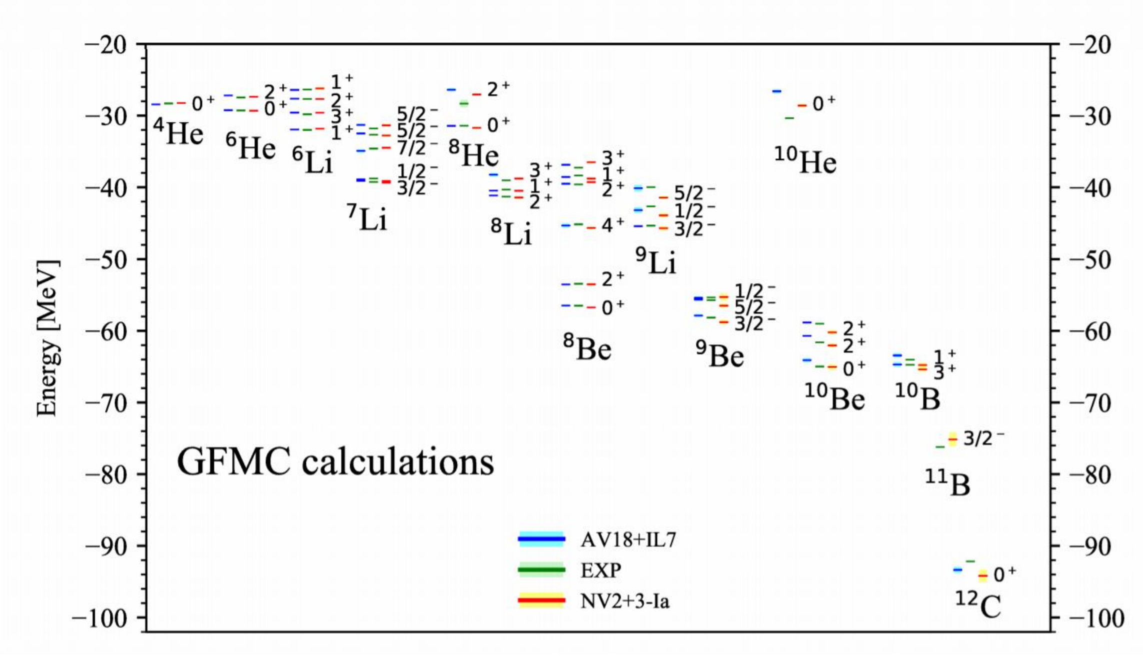

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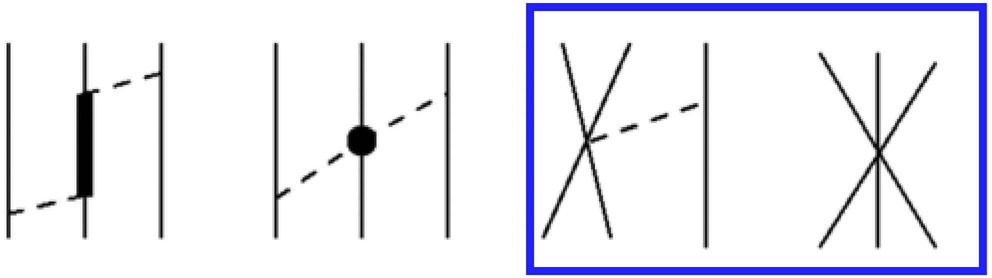


NV2+3 Charge and Currents

Need nuclear vector and axial current operators to study weak processes in light nuclei

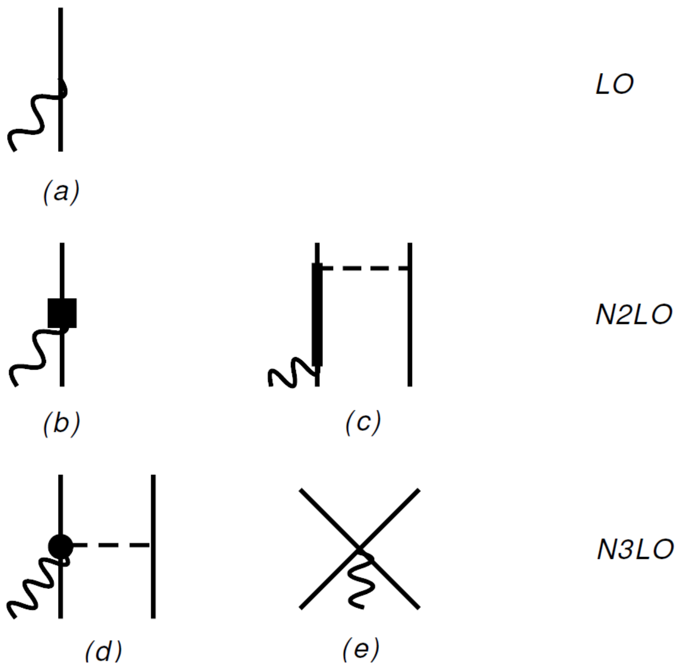
Schematically:

$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

External field interacts with single nucleons and correlated pairs of nucleons

Use vector and axial currents consistent with NV2+3 derived by JLAB-Pisa group: Pastore et al. PRC 80, 034004 (2009), Pastore et al. PRC 84, 024001 (2011), Piarulli et al. PRC 87, 014006 (2013), Schiavilla et al. PRC 99, 034005 (2019), Baroni et al. PRC 93, 049902 (2016), …

Example: Axial current at zero momentum transfer



Variational Monte Carlo (VMC)

Want to solve: $H\Psi(JMTT_z) = E\Psi(JMTT_z)$ with $H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$

$$|\Psi_V\rangle = \left[\mathcal{S}\prod_{i<j}(1 + U_{ij} + \sum_{k\neq i,j} U_{ijk})\right]\left[\sum_{i<j} f_c(r_{ij})\right] |\Phi_A(JMTT_z)\rangle$$

Slater determinant of nucleons in s- and p-shell coupled to the appropriate quantum numbers

Pair correlation operator encoding appropriate cluster structure

Two- and three-body correlation operator to reflect impact of nuclear interaction at short distances

Variational Monte Carlo (VMC) is used to find wavefunctions that minimize: $E_V = \frac{\langle\Psi_V|H|\Psi_V\rangle}{\langle\Psi_V|\Psi_V\rangle} \geq E_0$

Carlson et al. Rev. Mod. Phys. 87, 1607 (2015)

Green's Function Monte Carlo (GFMC)

The variational estimate can be further improved by acting with an imaginary time propagator

$$\Psi(\tau) = e^{-(H-E_0)\tau}\Psi_V = \left[e^{-(H-E_0)\Delta\tau}\right]^n \Psi_V$$

In general, variational state can be expanded in exact eigenstates of the Hamiltonian

$$|\Psi_V\rangle = \sum_{i=1}^{n} c_n|\psi_n\rangle$$

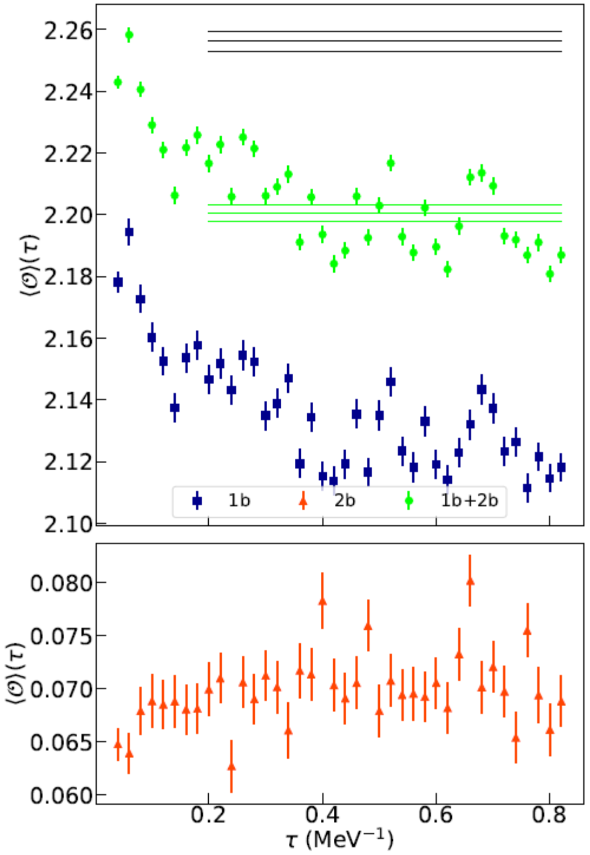
In the limit of infinite imaginary time

$$\lim_{\tau\to\infty} e^{-(H-E_0)\tau}\Psi_V \to c_0\psi_0$$

Carlson et al. Rev. Mod. Phys. 87, 1607 (2015)

Transition Matrix Element from GFMC

^{6}He → ^{6}Li GT RME extrapolation



Assume small correction to VMC: $\Psi(\tau) = \Psi_V + \delta\Psi$

Mixed estimate for off-diagonal transitions:

$$\langle \mathcal{O}(\tau) \rangle = \frac{\langle \Psi^f(\tau) | \mathcal{O} | \Psi^i(\tau) \rangle}{\sqrt{\langle \Psi^f(\tau) | \Psi^f(\tau) \rangle} \sqrt{\langle \Psi^i(\tau) | \Psi^i(\tau) \rangle}}$$

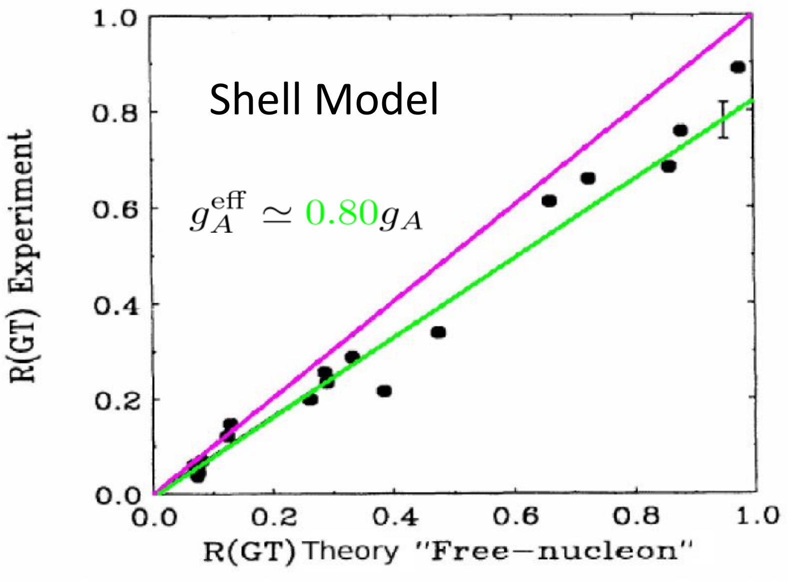
$$\simeq \langle \mathcal{O}(\tau) \rangle_{M_f} + \langle \mathcal{O}(\tau) \rangle_{M_i} - \langle \mathcal{O} \rangle_{\mathrm{VMC}}$$

where

$$\langle \mathcal{O}(\tau) \rangle_{M_f} = \frac{\langle \Psi^f(\tau) | \mathcal{O} | \Psi^i_V \rangle}{\langle \Psi^f(\tau) | \Psi^i_V \rangle} \frac{\sqrt{\langle \Psi^f_V | \Psi^f_V \rangle}}{\sqrt{\langle \Psi^i_V | \Psi^i_V \rangle}}$$

