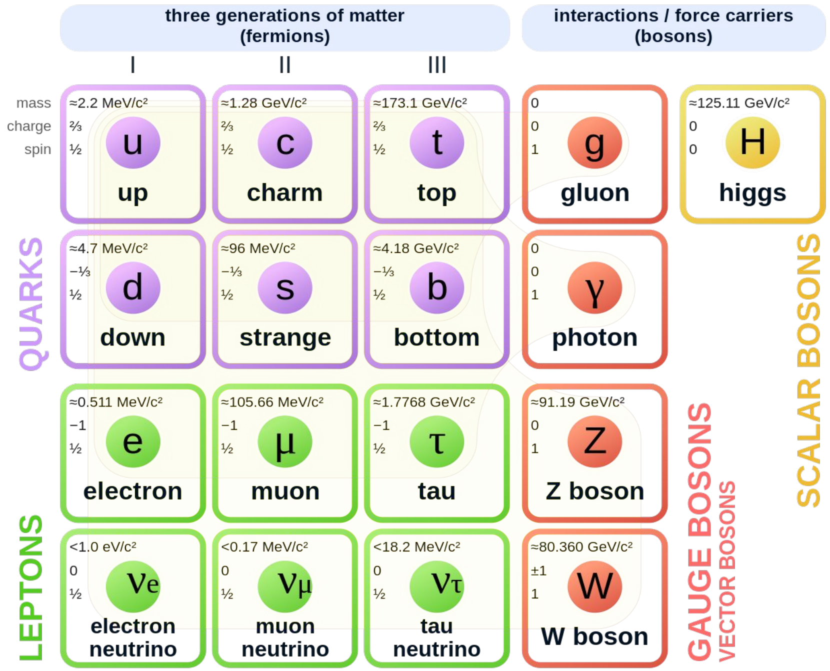
Recent advances in electroweak processes with quantum Monte Carlo methods

Garrett King

PRISMA+ Colloquium
Johannes Gutenberg University Mainz
5/14/2025

LA-UR-25-#####

The Standard Model



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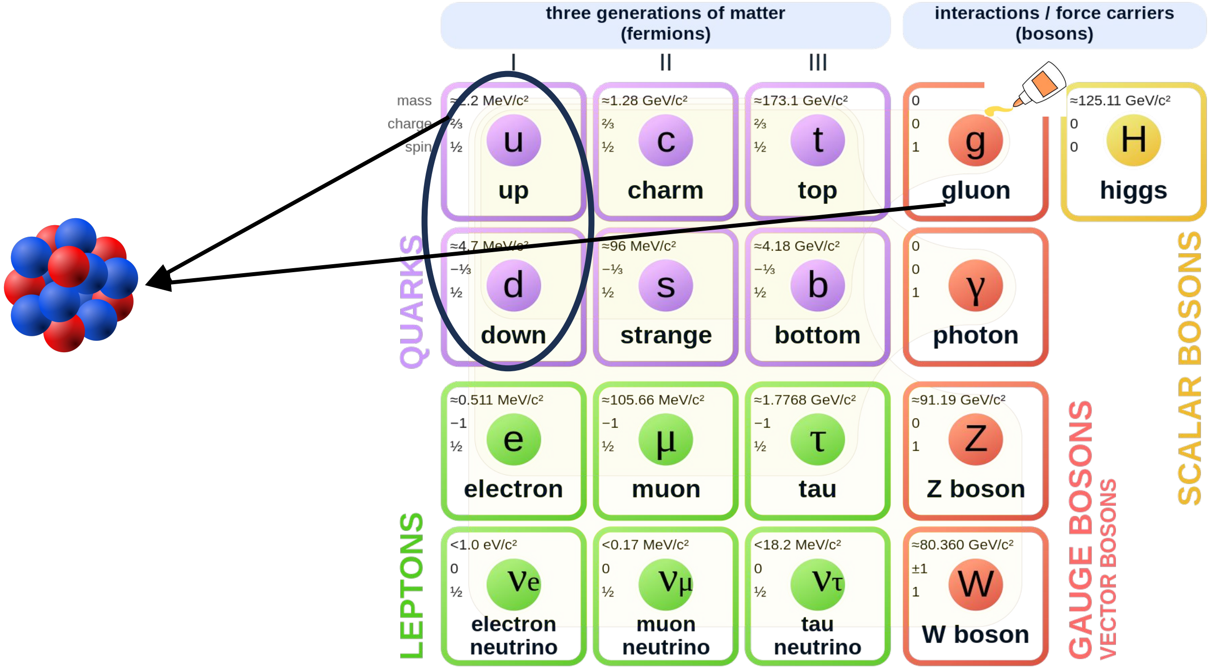

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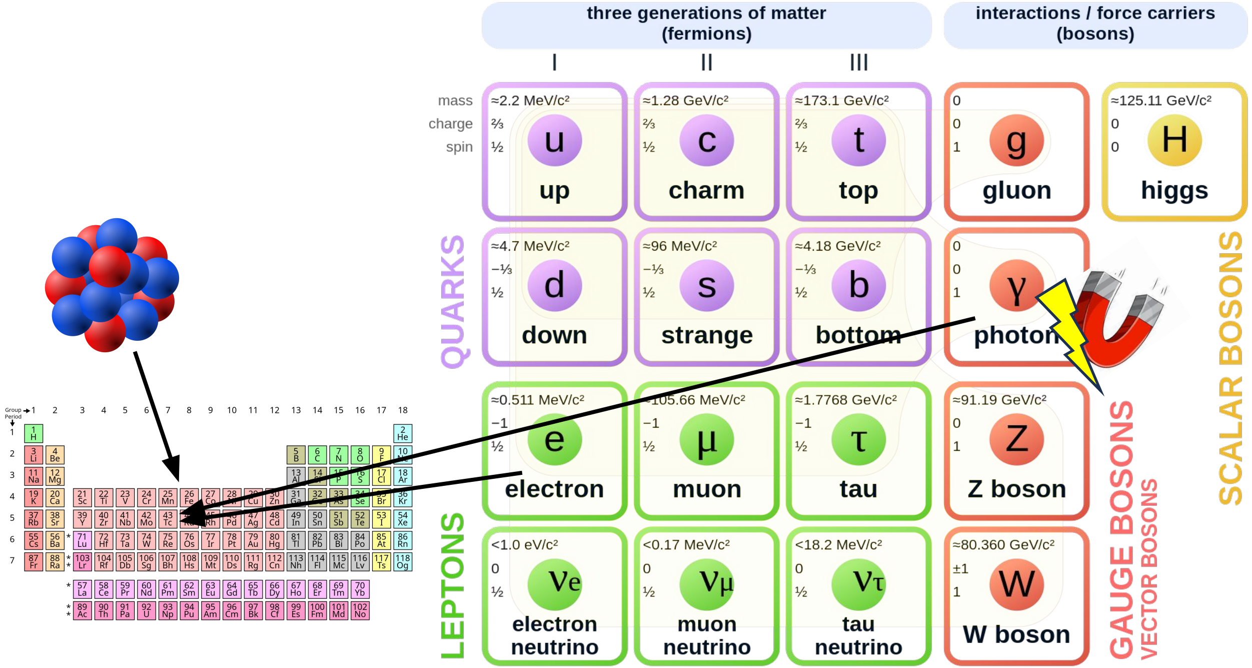

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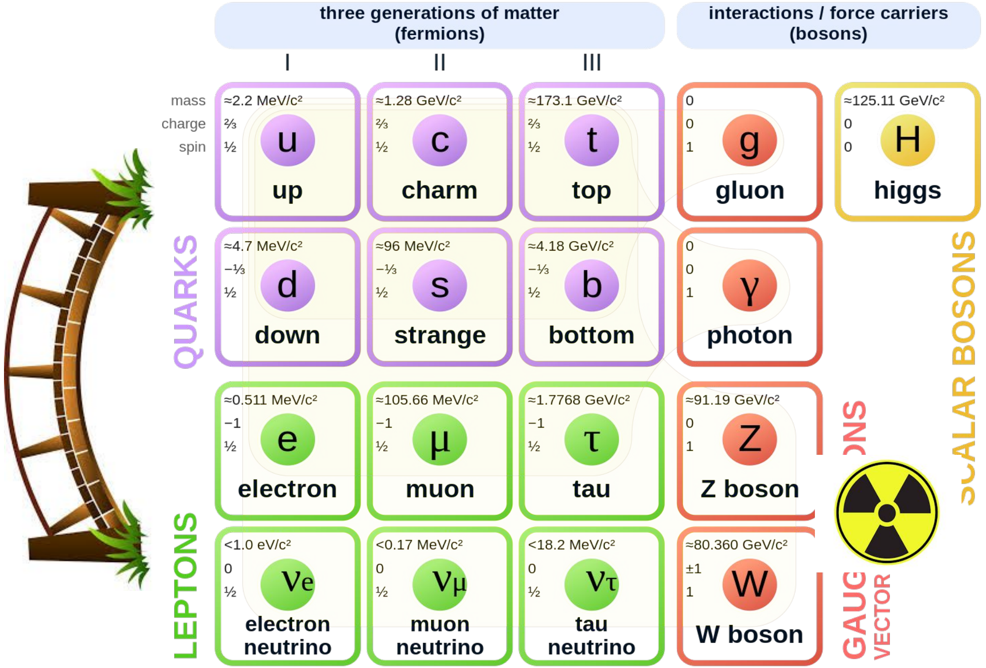

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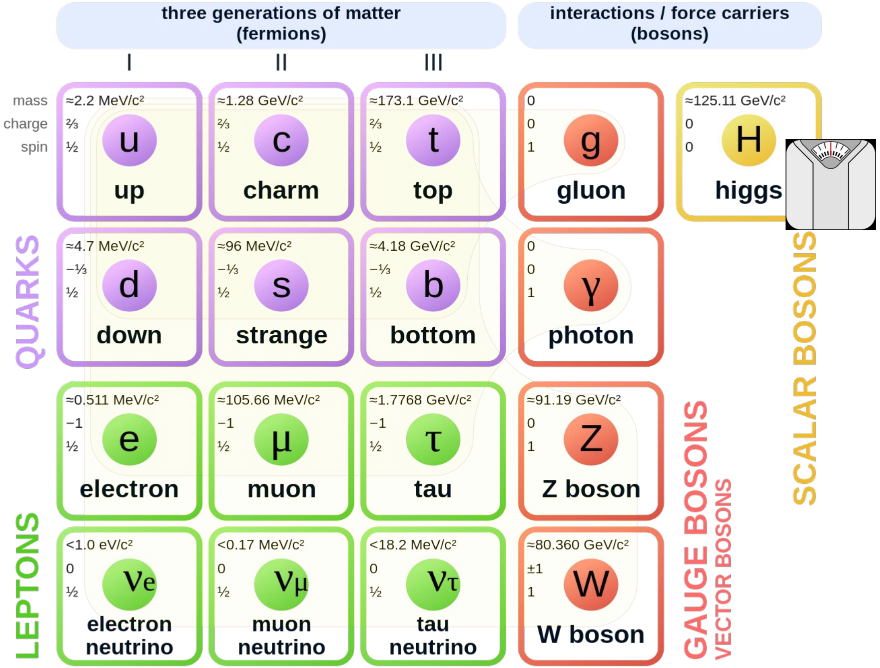

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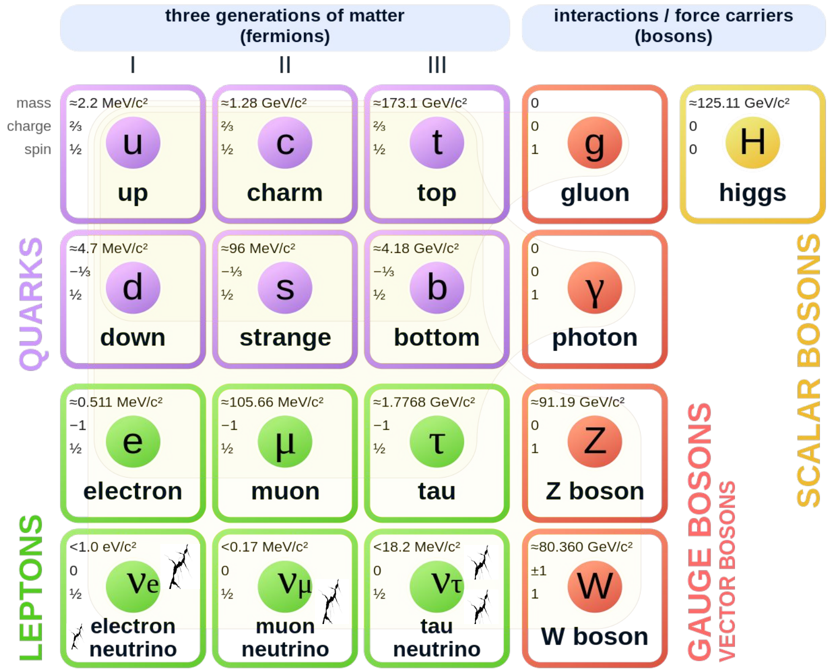

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Neutrino oscillations

Fermilab / Sandbox Studio, Chicago

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

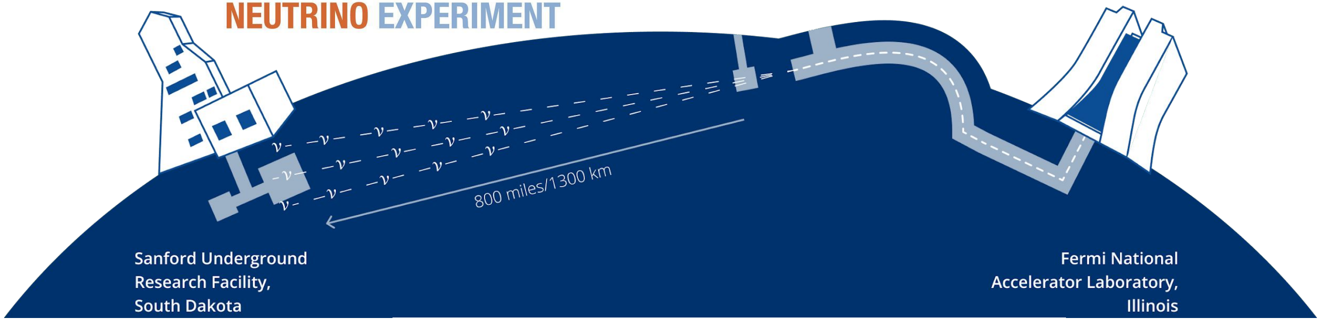
Flavors

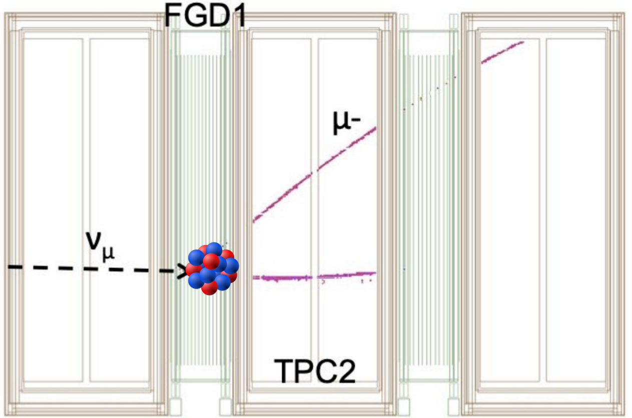
Mass

Neutrino oscillations

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Fermilab / Sandbox Studio, Chicago





Adapted from K. Mahn,
"The Theoretical Cross Section Needs of Future Long Baseline Experiments"
at INT WORKSHOP INT-23-86W

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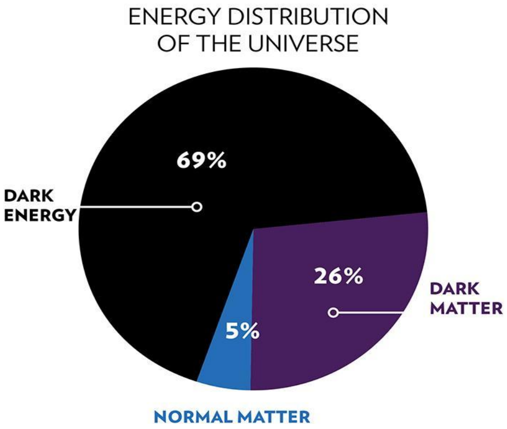
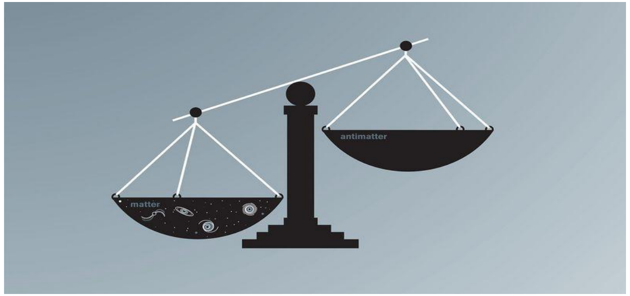
Why beyond Standard Model (BSM) physics?

