Nuclear beta decay for fundamental science

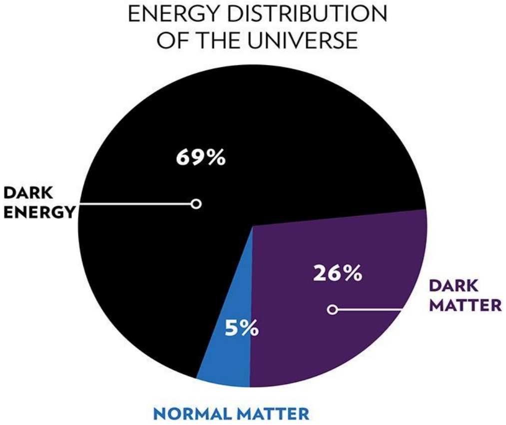
Garrett King

INT Workshop 26-95W
Testing the Standard Model in Charged-Weak Decays
1/14/2026

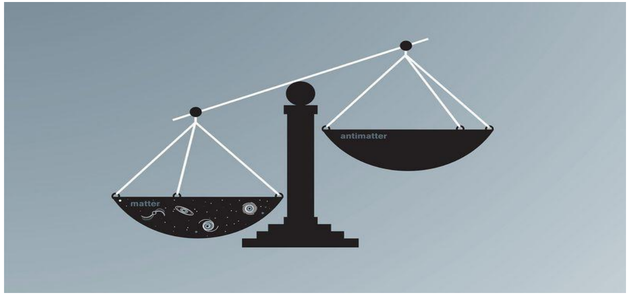
LA-UR-25-32298

Why beyond Standard Model (BSM) physics?

Fermilab / Sandbox Studio, Chicago

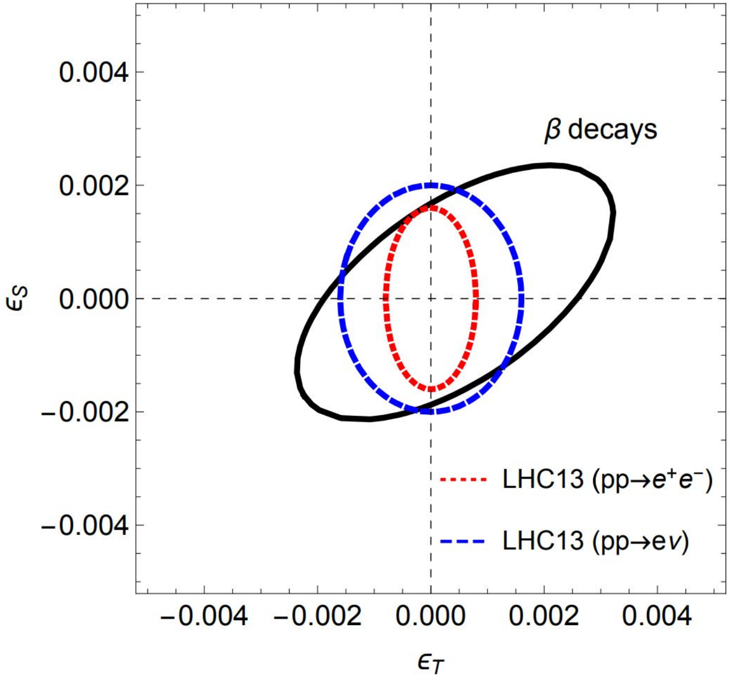


NASA / Chandra X-ray Center/ K. Divona



Symmetry Magazine / Sandbox Studio, Chicago

New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

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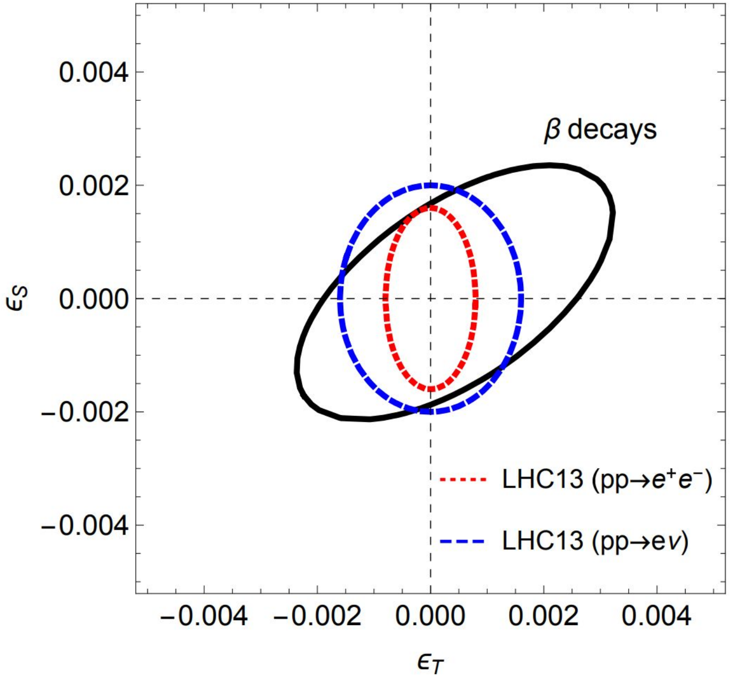
New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

Question: How reliable are the estimates of nuclear uncertainties?

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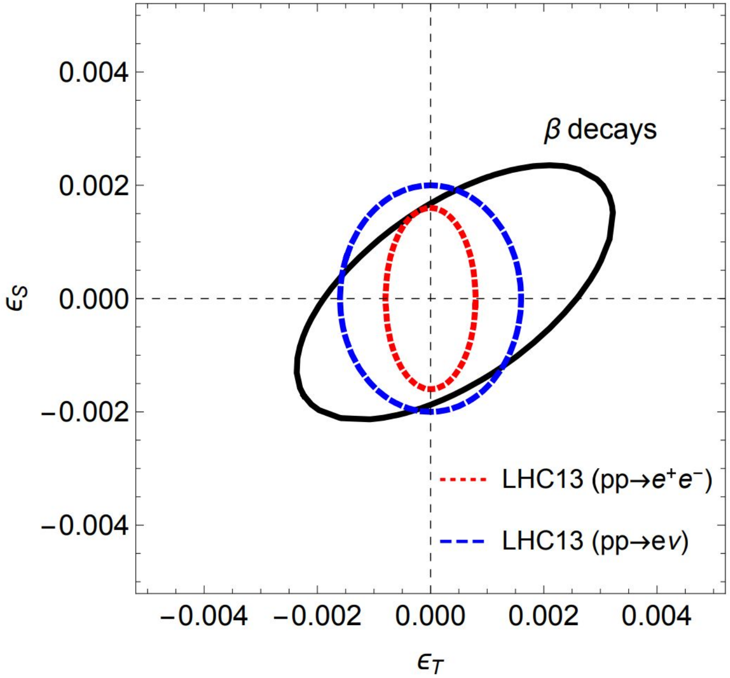
New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

Question: How reliable are the estimates of nuclear uncertainties?

To answer, we need *precise* and *accurate* calculations of nuclear observables

Landscape of *ab initio* calculations

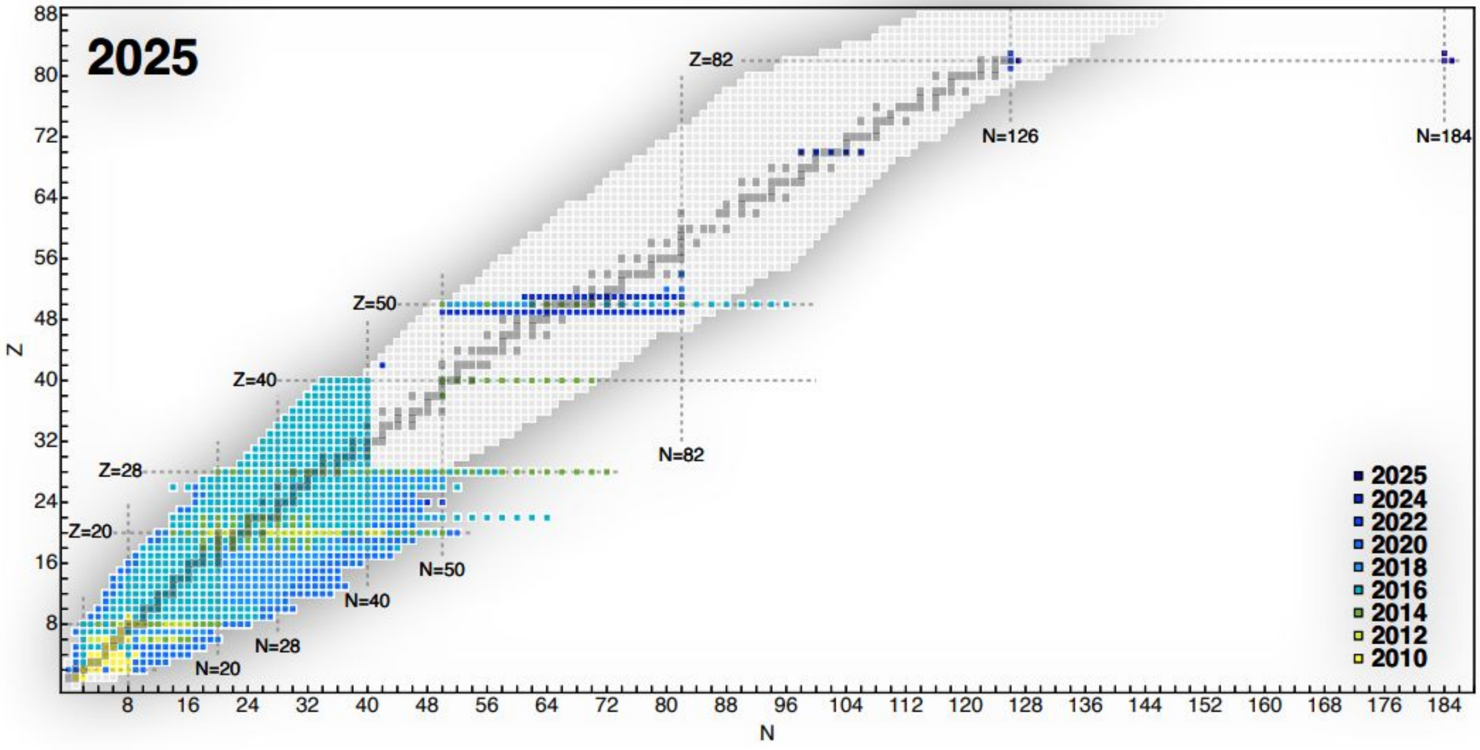


Figure courtesy of Heiko Hergert

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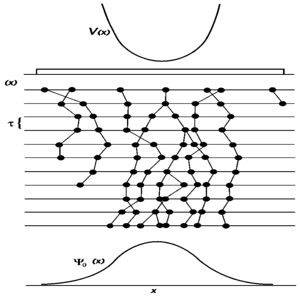
Many-body approaches

- **Coordinate space:**
  - Quantum Monte Carlo
  - Lattice EFT
- **Configuration Space (Particle-Hole Expansions):**
  - No-core shell model (NCSM)
  - Coupled Cluster (CC)
  - In-medium SRG (IMSRG)
  - Self-consistent Green's Functions (SCGF)
  - Many-body perturbation theory (MBPT)
- **Configuration Space (Geometric Expansions):**
  - Symmetry-adapted NCSM
  - Projected GCM
  - Deformed HFB + projection

Foulkes et al. Rev. Mod. Phys. 73, 33 (2001)



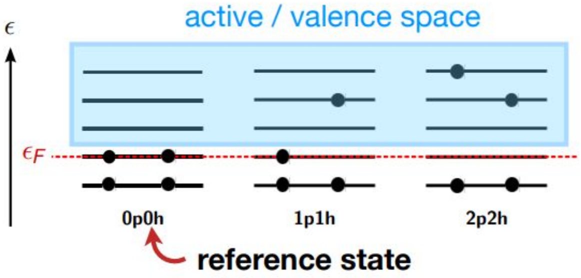


Figure: H. Herget

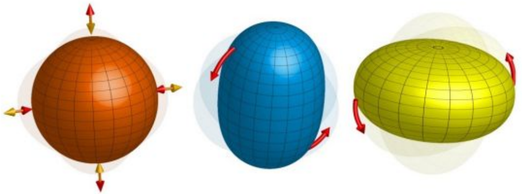


Figure: H. Herget

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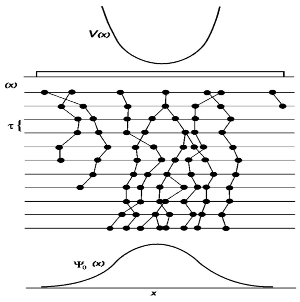