Pervin, Pieper, and Wiringa PRC 76, 064319 (2007)

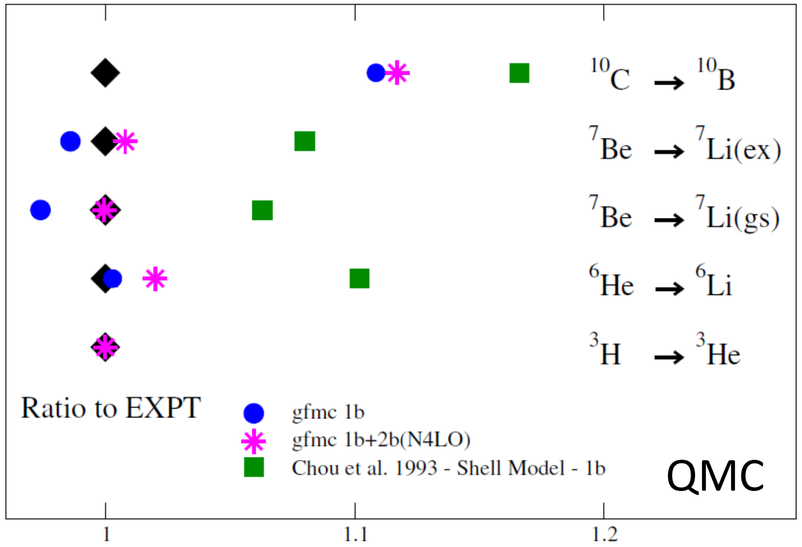
Validation with GT reduced matrix elements



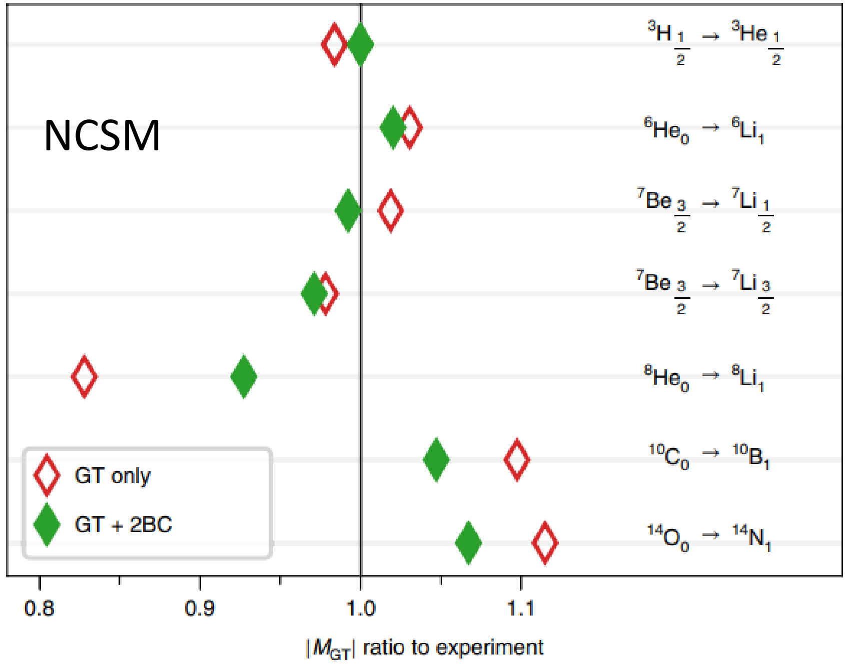
Chou et al. PRC 47, 167 (1993)

ω ~ few MeV, q ~ 0

The "g_A quenching" problem for shell model calculations of beta decay rates resolved by the inclusion of two-body electroweak transition operators

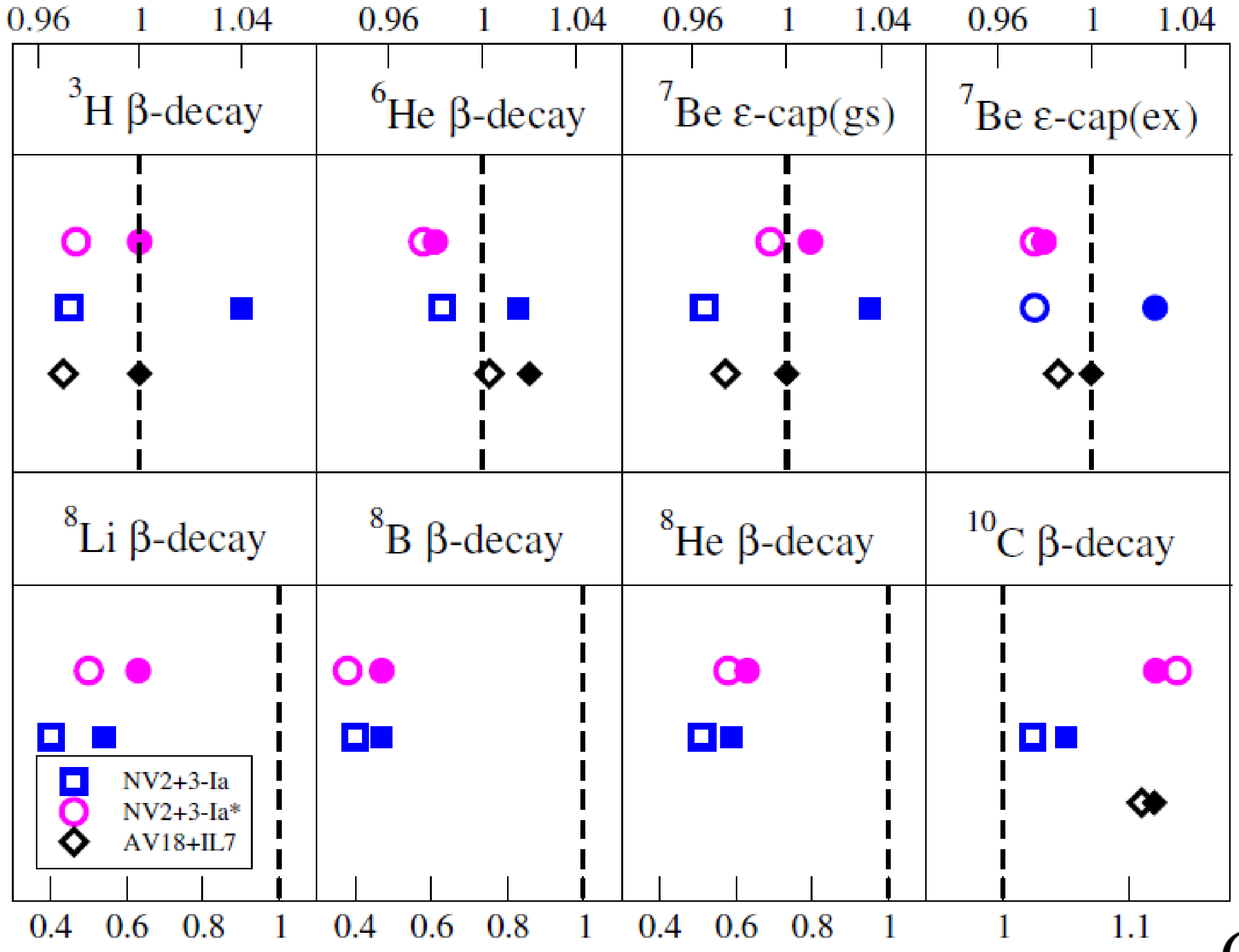


Pastore et al. PRC 97, 022501 (2018)



P. Gysbers et al. Nature Physics 15, 428 (2019)

GFMC GT Reduced Matrix Elements



NV2+3-Ia: Three-body constrained with only strong data

NV2+3-Ia*: Three-body constrained with strong and weak data

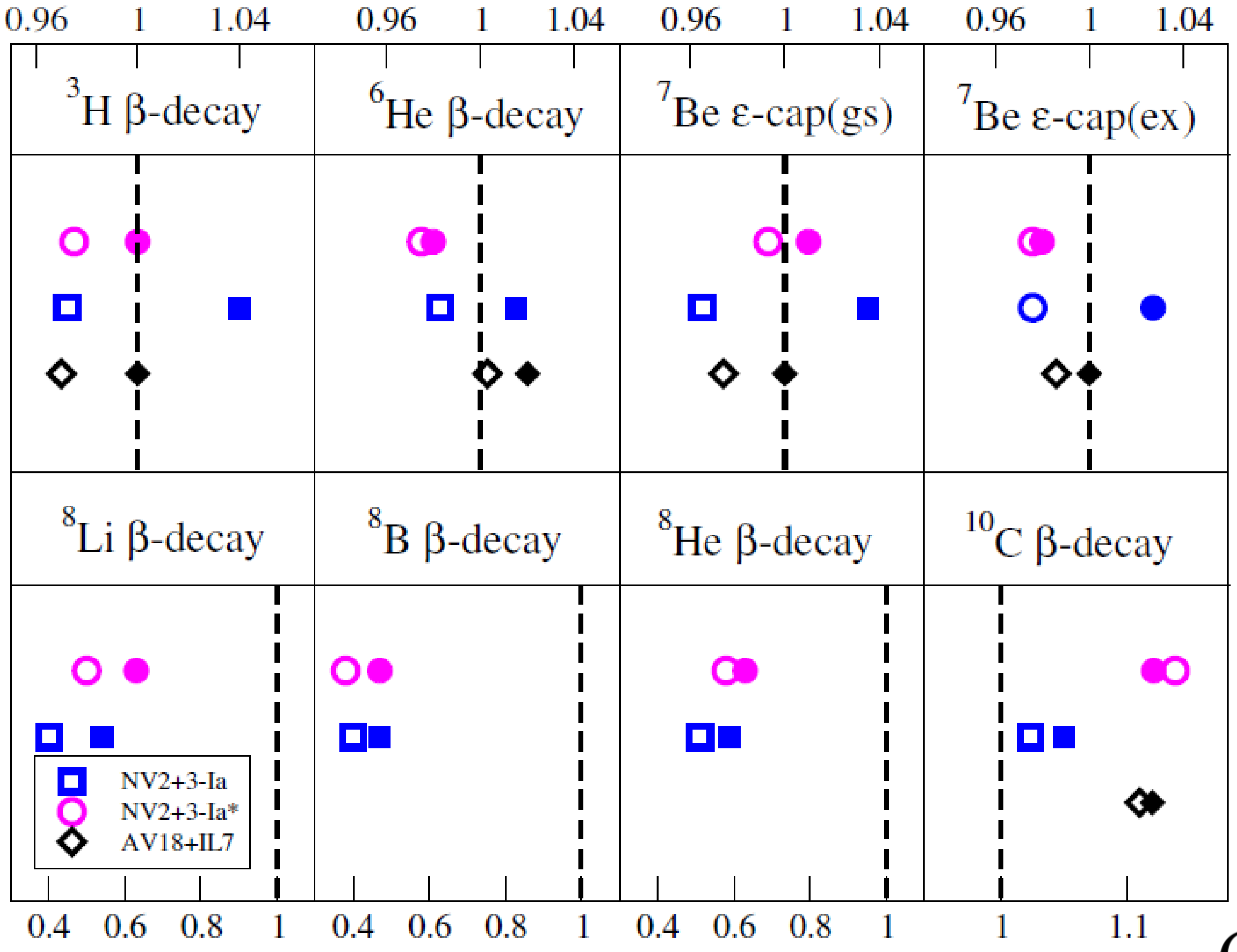
GFMC GT matrix elements compared with results using the AV18+IL7 in **Pastore et al. PRC 97, 022501 (2018)**