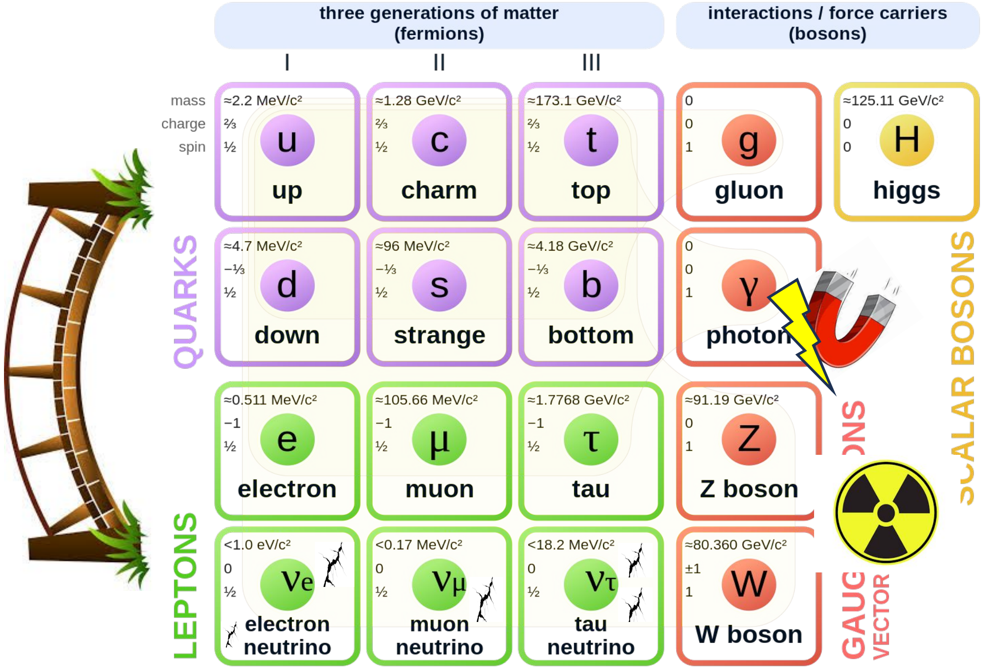


NASA / Chandra X-ray Center/ K. Divona



Symmetry Magazine / Sandbox Studio, Chicago

Nuclei as laboratories for new physics



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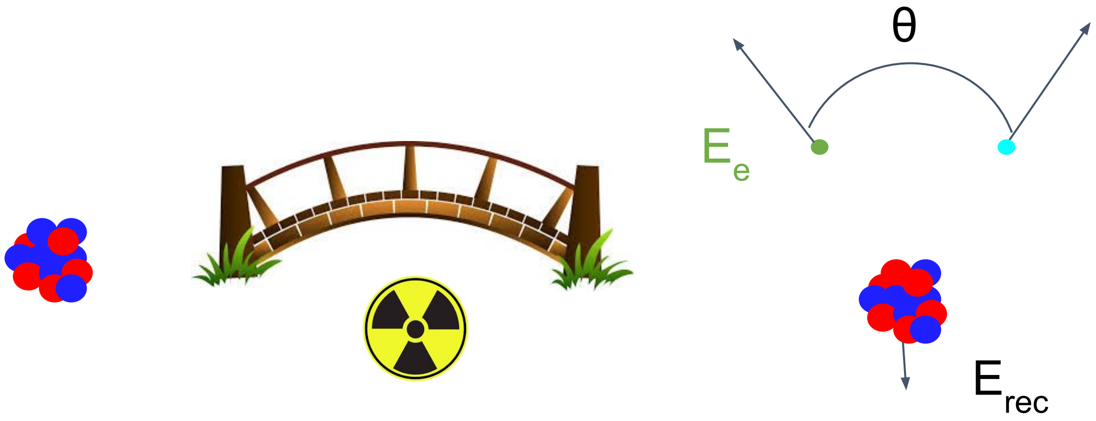
β-decays as a bridge to new physics



Neutron is converted into a proton, electron, and an electron antineutrino

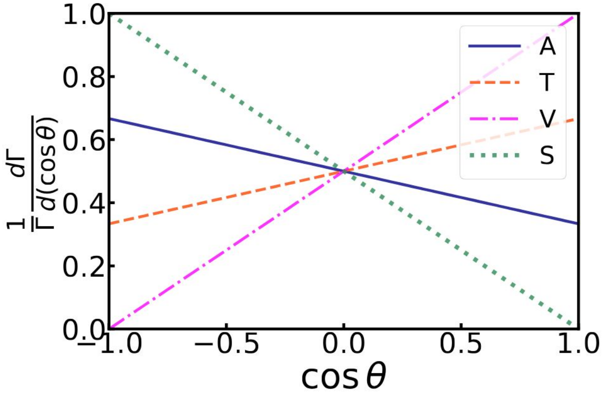
β-decays as a bridge to new physics

Weak currents with different transformation properties prefer different lepton angles

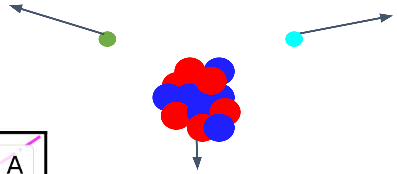
Standard Model is a vector minus axial theory

BSM tensor and scalar currents could interfere with standard curr, changing kinematics

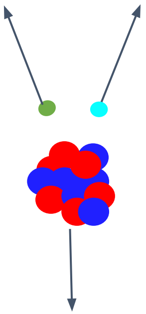
Neutrino mass would remove some phase space for the outgoing electron



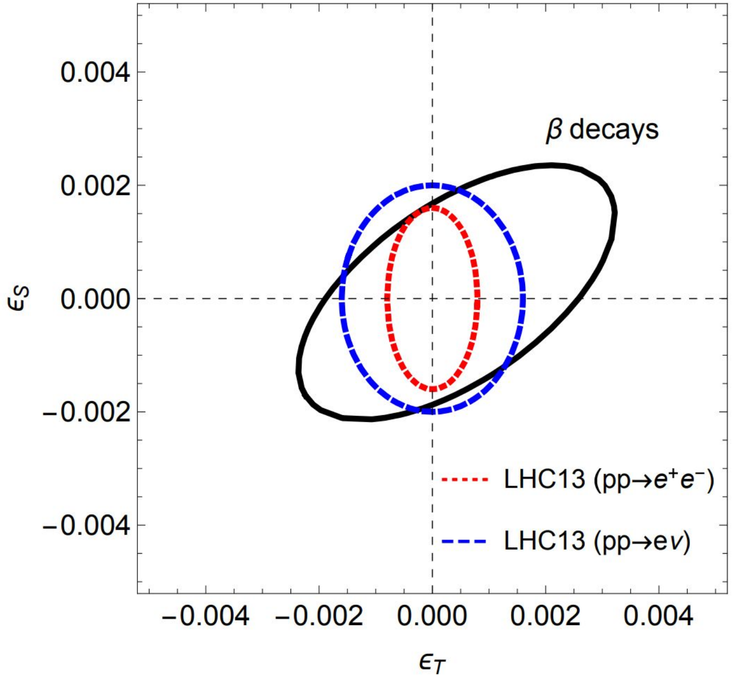
θ ~ 180°



θ ~ 0°



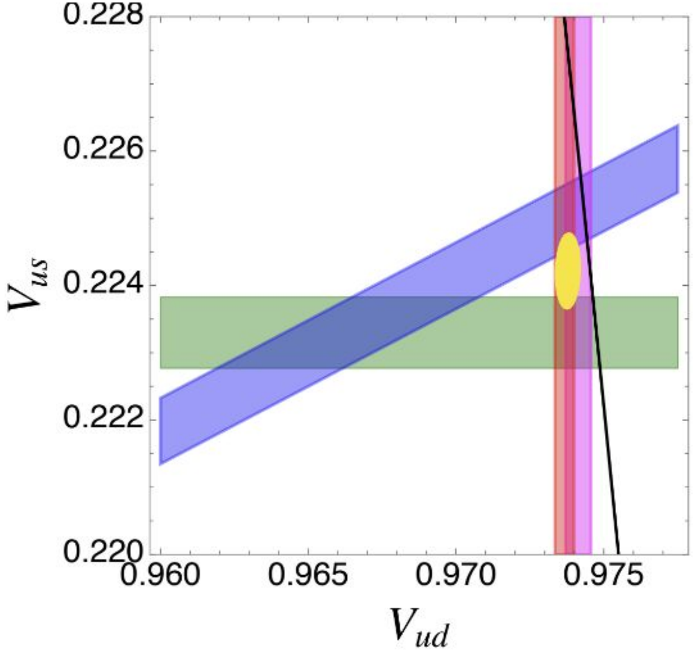
New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

Competitive bounds on BSM currents that complement high-energy searches

New physics impact of nuclear β-decays



Cirigliano et al., PLB 838 (2023) 137748

Competitive bounds on BSM currents that complement high-energy searches

Tests of CKM unitarity

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

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

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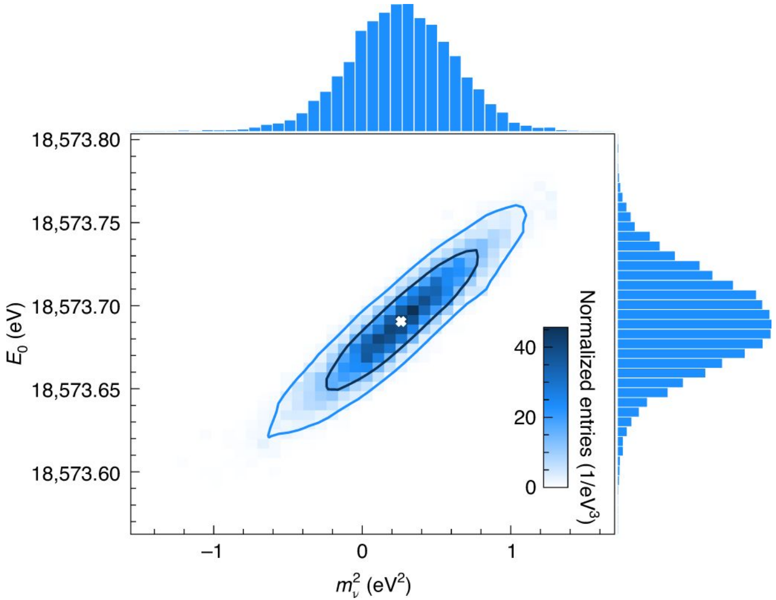
New physics impact of nuclear β-decays



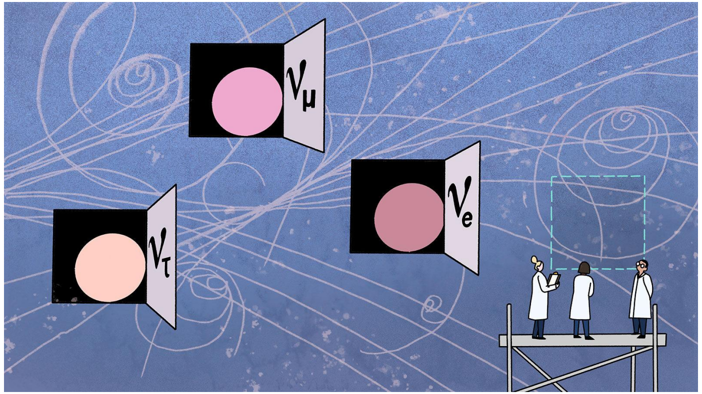
Competitive bounds on BSM currents that complement high-energy searches

Tests of CKM unitarity

Access to the scale of neutrino masses

The KATRIN Collaboration, Nature Phys. 18, 160–166 (2022)

New physics impact of nuclear β-decays



Symmetry Magazine / Sandbox Studio, Chicago

Competitive bounds on BSM currents that complement high-energy searches

Tests of CKM unitarity

Access to the scale of neutrino masses

Bounds on sterile neutrinos

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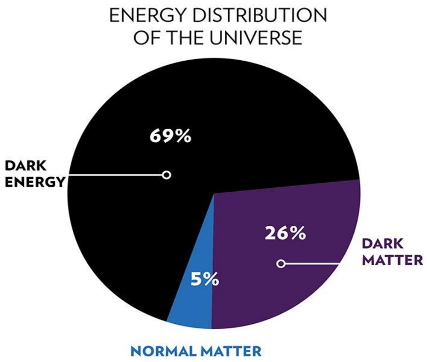

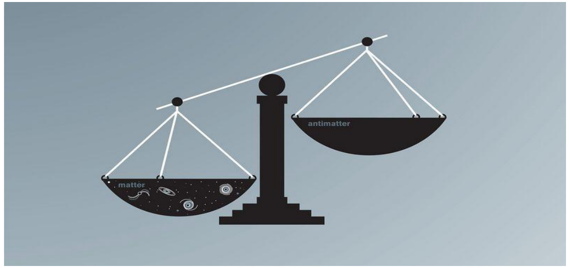

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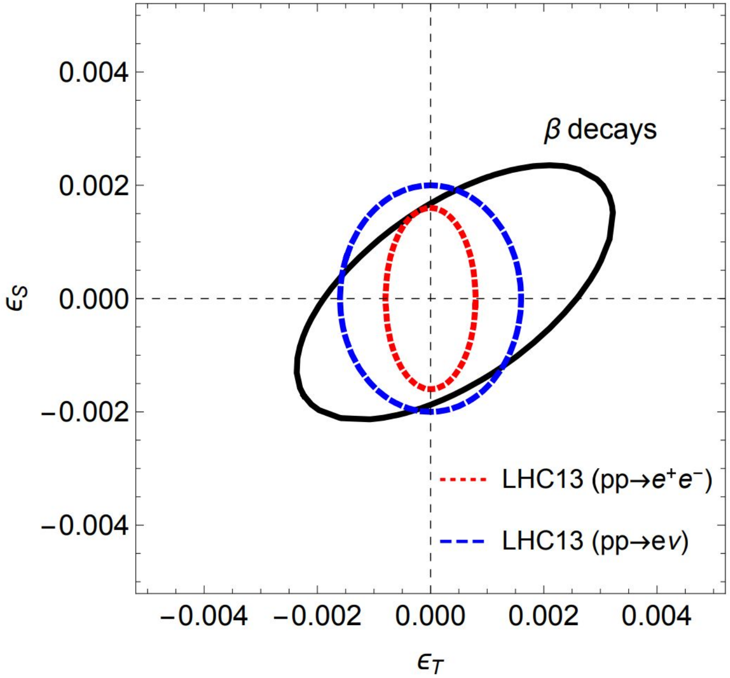
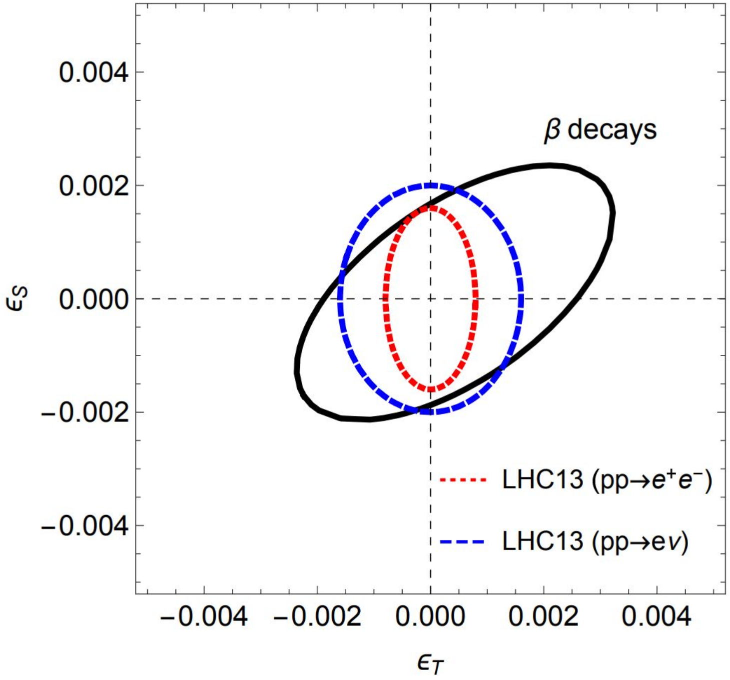
New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

Question: How reliable are the estimates of nuclear uncertainties?