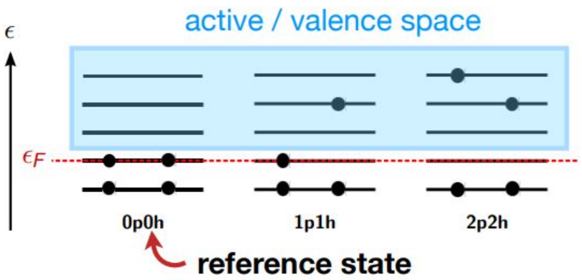

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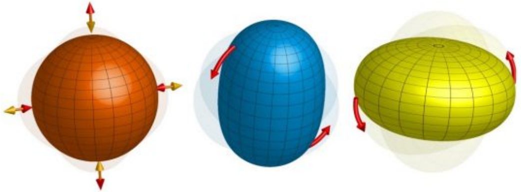
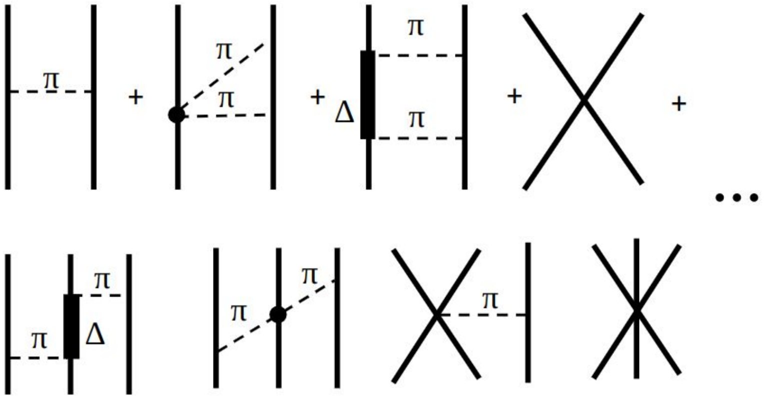


Figure: H. Herget

Chiral effective field theory schematic



*In principle

Procedure to root NN interaction in symmetries of Quantum Chromodynamics*

Scales: Nucleon momentum $Q \sim m_\pi \sim m_N - m_\Delta$ vs. heavier mesons at the scale $\Lambda \sim 1$ GeV -> ***Systematically improvable expansion****

Low-energy constants (LECs) subsume the underlying QCD

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

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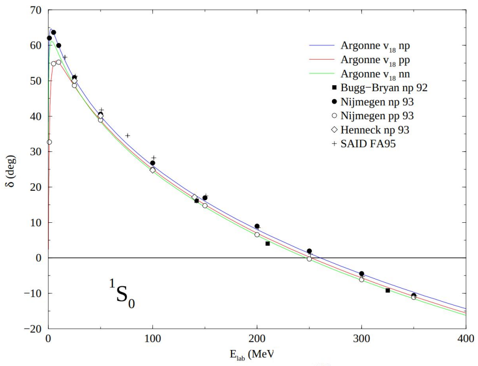
The Argonne v18 (AV18) interaction

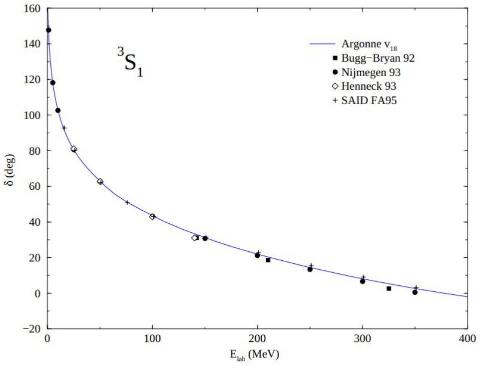
Phenomenological nuclear Hamiltonian with 18 operators, 40 parameters

Includes one- and two-pion exchange, and contact terms

Fit to np, pp phase shift data through F waves

Used in conjunction with three-body forces (ex: IL7)





https://www.phy.anl.gov/theory/research/av18/

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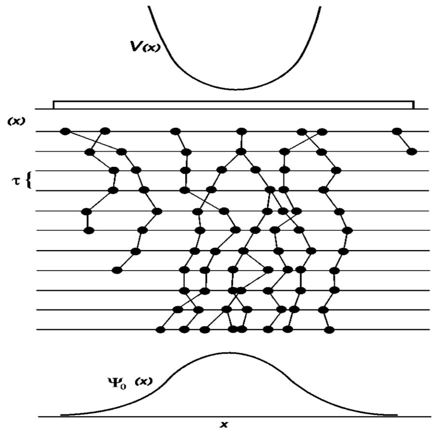
Wiringa, Stoks, Schiavilla PRC 51, 38 (1995)

Quantum Monte Carlo

Solving the many-body problem using random sampling to compute integrals

Variational MC wave function $|\Psi_T\rangle = \mathcal{F}|\Phi\rangle$ contains model wave function and many-body correlations optimized by minimizing:



$$E_V = \min\left\{\frac{\langle\Psi_T|H|\Psi_T\rangle}{\langle\Psi_T|\Psi_T\rangle}\right\} \geq E_0$$

Green's function MC improves by ***removing excited state contamination and gives the exact ground state***

$$\lim_{\tau\to\infty} e^{-(H-E_0)\tau}\Psi_V = \lim_{\tau\to\infty} e^{-(H-E_0)\tau}\left(c_0\psi_0 + \sum_{i=1}^{N} c_i\psi_i\right) \to c_0\psi_0$$

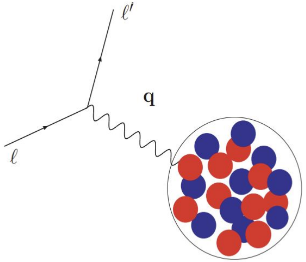
Foulkes et al. Rev. Mod. Phys. 73, 33 (2001)

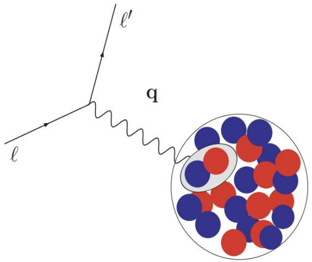
Electroweak charge and current operators

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





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), …

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^{6}He β-decay spectrum: Overview

Differential rate: $$\frac{d\Gamma_0}{dE_e} = |M|^2 G_\beta(E_e)$$

New physics can distort this: $$\frac{d\Gamma}{dE_e} = \frac{d\Gamma_0}{dE_e}\left[1 + b\frac{m_e}{E_E}\right]$$

Similar distortions can be generated when accounting for nuclear recoil

Performed calculation with recoil corrections and two-body physics effects

Vector
Scalar
→ **Fermi**

Axial
Tensor
Pseudoscalar
→ **GT**

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^{6}He β-decay spectrum: Multipole decomposition

$$\begin{aligned} d\Gamma &= 2\pi\delta(M_i - E_f - E_e - E_\nu) G_F^2 V_{ud}^2 \frac{4\pi}{2J_i+1} \\ &\Bigg[(1+\mathbf{v}_e\cdot\mathbf{v}_\nu)\sum_{l\geq 0}|C_l(q)|^2 + (1-\mathbf{v}_e\cdot\mathbf{v}_\nu + 2\mathbf{v}_e\cdot\hat{\mathbf{q}}\,\mathbf{v}_\nu\cdot\hat{\mathbf{q}})\sum_{l\geq 0}|L_l(q)|^2 \\ &-2\hat{\mathbf{q}}\cdot(\mathbf{v}_e+\mathbf{v}_\nu)\sum_{l\geq 0}\mathrm{Re}\left[C_l(q)L_l^\star(q)\right] + (1-\mathbf{v}_e\cdot\hat{\mathbf{q}}\,\mathbf{v}_\nu\cdot\hat{\mathbf{q}})\sum_{l\geq 1}\left[|M_l(q)|^2+|E_l(q)|^2\right] \\ &\pm 2\hat{\mathbf{q}}\cdot(\mathbf{v}_\nu-\mathbf{v}_e)\sum_{l\geq 1}\mathrm{Re}\left[M_l(q)E_l^\star(q)\right]\Bigg] \frac{d^3\mathbf{p}_e}{(2\pi)^3}\frac{d^3\mathbf{p}_\nu}{(2\pi)^3} \end{aligned}$$

Spectrum can be written in terms of multipole operators (C, L, M, E)

Low q value of the decay means we can consider expansion of multipoles

Expand multipoles, kinematics to write down spectrum differential in electron energy

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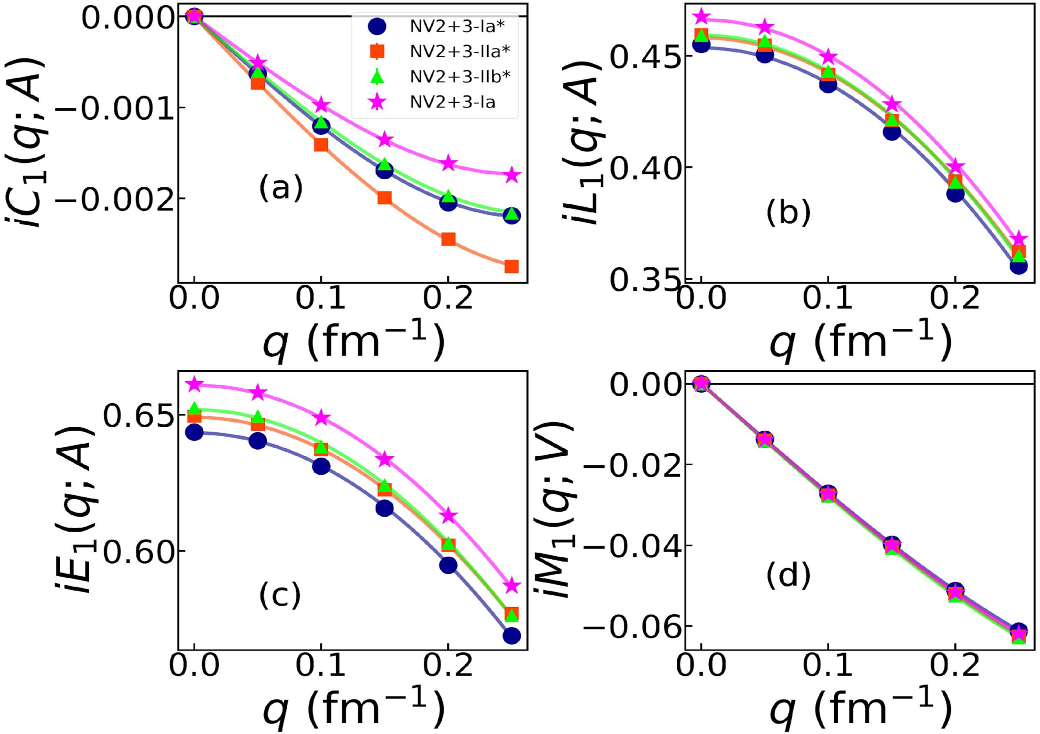
^{6}He β-decay spectrum: Multipoles

Distortion term is a function of four nuclear matrix elements:

$$
\begin{aligned}
C_1(q;A) &= \frac{i}{\sqrt{4\pi}}\langle {}^6\mathrm{Li},10|\rho_+^\dagger(q\hat{\mathbf{z}};A)|{}^6\mathrm{He},00\rangle \\
L_1(q;A) &= \frac{i}{\sqrt{4\pi}}\langle {}^6\mathrm{Li},10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{z}};A)|{}^6\mathrm{He},00\rangle \\
E_1(q;A) &= -\frac{i}{\sqrt{2\pi}}\langle {}^6\mathrm{Li},10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};A)|{}^6\mathrm{He},00\rangle \\
M_1(q;V) &= -\frac{1}{\sqrt{2\pi}}\langle {}^6\mathrm{Li},10|\hat{\mathbf{y}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};V)|{}^6\mathrm{He},00\rangle
\end{aligned}
$$



King et al. PRC 107, 015503 (2023)

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^{6}He β-decay spectrum: Multipoles