Empty symbols are results up to LO, solid symbols up to N3LO

$$\mathrm{GT\ RME} = \frac{\sqrt{2J_f+1}}{g_A}\frac{\langle J_f\, M|j^z_{\pm,5}(\mathbf{q}\to 0)|J_i\, M\rangle}{\langle J_i\, M,10|J_f\, M\rangle}$$

King et al. PRC 121, 025501 (2020)

GFMC GT Reduced Matrix Elements



In most cases, two-body correction is small (~ few %) and additive

NV2+3-Ia has an enhanced two-body correction relative to the NV2+3-Ia*

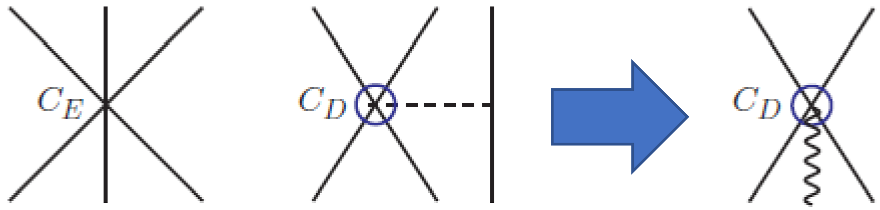
A=8 suppressed at leading order, larger two-body corrections

A=10 for NV2+3-Ia* has a negative two-body correction

$$\text{GT RME} = \frac{\sqrt{2J_f+1}}{g_A}\frac{\langle J_f\, M | j^z_{\pm,5}(\mathbf{q}\to 0) | J_i\, M\rangle}{\langle J_i\, M, 10 | J_f\, M\rangle}$$

King et al. PRC 121, 025501 (2020)

Three-body LECs and N3LO-CT



$$\mathbf{j}_{5,a}^{\rm N3LO}(\mathbf{q};{\rm CT}) = z_0 {\rm e}^{i\,\mathbf{q}\cdot\mathbf{R}_{ij}} \frac{{\rm e}^{-z_{ij}^2}}{\pi^{3/2}} \left(\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j\right)_a \left(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j\right)$$

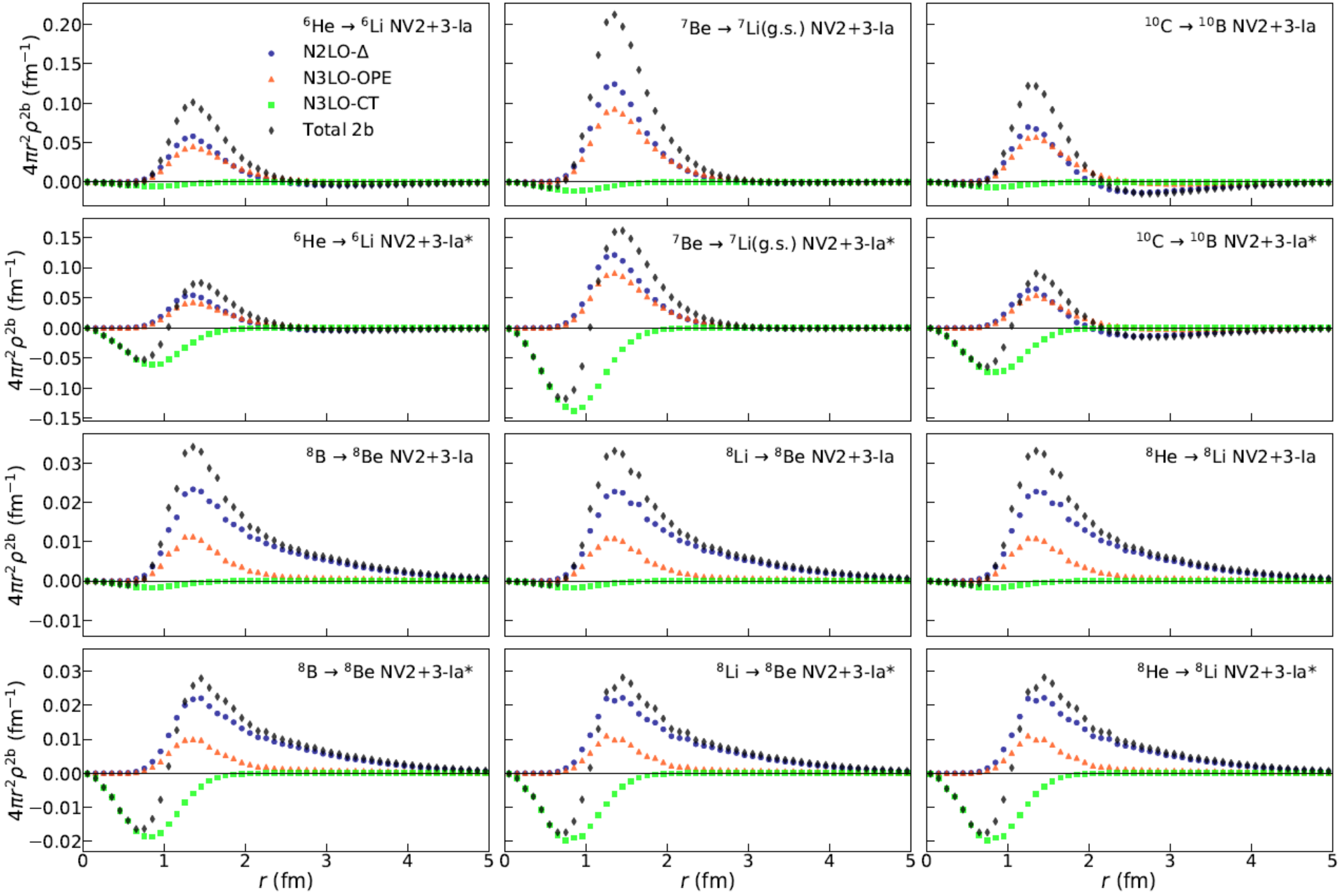
$$z_0 = \frac{g_A}{2}\frac{m_\pi^2}{f_\pi^2}\frac{1}{(m_\pi R_{\rm S})^3}\left[-\frac{m_\pi}{4\,g_A\,\Lambda_\chi}c_D + \frac{m_\pi}{3}(c_3+2c_4) + \frac{m_\pi}{6\,m}\right]$$

The NV2+3-Ia model fits the LECS using the *nd* doublet scattering length and trinucleon energies

The NV2+3-Ia* model fits trinucleon energies and the triton Gamow-Teller matrix element

Gardestig and Phillips PRL 96, 232301 (2006)

Two-body VMC transition densities



Ia

Ia*

Ia

Ia*

The N3LO-CT term is a negative contribution is enhanced in the NV2+3-Ia*

N2LO-Δ and N3LO-OPE terms are consistent independent of the data used to constrain the three-body force

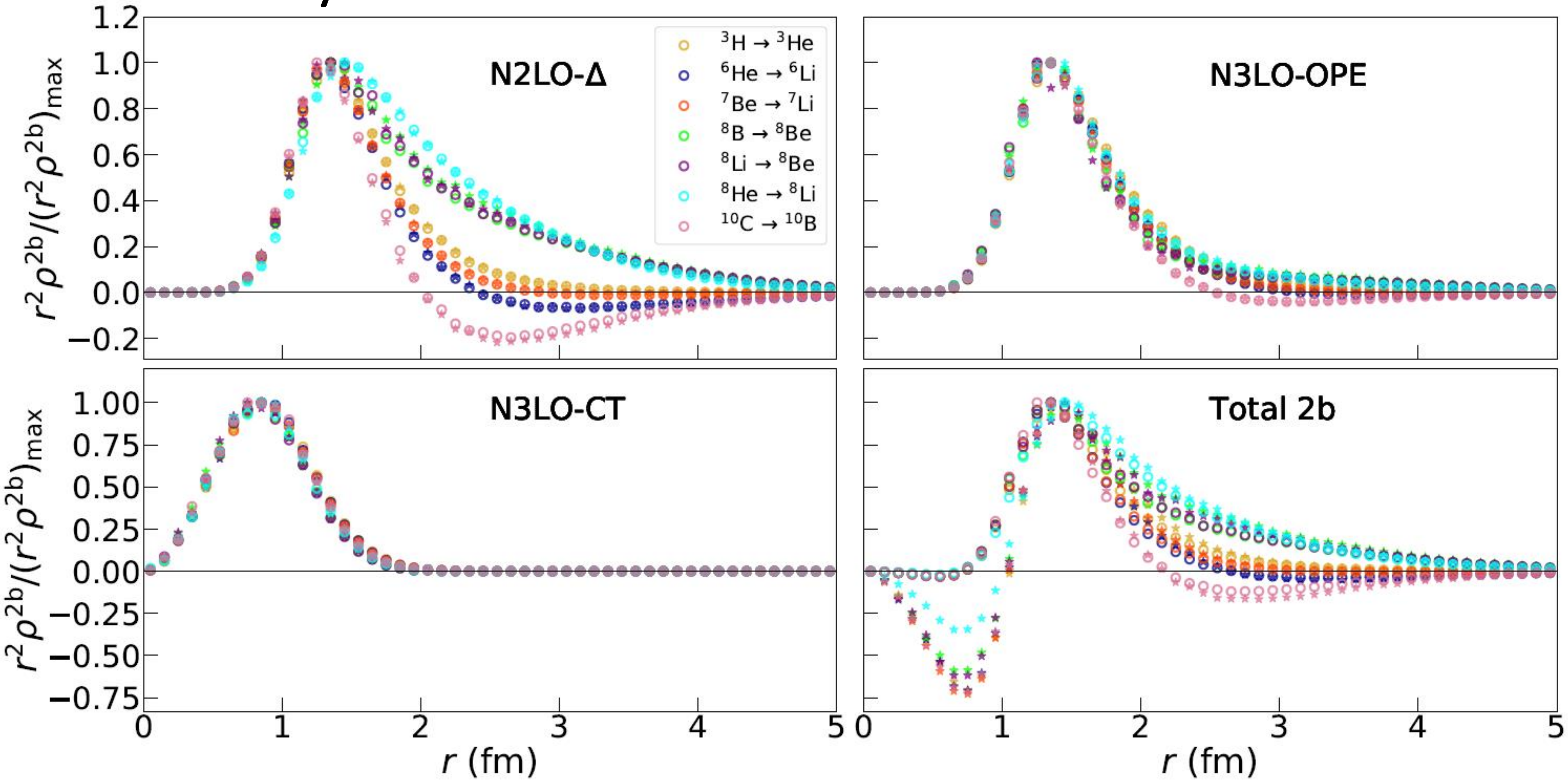
$$\mathrm{RME(2b)} = \int dr_{ij} 4\pi r_{ij}^2 \rho^{2b}(r_{ij})$$

King et al. PRC 121, 025501 (2020)

Scaled Two-body Transition Densities

Long-range N2LO-Δ and N3LO-OPE are transition dependent

Universal shape of the short-range transition density



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King et al. PRC 121, 025501 (2020)