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

Understanding structure and dynamics

Validate on available data → **Predict relevant quantities**

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Validate on available data	→	**Predict relevant quantities**
Decay rates, magnetic moment	→	Precision decays, moments
Electron scattering	→	Neutrino scattering

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Understanding structure and dynamics

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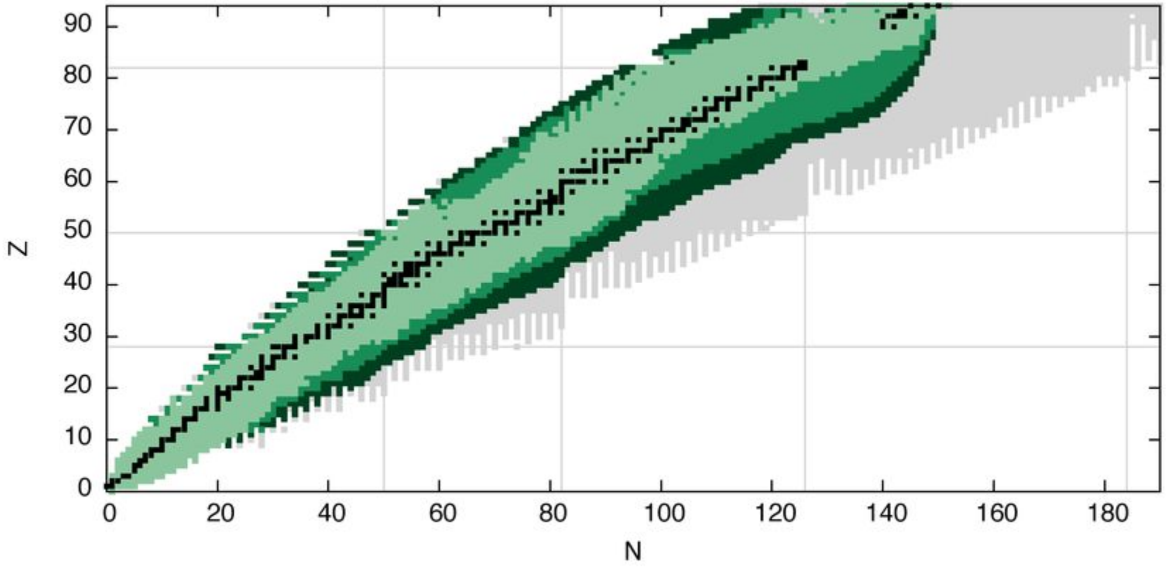
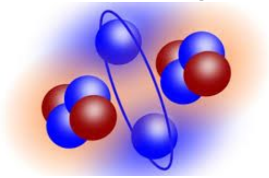
Connection to nuclear science



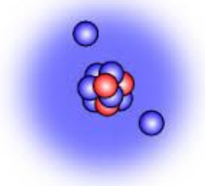
Surman and Mumpower, EPJ Conf. 178:04002 (2018)

Clustering

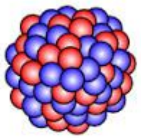


Halos

^{11}Li



^{208}Pb



Deformations

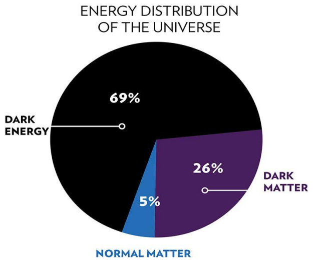
Connection to nuclear science

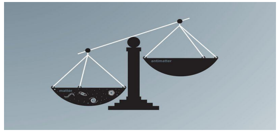
To benefit new physics searches, we must understand…

- How structure changes near the limit of stability
- What role clustering plays in exotic systems
- The nature of the nuclear force
- How nuclei interact with external probes

Direct relation to the science that is probed at rare isotope beam (RIB) facilities

Bridging new physics and nuclear science





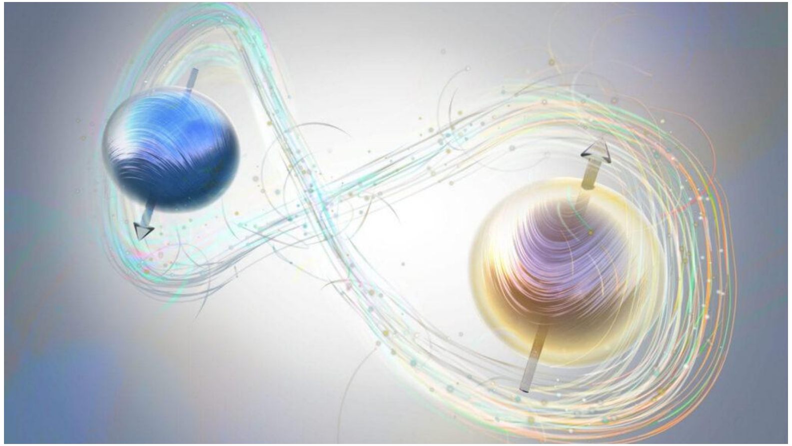
Nuclear Theory

Microscopic description of the nucleus

The quantum many-body problem

Interaction generates *entanglement* in solution of the Schrödinger equation

$$H|\Psi\rangle = E|\Psi\rangle$$



Goal: Model the nucleus in terms of interacting proton and neutron (nucleon) degrees of freedom

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The quantum many-body problem

Wave function of ***A* nucleons** containing information about ***coordinates*, *spins*, *and isospins***

$$\Psi(r_1, r_2, \ldots, r_A; s_1, s_2, \ldots, s_A; t_1, t_2, \ldots, t_A)$$

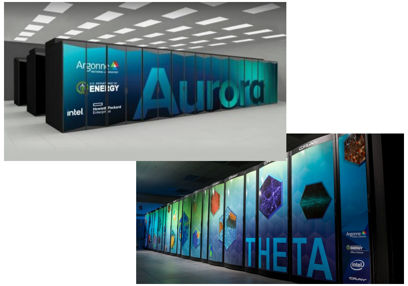
$$\dim(\Psi) = 3A \times 2^A \times \frac{A!}{N!Z!}$$

$$\dim\left({}^4\mathrm{He}\right) = 1152$$

$$\dim\left({}^6\mathrm{Li}\right) \approx 2.3 \times 10^4$$

$$\dim\left({}^{12}\mathrm{C}\right) \approx 1.4 \times 10^8$$

NERSC



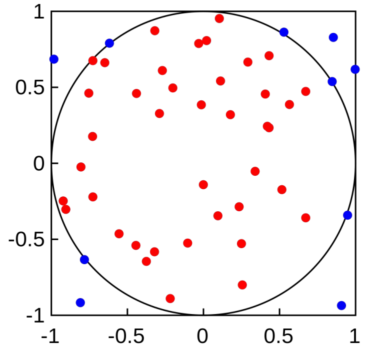
ALCF

Quantum Monte Carlo (QMC) methods

Stochastic approaches to solve the Schrödinger Equation

Allows you to solve large-dimensional integrals via random sampling

In this talk: **Variational** and **Green's function** (or Diffusion) Monte Carlo



MC Example: Estimating π

100 samples = 3.28000 (4.4%)

1,000 samples = 3.16400 (0.71%)

1,000,000 samples = 3.14216 (0.02%)

```
import numpy as np

exact = 4.*np.arctan(1.)

nsamp = 10**2

accepted = 0

for i in range(nsamp):

   x,y = np.random.rand(2)
   if ( (x**2. + y**2.) < 1. ):
      accepted += 1

area = 4.*(accepted/nsamp)

acc = 100.*np.abs(area-exact)/exact

print("pi = %.8f" % area )
print("accuracy = %.8f %%" % acc)
```

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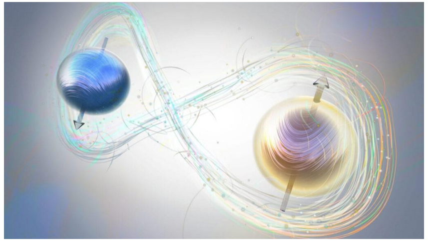
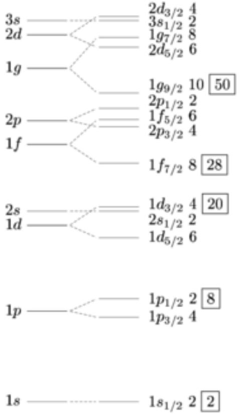
Variational Monte Carlo for correlated fermions

$$|\Psi_T\rangle = \hat{F}(\{\mathbf{r}_i\}, \{\mathbf{s}_i\}, \{\mathbf{t}_i\})|\Phi\rangle$$





Encodes entanglement between nucleons

Contains the variational parameters

Mean-field description

Encodes long-range structure, quantum numbers

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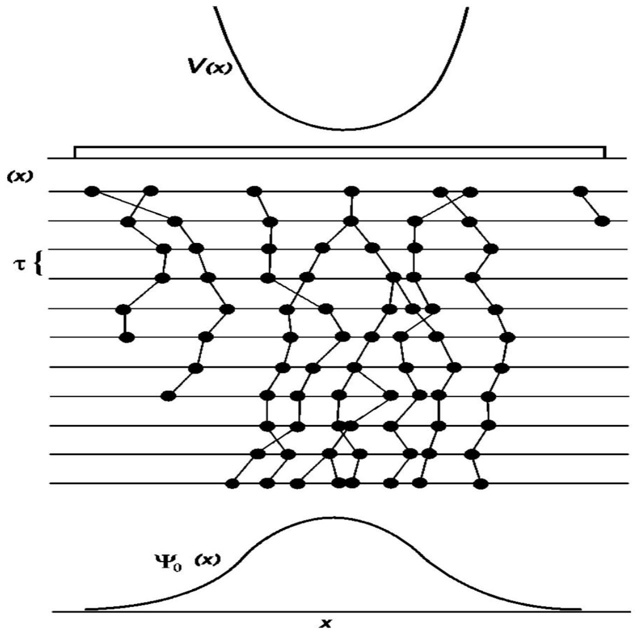
Green's Function (or Diffusion) Monte Carlo



Can recast the Schrödinger Equation as a Diffusion equation

Sample the path integral with Monte Carlo

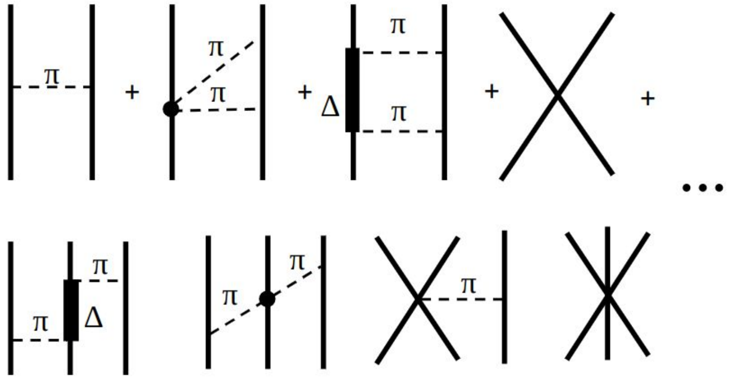
$$\lim_{\tau \to \infty} |\Psi_T\rangle \to c_0 \psi_0$$

Non-perturbative approach to obtain exact solution

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

Nuclear interactions

$$H = \sum_i T_i + \sum_{ij} v_{ij} + \sum_{ijk} V_{ijk} + \ldots$$



Contains kinetic energies, plus two-body and three-body interactions

Long-range attraction mediated by the lightest meson, the pion (π)

Intermediate range attraction involving two pions, and sometimes excitation of nucleons (ex: the Δ)

Short-range repulsion from heavier intermediaries represented by “contact” terms

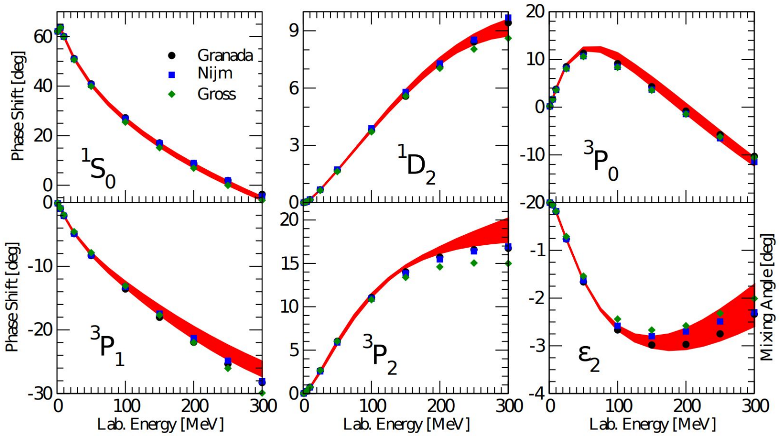
Need for three-body forces to bind light systems

Systematic uncertainty

Interaction between nucleons is not fundamental

Phenomenological models available that must fit to data, but have uncertainties

Systematic expansions as effective theory of fundamental theory exist, but work remains to study convergence



Piarulli et al. PRC 91, 024003 (2014)

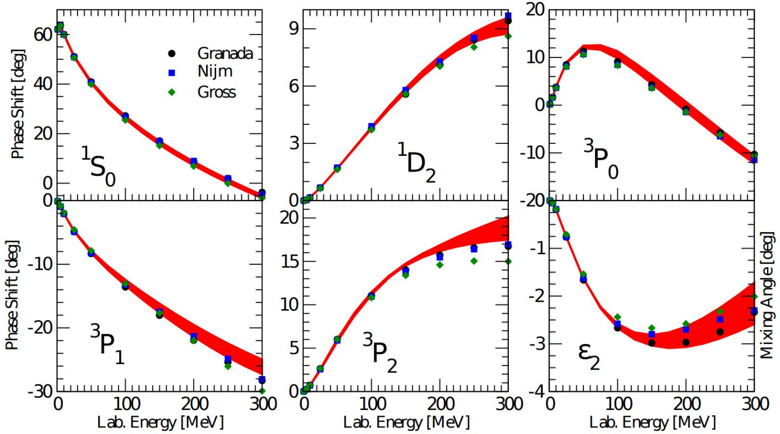
Systematic uncertainty

Interaction between nucleons is not fundamental

Phenomenological models available that must fit to data, but have uncertainties

Systematic expansions as effective theory of fundamental theory exist, but work remains to study convergence

This systematic has to be accounted for in calculations



Piarulli et al. PRC 91, 024003 (2014)

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Nuclear matrix elements

Use QMC to compute

$$M = \langle \Psi_\beta | \mathcal{O} | \Psi_\alpha \rangle$$

Related to physics quantities of interest

$$|M|^2 \propto \Gamma,\ \tau_{1/2}^{-1},\ d\sigma/d\Omega, \ldots$$

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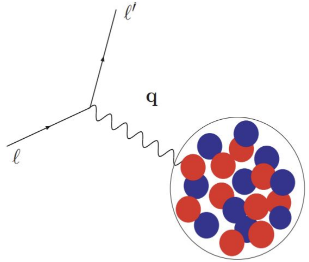
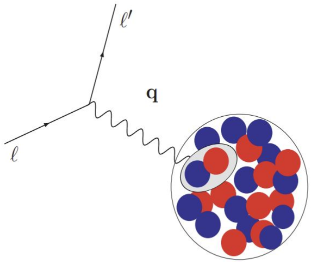
Electroweak charge and current operators

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



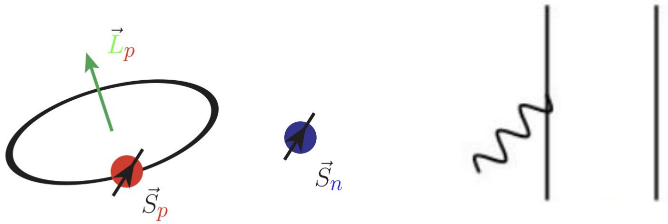


Pastore et al. PRC 80, 034004 (2009), Pastore et al. PRC 84, 024001 (2011), Piarulli et al. PRC 87, 014006 (2013), Schiavilla et al. PRC 99, 034005 (2019), Baroni et al. PRC 93, 049902 (2016), …

Two-body currents intuition (magnetic moments)

We know that it will arise from charges moving in the system

Expect proton orbital, proton spin, and neutron spin contributions



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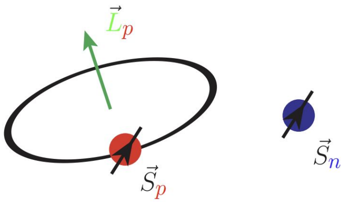
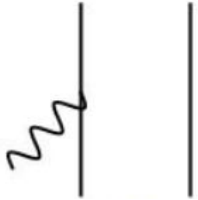




Expect proton orbital, proton spin, and neutron spin contributions

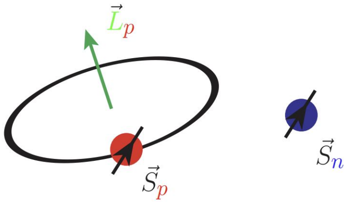
Protons are not the only charged objects (pions, Δ's, heavier mesons,...)