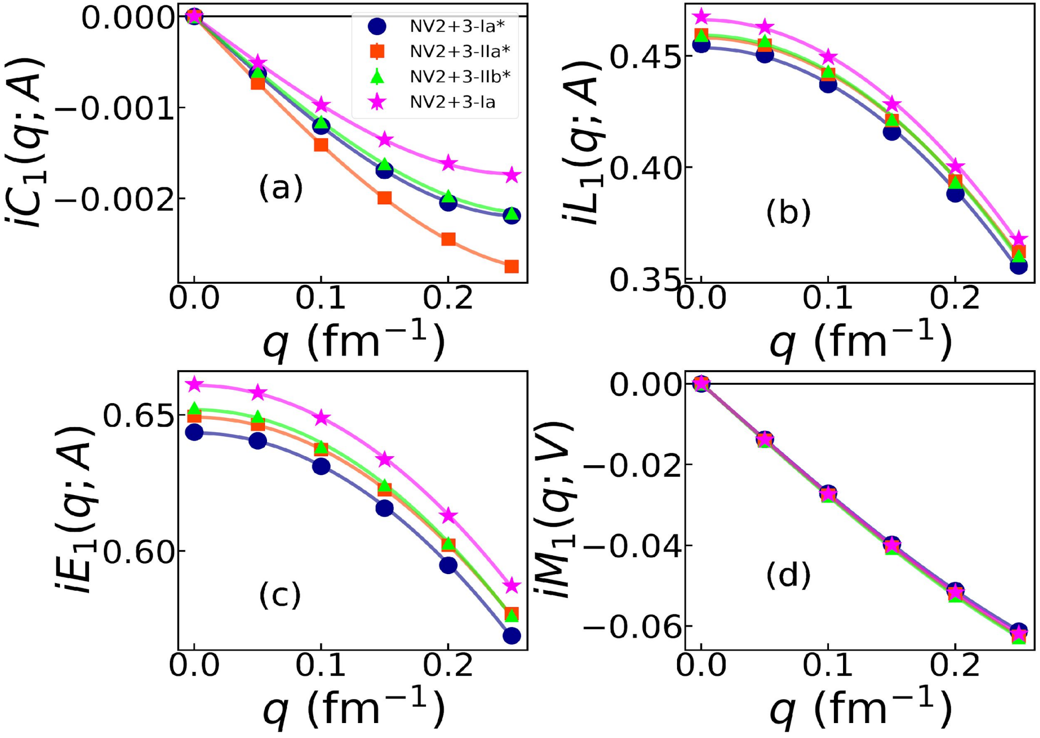
Distortion term is a function of four nuclear matrix elements:

$$C_1(q;A) = -i\frac{qr_\pi}{3}\left(C_1^{(1)}(A) - \frac{(qr_\pi)^2}{10}C_1^{(3)}(A) + \mathcal{O}\left[(qr_\pi)^4\right]\right)$$

$$L_1(q;A) = -\frac{i}{3}\left(L_1^{(0)}(A) - \frac{(qr_\pi)^2}{10}L_1^{(2)}(A) + \mathcal{O}\left[(qr_\pi)^4\right]\right)$$

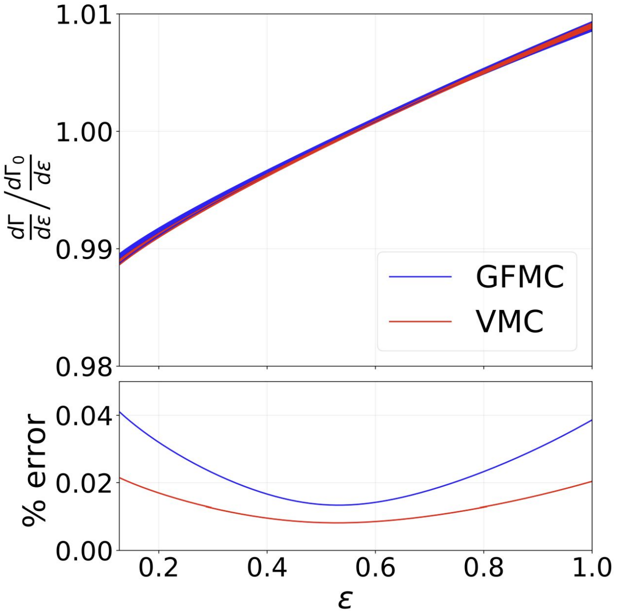
$$M_1(q;V) = -i\frac{qr_\pi}{3}\left(M_1^{(1)}(V) - \frac{(qr_\pi)^2}{10}M_1^{(3)}(V) + \mathcal{O}\left[(qr_\pi)^4\right]\right)$$

$$E_1(q;A) = -\frac{i}{3}\left(E_1^{(0)}(A) - \frac{(qr_\pi)^2}{10}E_1^{(2)}(A) + \mathcal{O}\left[(qr_\pi)^4\right]\right)$$



King et al. PRC 107, 015503 (2023)

^{6}He β-decay spectrum: Standard Model results



$$\frac{d\Gamma}{d\varepsilon} = (1+\Delta_R^V)(1+\delta_R(Z,\varepsilon))\frac{G_F^2 W_0^5 V_{ud}^2}{2\pi^3}\sqrt{1-\frac{\mu_e^2}{\varepsilon^2}}\,\varepsilon^2(1-\varepsilon)^2 F_0(Z,\varepsilon)L_0(Z,\varepsilon)S(Z,\varepsilon)R_N(\varepsilon)$$

$$\frac{4\pi}{2J_i+1}\frac{1}{9}\Bigg\{3\left|L_1^{(0)}\right|^2\left[1+\alpha Z W_0 R\left(\frac{2}{35}-\frac{233}{630}\frac{\alpha Z}{W_0 R}-\frac{1}{70}\frac{\mu_e^2}{\varepsilon}-\frac{4}{7}\varepsilon\right)\right]$$

$$+2W_0 r_\pi\left[\left(1-2\varepsilon+\frac{\mu_e^2}{\varepsilon}\right)\mathrm{Re}(E_1^{(0)}M_1^{(1)*})-\left(1-\frac{\mu_e^2}{\varepsilon}\right)\mathrm{Re}(L_1^{(0)}C_1^{(1)*})\right]$$

$$+\frac{(W_0 r_\pi)^2}{3}\Bigg[\left(3-4\varepsilon(1-\varepsilon)-\mu_e^2\frac{2+\varepsilon}{\varepsilon}\right)|C_1^{(1)}|^2-\frac{3}{5}\left(1-\frac{\mu_e^2}{\varepsilon}(2-\varepsilon)\right)\mathrm{Re}\left(L_1^{(0)}L_1^{(2)*}\right)$$

$$+\left(3-10\varepsilon(1-\varepsilon)+\mu_e^2\frac{4-7\varepsilon}{\varepsilon}\right)\left(\left|M_1^{(1)}\right|^2-\frac{1}{5}\mathrm{Re}\left(E_1^{(0)}E_1^{(2)}\right)\right)\Bigg]$$

$$-\frac{4}{7}\frac{\alpha Z W_0 r_\pi^2}{R}(1-\varepsilon)\left(\frac{E_1^{(0)}E_1^{(2)}}{2}-L_1^{(0)}L_1^{(2)}\right)\Bigg\}$$

Fully expanded spectrum in terms of multipole coefficients with Behrens-Bühring RC, Coulomb, shielding, and recoil corrections

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

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King et al. PRC 107, 015503 (2023)

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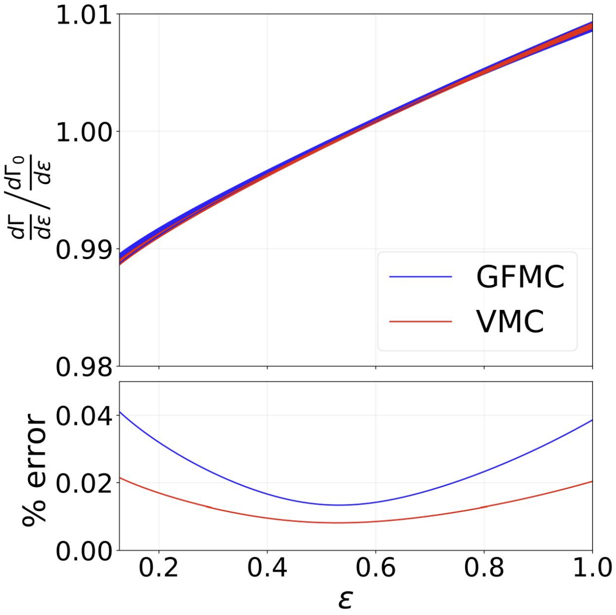
lpc caen

^{6}He β-decay spectrum: Standard Model results



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

Model uncertainty plus two-body contribution brings theory precision within needs of experiment

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)]

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King et al. PRC 107, 015503 (2023)

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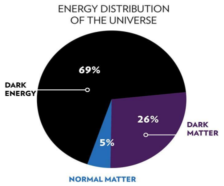
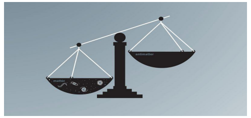
^{6}He β-decay spectrum: Probing new forces

Included transition operators associated with new physics

With permille precision, it will be possible to further constrain new physics

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





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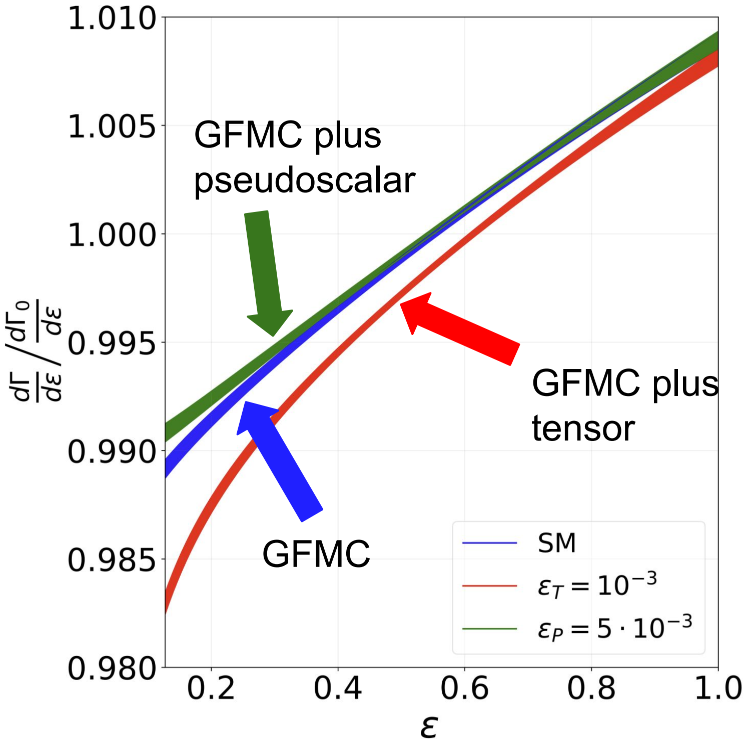
^{6}He-CRES

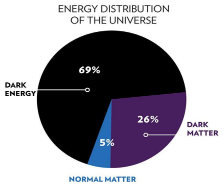


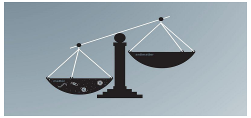
King et al. PRC 107, 015503 (2023)

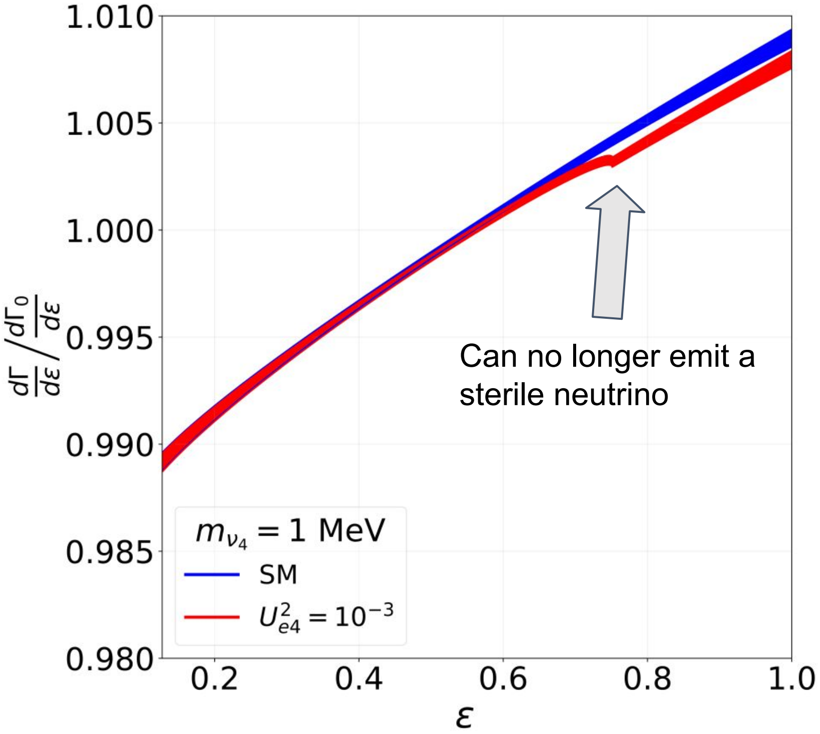
^{6}He β-decay spectrum: Probing neutrino physics

Can also investigate impacts from production of ~1 MeV sterile neutrinos

The shape of the decay endpoint can exclude some parameter space and probe BSM scenarios