B(GT) for A=11 nuclei

$$\mathrm{GT} = \frac{\sqrt{2J_f+1}}{g_A} \frac{\langle J_F M | j^z_{\pm,5}(\mathbf{q}\to 0) | J_i M\rangle}{\langle J_i M, 10 | J_f M\rangle}$$

$$B(GT) = \frac{|\mathrm{GT}|^2}{2J_i+1}$$

Reduced matrix elements from QMC can be used to obtain transition strengths to exclusive final states

B(GT) may be obtained from charge exchange reactions at zero momentum transfer

Do not depend on any model assumptions for the structure of the system

Tests quality of *ab initio* wave functions and many-body methods

B(GT) for A=11 nuclei

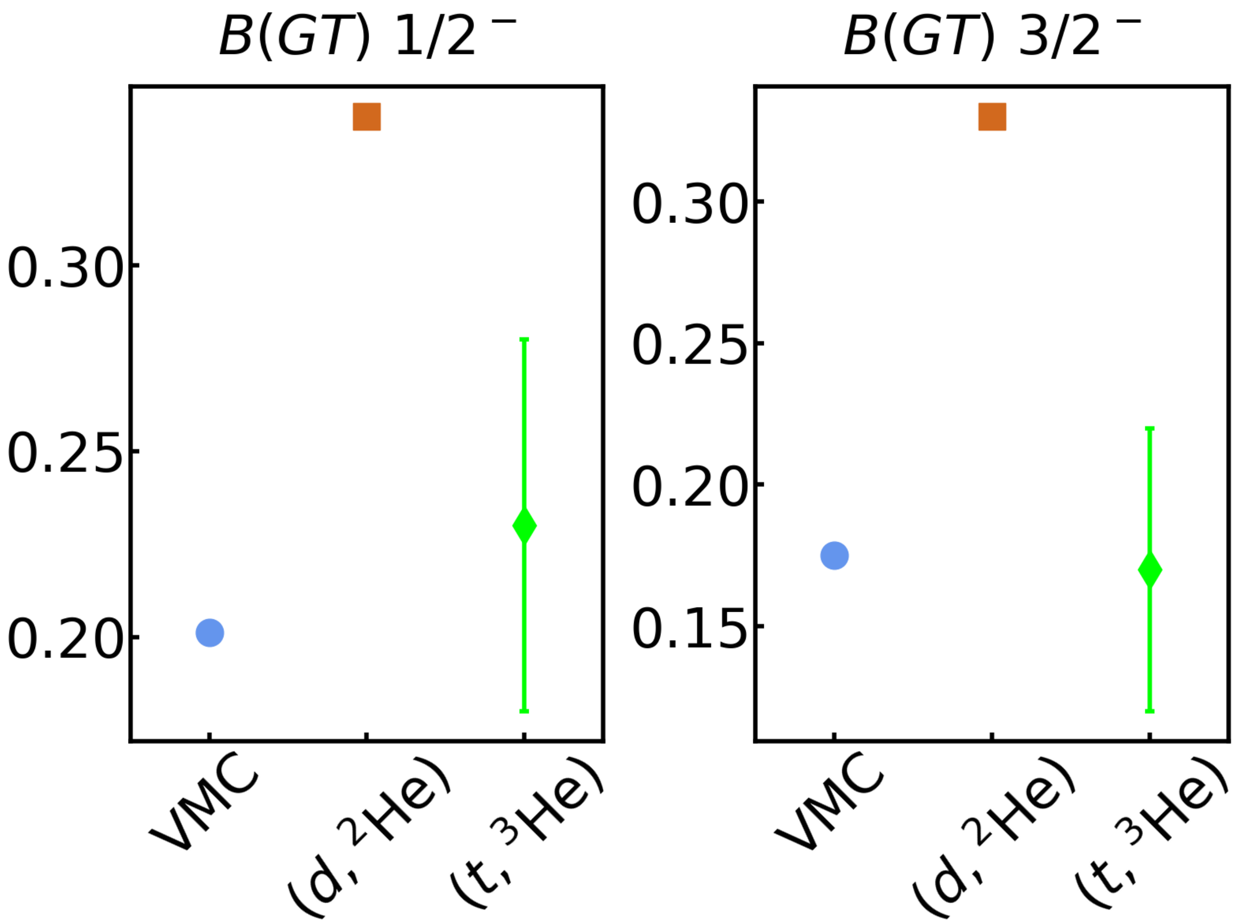
^{11}B(g.s.) → ^{11}Be*

NV2+3-Ia* VMC agrees well with the value extracted from *(t,^{3}He)*

(d,^{2}He) data consistent with unquenched shell model calculation

Two-body effects ~2%-3% and subtractive

$$B(GT) = \frac{|\mathrm{GT}|^2}{2J_i+1}$$



***(d,^{2}He)* – Ohnishi et al., Nucl. Phys. A 687 (2001)**
***(t,^{3}He)* – Daito et al., Phys. Lett. B (1998)**

Schmitt, GBK, et al. PRC 106, 054323 (2022)

B(GT) for A=11 nuclei

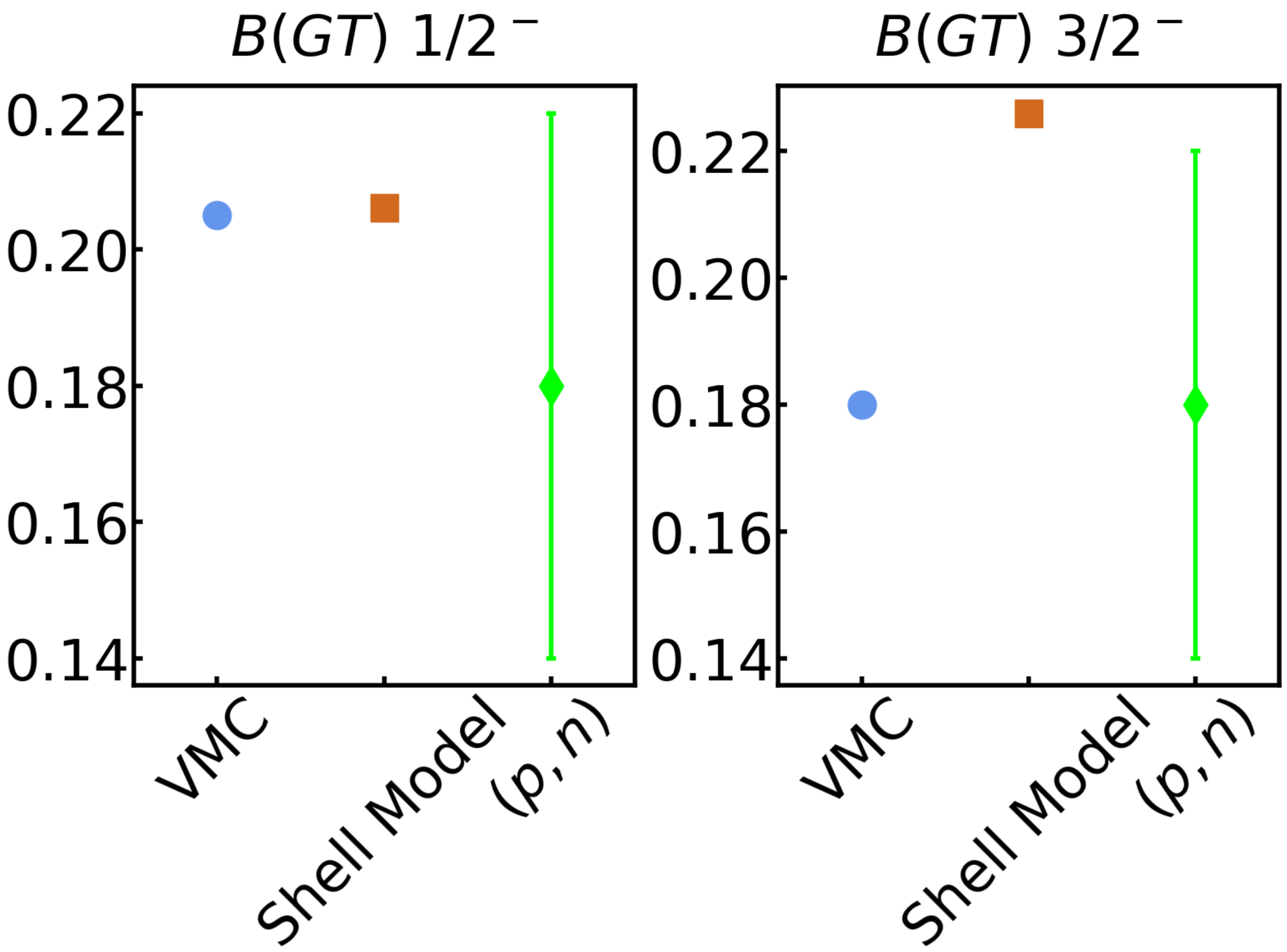
^{11}C(g.s.) → ^{11}N*

NV2+3-Ia* VMC result consistent under isospin symmetry when studying mirror transition

Good agreement between central value of VMC and experimental error bars

Two-body effects ~2%-4% and subtractive

$$B(GT) = \frac{|\mathrm{GT}|^2}{2J_i+1}$$



Shell Model – B. A. Brown (MSU)
***(p,n)* – J. Schmitt (MSU)**

Schmitt, GBK, et al. PRC 106, 054323 (2022)

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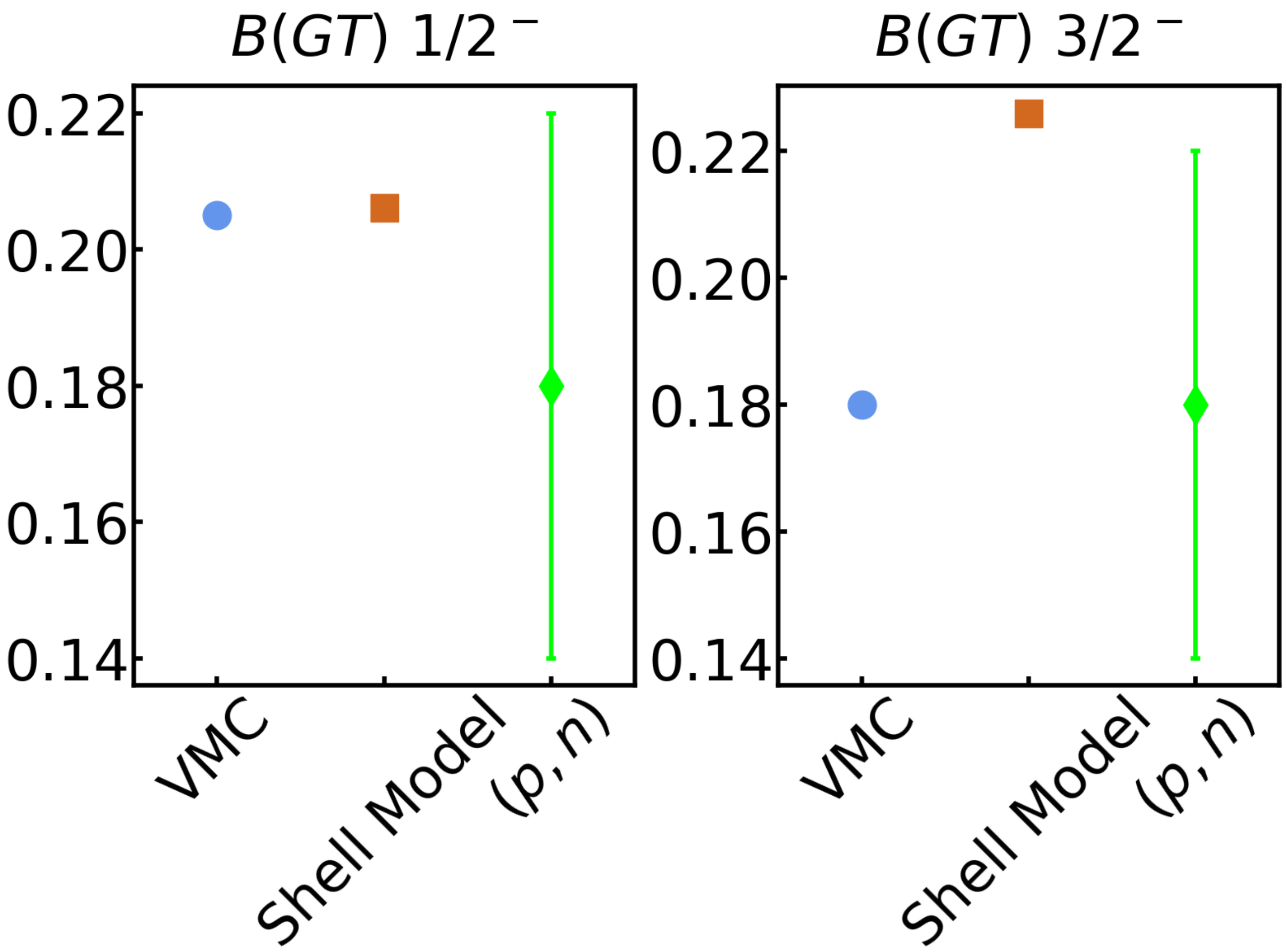
Outlook: Systematic study of GT transitions for nuclei with A ≥ 11 at GFMC level