Ex: Pion couplings to an external electromagnetic field

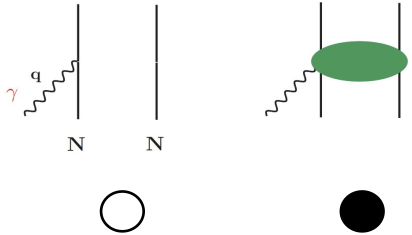
Magnetic moments

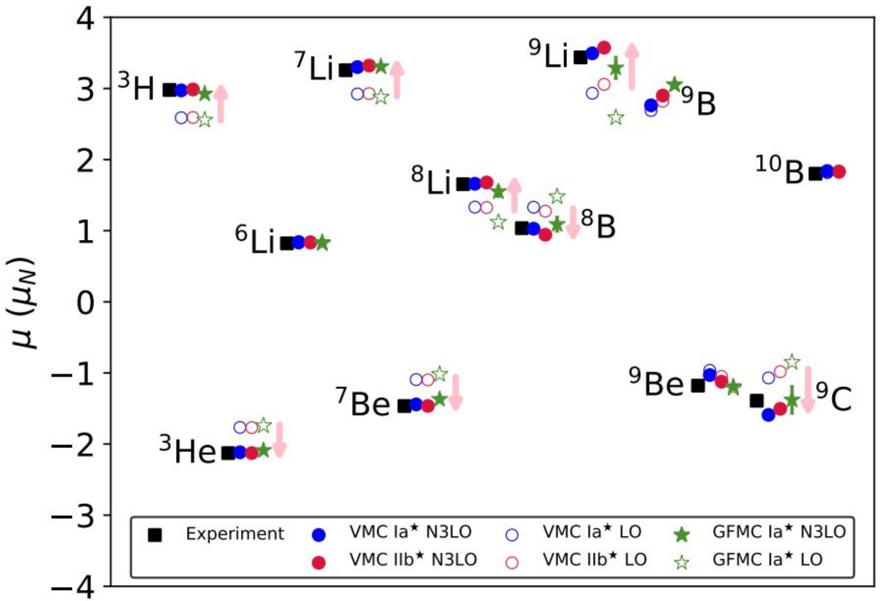
One-body picture:

$$\mu^{LO} = \sum_i (L_{i,z} + g_p S_{i,z}) \frac{1+\tau_{3,i}}{2} + g_n S_{i,z} \frac{1-\tau_{3,i}}{2}$$



Two-body currents can play a large role (up to ~33%) in describing magnetic dipole moments





Chambers-Wall, King, et al. PRL 133, 212501 (2024)
Chambers-Wall, King, et al. PRC 110, 054316 (2024)

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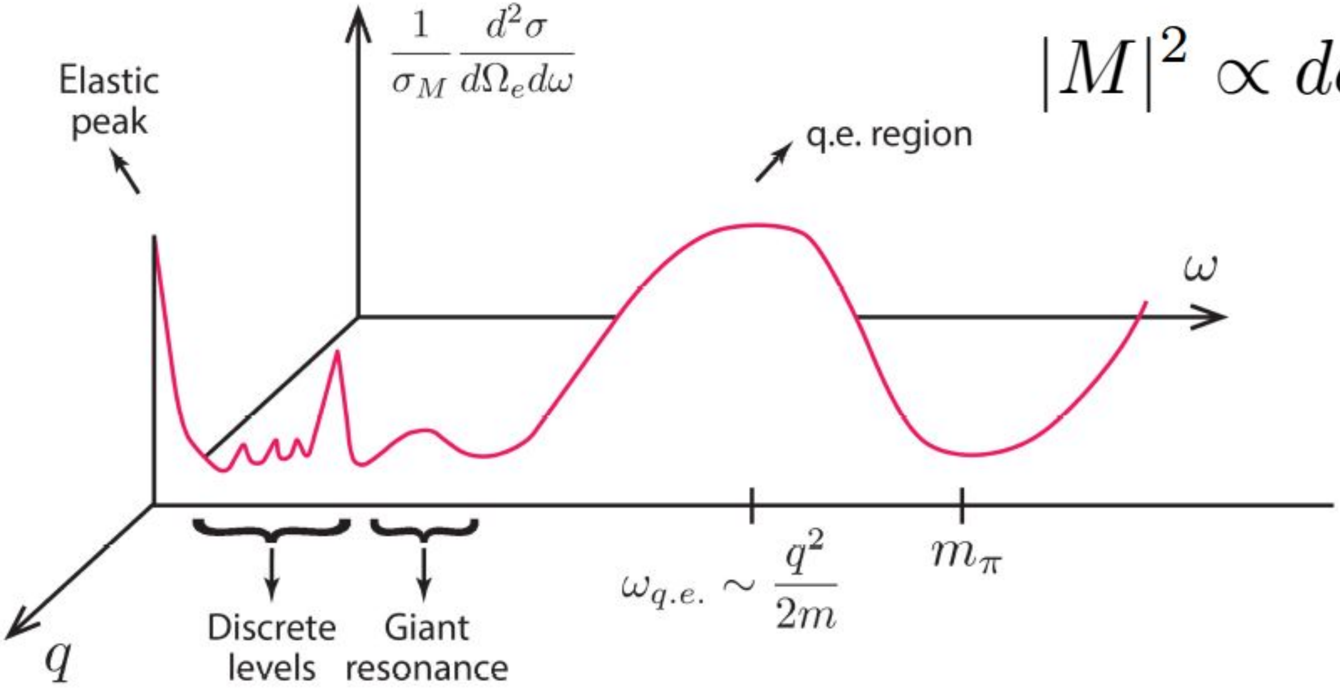
The kinematic regimes of lepton scattering



$$|M|^2 \propto d\sigma/d\Omega$$

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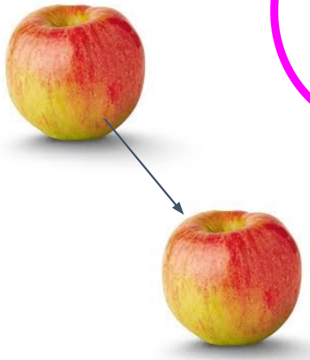
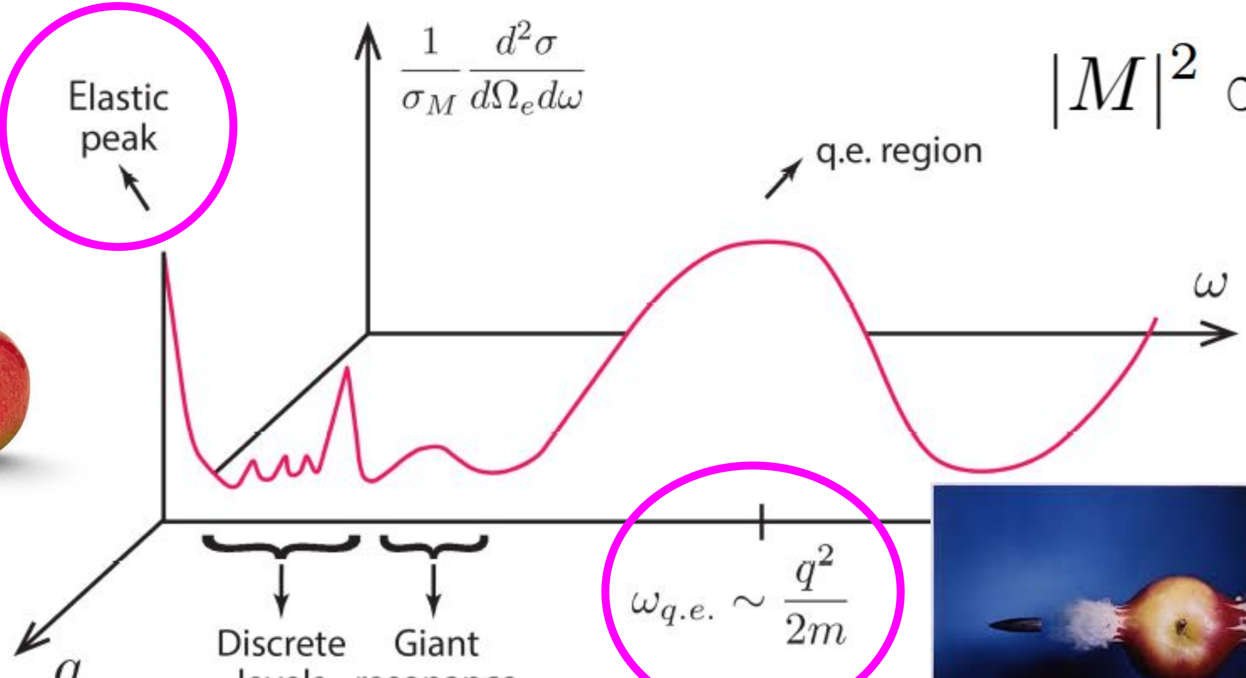
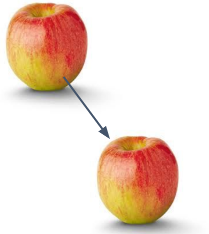
The kinematic regimes of lepton scattering

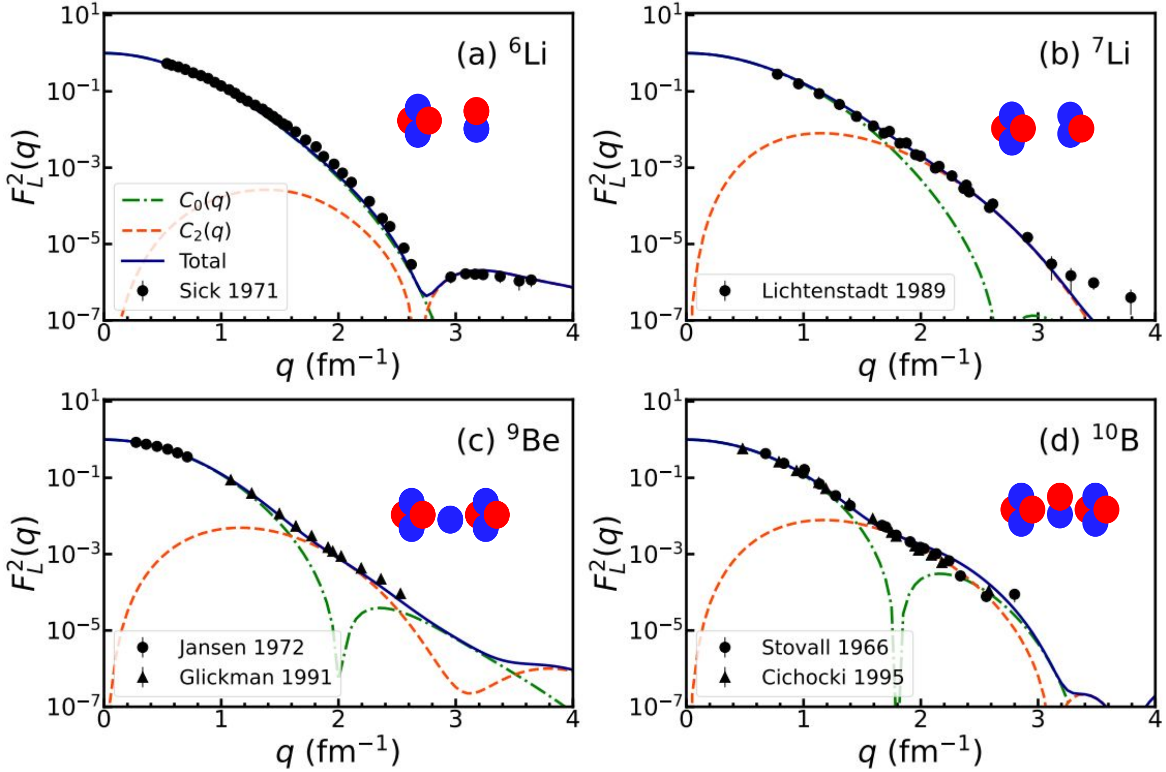




$$|M|^2 \propto d\sigma/d\Omega$$

Elastic electron scattering form factors





Charge form factor depends on sum of excited “multipolarities”

The l=0 term is related to spherically averaged charge density

l=2 is sensitive to quadrupole deformation of the nucleus

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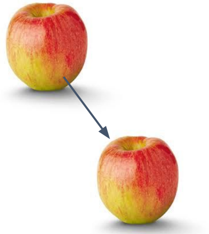
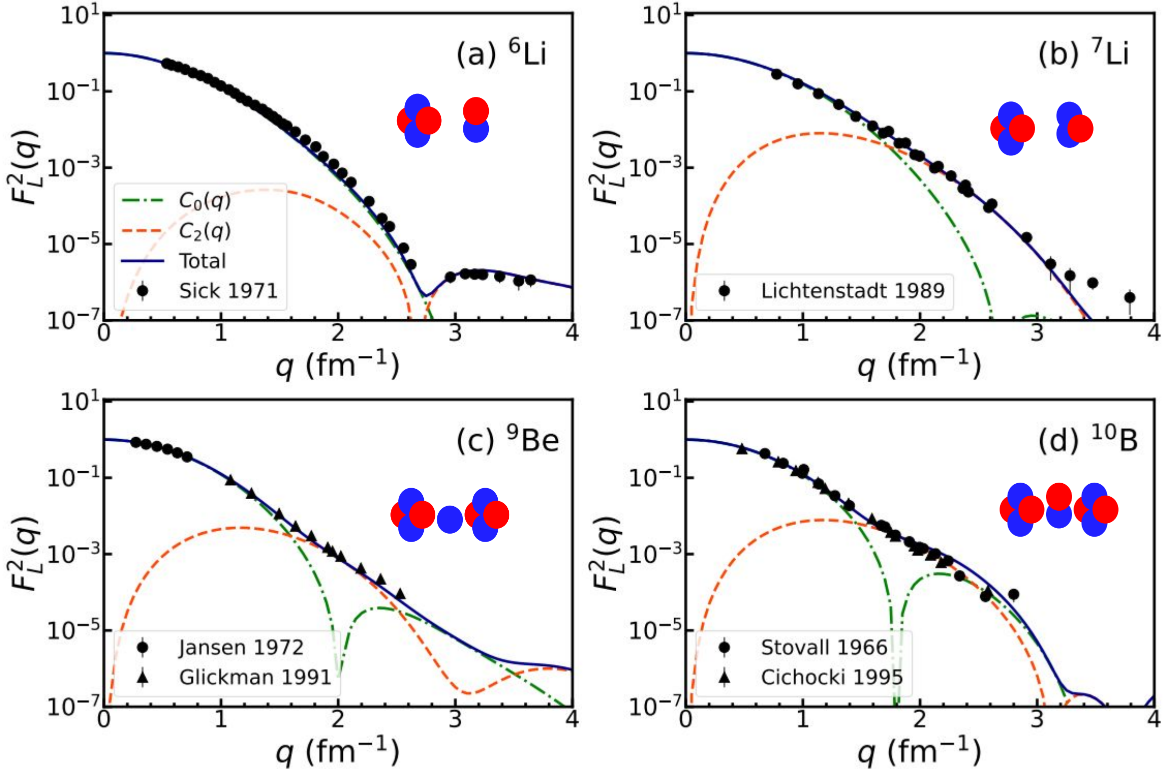
King et al. PRC 110, 054325 (2024)

Elastic electron scattering form factors

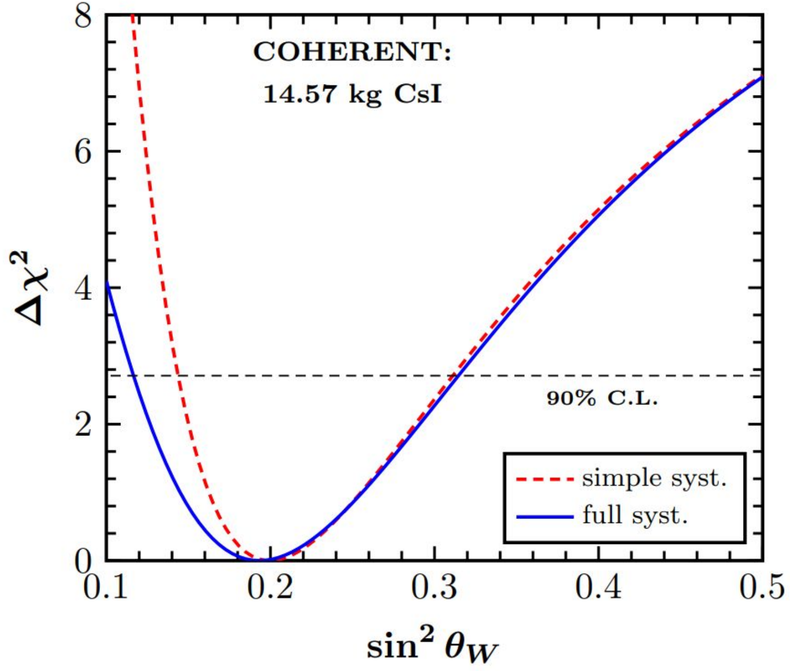




Capturing shape gives insight into the *clustering* and the *nature of the nuclear force*