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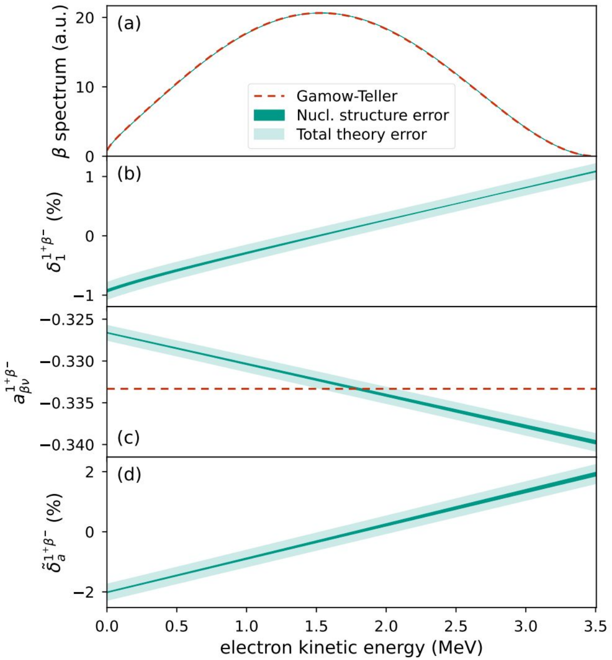
^{6}He-CRES

King et al. PRC 107, 015503 (2023)

Comparison with NCSM results



Glick-Magid et al. Phys. Lett. B 832 (2022) 137259

Favorable comparison with previous result using NCSM with LO currents

b(NCSM) = -1.52(18) x 10^{-3}

b(GFMC) = -1.47(03) x 10^{-3}

With two-body currents, uncertainty on b Fierz is reduced

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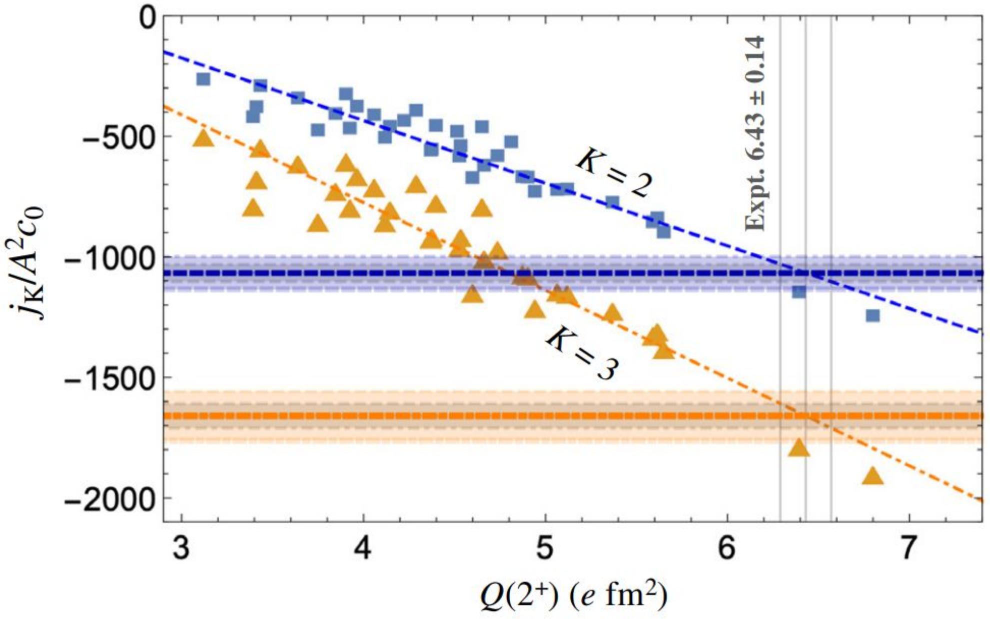
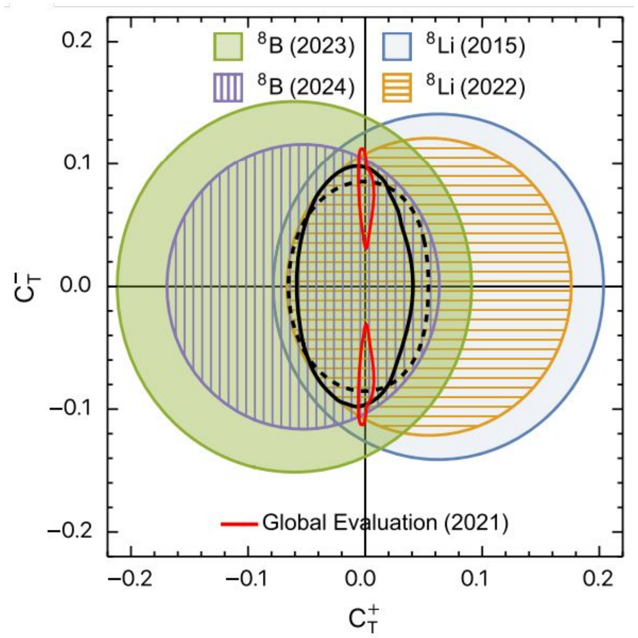
A=8 spectra with SA-NCSM





Longfellow et al. PRL 132, 142502 (2024)

Falkowski et al, JHEP04 (2021) 126

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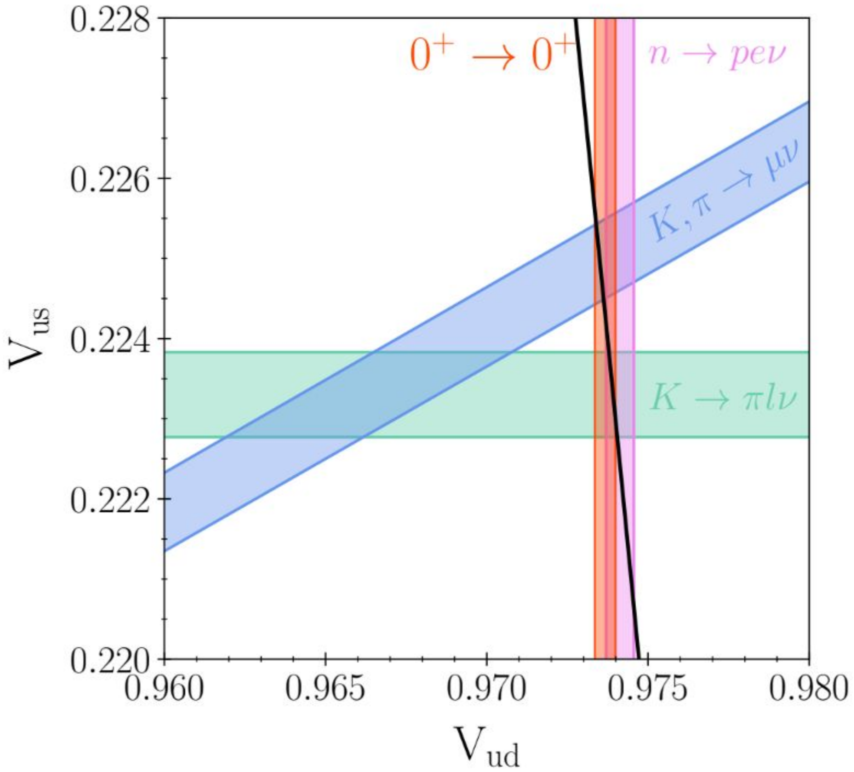
Nuclear β-decay for tests of CKM unitarity



Cirigliano et al., PLB 838 (2023) 137748

Superallowed $0^+ \rightarrow 0^+$ decays

$$\mathcal{F}t = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)} = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

Transition-independent single-nucleon corrections

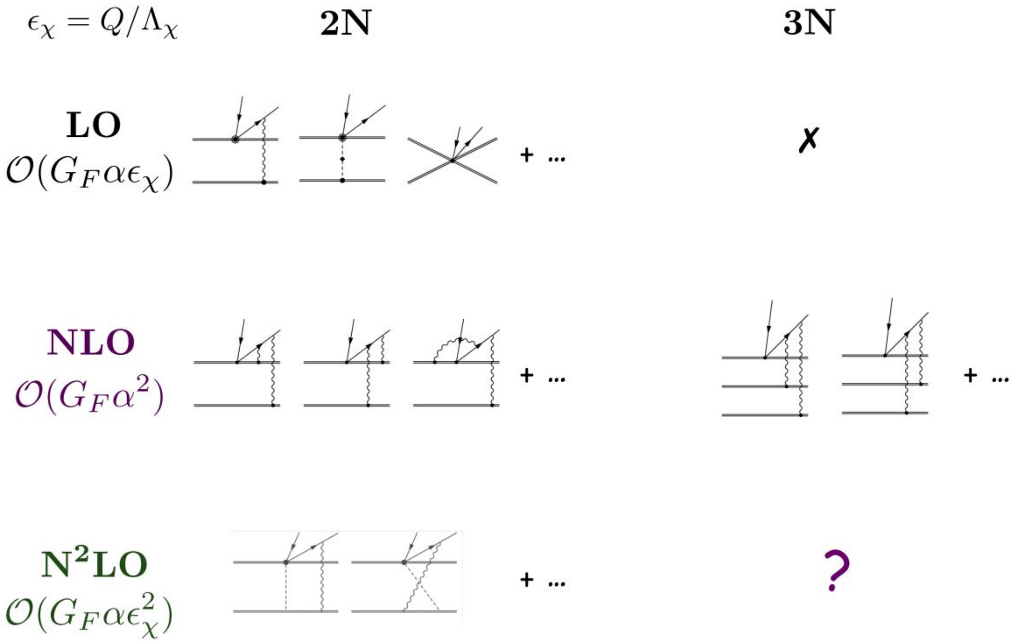
Correction sensitive to charge and electron energy

Sensitive to internal structure of the nucleus

Broken isospin symmetry between protons and neutrons

EFT approach to radiative corrections

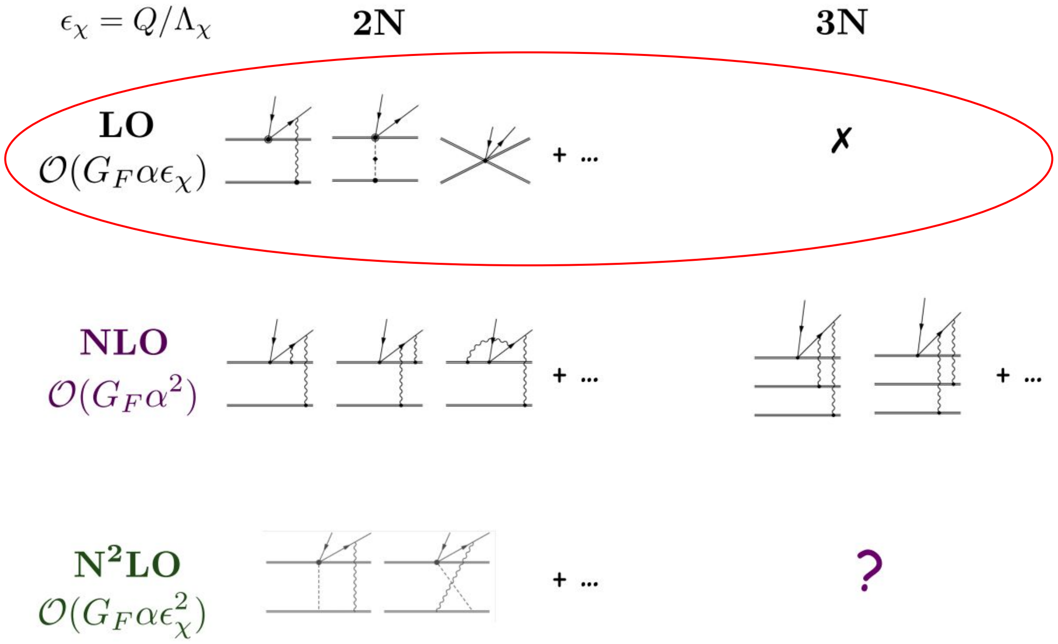
Cirigliano, Dekens, Hoferichter, Mereghetti, Tomalak, + …



Cirigliano et al. PRL 133, 211801 (2024)

EFT approach to radiative corrections

Cirigliano, Dekens, Hoferichter, Mereghetti, Tomalak, + …



Cirigliano et al. PRL 133, 211801 (2024)

