Los Alamos
NATIONAL LABORATORY

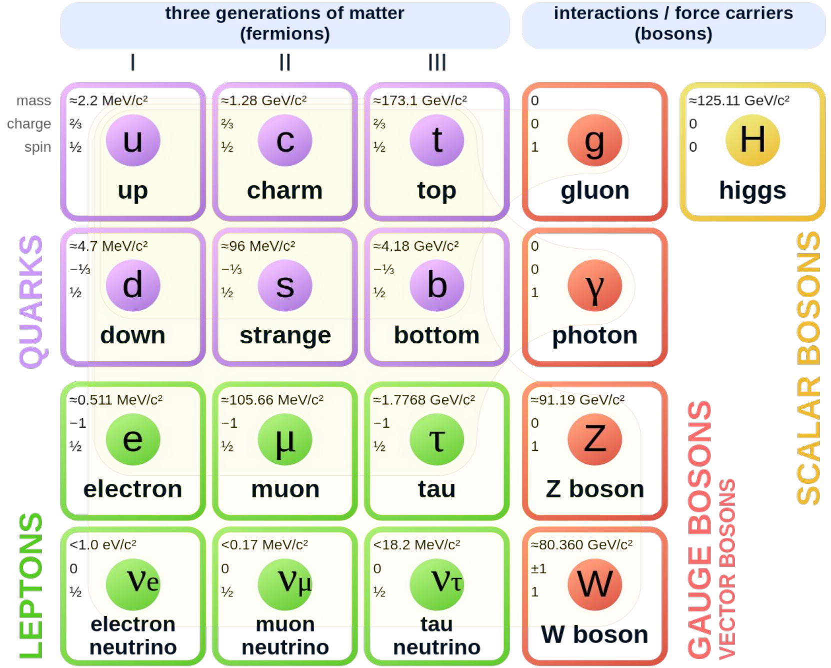
Low-energy nuclear physics for fundamental science