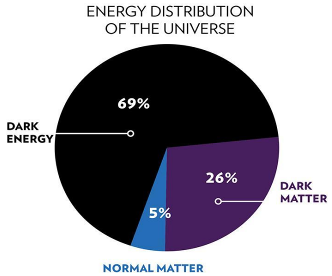
King et al. PRC 110, 054325 (2024)

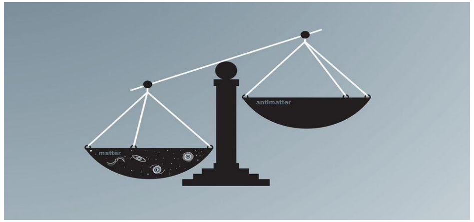
Elastic neutrino scattering



Sensitive to the *weak* form factor of the nucleus

Provides constraints on weak mixing angle, non-standard couplings





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Charge radii

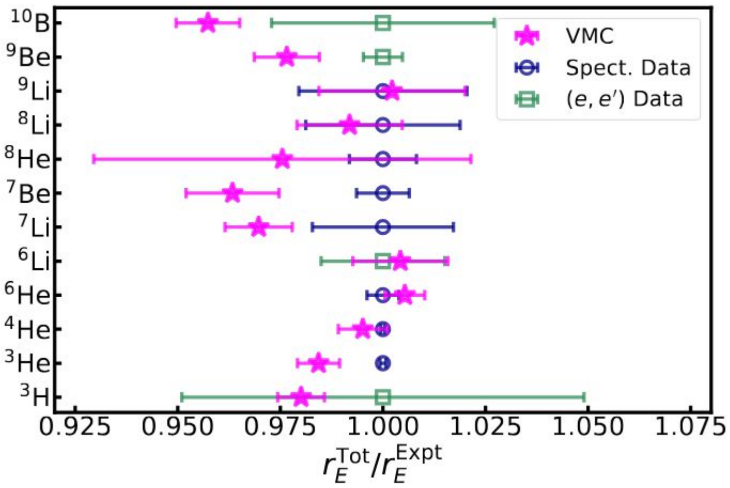
Agreement of ~5% or better across the board

Model successful for He and Li isotopes, less so for Be

Same framework could be used for radioisotopes in the future

Uncertainty is statistical, form factor dependence may also be important

NV2+3-IIb* nuclear interaction model



$$\frac{1}{Z}\langle JJ|\rho(q\hat{\mathbf{z}})|JJ\rangle \approx 1 - \frac{1}{6}r_E^2 q^2 + \mathcal{O}(q^4)$$

King et al., arXiv:2504.04201

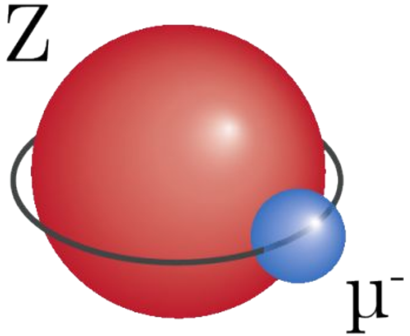
Charge radii for new physics

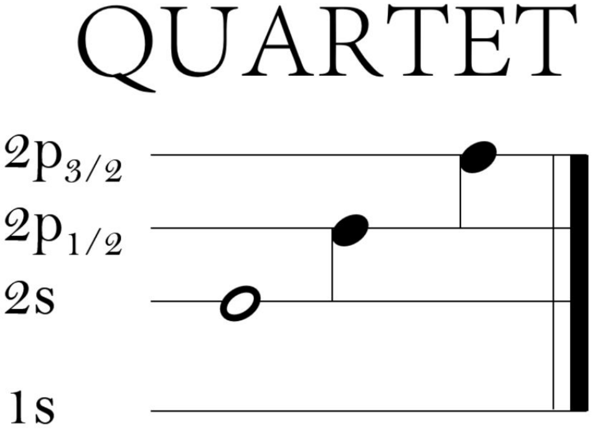
Muonic atoms have a ~200 times smaller Bohr radius

Sensitive to finite size of the nucleus

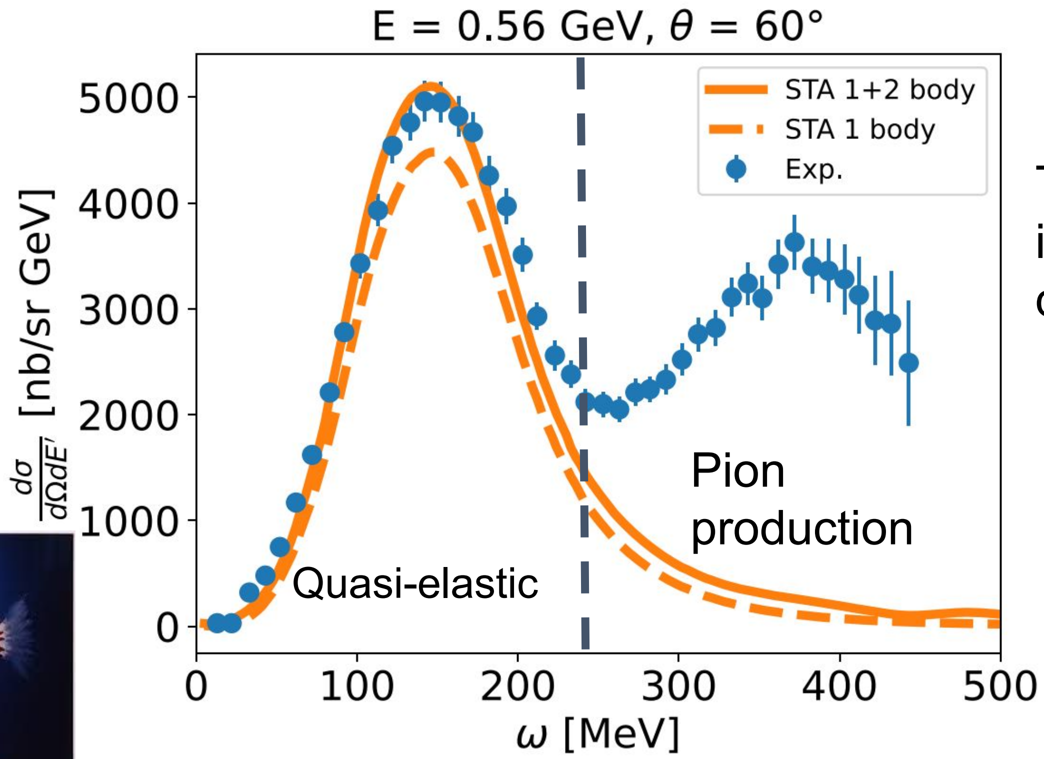
New measurements of Li to Ne isotopes planned

Uncertainties from charge radius of nucleus and nuclear structure corrections to hyperfine splitting





Quasi-elastic electron scattering on ^{12}C



$$\frac{d\sigma}{d\Omega dE'} \propto \sum_i K_i |\langle\Psi|\mathcal{O}_i|\Psi\rangle|^2$$

Two-body physics plays an important role in describing quasi-elastic cross sections

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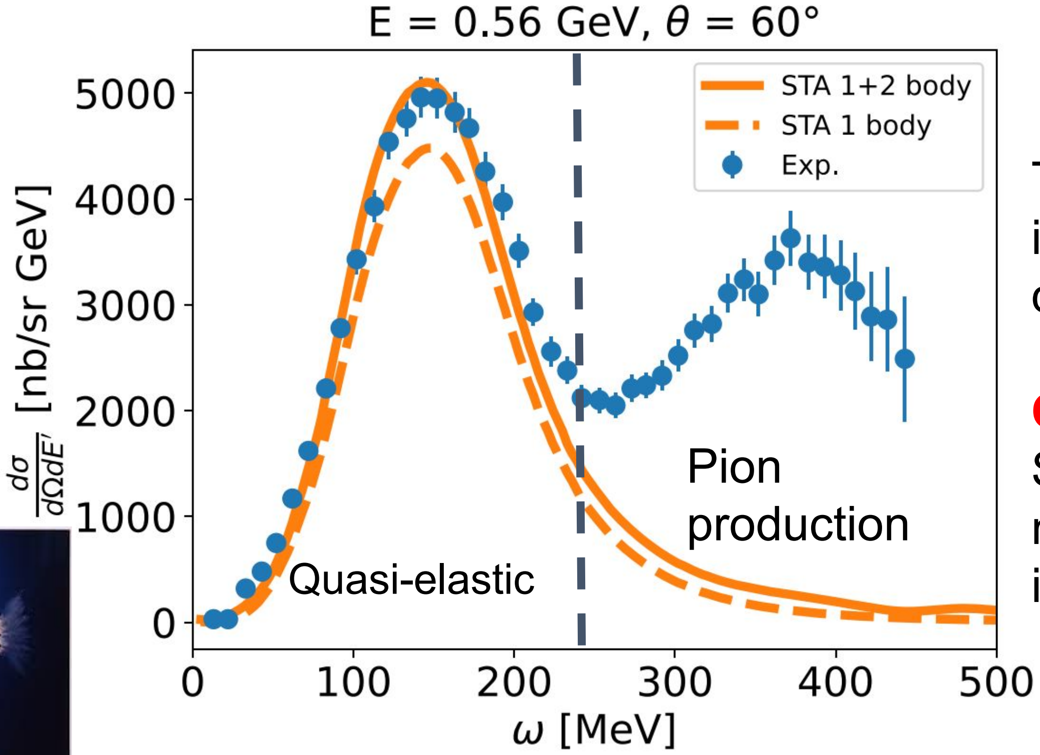
Andreoli, King, et al. PRC 110, 064004 (2024)

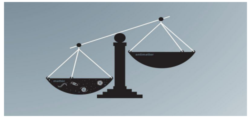
Quasi-elastic electron scattering on ^{12}C



$$\frac{d\sigma}{d\Omega dE'} \propto \sum_i K_i |\langle \Psi | \mathcal{O}_i | \Psi \rangle|^2$$

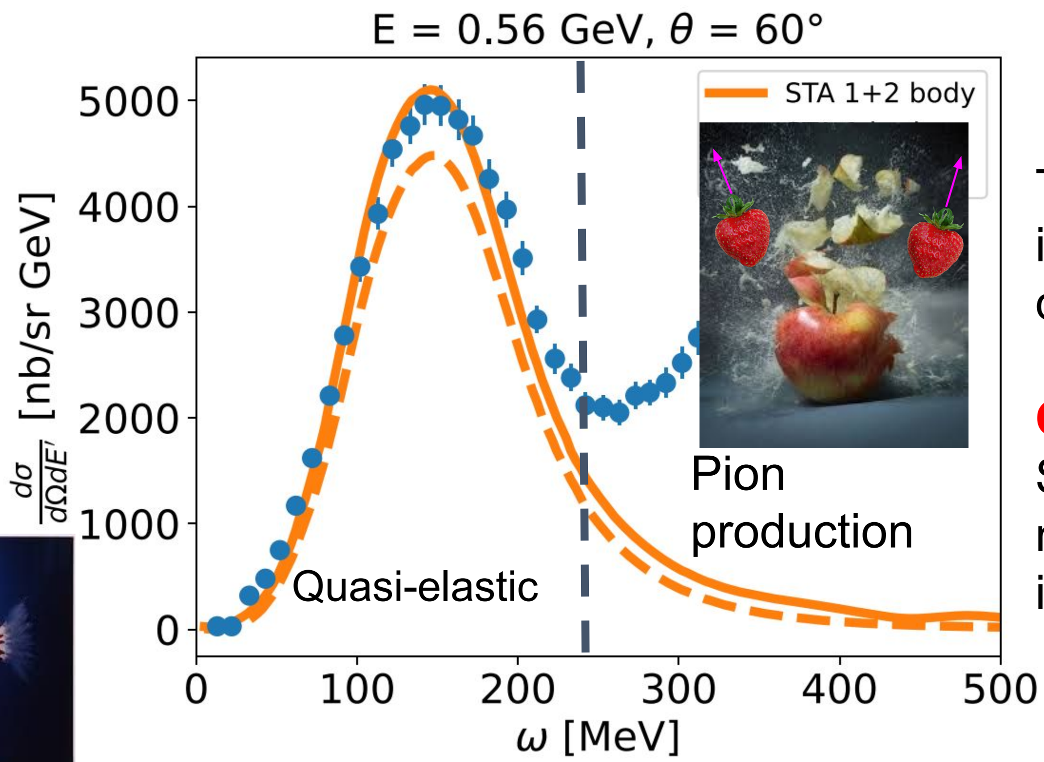
Two-body physics plays an important role in describing quasi-elastic cross sections

Outlook:
Study of quasi-elastic neutrino scattering and inclusion of pion production



Andreoli, King, et al. PRC 110, 064004 (2024)

Quasi-elastic electron scattering on ^{12}C



$$\frac{d\sigma}{d\Omega dE'} \propto \sum_i K_i |\langle \Psi | \mathcal{O}_i | \Psi \rangle|^2$$

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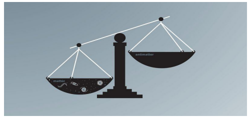

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Andreoli, King, et al. PRC 110, 064004 (2024)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Example: Nuclear β-decay

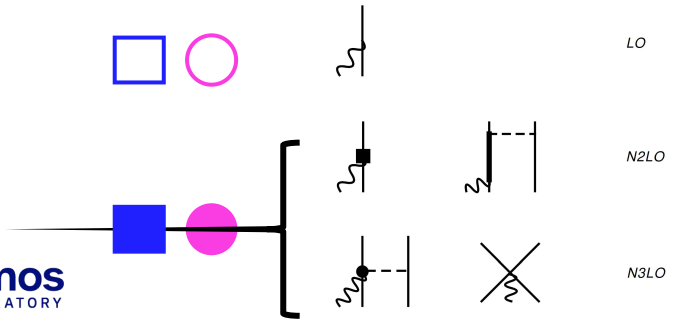
β-decay rates

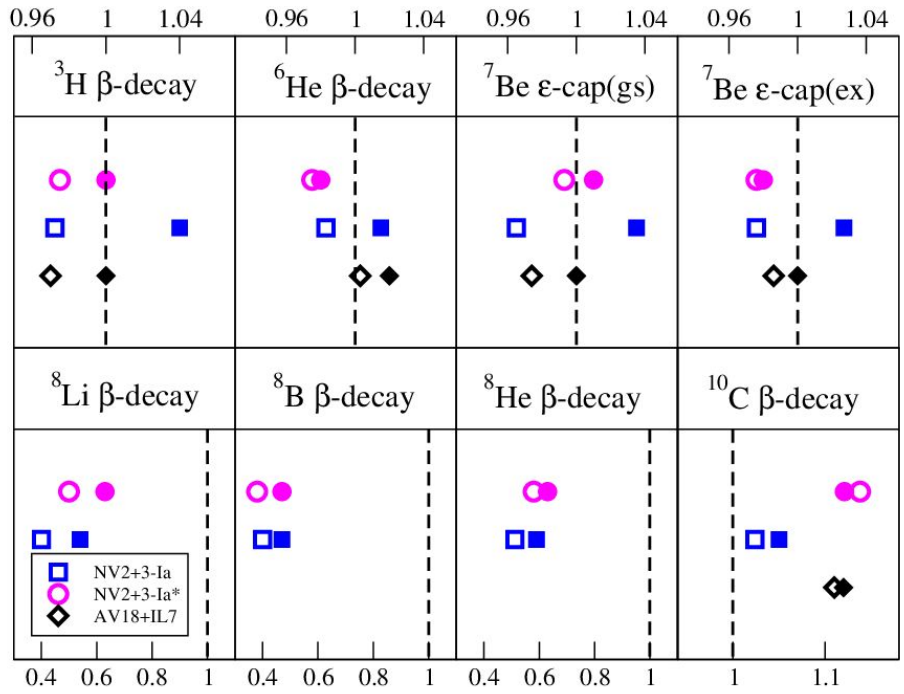
Computed with two models:

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)

^{6}He β-decay spectrum: Overview

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

New physics can distort this: $$\frac{d\Gamma}{dE_e} = \frac{d\Gamma_0}{dE_e}[1 + \Delta(E)]$$