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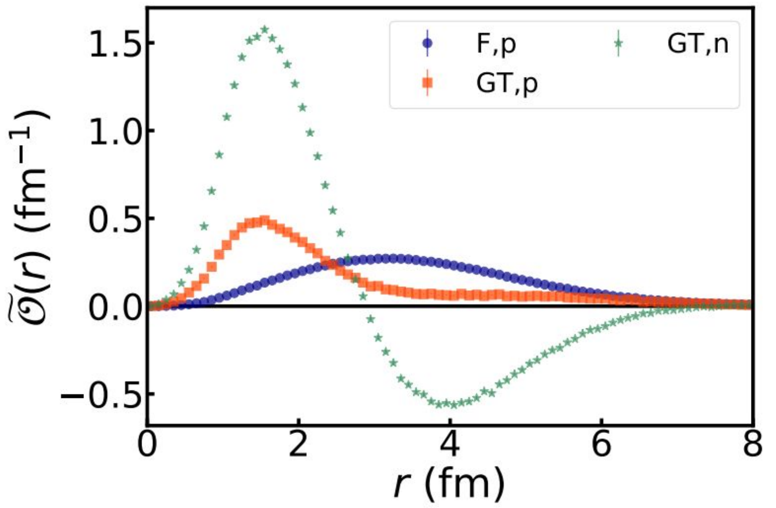
$^{10}C(0^+) \rightarrow {}^{10}B(0^+)$ β-decay

In an effective field theory approach:

$$\delta_{\rm NS} = \sum_{m,n,i} \alpha^m E_0^n c_{m,n} M_{m,n}^i$$

Can also evaluate: $$M = \int dr C(r)\widetilde{\mathcal{O}}(r)$$



King et al., arXiv:2509.07310v1

GFMC: $\delta_{\rm NS} = -4.46(48)\times 10^{-3} - -4.64(77)\times 10^{-3}$

Hardy and Towner: $\delta_{\rm NS} = -4.0(5)\times 10^{-3}$

Gennari et al PRL 134, 012501: $\delta_{\rm NS} = -4.22(32)\times 10^{-3}$

Auxiliary Field Diffusion Monte Carlo (AFDMC)

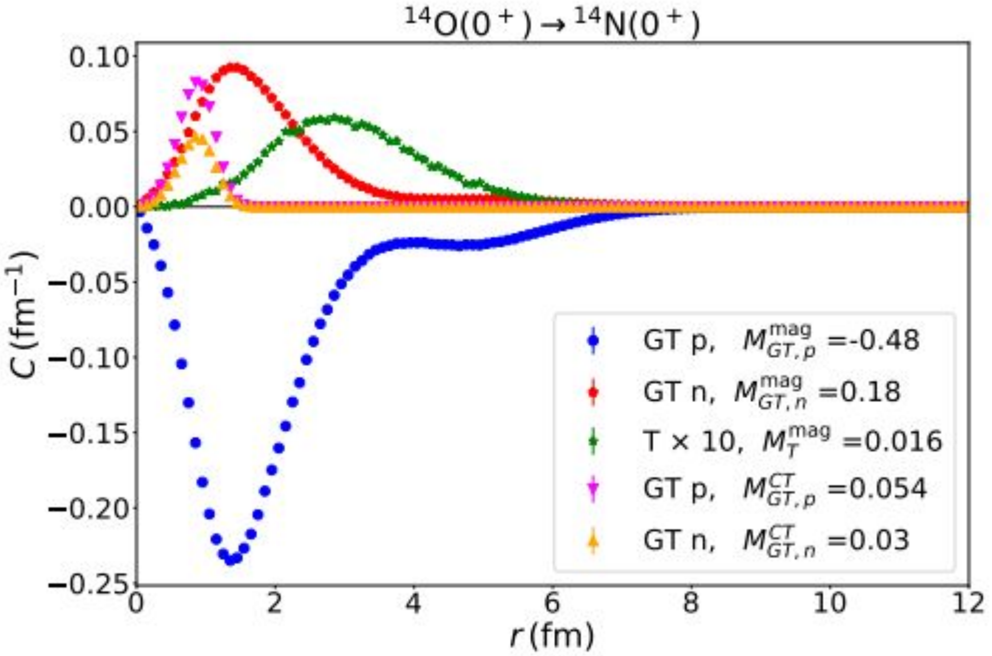
Use the single particle basis: $\langle S|\Psi\rangle \propto \xi_{\alpha_1}(s_1)\,\xi_{\alpha_2}(s_2)\ldots\,\xi_{\alpha_A}(s_A)$

Can linearize two-body operators: $e^{-\frac{\lambda}{2}\mathcal{O}^2} = \frac{1}{\sqrt{2\pi}}\int dx e^{-\frac{x^2}{2}} e^{x\sqrt{-\lambda}\mathcal{O}}$

Polynomial scaling in particle number, but technically more complicated to operate on the wave function

Lonardoni *et al.*, PRC 97, 044318 (2018)

$^{14}O(0^+)$ decay using AFDMC



Cirigliano et al. PRC 110, 055502 (2024)

Evaluation using one chiral EFT potential

Results in $\delta_{\mathrm{NS}} = -2.84(88) \times 10^{-3}$

Agrees with standard result:

$$\delta_{\mathrm{NS}} = -2.83(64) \times 10^{-3}$$

Future work to quantify uncertainty by varying interactions

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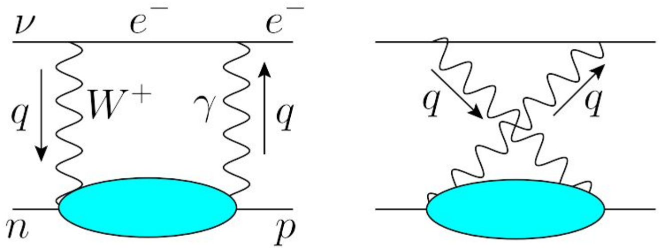
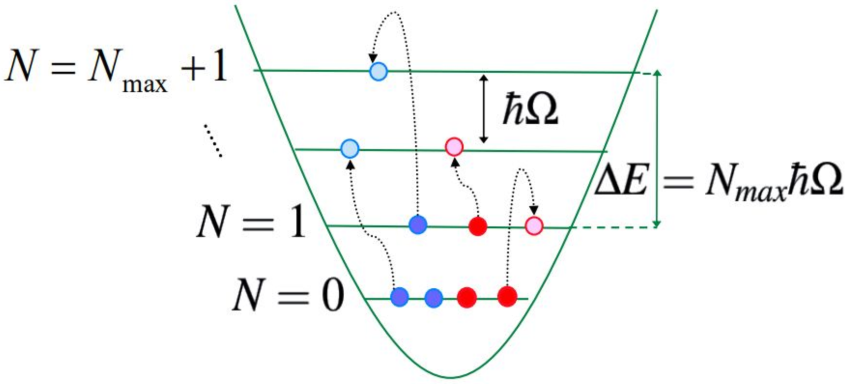
NCSM + Dispersive approach

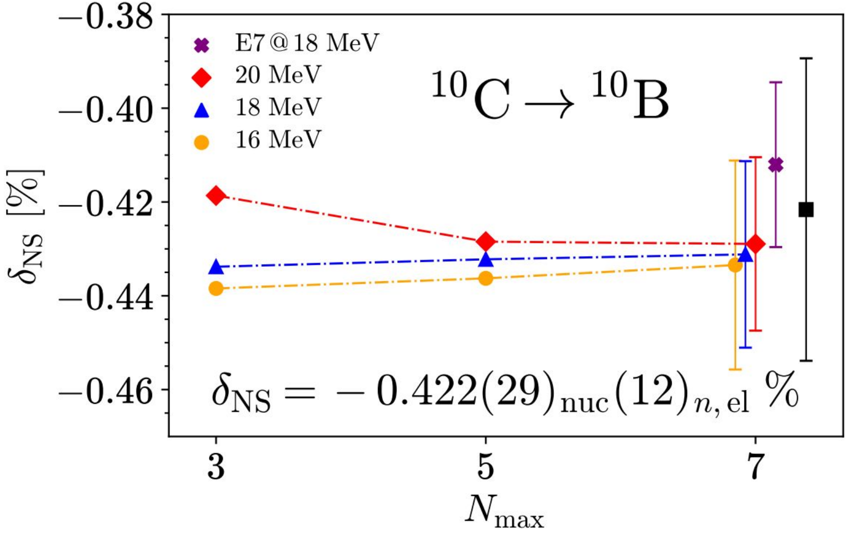


C.-Y. Seng PRD 100, 013001 (2019)

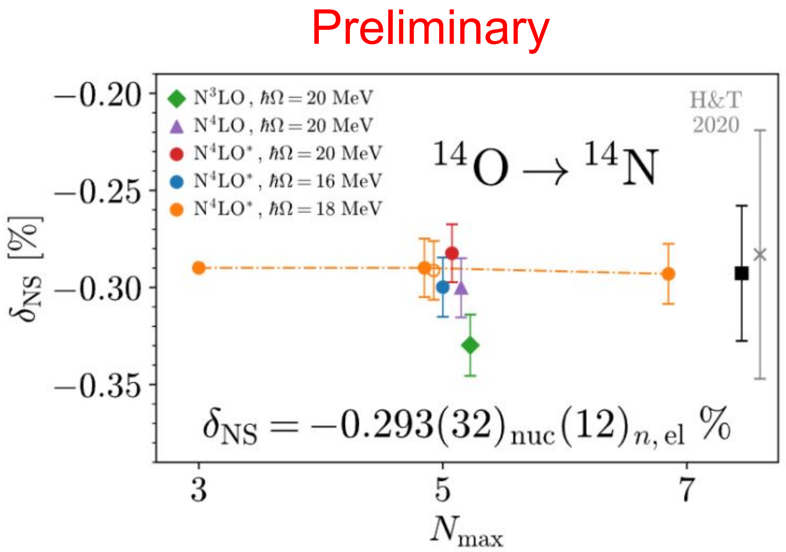


cf. talk by Misha Gorshteyn

NCSM + Dispersive approach



M. Gennari et al. PRL 134, 012501 (2025)



M. Gennari, “Electroweak Radiative Corrections in Super-Allowed Beta Decays from Ab Initio Theory” (2025)

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Outlook: Benchmark QMC + Coupled-cluster

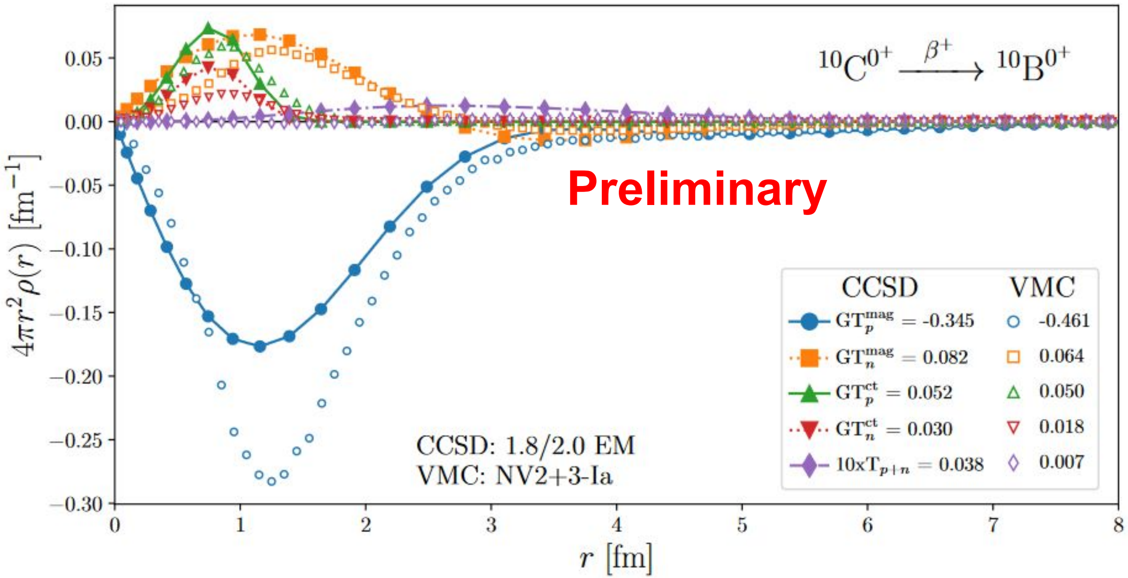

Figure courtesy of Sam Novario

Benchmarking different models, methods in first step toward global analysis

Qualitative agreement, but further analysis necessary

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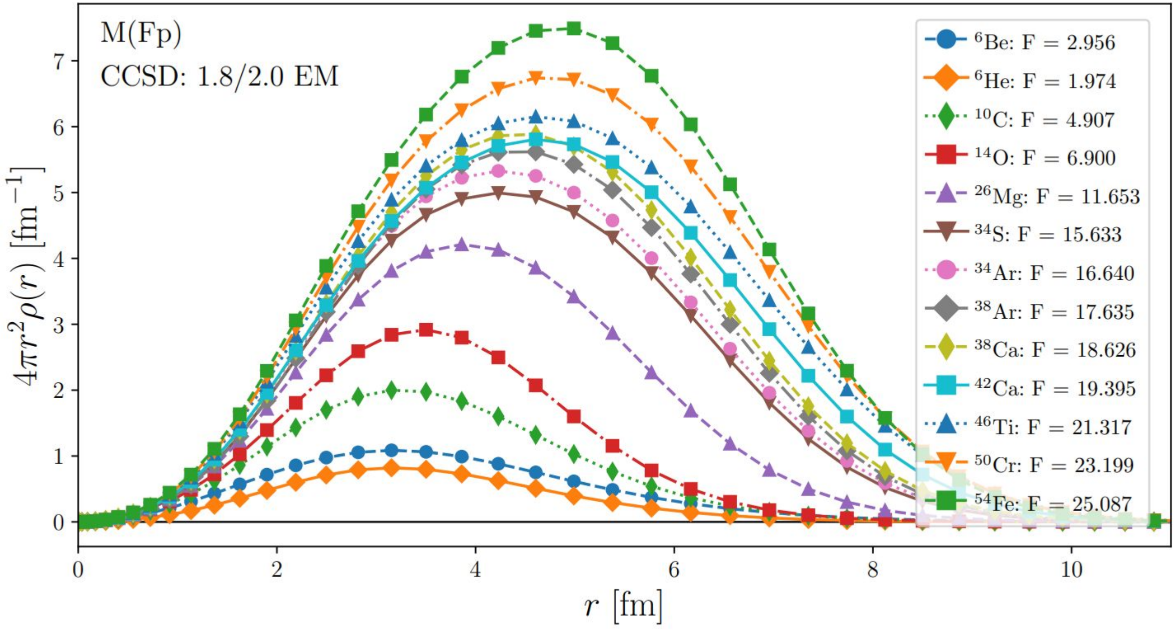
Outlook: Global analysis Coupled-cluster