Garrett King

Dehmelt Seminar
University of Washington
1/8/2026

LA-UR-25-32298

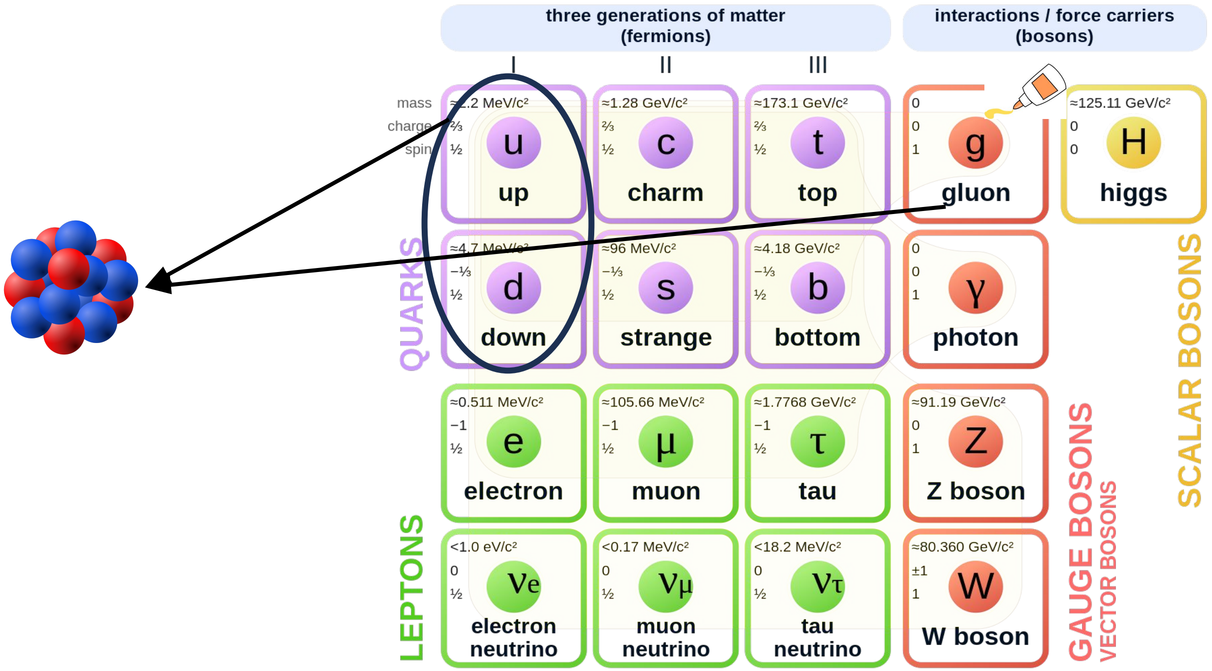
The Standard Model



https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

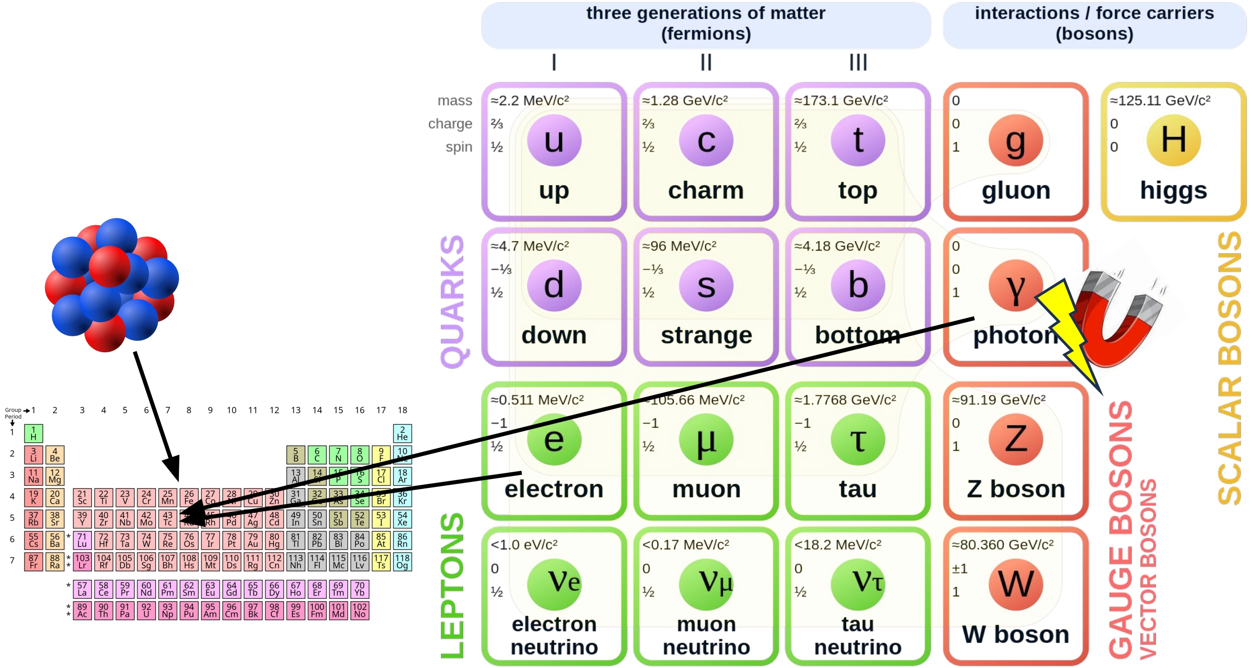