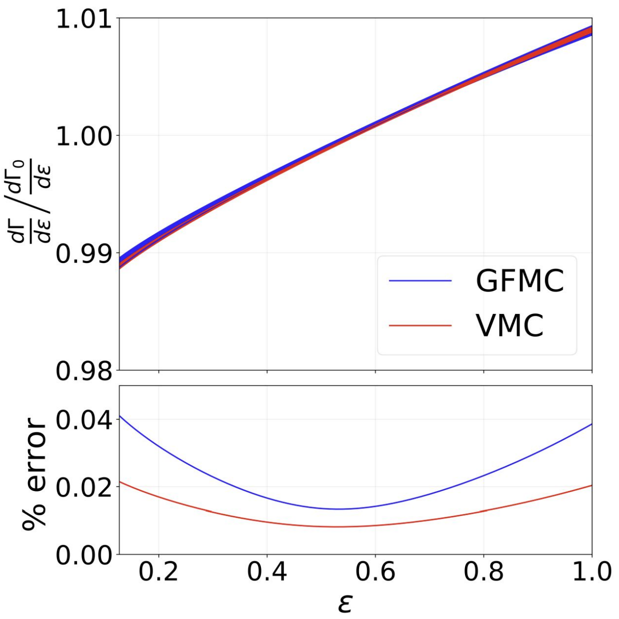
Similar distortions can be generated when accounting for nuclear recoil

Performed calculation with recoil corrections and two-body physics effects

Vector
Scalar
→ **Fermi**

Axial
Tensor
Pseudoscalar
→ **GT**

^{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)]

King et al. PRC 107, 015503 (2023)

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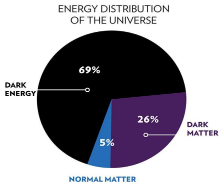
FRIB

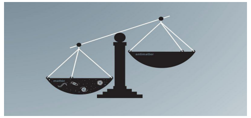
^{6}He β-decay spectrum: Probing new forces

Included transition operators associated with new physics

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

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





FRIB

^{6}He-CRES

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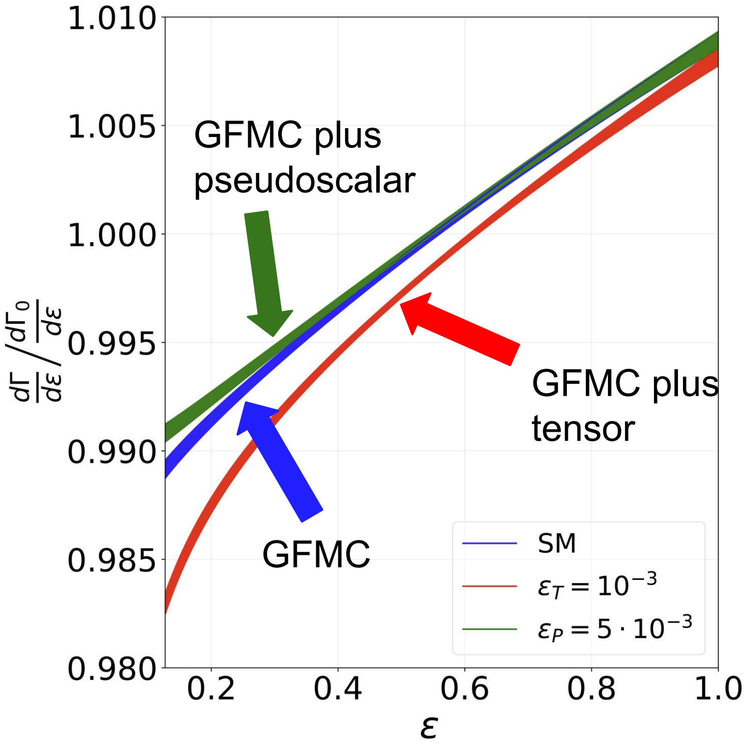
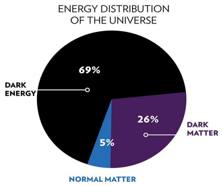


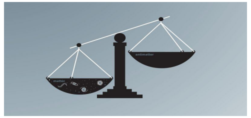
King et al. PRC 107, 015503 (2023)

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

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

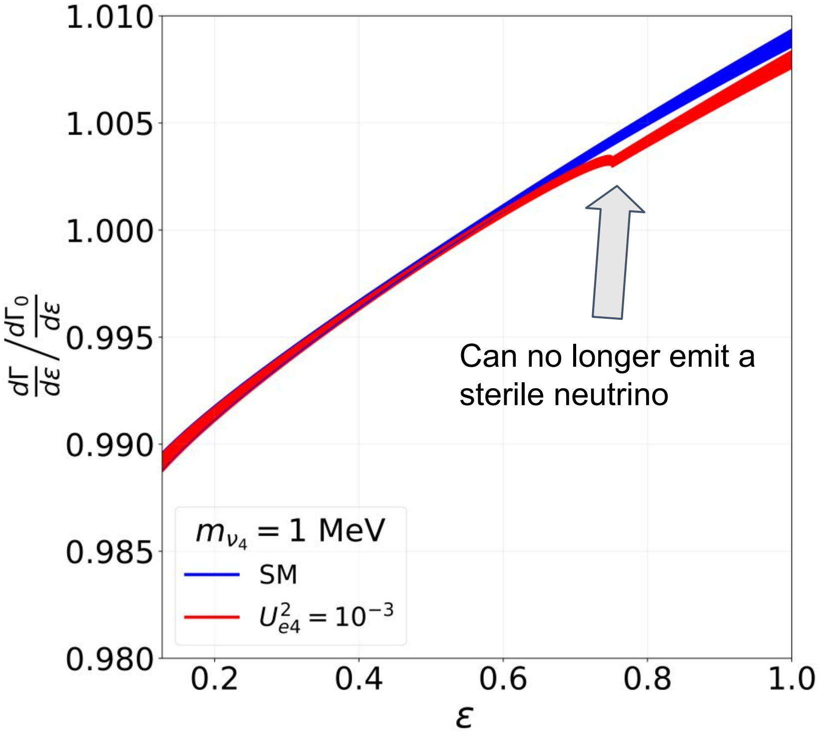
The shape of the decay endpoint can exclude some parameter space and probe BSM scenarios





FRIB

^{6}He-CRES



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King et al. PRC 107, 015503 (2023)

Conclusions

Accurate many-body calculations of interacting nucleons provide a powerful way to understand the impact of the nuclear dynamics on electroweak structure

QMC allows for ***understanding*** and ***interpretation*** of these impacts

This work can help to bridge precision searches and RIB physics

Acknowledgements

WUSTL: Pastore, Piarulli
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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

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NERSC

Funding from DOE/NNSA Stewardship Science Graduate Fellowship and the LDRD Project 20240742PRD1

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:

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

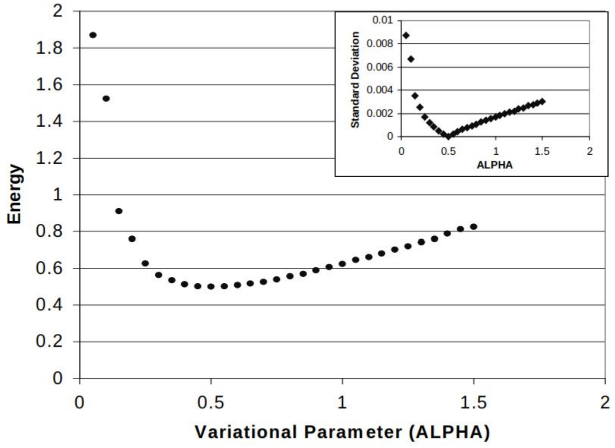
Carlson et al. Rev. Mod. Phys. 87, 1607 (2015)

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

Green's function Monte Carlo

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

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

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

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

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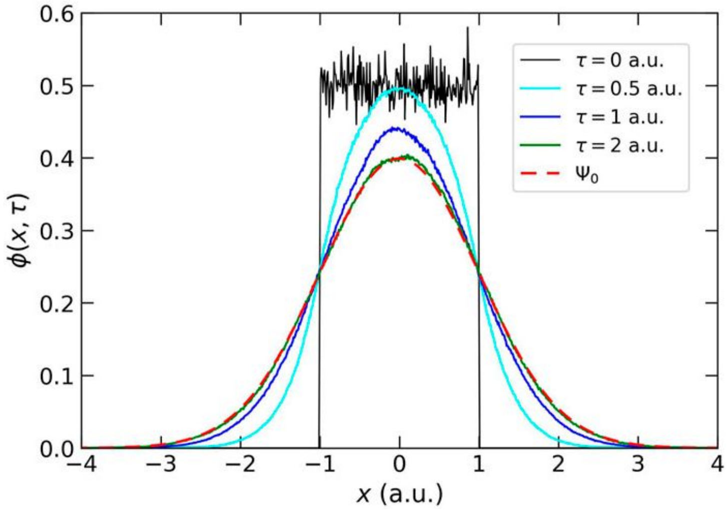
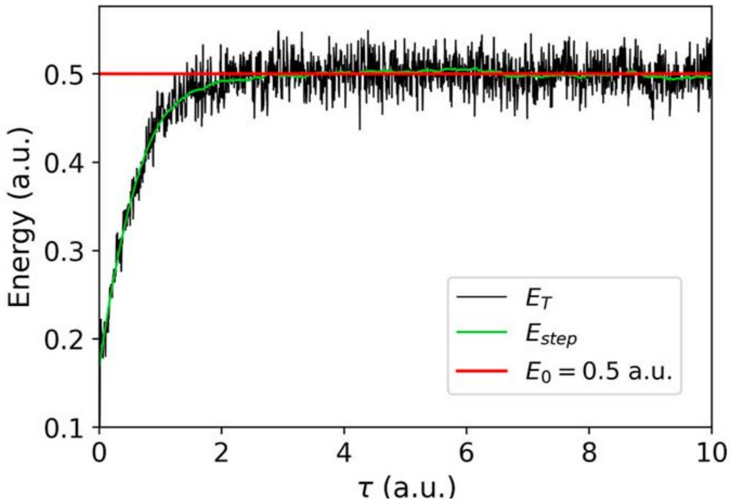
Green's function Monte Carlo: 1D example





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

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

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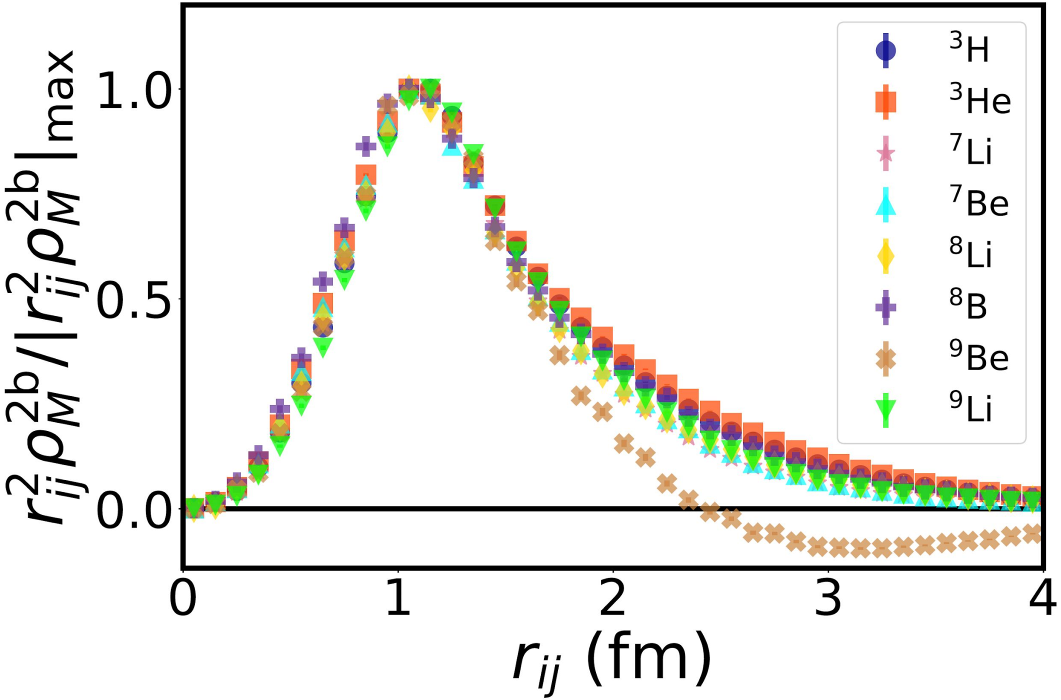
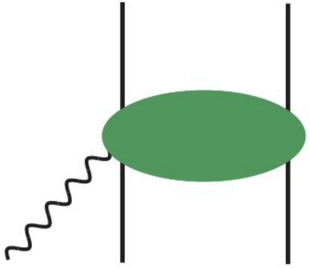
Annarelli et al, J. Chem. Phys. 161, 241501 (2024)

Universality in magnetic densities

NV2+3-IIb*





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

Chambers-Wall, King, et al. PRC 110, 054316 (2024)

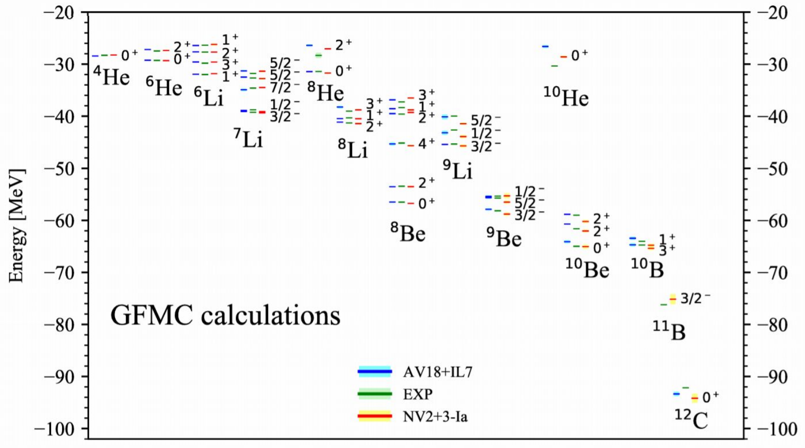
The Norfolk (NV2+3) interactions

Semi-phenomenological model based on χEFT with pion, nucleon, and delta degrees of freedom by **Piarulli et al. [PRL 120, 052503 (2018)]**

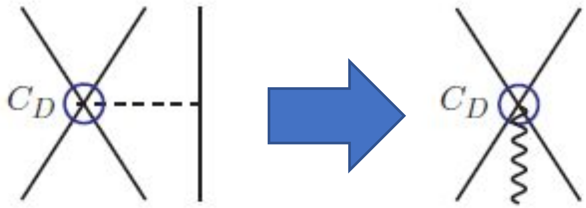
$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

NV2 contains 26 unknown LECs in contacts, two more from the NV3

Eight model classes arrived at from different procedures to constrains the unknown LECs



Three-body LECs and sub-leading contact



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

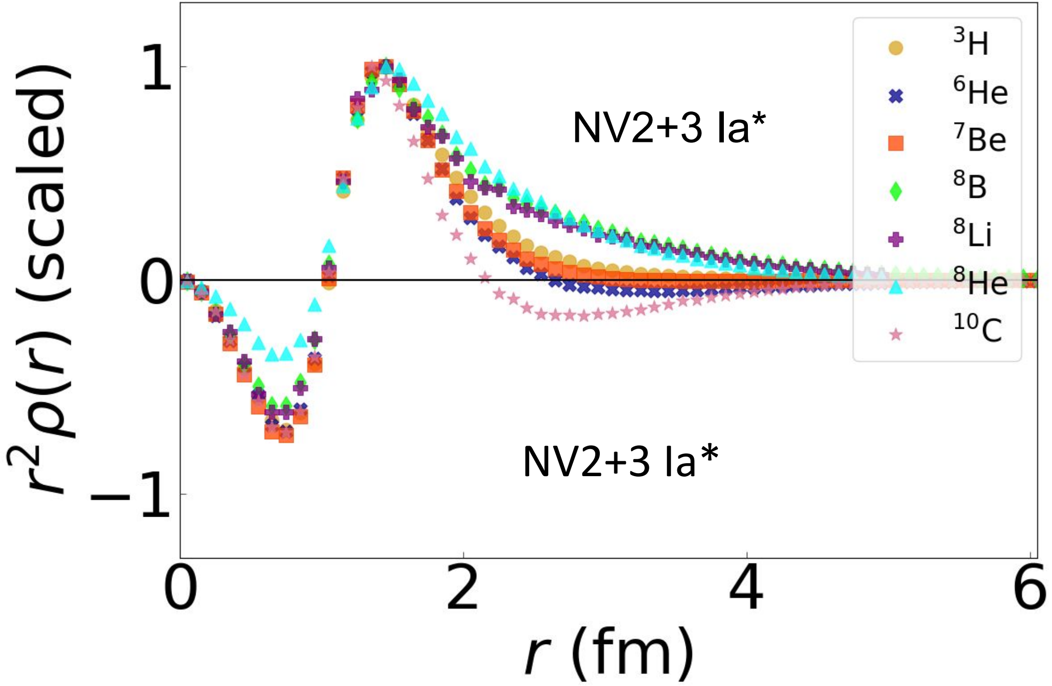
$$z_0 \propto (c_D + \text{ known LECs})$$