Preliminary



S. J. Novario, "Nuclear-Structure Corrections in Superallowed Beta Decay" (2025)

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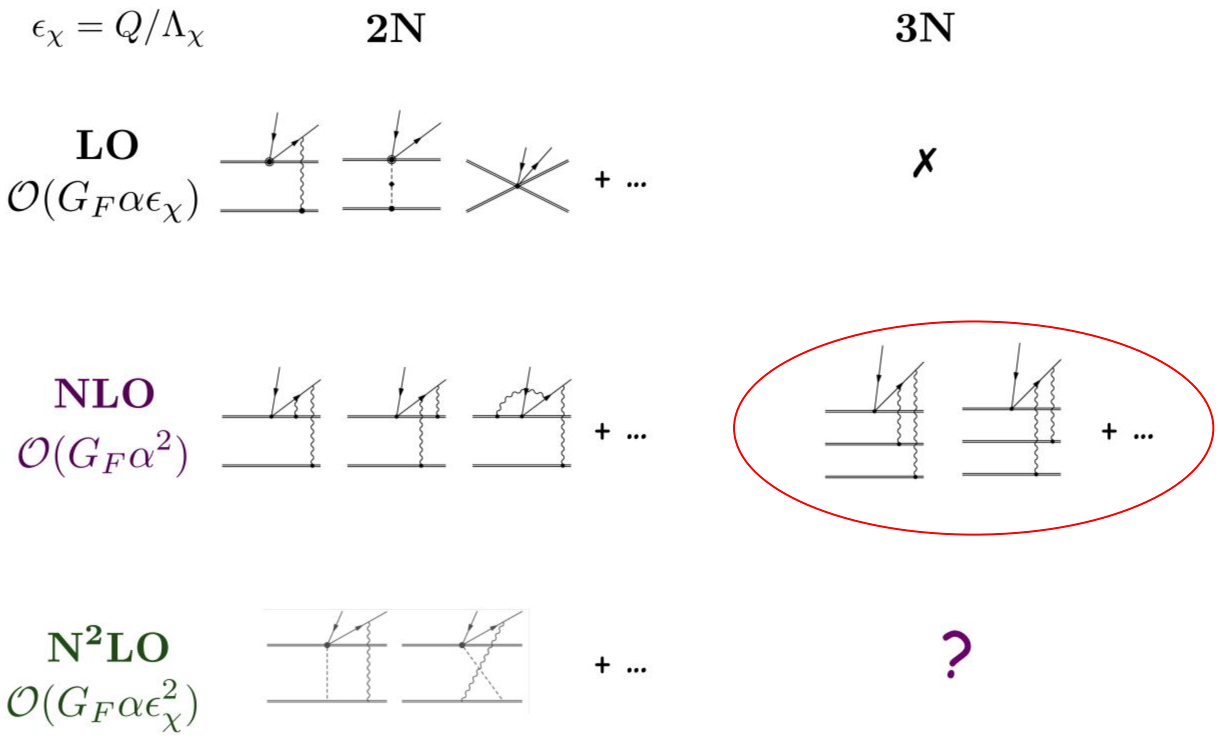
Outlook: Higher-order EFT operators

G. Chambers-Wall, Cirigliano, Dekens, Hoferichter, Mereghetti, Tomalak, + …



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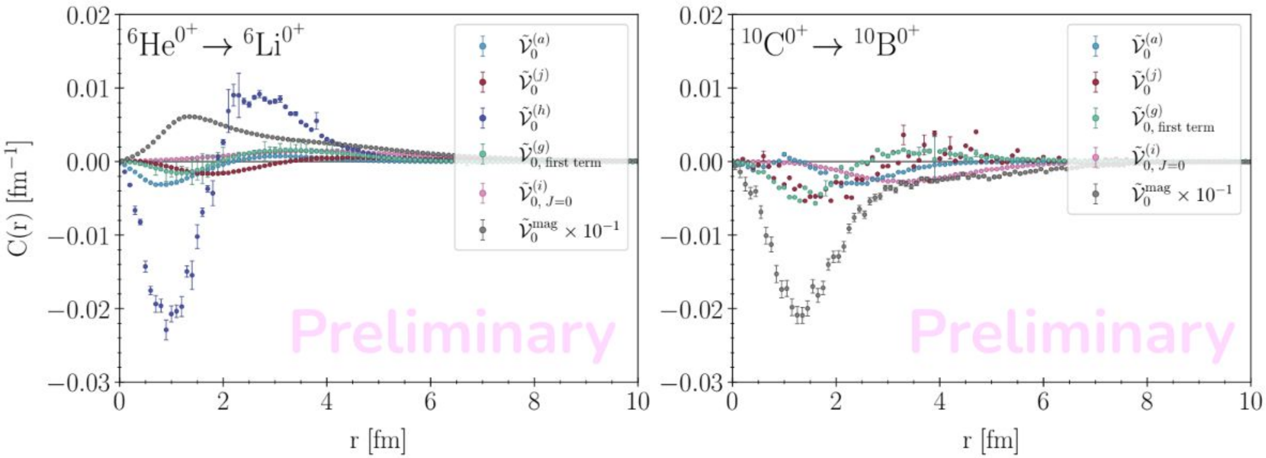
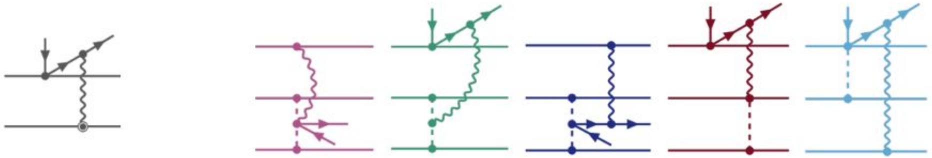
Outlook: Higher-order EFT operators

G. Chambers-Wall



Preliminary calculation of NLO contributions

~5% corrections to LO two-body from NLO

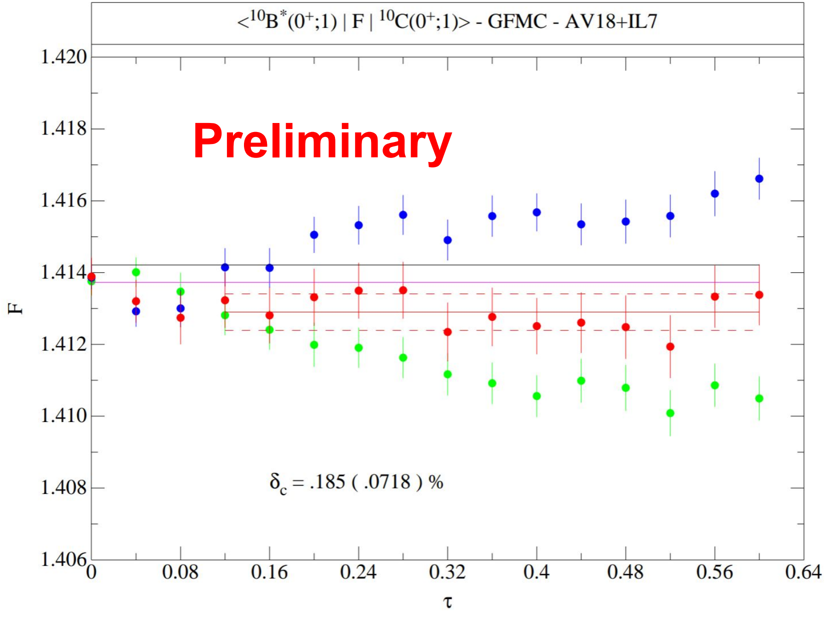


Isospin breaking corrections with GFMC

Fermi matrix element evaluated using wave functions with isospin breaking correlations

AV18+IL7 results consistent with Hardy and Towner with ~2.6 times smaller error bar

Chiral interaction predicts ~1.4 times larger correction, ~2 times larger error



Piarulli, Lovato, Wiringa

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Outlook

Two questions/challenges

Model uncertainty procedures are presently ad hoc– can we leverage emulations techniques in order to provide robust error bars on theory?

There are a number of EFT interactions on the market– how can we establish consistent benchmarks between the methods?

Conclusions

Reach of ab initio methods has progressed over the last 15 years

Recent studies of spectra, superallowed decays in light nuclei contributing to precision beta decay studies

Methods amenable to heavy nuclei can expand reach of cases ab initio nuclear theory can help interpret

Uncertainties and benchmarks remain a challenge, should be addressed

Acknowledgements

WUSTL: Chambers-Wall, Pastore, Piarulli
ANL: Wiringa
JLab+ODU: Andreoli, Gnech, Schiavilla
LANL: Carlson, Gandolfi, Mereghetti
LPC Caen: Hayen
ORNL: Baroni
UW: Cirigliano

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

Argonne NATIONAL LABORATORY

NERSC

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Computational resources provided by Argonne ALCF and NERSC

Additional slides

Variational Monte Carlo

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

Optimize when you minimize:

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

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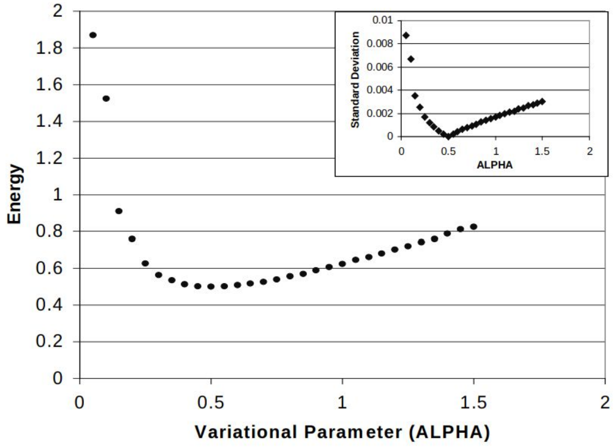
Carlson et al. Rev. Mod. Phys. 87, 1607 (2015)

Variational Monte Carlo: 1D Example

$$V(x) = \frac{1}{2}x^2$$

$$\Psi_0(x) = \left(\frac{1}{\pi}\right)^{1/4} e^{-x^2/2}$$

$$E_0 = \frac{1}{2}$$



Pottorf et al, Eur. J. Phys. 20 205 (1999)

Use Monte Carlo to compute:

$$\frac{\langle \Psi_T | H | \Psi_T \rangle}{\langle \Psi_T | \Psi_T \rangle} = \frac{\int d\mathbf{R} |\Psi_T(\mathbf{R})|^2 E_L(\mathbf{R})}{\int d\mathbf{R} |\Psi_T(\mathbf{R})|^2}; \; E_L(\mathbf{R}) = \frac{H\Psi_T(\mathbf{R})}{\Psi_T(\mathbf{R})}$$

Can tune $\Psi_T = \left(\frac{2\alpha}{\pi}\right)^{1/4} e^{-\alpha x^2}$ to solve

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Green's function Monte Carlo

Recast $i\frac{\partial}{\partial t}|\Psi(t)\rangle = (H - E_T)|\Psi(t)\rangle$ as $-\frac{\partial}{\partial \tau}|\Psi(\tau))\rangle = (H - E_T)|\Psi(\tau)\rangle$

Solution: $$|\Psi(\tau)\rangle = e^{-(H-E_T)\tau}|\Psi(0)\rangle$$

Recall $|\Psi(0)\rangle = \sum_i c_i|\psi_i\rangle$ and note $e^{-(H-E_0)\tau}|\Psi(0)\rangle = c_0\psi_0 + \sum_i e^{-\alpha_i\tau}c_i|\psi_i\rangle\,;\ \alpha_i > 0$