Los Alamos NATIONAL LABORATORY

The Standard Model



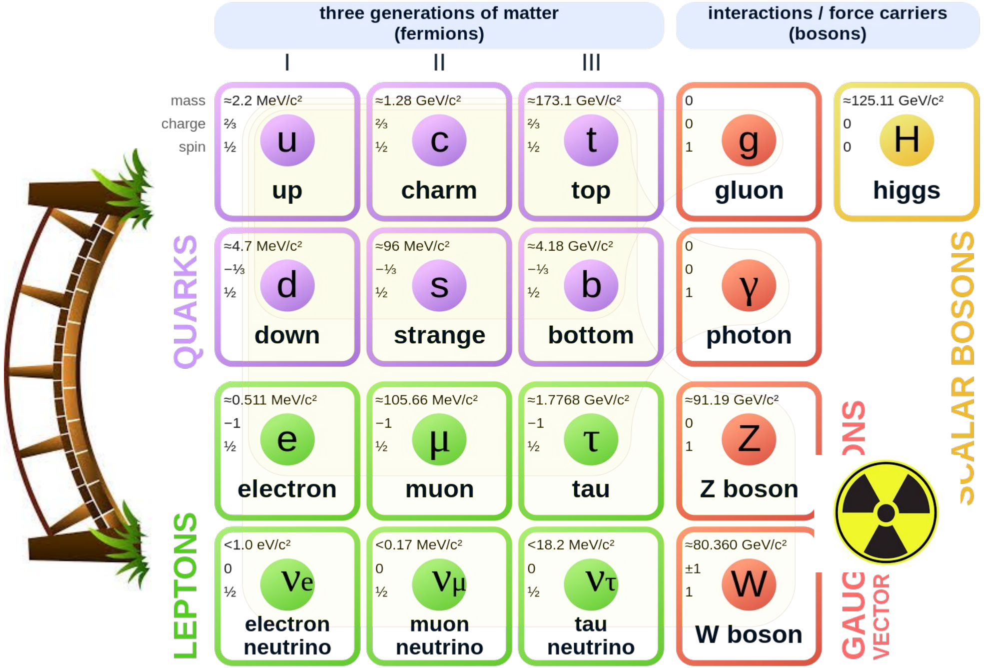
https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model



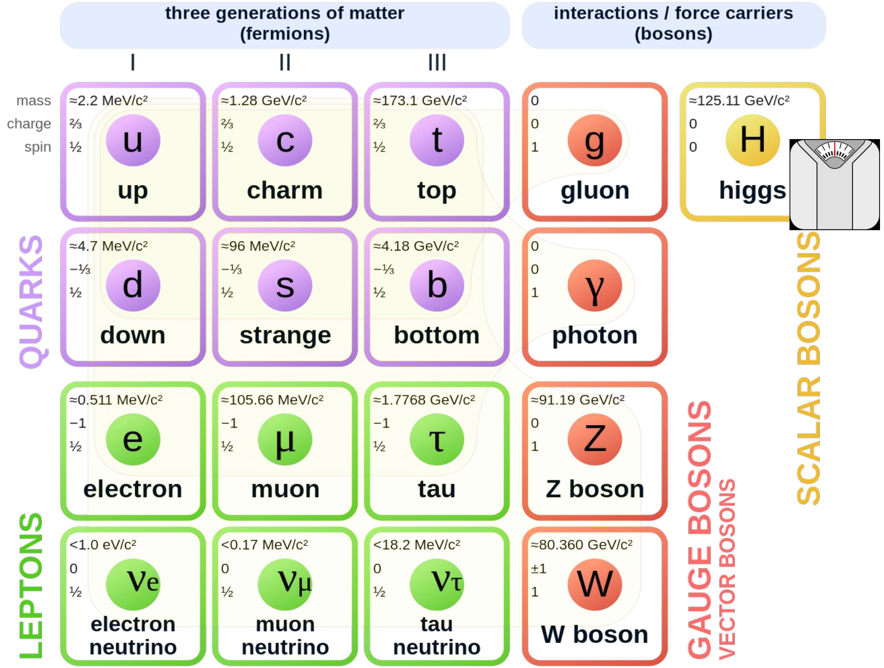
https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model