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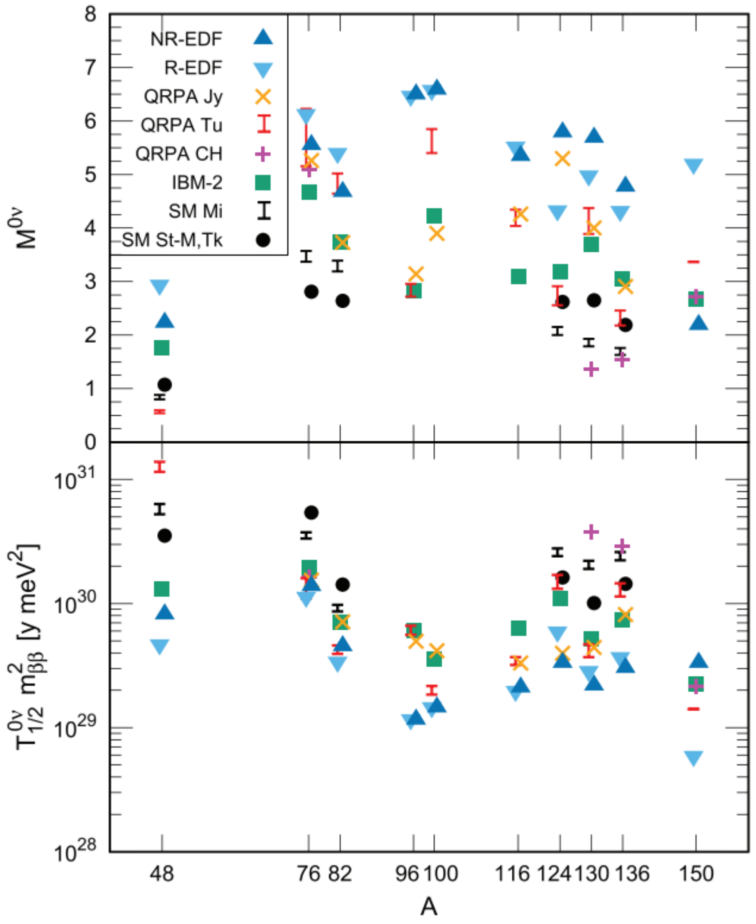
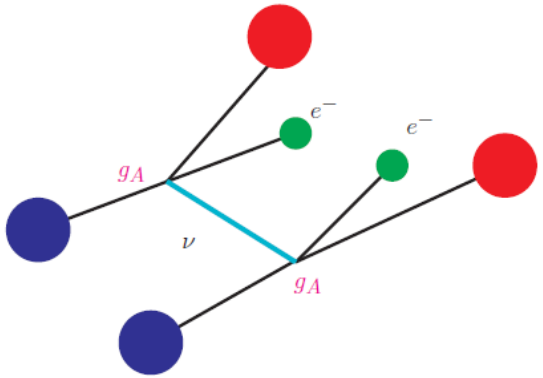
Schmitt, GBK, et al. PRC 106, 054323 (2022)

Validation of vector current



Engel and Menéndez Rep. Prog. Phys. 80 046301 (2017)



ω ~ few MeV, q ~ 100 MeV: Muon capture, Neutrinoless ββ-decay

Goal: Validate weak transition operators with less restrictive selection rules at a non-zero momentum transfer with muon capture

Partial Muon Capture Rates with QMC

$$H_W = \frac{G_V}{\sqrt{2}} \int d\mathbf{x} e^{-i\mathbf{k}_\nu \cdot \mathbf{x}} \tilde{l}_\sigma(\mathbf{x}) j^\sigma(\mathbf{x})$$

Momentum transfer q ~ 100 MeV

Validation of vector and axial charges and currents

For light nuclei, you can approximate the muon as at rest in a Hydrogen-like 1s orbital

Partial Muon Capture Rates with QMC

Assuming a muon at rest in a Hydrogen-like 1s orbital:

$$\Gamma = \frac{G_V^2}{2\pi} \frac{|\psi_{1s}^{\rm av}|^2}{(2J_i+1)} \frac{E_\nu^{*2}}{\rm recoil} \sum_{M_f, M_i} |\langle J_f, M_f|\rho(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle|^2 + |\langle J_f, M_f|\mathbf{j}_z(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle|^2$$

$$+ 2\,{\rm Re}\left[\langle J_f, M_f|\rho(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle\, \langle J_f, M_f|\mathbf{j}_z(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle^*\right] + |\langle J_f, M_f|\mathbf{j}_x(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle|^2$$

$$+ |\langle J_f, M_f|\mathbf{j}_y(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle|^2 - 2\,{\rm Im}\left[\langle J_f, M_f|\mathbf{j}_x(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle\, \langle J_f, M_f|\mathbf{j}_y(E_\nu^* \hat{\mathbf{z}})|J_i, M_i\rangle^*\right]$$

King et al. PRC 105, L042501 (2022)

Partial Muon Capture Rates with QMC

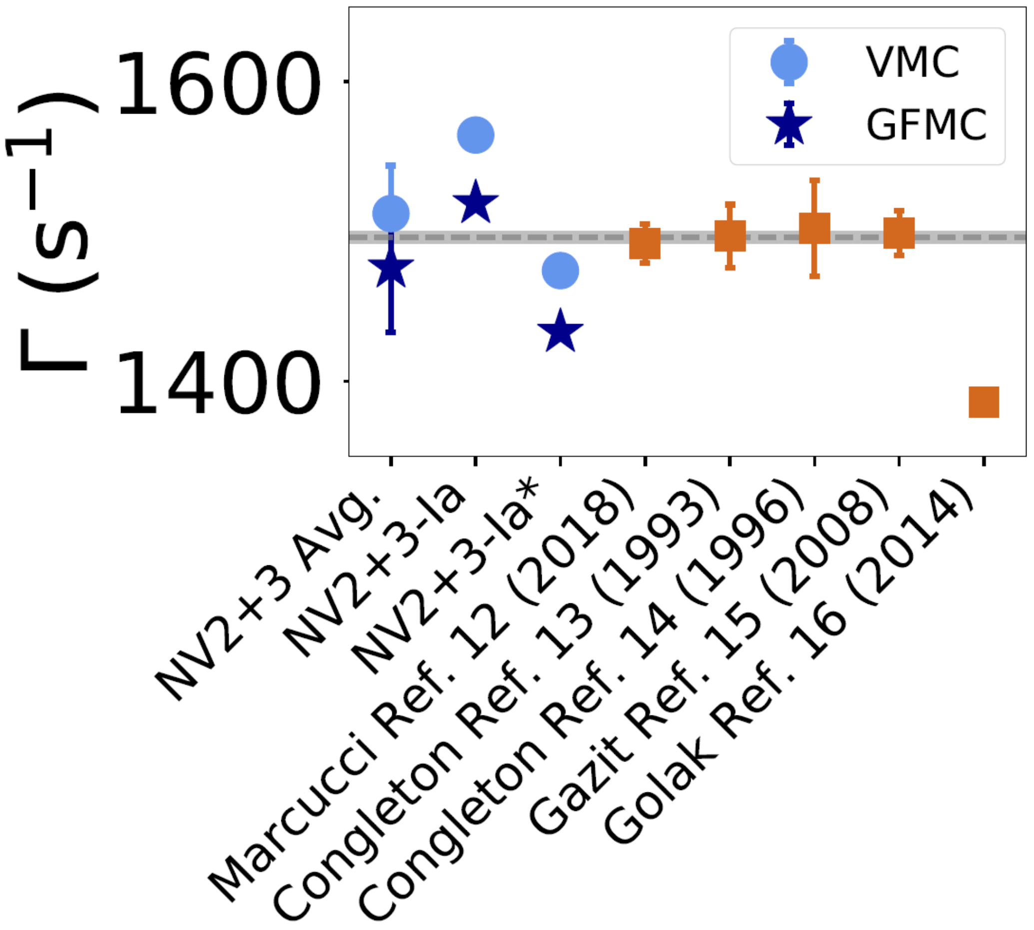
QMC rate for ^{3}He(1/2$^+$;1/2) → ^{3}H(1/2$^+$;1/2)

Γ_{VMC} = 1512 s^{-1} ± 32 s^{-1}

Γ_{GFMC} = 1476 s^{-1} ± 43 s^{-1}

Γ_{expt} = 1496.0 s^{-1} ± 4.0 s^{-1}

[Ackerbauer et al. Phys. Lett. B 417 (1998)]



VMC uncertainty estimates:

- Cutoff: 8 s^{-1} (0.7%)
- Energy range of fit: 11 s^{-1} (0.5%)
- Three-body fit: 27 s^{-1} (1.8%)
- Systematic: 9 s^{-1} (0.6%)

King et al. PRC 105, L042501 (2022)