For a proper offset $$\lim_{\tau\to\infty} e^{-(H-E_0)\tau}|\Psi(0)\rangle \to c_0\psi_0$$

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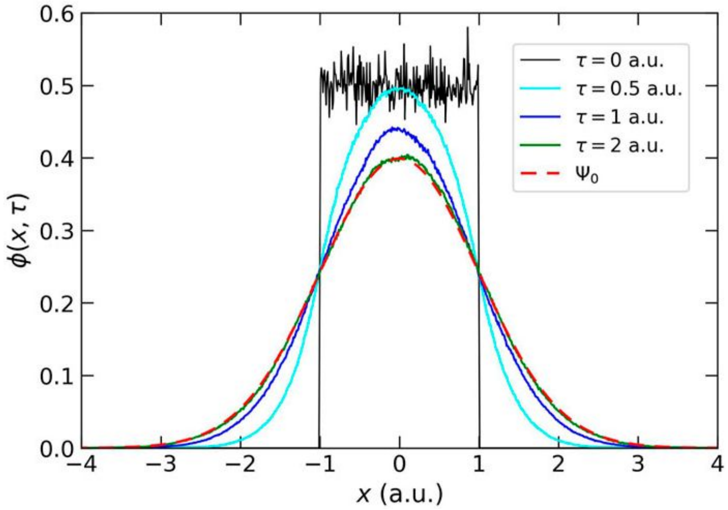
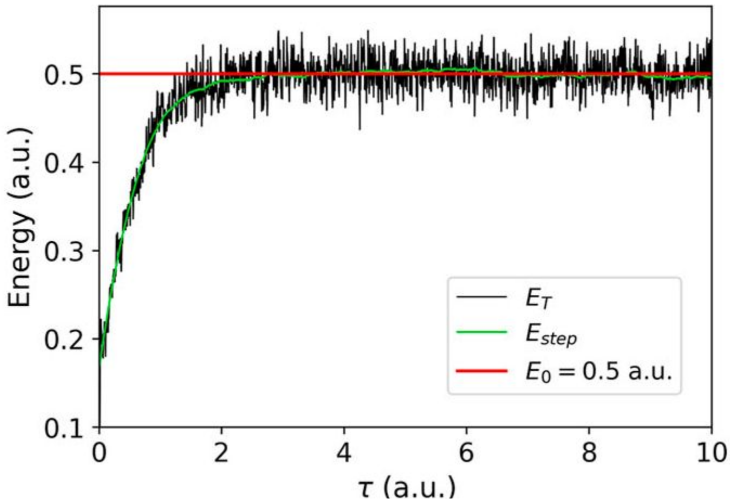
Green's function Monte Carlo: 1D example





$$G(\mathbf{R}', \mathbf{R}) = \langle \mathbf{R}' | e^{-(H-E_0)\Delta\tau} | \mathbf{R} \rangle$$

$$\Psi(\mathbf{R}_N; \tau) = \int d\mathbf{R}_{N-1} \ldots d\mathbf{R}_1 d\mathbf{R}_0 G(\mathbf{R}_N, \mathbf{R}_{N-1}) \ldots G(\mathbf{R}_2, \mathbf{R}_1) G(\mathbf{R}_1, \mathbf{R}_0) \Psi(\mathbf{R}_0; 0)$$

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Annarelli et al, J. Chem. Phys. 161, 241501 (2024)

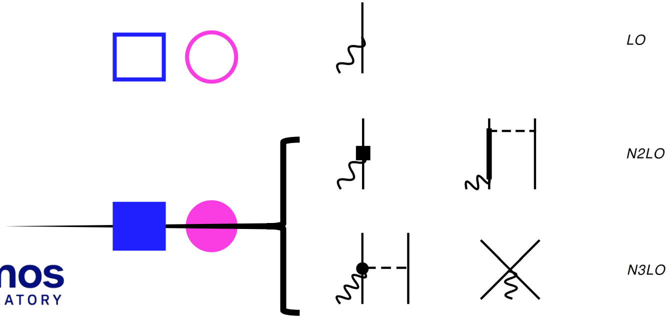
β-decay rates

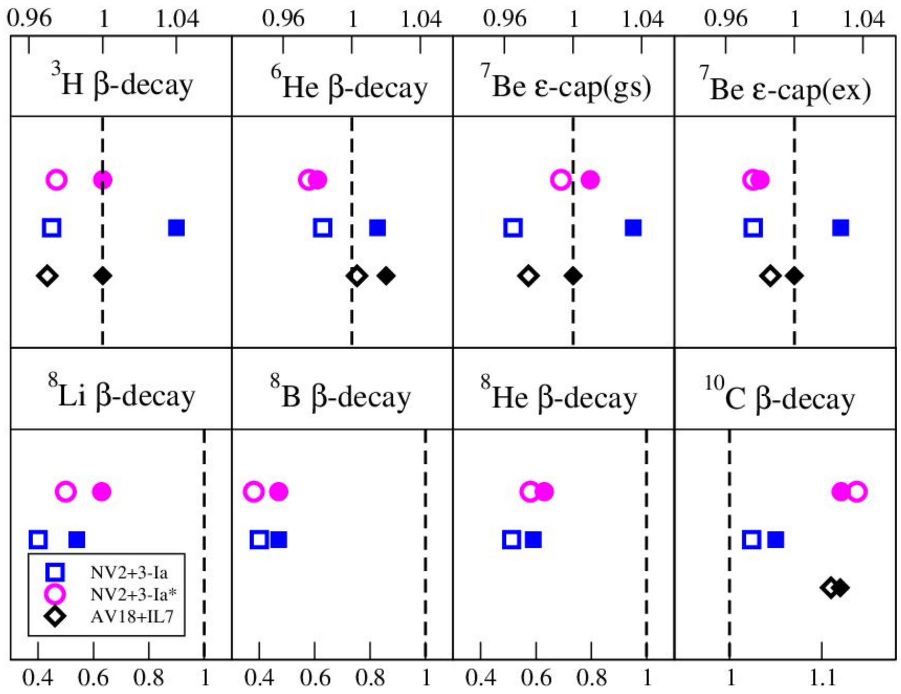
Computed with two models:

Fit to 3H beta decay or purely strong data

Many-body correlations important

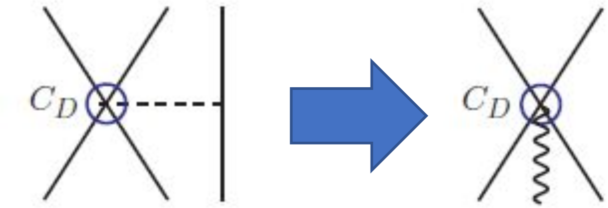
Two-body can be ~few % to several %





King et al. PRC 121, 025501 (2020)

Three-body LECs and sub-leading contact



$$\mathbf{j}_{5,a}^{\mathrm{N3LO}}(\mathbf{q};\mathrm{CT}) = z_0 \mathcal{O}_{ij}(\mathbf{q})$$

$$z_0 \propto (c_D + \text{ known LECs})$$

Specific parameter in the three-nucleon force is ***connected to*** a parameter in the two-body weak transition operator

Short-range dynamics will depend on these values, influenced by fit

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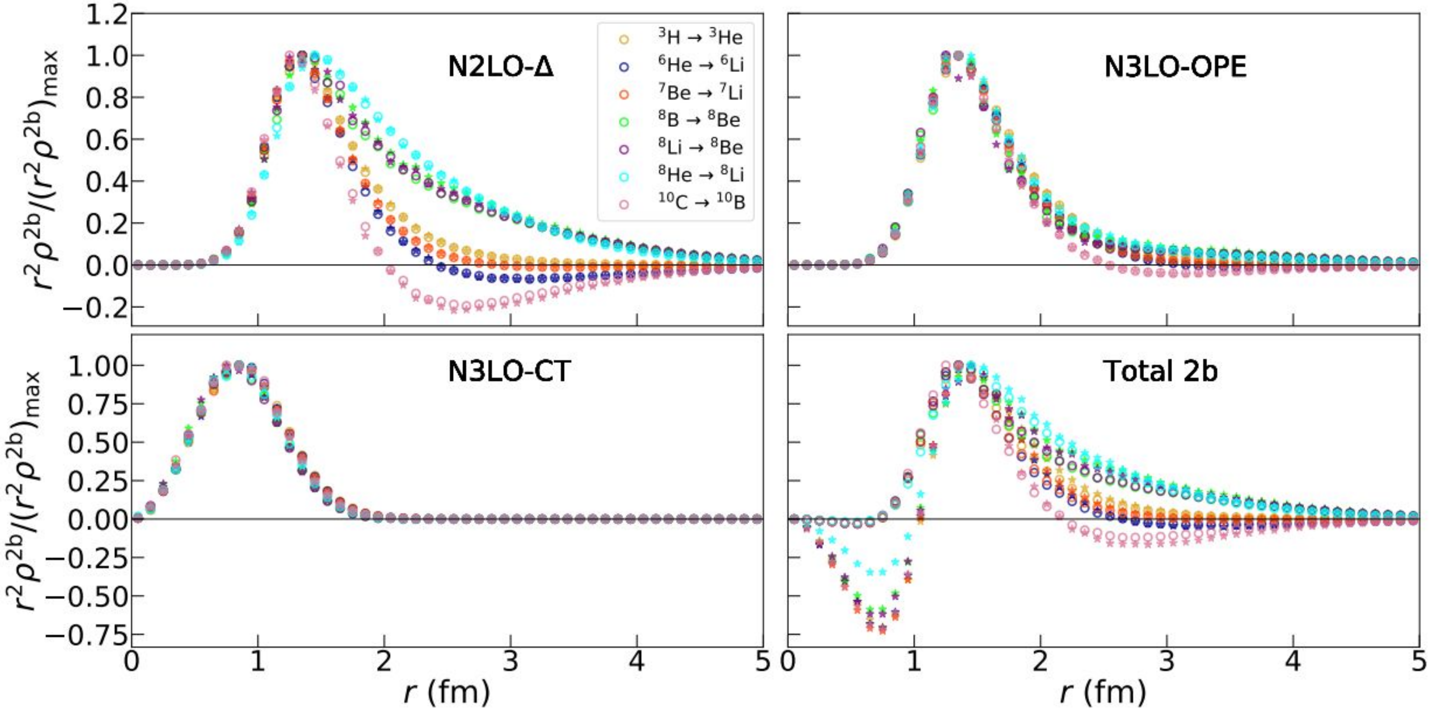
Gardestig and Phillips PRL 96, 232301 (2006)

Universal behavior in GT densities



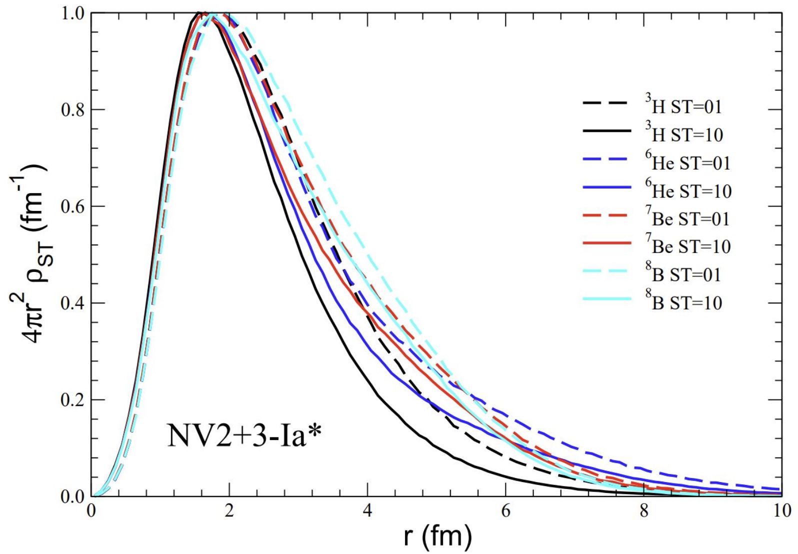
King et al. PRC 121, 025501 (2020)

Interpreting universal and tail behaviors

Decay takes nn/np (ST=01/10) pair to an np/pp (ST=10/01) pair

The ST=01 and 10 pair densities at short distances scale

Consequence of how pairs form in the nucleus



$$N_{ST} = \int dr_{ij} 4\pi r_{ij}^2 \rho_M^{2b}(r_{ij})$$

King et al. PRC 121, 025501 (2020)