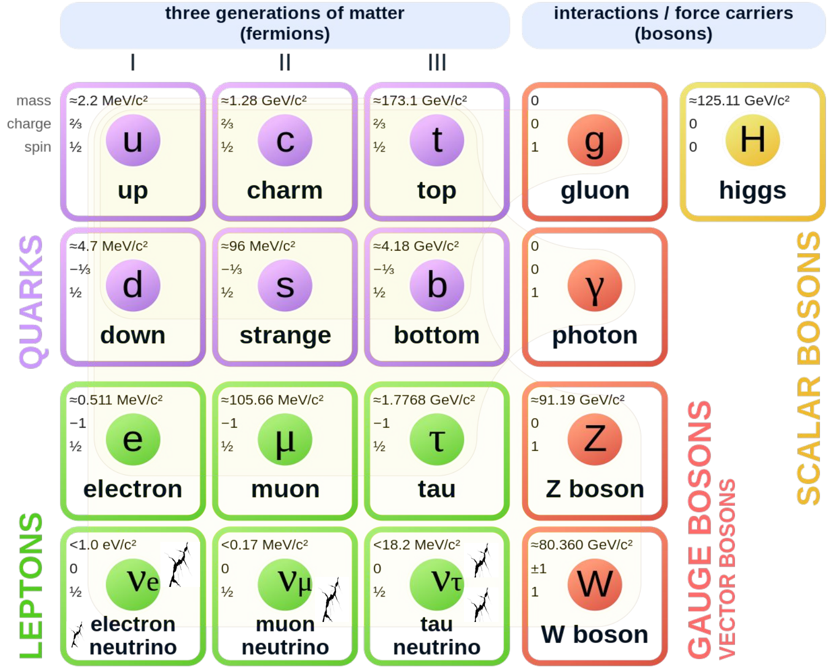
https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model



https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model



https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

Los Alamos NATIONAL LABORATORY

Neutrino oscillations

Fermilab / Sandbox Studio, Chicago

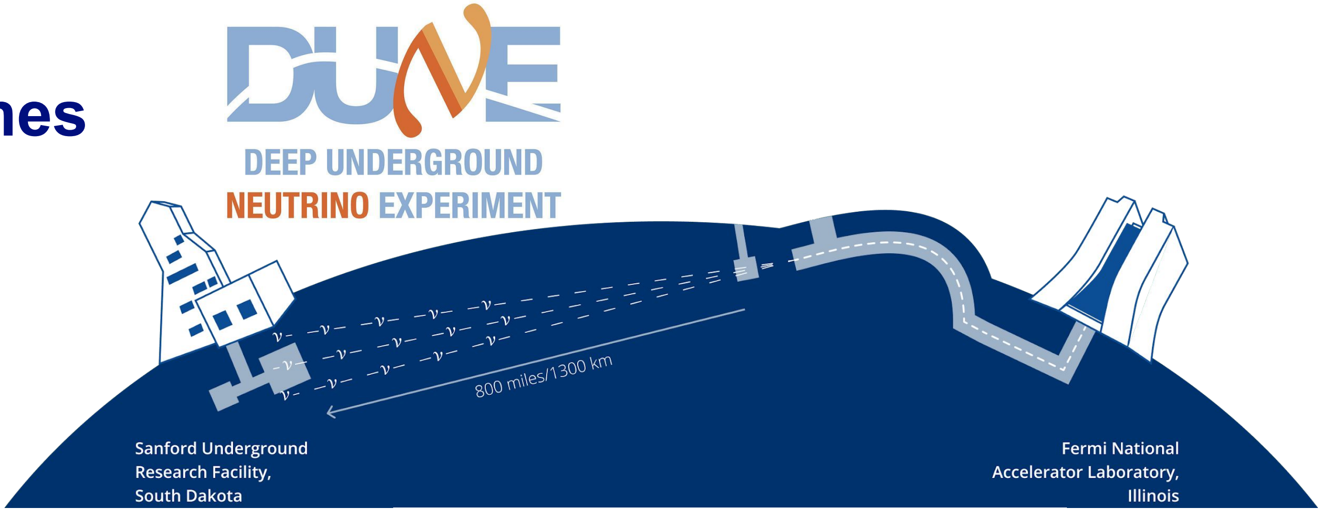
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