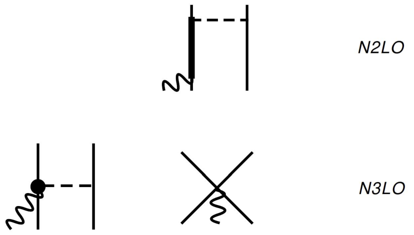
Specific parameter in the three-nucleon force is ***connected to*** a parameter in the two-body weak transition operator

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

Gardestig and Phillips PRL 96, 232301 (2006)

Scaled total two-body transition densities





$$M_{\mathrm{GT}}^{2\mathrm{b}} = \int dr_{ij} 4\pi r_{ij}^2 \rho_{\mathrm{GT}}^{2\mathrm{b}}(r_{ij})$$

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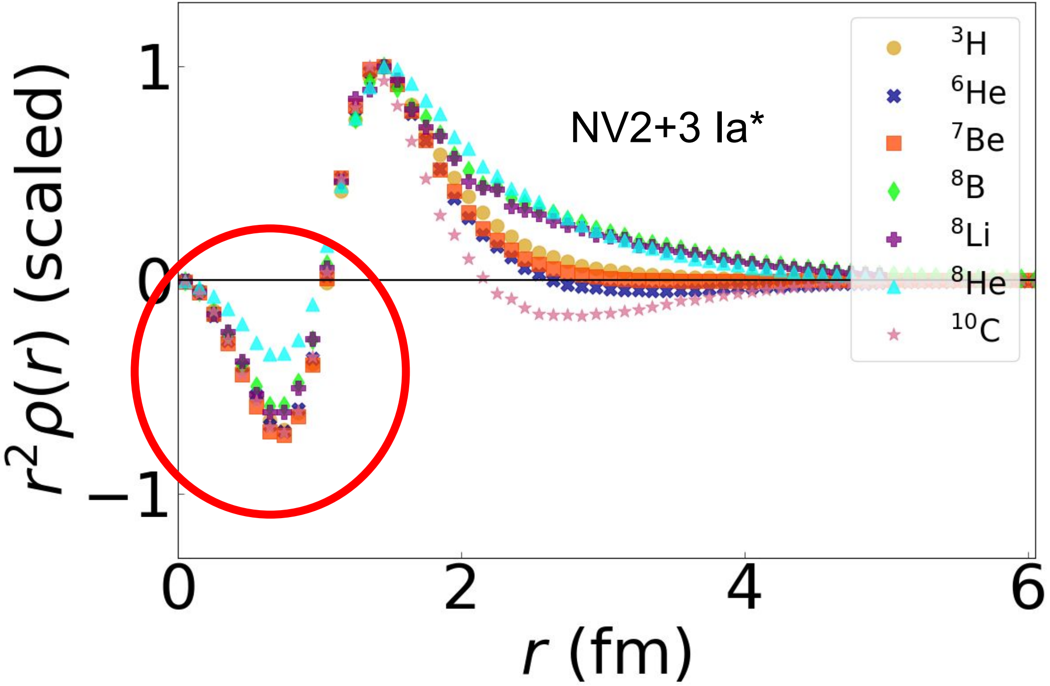
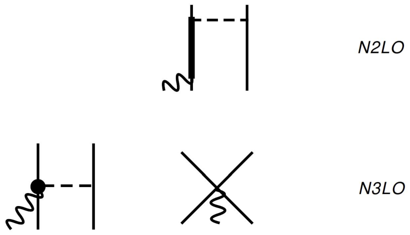
King et al. PRC 121, 025501 (2020)

Scaled total two-body transition densities



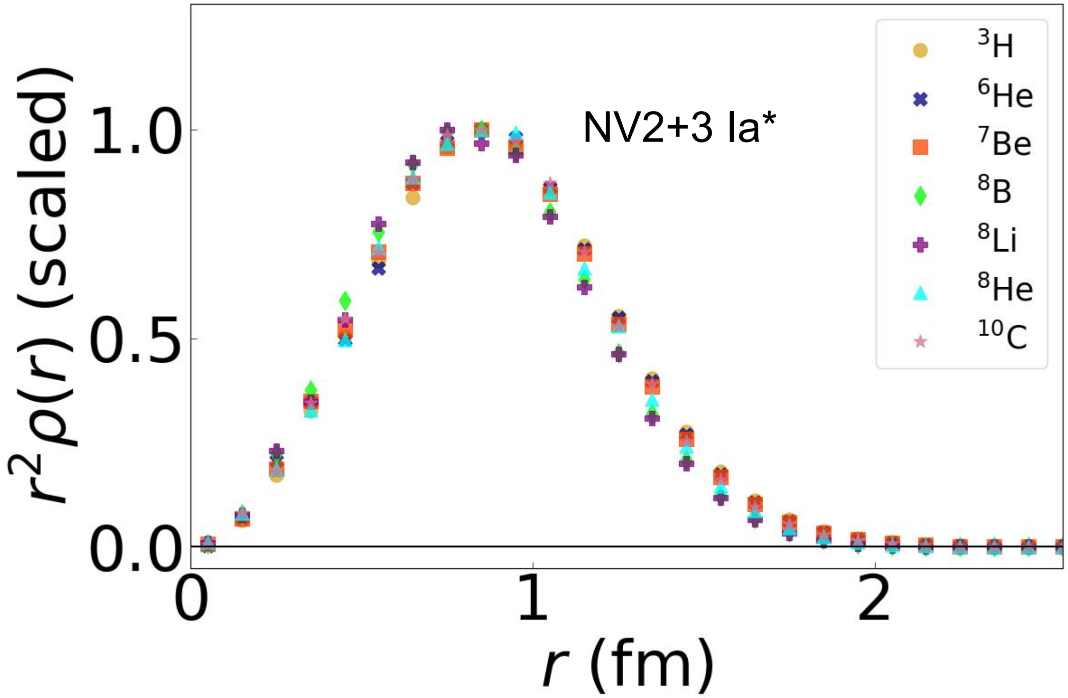


We can isolate the short-range contact piece

$$M_{\mathrm{GT}}^{2\mathrm{b}} = \int dr_{ij} 4\pi r_{ij}^2 \rho_{\mathrm{GT}}^{2\mathrm{b}}(r_{ij})$$

King et al. PRC 121, 025501 (2020)

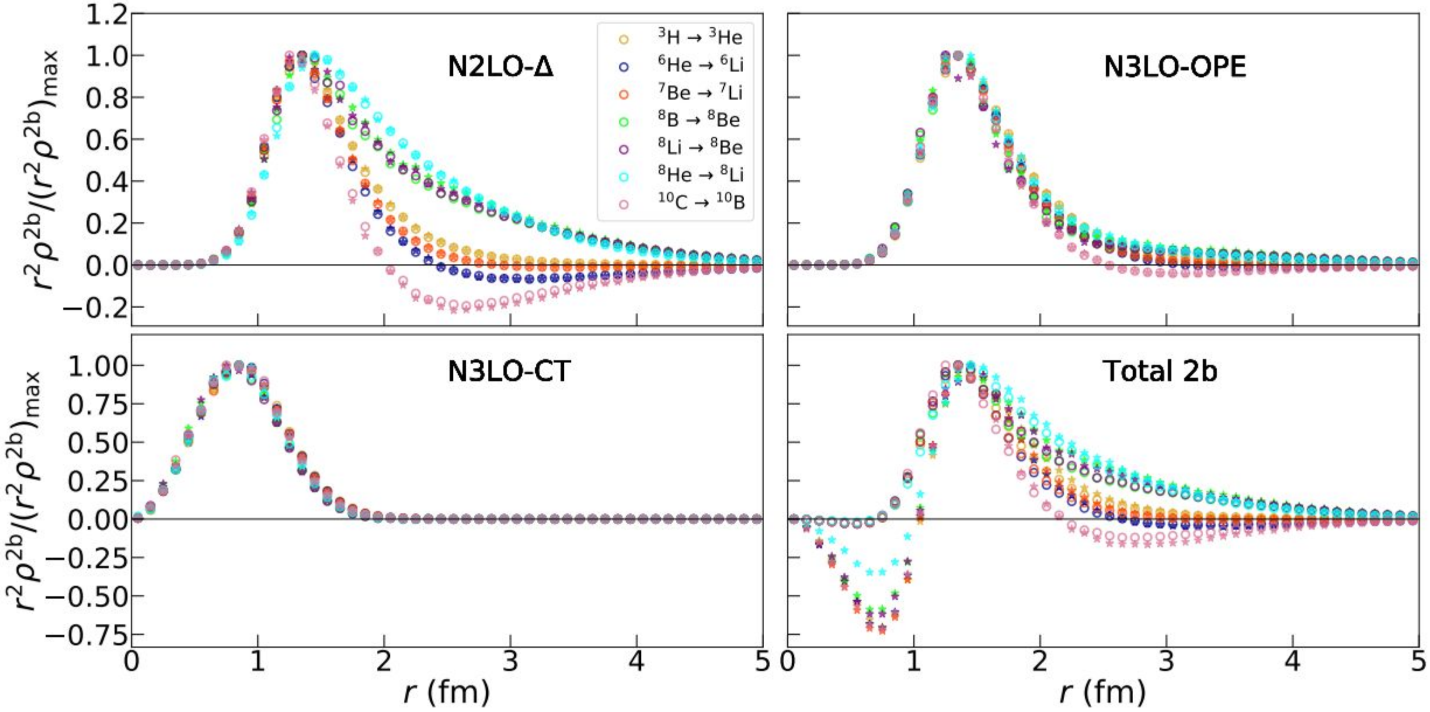
Scaled contact two-body transition densities



$$M_{\rm GT}^{\rm CT} = \int dr_{ij} 4\pi r_{ij}^2 \rho_{\rm GT}^{\rm CT}(r_{ij})$$

King et al. PRC 121, 025501 (2020)

Universal behavior in GT densities



King et al. PRC 121, 025501 (2020)

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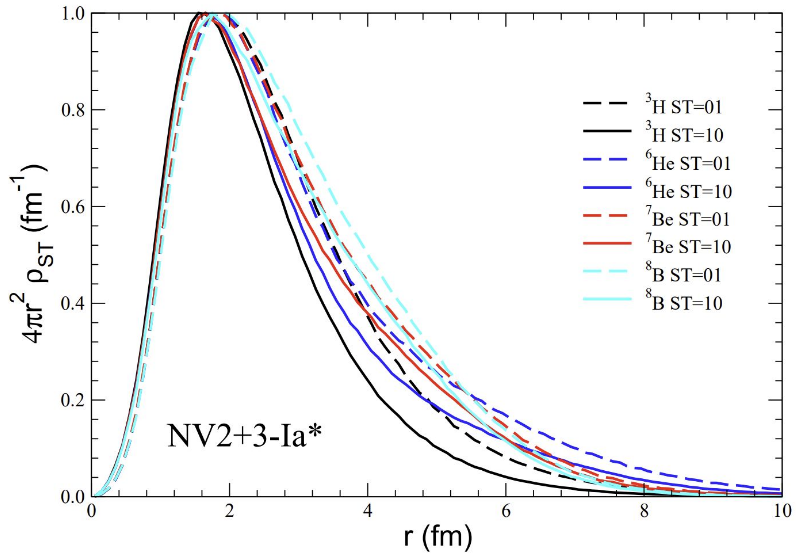
Interpreting universal and tail behaviors

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



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

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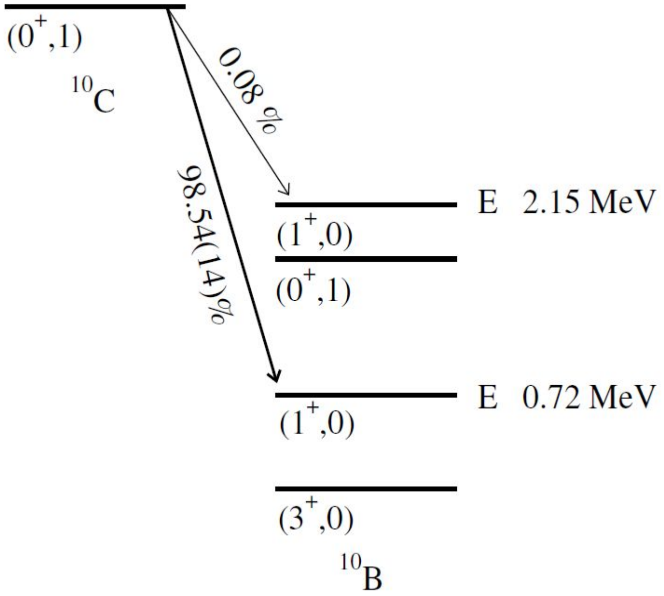
King et al. PRC 121, 025501 (2020)

^{10}B β-decay



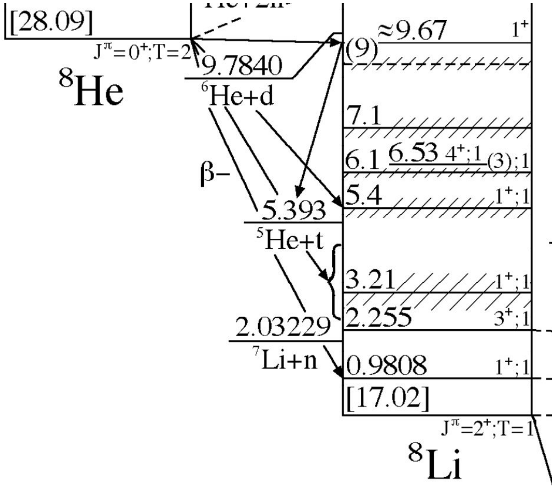
https://nucldata.tunl.duke.edu/

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

^{8}He β-decay



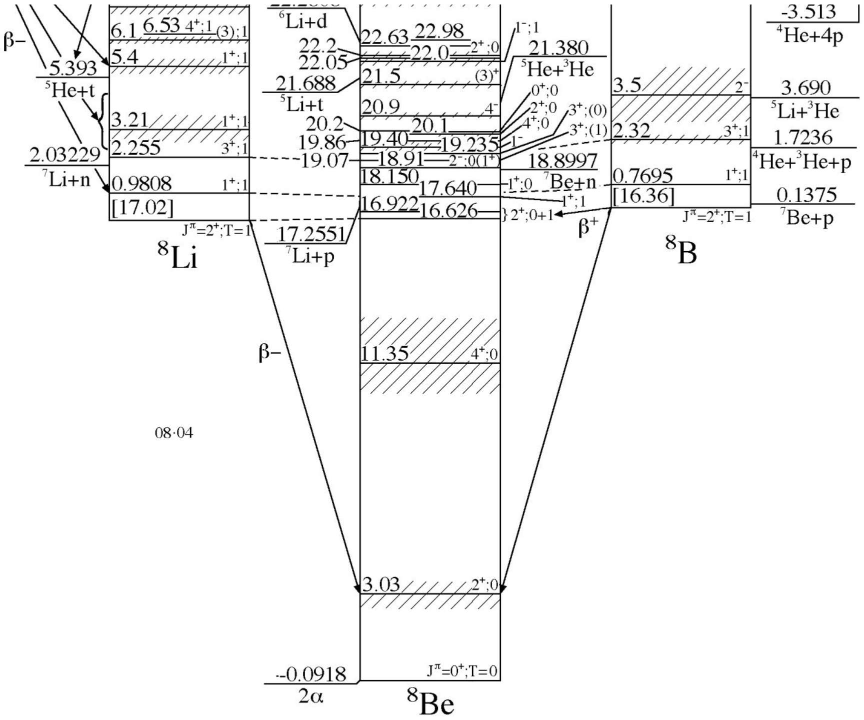
https://nucldata.tunl.duke.edu/

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.