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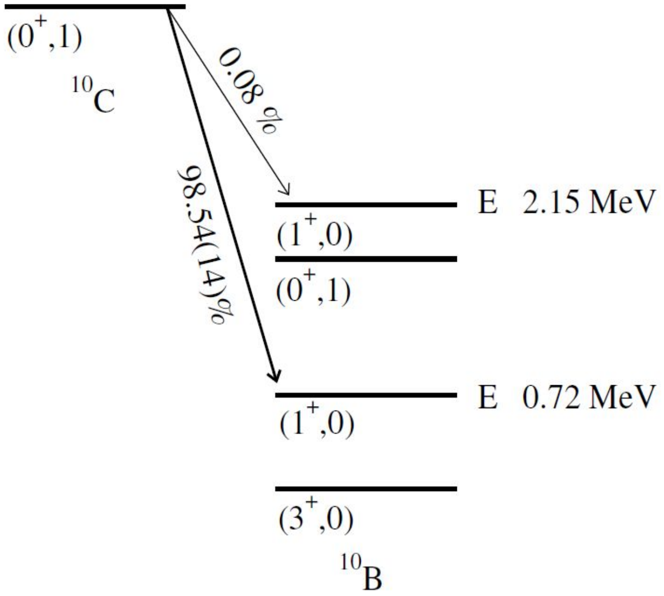
^{10}B β-decay



https://nucldata.tunl.duke.edu/

Two states of the same quantum numbers nearby

The result depends strongly on the *LS* mixing of the *p*-shell

Particularly sensitive to the $^3S_1$ and $^3D_1$ mixing because *S* to *S* produces a larger m.e. and ^{10}C is predominantly *S* wave

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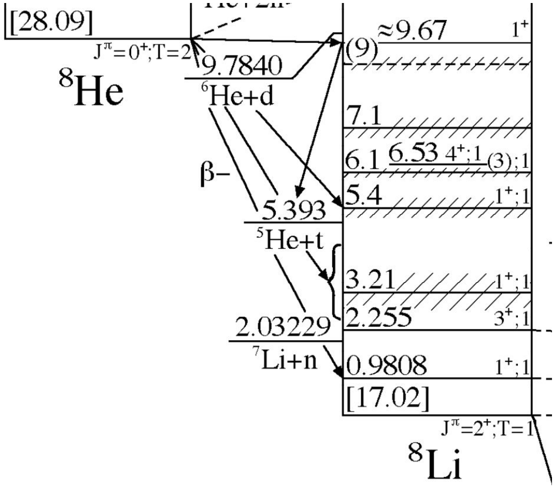
^{8}He β-decay



https://nucldata.tunl.duke.edu/

Three (1^{+};1) states within a few MeV

Different dominant spatial symmetries → sensitivity to the precise mixing of small components in the wave function

Improving the mixing of the small components in the (1^{+};1) states is crucial to getting an improved m.e.

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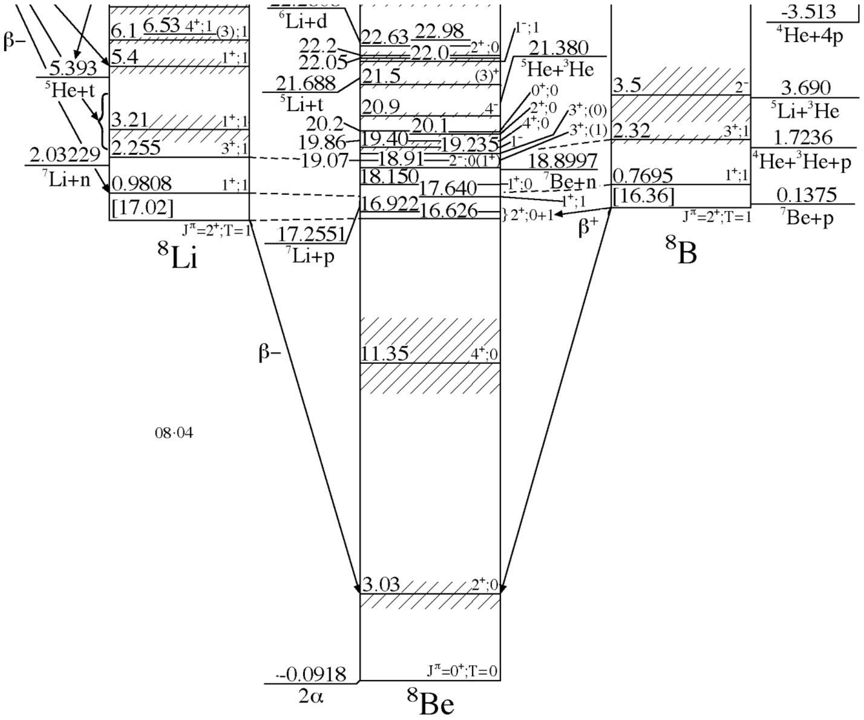
A=8 level scheme



https://nucldata.tunl.duke.edu/

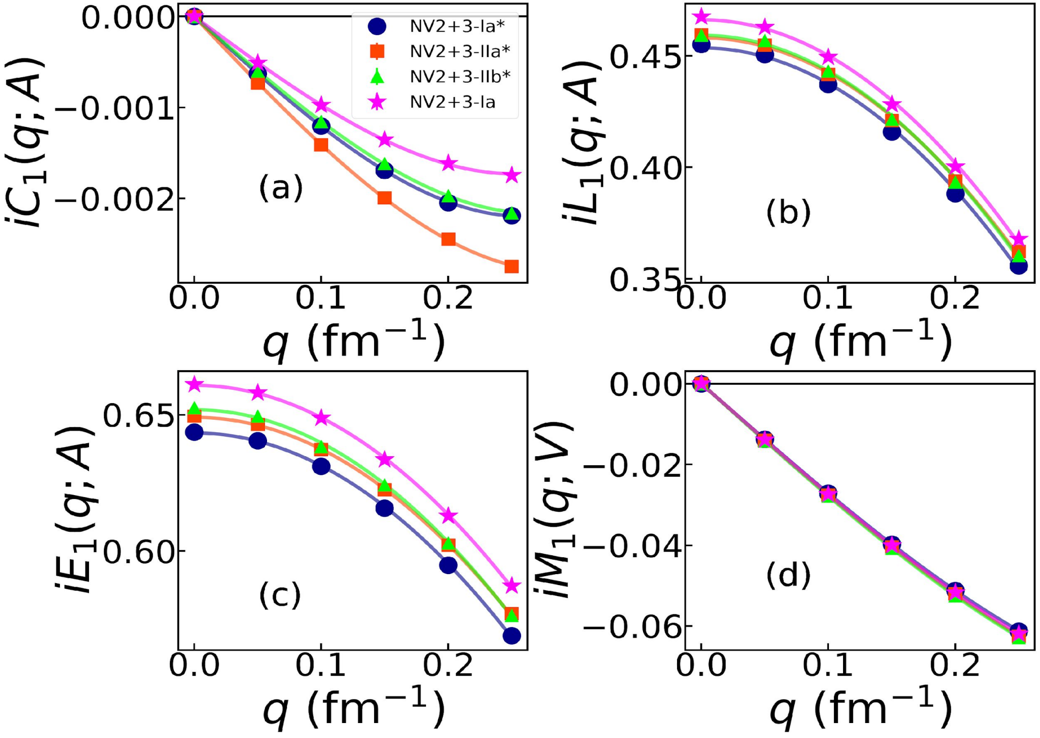
^{6}He β-decay spectrum: Multipoles

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

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

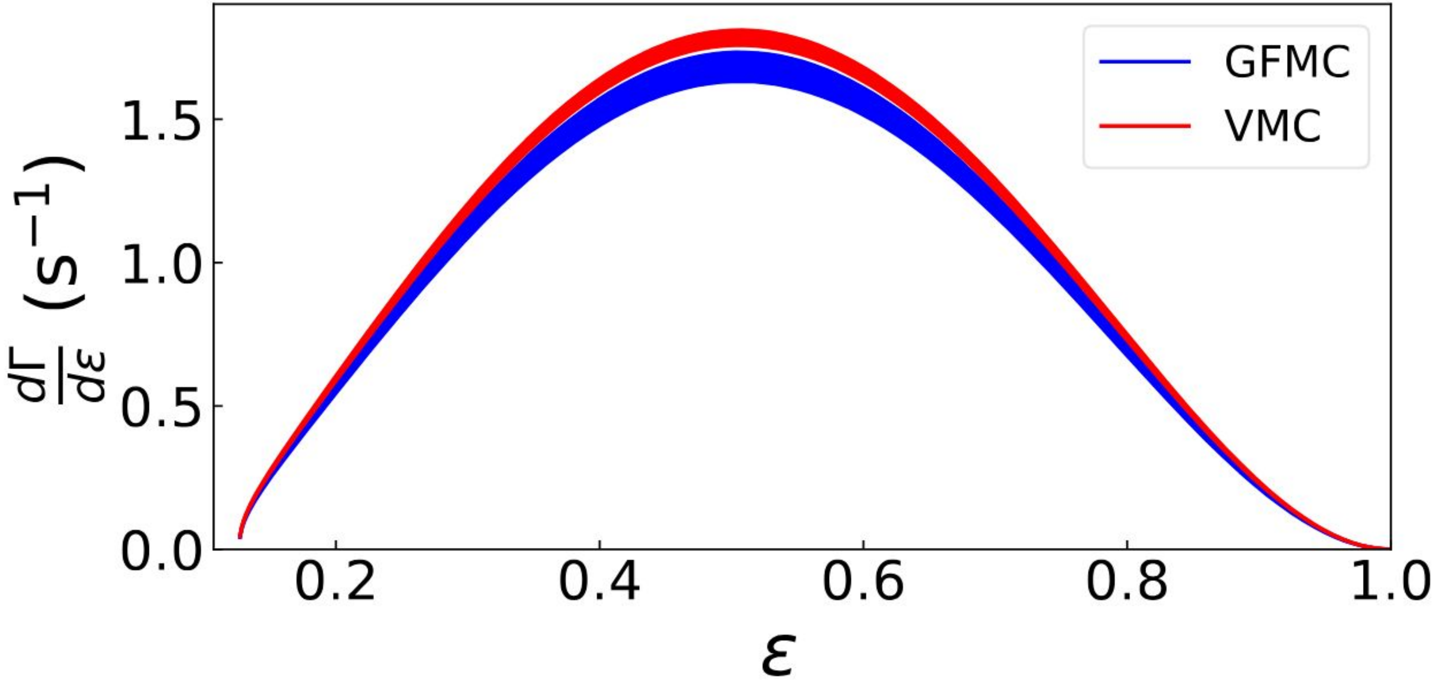
$$E_1(q;A) = -\frac{i}{\sqrt{2\pi}}\langle {}^6\mathrm{Li}, 10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};A)|{}^6\mathrm{He}, 00\rangle$$

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



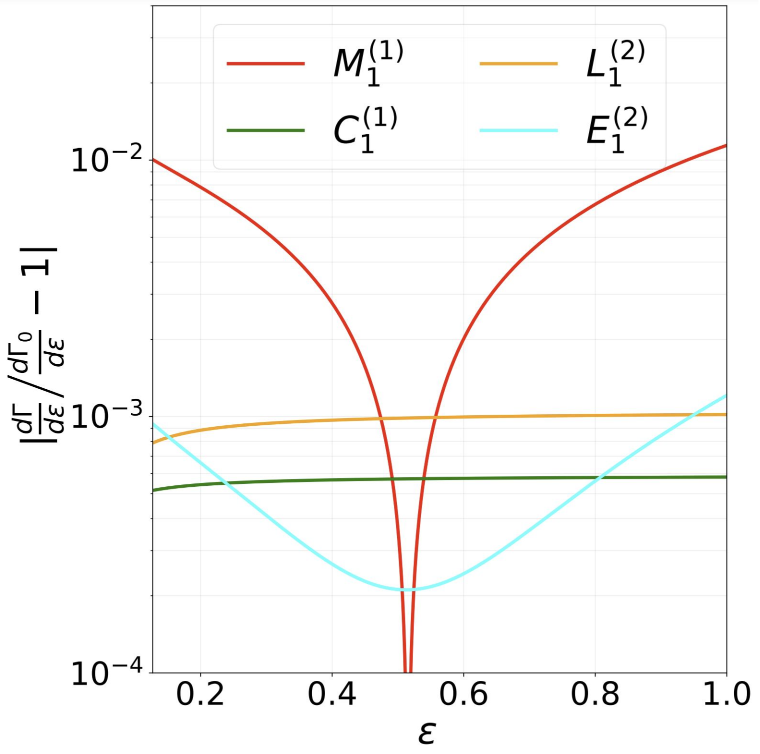
King et al. PRC 107, 015503 (2023)

^{6}He β-decay spectrum: Absolute spectrum



King et al. PRC 107, 015503 (2023)

^{6}He β-decay spectrum: SM corrections



King et al. PRC 107, 015503 (2023)

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