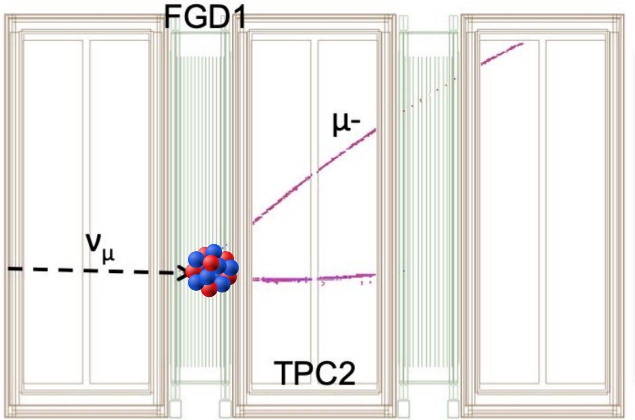
Flavors

Mass

Neutrino searches

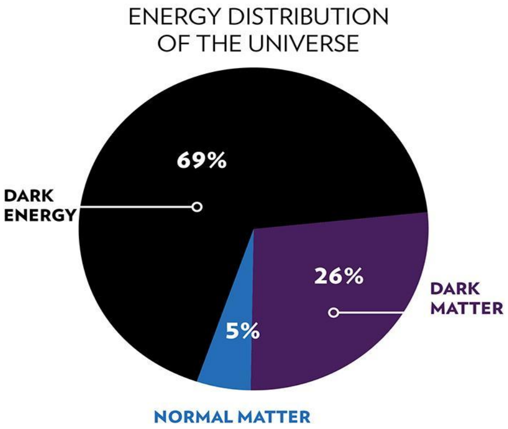
Fermilab / Sandbox Studio, Chicago



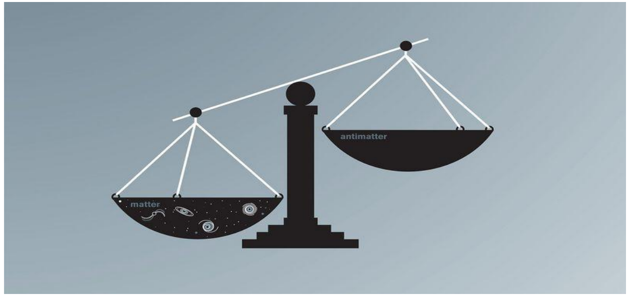


Adapted from K. Mahn,
"The Theoretical Cross Section Needs of Future Long Baseline Experiments"
at INT WORKSHOP INT-23-86W

Why beyond Standard Model (BSM) physics?