Partial Muon Capture Rates with QMC

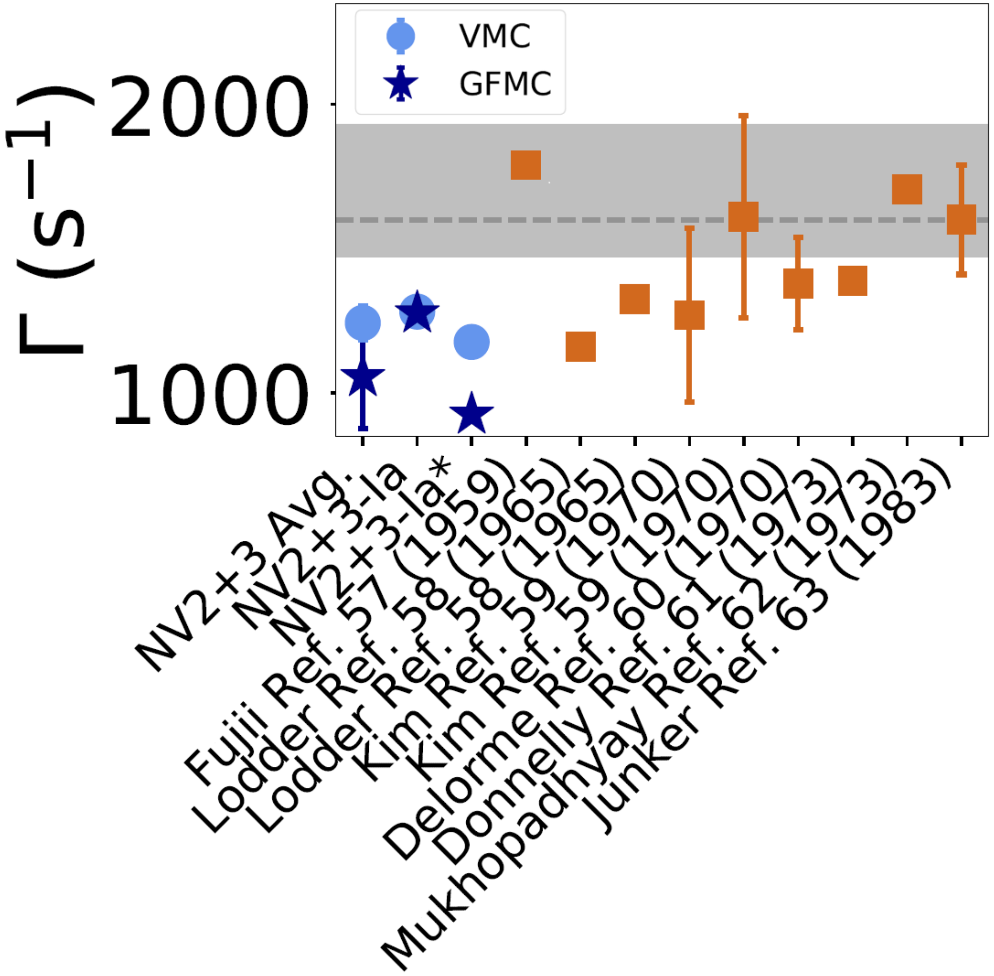
QMC rates for $^{6}Li(g.s.) \rightarrow {}^{6}He(g.s.)$:

Γ_{VMC}(avg.) = 1243 s^{-1} ± 59 s^{-1}

Γ_{GFMC}(avg.) = 1102 s^{-1} ± 176 s^{-1}

Γ_{expt} = 1600 s^{-1} +330/-129 s^{-1}

[Deutsch et al. Phys. Lett. B26, 315 (1968)]



VMC uncertainty estimates:

- Cutoff: 36 s^{-1} (2.9%)
- Energy range of fit: 36 s^{-1} (2.9%)
- Three-body fit: 30 s^{-1} (2.4%)
- Systematic: 7 s^{-1} (0.6%)

King et al. PRC 105, L042501 (2022)

^{6}He Beta Decay Spectrum

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left[-\frac{G_F}{\sqrt{2}} V_{ud} \sum_i \epsilon_i \bar{l} \gamma_\mu (1-\gamma_5)\nu_l \cdot \bar{u}\Gamma_i^\mu d + \text{h.c.} \right]$$

$$i \in \{A, V, P, S, T\} \qquad \epsilon_i \lesssim 10^{-3}$$

$$\Lambda_{\rm BSM} \sim \frac{v}{\sqrt{\epsilon_i}} \sim 1\text{–}10 \text{ TeV}$$

Beta decay in light nuclei is important for experiments searching for beyond standard model physics

Vector
Scalar
→ **Fermi**

Axial
Tensor
Pseudoscalar
→ **GT**

Precision beta-decay is competitive with accelerator constraints on new electroweak physics parameters

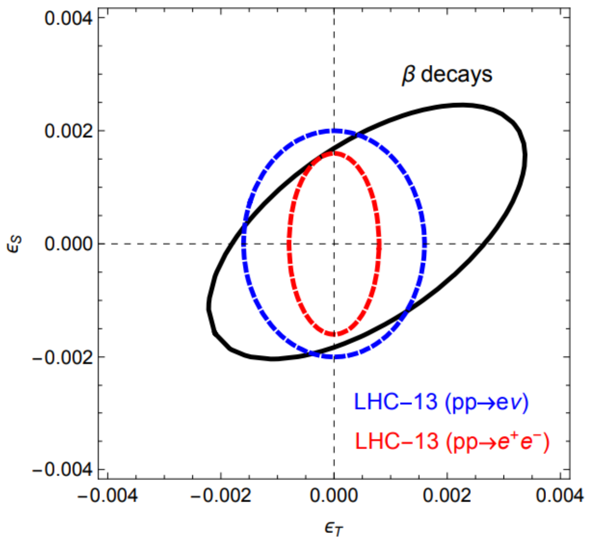
Goal: Predict beta decay spectrum for ^{6}He retaining one- and two-body electroweak currents

NSCL

He6 CRES

lpc caen

^{6}He beta-decay spectrum is being/will be measured for BSM searches **aiming for permille (0.1%) uncertainty**



Cirigliano et al. arXiv:1097.02164 (2019)

Falkowski, González-Alonso, and Naviliat-Cuncic J. High Energ. Phys. 2021, 126 (2021)

^{6}He Beta Decay Spectrum: Overview

Differential beta decay rate:

$$d\Gamma = \frac{2\pi}{2J_i+1} \sum_{s_e, s_\nu} \sum_{M_i, M_f} |\langle f|H_W|i\rangle|^2 \delta(\Delta E) \frac{d^3k_e}{(2\pi)^3} \frac{d^3k_\nu}{(2\pi)^3}$$

Traces of lepton tensor appearing in the rate depend on the electron and neutrino kinematics

In the $q \to 0$ limit:

$$d\Gamma = d\Gamma_0 \left[1 + a\hat{\boldsymbol{\nu}} \cdot \boldsymbol{\beta} + b\frac{m_e}{E_e} + \langle J \rangle (\ldots)\right]$$

Vanishes for 0^+ ground state of ^{6}He

Collaborators:

Mereghetti
Cirigliano
Baroni
Gandolfi
Hayen

Within the SM, the predicted values must be corrected for recoil contributions, which must be well-understood to infer new physics **[Glick-Magid et al. Phys. Lett. B 832 (2022)]**

In the integrated SM spectrum, for GT transition, only contributing term is $b = 0 + \delta_b^{\text{recoil}}$

^{6}He Beta Decay Spectrum: Multipoles

The (standard model) matrix element may be decomposed into reduced matrix elements of four multipoles operators:

$$\sum_{M_i}\sum_{M_f}|\langle f|H_W|i\rangle|^2 \propto \sum_{J=0}^{\infty}\left[(1+\hat{\boldsymbol{\nu}}\cdot\boldsymbol{\beta})|C_J(q)|^2+(1-\hat{\boldsymbol{\nu}}\cdot\boldsymbol{\beta}+2(\hat{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})(\hat{\mathbf{q}}\cdot\boldsymbol{\beta}))|L_J(q)|^2-\hat{\mathbf{q}}\cdot(\hat{\boldsymbol{\nu}}+\boldsymbol{\beta})2\mathrm{Re}(L_J(q)M_J^*(q)\right]$$

$$+\sum_{J=1}^{\infty}\left[(1-(\hat{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})(\hat{\mathbf{q}}\cdot\boldsymbol{\beta}))(|M_J(q)|^2+|E_J(q)|^2)+\hat{\mathbf{q}}\cdot(\hat{\boldsymbol{\nu}}-\boldsymbol{\beta})2\mathrm{Re}(M_J(q)E_J^*(q))\right]$$

With the standard operator definitions as **[Walecka 1975, Oxford University Press]**:

$$C_{JM}(q)=\int d^3x[j_J(qx)Y_{JM}(\Omega_x)](\rho(\mathbf{x};V)+\rho(\mathbf{x};J))$$

$$L_{JM}(q)=\frac{i}{q}\int d^3x\{\nabla[j_J(qx)Y_{JM}(\Omega_x)]\}\cdot(\mathbf{j}(\mathbf{x};V)+\mathbf{j}(\mathbf{x};A))$$

$$E_{JM}(q)=\frac{1}{q}\int d^3x[\nabla\times j_J(qx)\boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)]\cdot(\mathbf{j}(\mathbf{x};V)+\mathbf{j}(\mathbf{x};A))$$

$$M_{JM}(q)=\int d^3x[j_j(qx)\boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)\cdot(\mathbf{j}(\mathbf{x};V)+\mathbf{j}(\mathbf{x};A))$$

Parity and angular momentum selection rules preserve only the four *J*=1, positive parity multipoles for ^{6}He beta-decay

^{6}He Beta Decay Spectrum: Multipoles

$$C_1(q;A) = \frac{i}{\sqrt{4\pi}}\langle {}^6\text{Li},10|\rho_+^\dagger(q\hat{\mathbf{z}};A)|{}^6\text{He},00\rangle$$

$$L_1(q;A) = \frac{i}{\sqrt{4\pi}}\langle {}^6\text{Li},10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{z}};A)|{}^6\text{He},00\rangle$$

$$E_1(q;A) = -\frac{i}{\sqrt{2\pi}}\langle {}^6\text{Li},10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};A)|{}^6\text{He},00\rangle$$

$$M_1(q;V) = -\frac{1}{\sqrt{2\pi}}\langle {}^6\text{Li},10|\hat{\mathbf{y}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};V)|{}^6\text{He},00\rangle$$

The multipoles in the differential rate can be written in terms of matrix elements that can be evaluated with QMC

Schiavilla and Wiringa PRC 65, 054302 (2002)

^{6}He Beta Decay Spectrum: Multipoles

$$
\begin{aligned}
C_1(q;A) &= -i\frac{qr_\pi}{3}\left(C_1^{(1)}(A) - \frac{(qr_\pi)^2}{10}C_1^{(3)}(A) + \mathcal{O}\left((qr_\pi)^4\right)\right) \\
L_1(q;A) &= -\frac{i}{3}\left(L_1^{(0)}(A) - \frac{(qr_\pi)^2}{10}L_1^{(2)}(A) + \mathcal{O}\left((qr_\pi)^4\right)\right) \\
M_1(q;V) &= -i\frac{qr_\pi}{3}\left(M_1^{(1)}(V) - \frac{(qr_\pi)^2}{10}M_1^{(3)}(V) + \mathcal{O}\left((qr_\pi)^4\right)\right) \\
E_1(q;A) &= -\frac{i}{3}\left(E_1^{(0)}(A) - \frac{(qr_\pi)^2}{10}E_1^{(2)}(A) + \mathcal{O}\left((qr_\pi)^4\right)\right)
\end{aligned}
$$

The multipoles in the differential rate can be written in terms of matrix elements that can be evaluated with QMC

Because q is limited by the reaction Q-value, it is limited to small values (<< m_π) and thus one can consider the multipoles expanded for small q

Multipoles have standard definitions in terms of Bessel functions and so can be shown to be purely even or odd in q

$$r_\pi = 1/m_{\pi^+} = 1.41382 \text{ fm}$$

$$qr_\pi \lesssim 0.03$$

King et al. PRC 107, 015503 (2023)