A=8 level scheme



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

Computation of reduced multipoles

Reduced multipoles are defined by **[Carlson and Schiavilla RMP 70 (1998)]**:

$$\langle J_f M|\rho^\dagger(q)|J_i M\rangle = (-1)^{J_i-M}\sum_L \sqrt{4\pi}(-i)^L P_L(\cos\theta)c^M_{J_f J_i L} C_L(q)\,,$$

$$\langle J_f M|\hat{e}^*_\lambda\cdot\mathbf{j}^\dagger(q)|J_i M\rangle = (-1)^{J_i-M+1}\sum_{L\geq 1}\sqrt{8\pi^2}\frac{(-i)^L}{\sqrt{2L+1}}Y^*_{LM}(\theta,\phi)c^M_{J_f J_i L}M_L(q)$$

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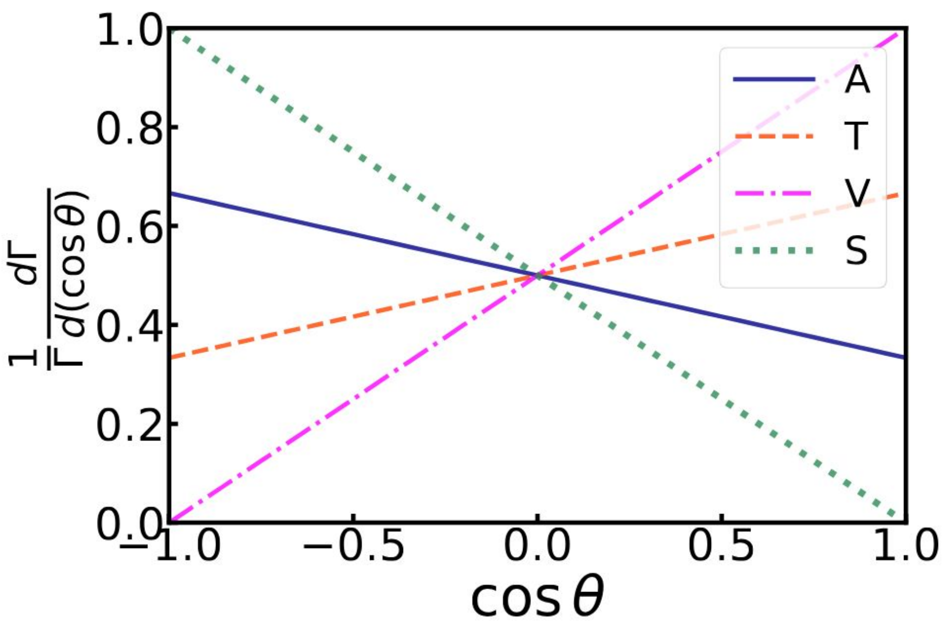
Cross section

$$\frac{d\sigma}{d\Omega} = 4\pi\sigma_M f_{\mathrm{rec}}^{-1} \left[\frac{Q^4}{q^4} F_L^2(q) + \left(\frac{Q^2}{2q^2} + \tan^2\theta_e/2\right) F_T^2(q)\right]$$

In elastic scattering:

$$F_T^2(q) = F_M^2(q) = \frac{1}{2J_i+1}\sum_{L=1}^{\infty} |\langle J_f || M_L(q) || J_i\rangle|^2 \qquad F_L^2(q) = \frac{1}{2J_i+1}\sum_{L=0}^{\infty} |\langle J_f || C_L(q) || J_i\rangle|^2$$

BSM current effects on decay correlations



Axial, tensor, vector, and scalar currents preferentially emit electrons at certain angles

A/T, V/S interfere with one another in BSM scenarios

Tensor operator flips electron chirality -> interference at low energy, coherently sums with axial at large energy

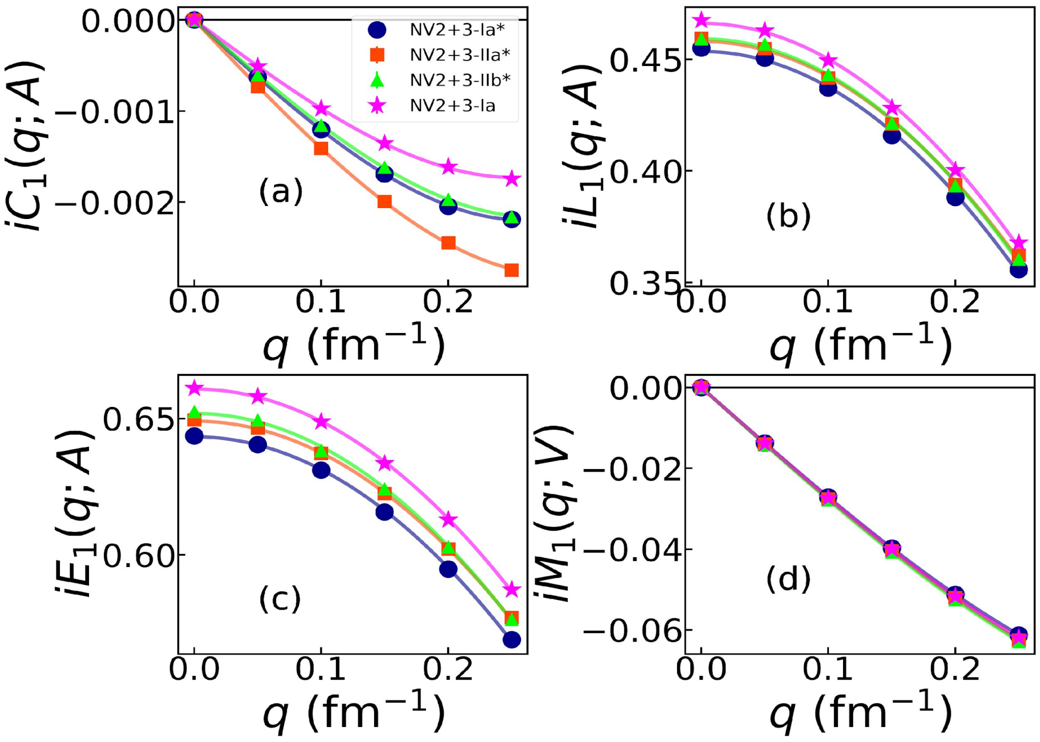
^{6}He β-decay spectrum: Multipoles

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

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

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

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



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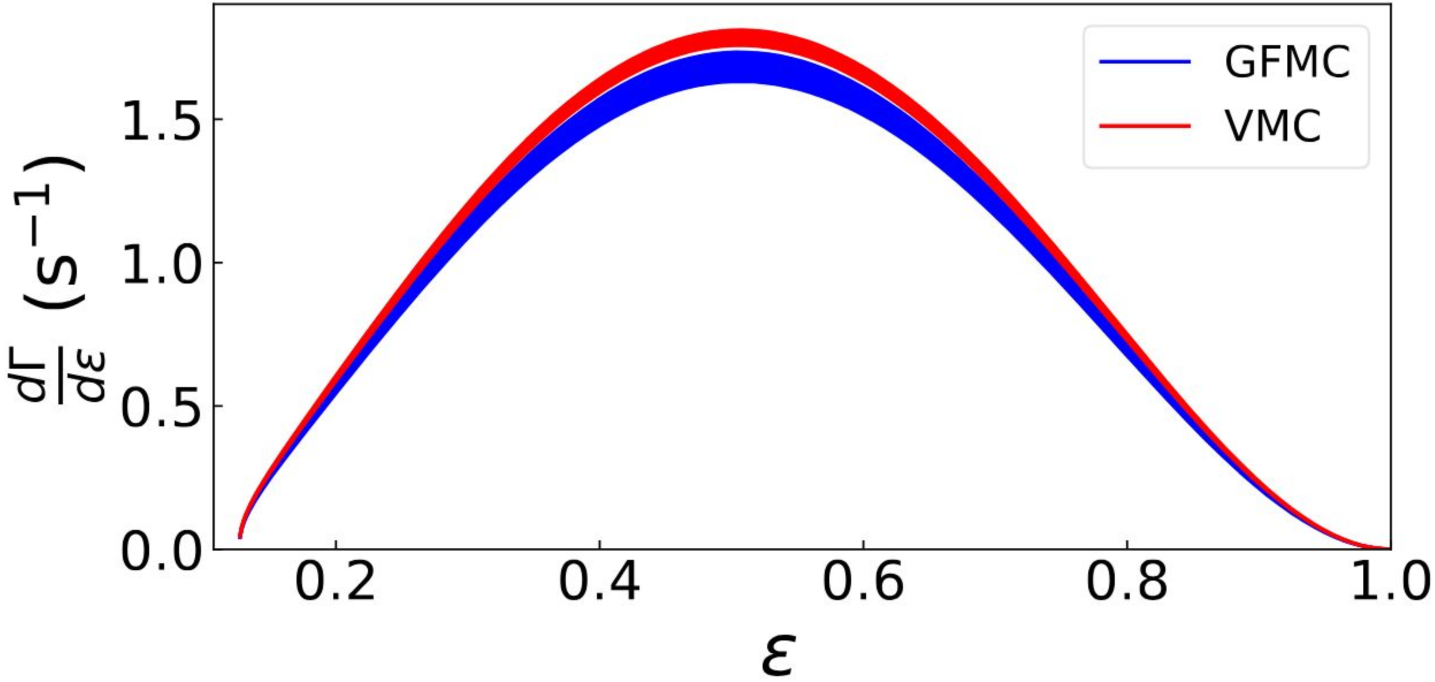
^{6}He β-decay spectrum: Absolute spectrum



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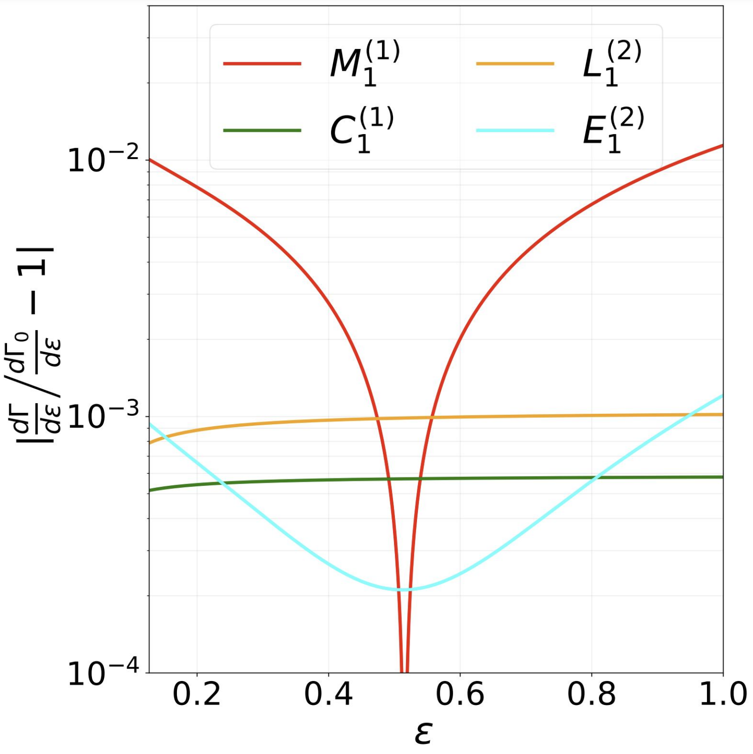
^{6}He β-decay spectrum: SM corrections



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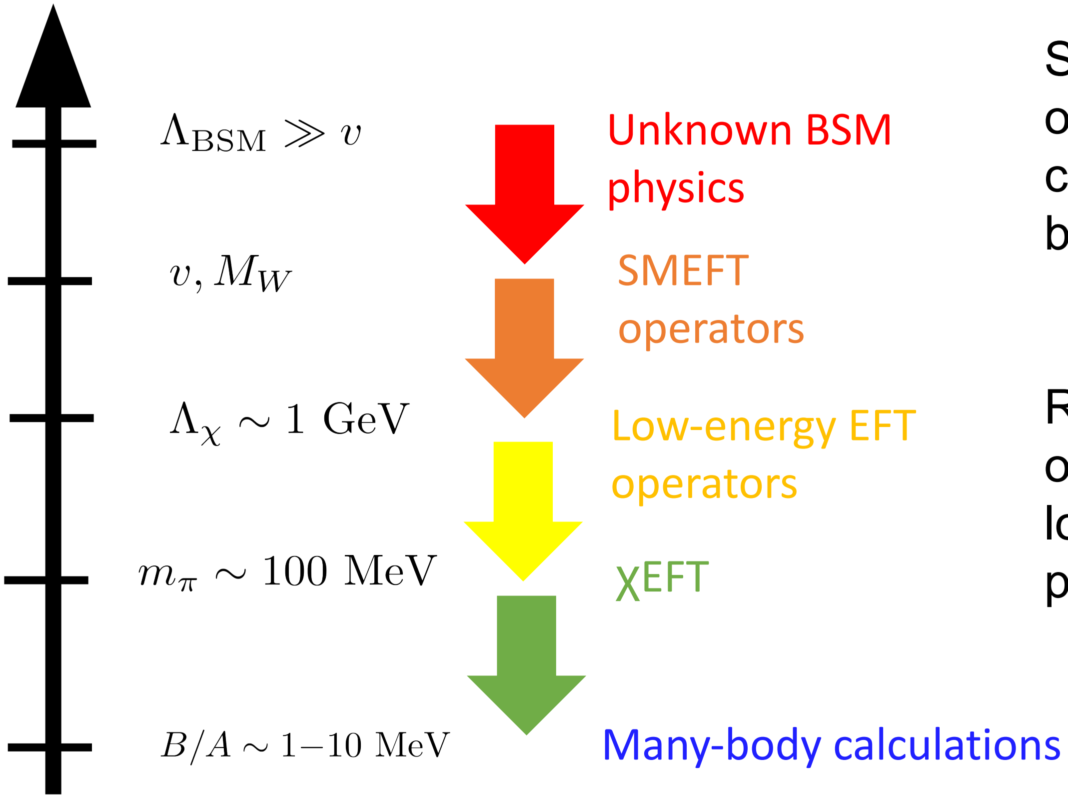
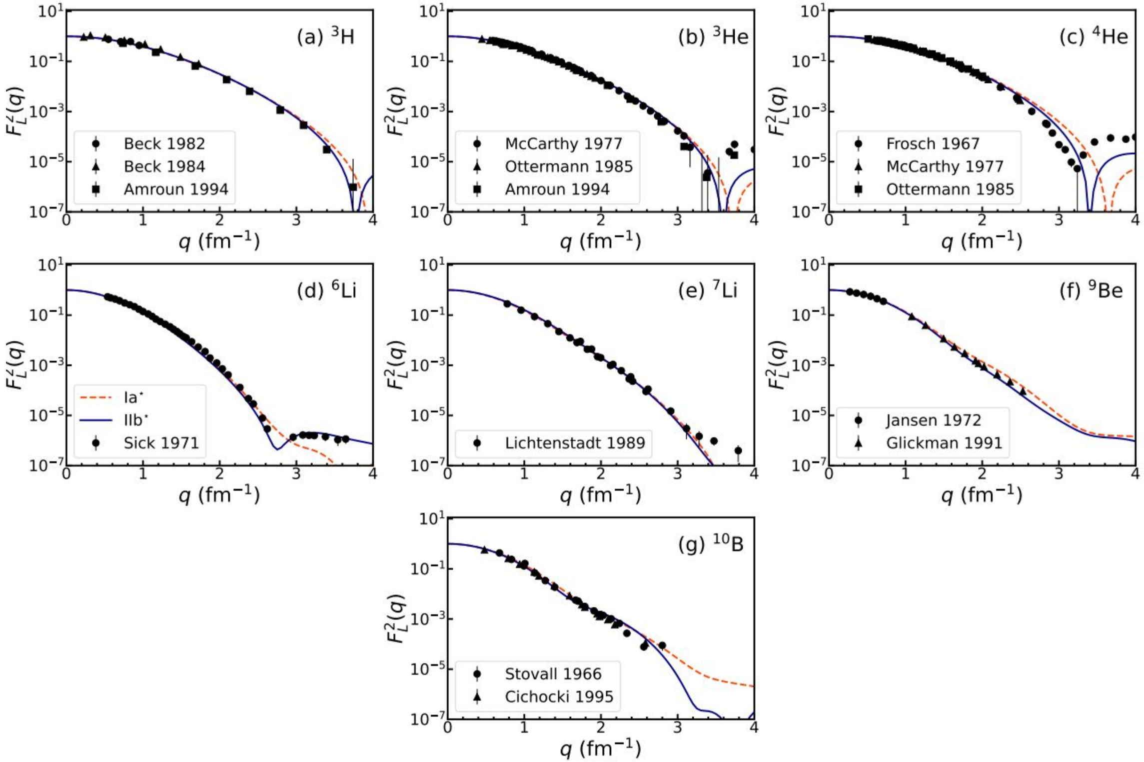
^{6}He β-decay spectrum: SMEFT



Start with most general operators in SMEFT that can contribute to GT beta decay

Run the coupling and obtain operators at the low-energy nuclear physics scale

Model variation of charge form factors



King et al. PRC 110, 054325 (2024)