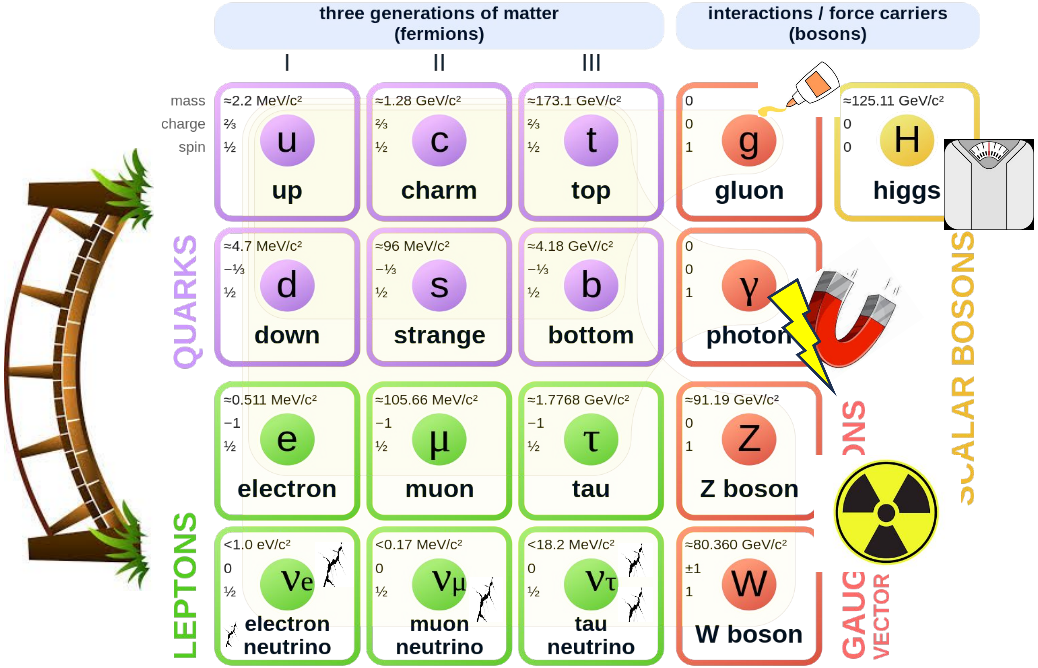


NASA / Chandra X-ray Center/ K. Divona



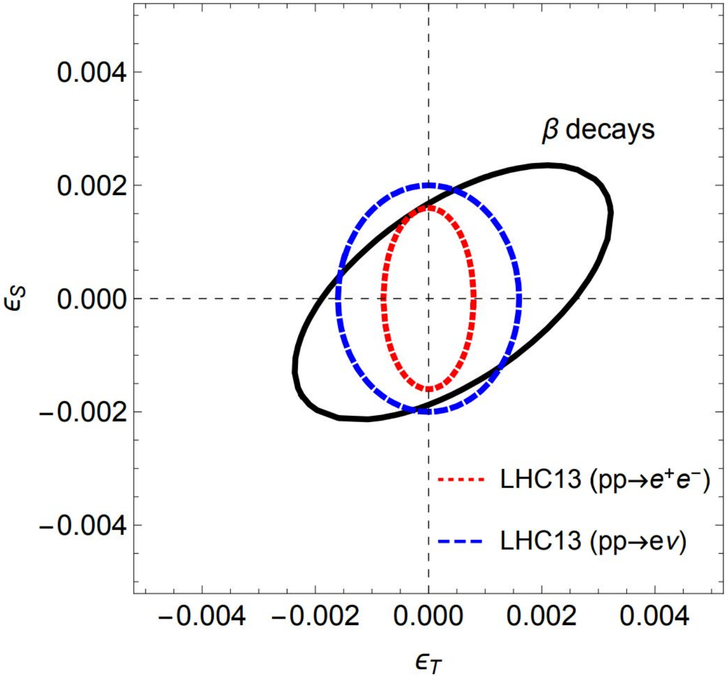
Symmetry Magazine / Sandbox Studio, Chicago