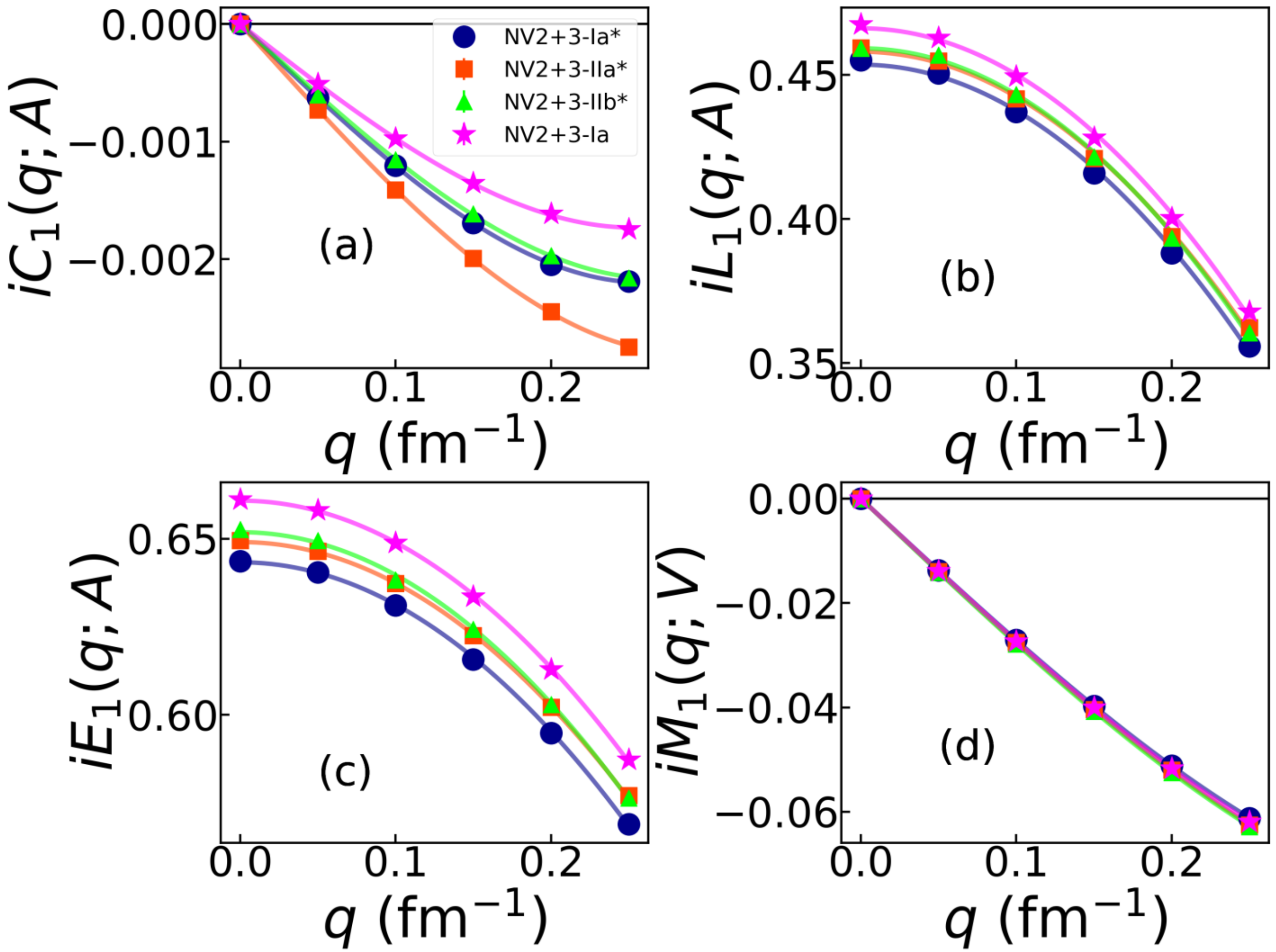
^{6}He Beta Decay Spectrum: SM Results

The strategy: Calculate necessary matrix elements for several small *q* values and fit the small q expansions

Dominant terms $L_1^{(0)}$ and $E_1^{(0)}$ have model dependence of ~1% to ~2%

Linear term model dependencies ~few percent

Quadratic expansion coefficients have significant model dependence, suppressed by q^2 in the differential rate



VMC multipoles

King et al. PRC 107, 015503 (2023)

^{6}He Beta Decay Spectrum: SM Results

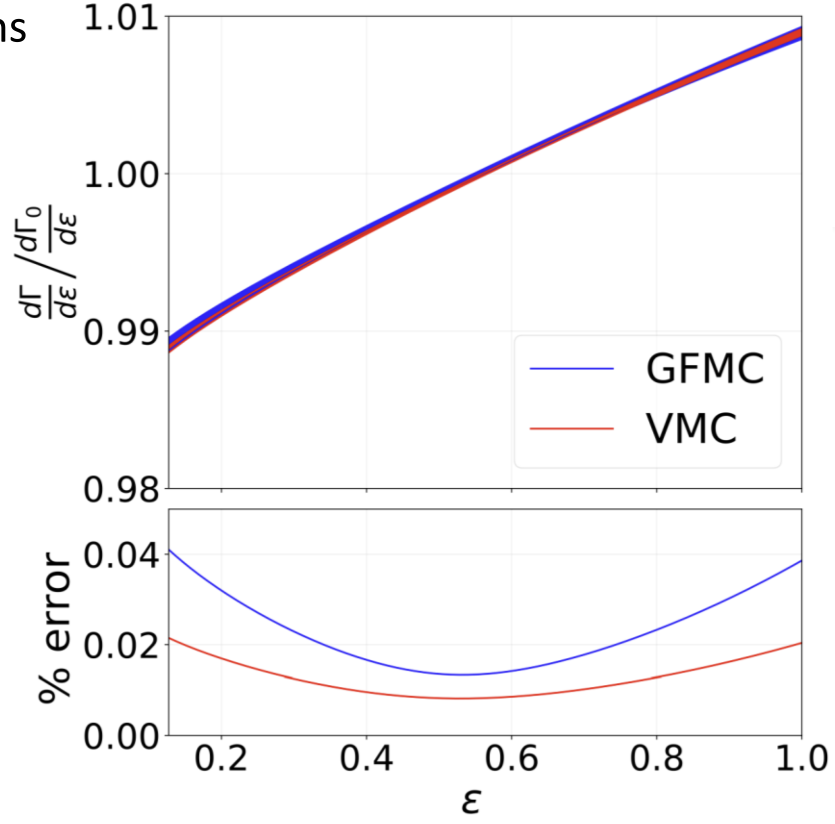
Coefficients fit to VMC and GFMC calculations can be plugged back into decay rate formula

~1% correction arising from retaining *q* dependence in the Standard Model

VMC and GFMC average rates:

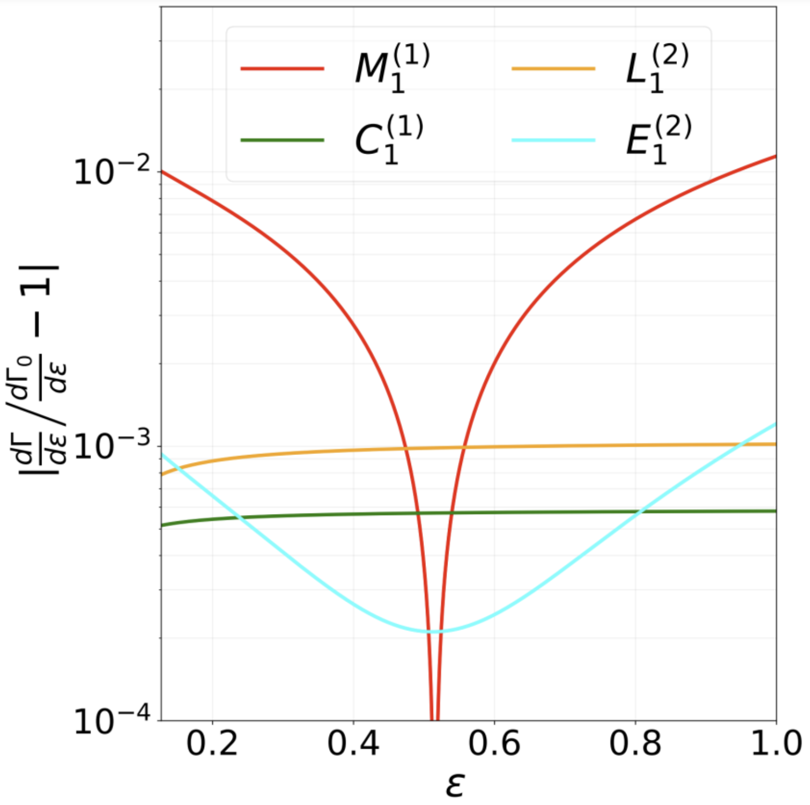
τ_{VMC} = 762 +/- 11 ms
τ_{GFMC} = 808 +/- 24 ms
$\tau_{Expt.}$ = 807.25 +/- 0.16 +/- 0.11 ms
[Kanafani et al. PRC 106, 045502 (2022)]

Cutoff, energy range, and 3N force uncertainties estimated on multipoles from the available model calculations



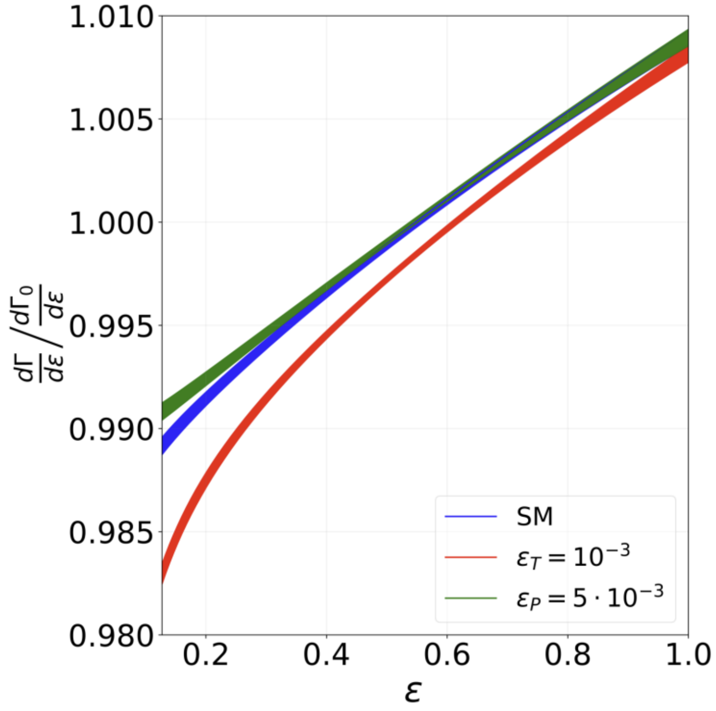
$$\varepsilon = \frac{E_e}{\omega}$$

w/ radiative corrections from **Hayen**



King et al. PRC 107, 015503 (2023)

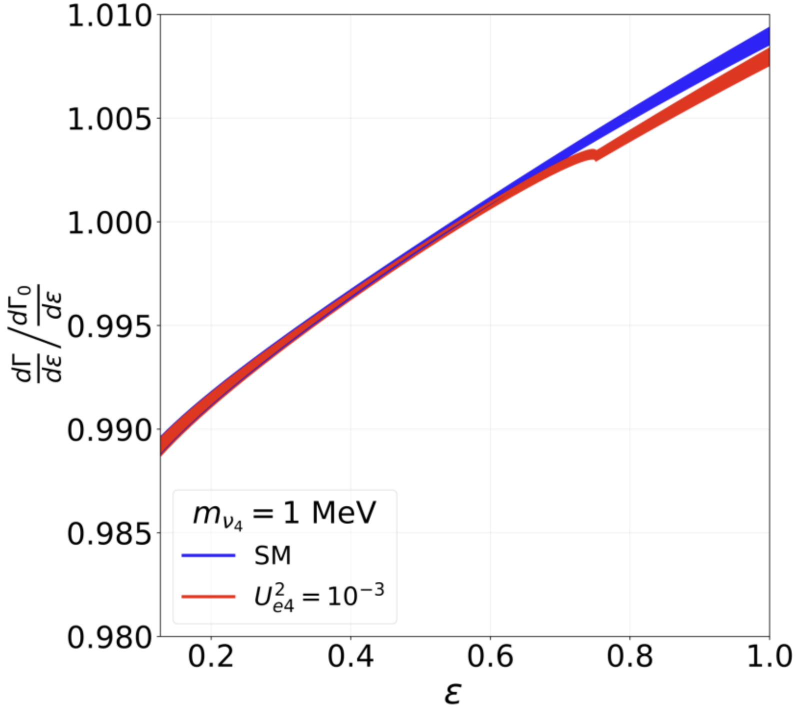
^{6}He Beta Decay Spectrum: BSM Connections



Non-standard CC interactions involving left-handed neutrino

$$\Lambda_{\rm BSM} \sim \frac{v}{\sqrt{\epsilon_i}} \sim 1\text{–}10 \text{ TeV}$$

1 MeV sterile neutrino



Investigate the signatures of BSM physics in ^{6}He β-decay spectrum

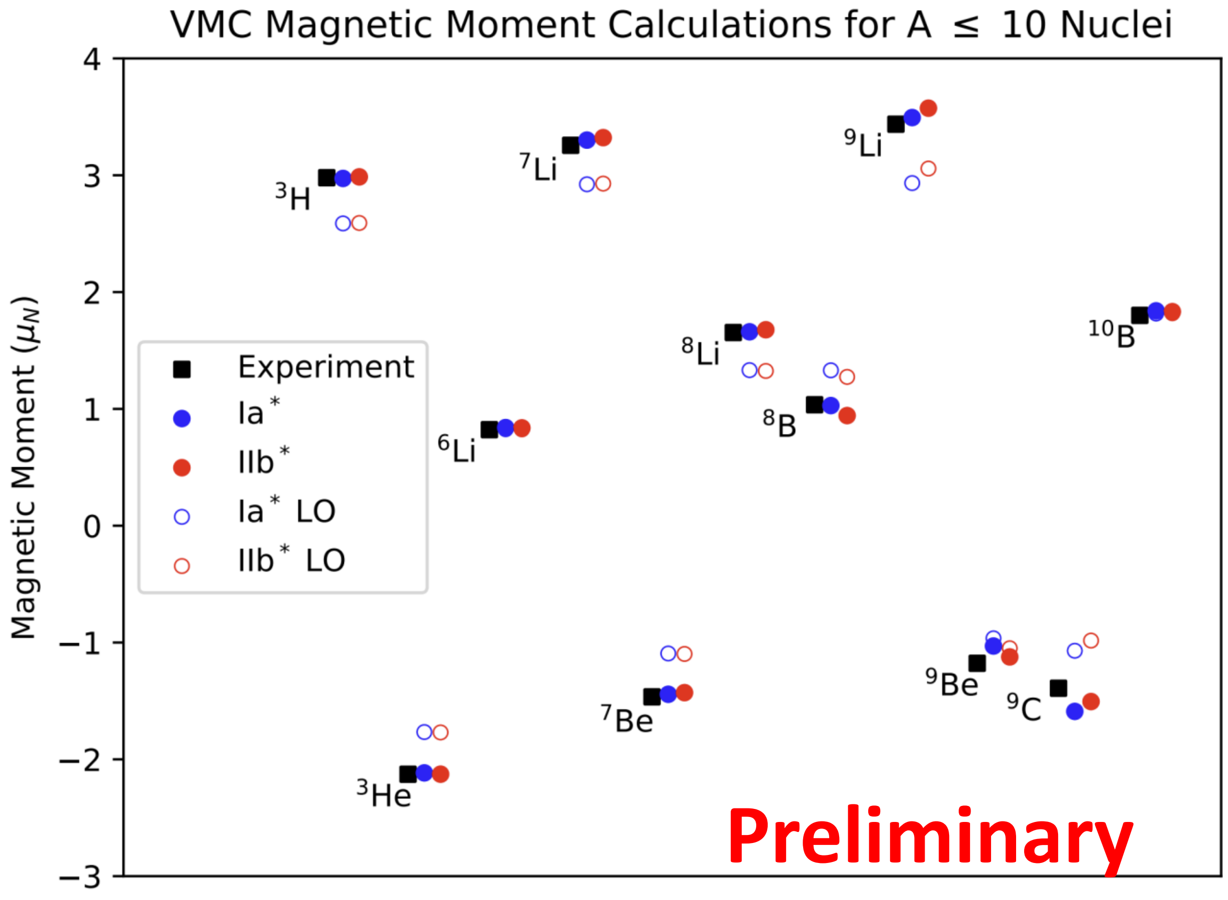
BSM matched to χEFT for non-standard tensor and pseudoscalar currents, 1 MeV sterile neutrino **(Baroni, *Cirigliano, Mereghetti*)**

Sensitive to tensor, less so to pseudoscalar, in next-gen experiments

Sensitivity to ~1 MeV sterile neutrino

King et al. PRC 107, 015503 (2023)

On-going work: χEFT Magnetic Moments



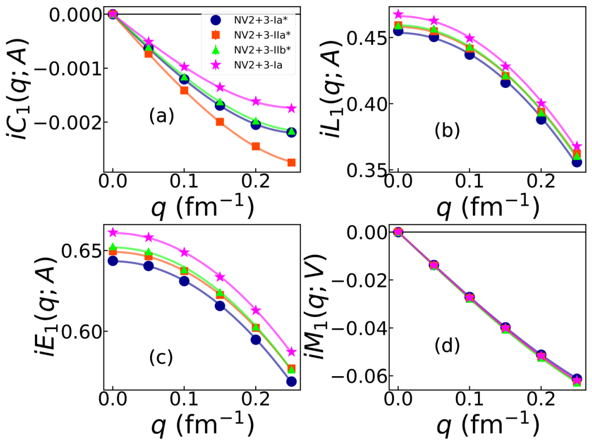
G. Chambers-Wall, 2023

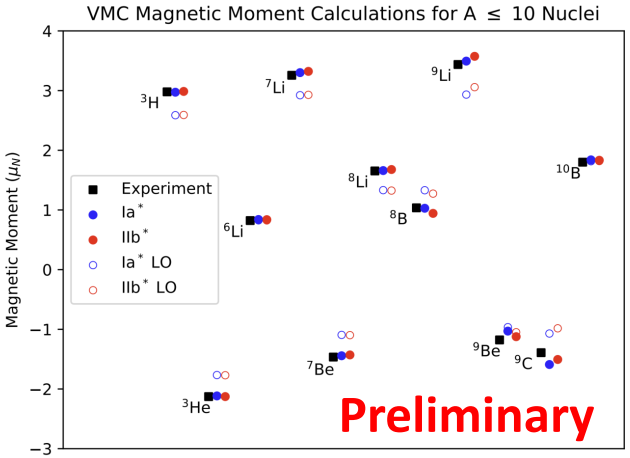
QMC study of magnetic moments and form factors for A ≤ 10 nuclei

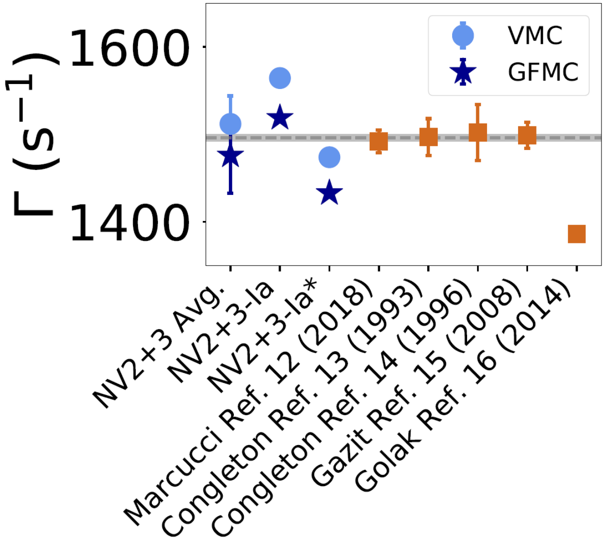
Systematic study with various NV2+3 model classes to estimate effects of fitting choices

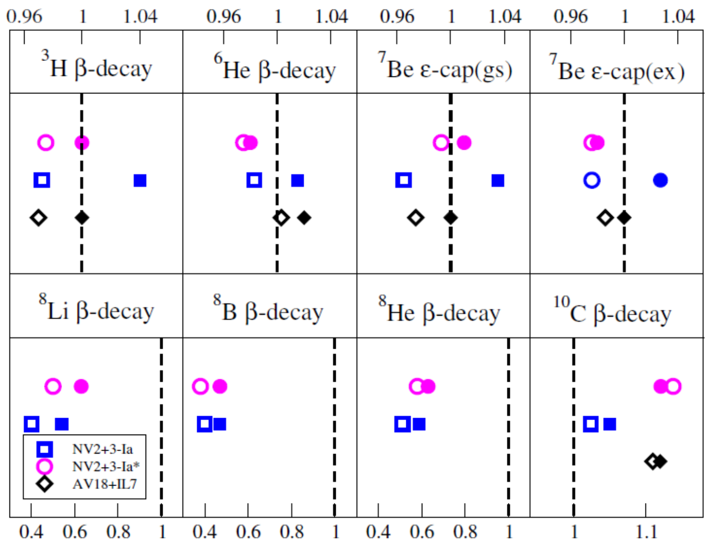
Outlook: Two-body magnetic densities in χEFT, GFMC results

Conclusions and Outlook









QMC methods combined with the NV2+3 interactions provide a powerful tool to understand electroweak structure and reactions in light nuclei

Effects of several choices in chiral interactions manifest in the results seen for beta decay and muon capture

Systematic studies with various NV2+3 models allow one to better understand relevant physics and estimate theoretical uncertainties

Future work: magnetic densities, radiative corrections to superallowed beta decays, neutrinoless double beta decay

Collaborators/Acknowledgements

Wash U QMC: Bub (GS), Chambers-Wall (GS)
Andreoli (PD), McCoy (PD), Pastore (PI), Piarulli (PI)

ANL: Wiringa

ECT*/Trento: Gnech

JLab+ODU: Schiavilla

LANL: Baroni, Carlson, Gandolfi, Mereghetti

MSU+FRIB: Brown, Schmitt, Zegers

NC State: Hayen

UW: Cirigliano

Funding from DOE/NNSA Stewardship Science Graduate Fellowship

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