Nuclei as laboratories for new physics



https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

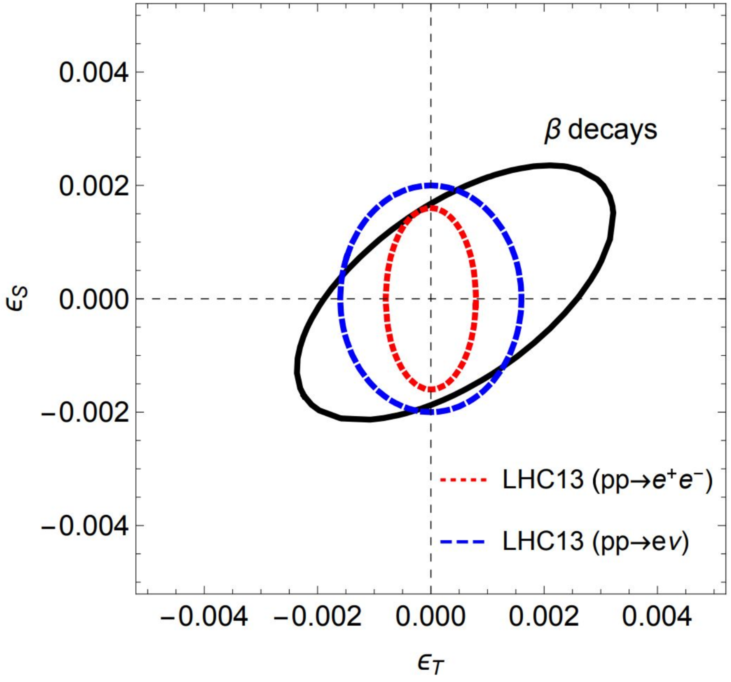
New physics impact of nuclear β-decays



Falkowski et al, JHEP04 (2021) 126

Competitive bounds on BSM currents that complement high-energy searches

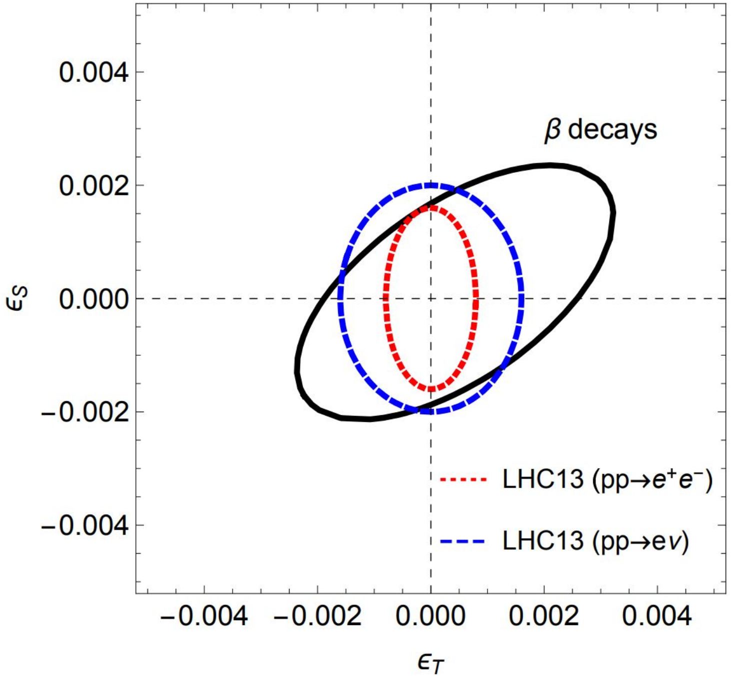
New physics impact of nuclear β-decays



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

Los Alamos NATIONAL LABORATORY

Understanding structure and dynamics

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

Understanding structure and dynamics

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

Understanding structure and dynamics

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

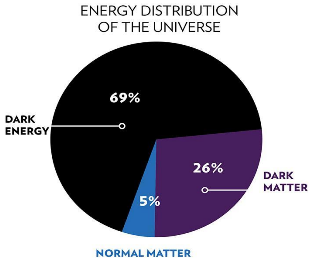
Connection to nuclear science

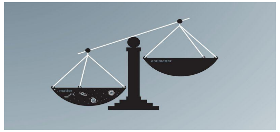
To benefit new physics searches, we must understand…

- 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

Strong global capabilities to validate models of nuclear structure used for BSM predictions

Bridging new physics and nuclear science





Nuclear Theory

CENPA
Center for Experimental
Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

FRIB

GANIL

GSI

RIKEN

ISOLDE

TRIUMF

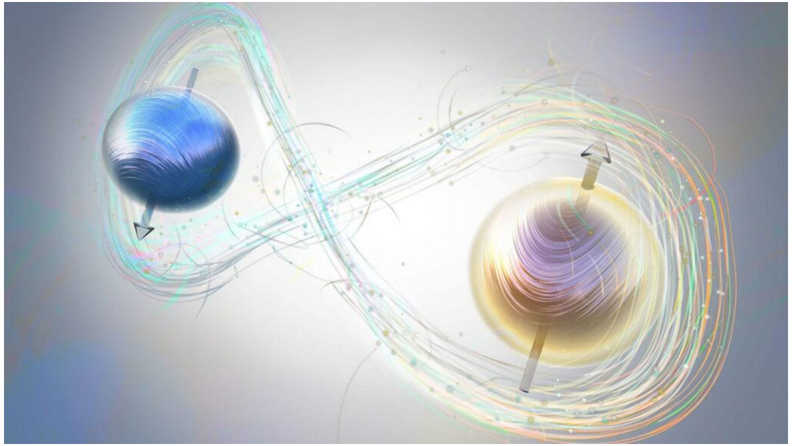
Los Alamos
NATIONAL LABORATORY

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

The quantum many-body problem

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

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

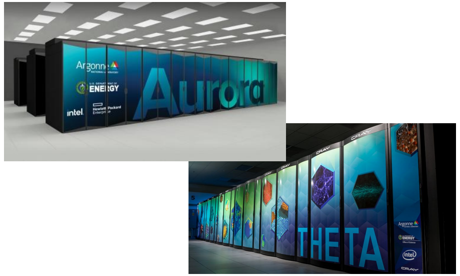
$$\dim(\Psi) = 3A \times 2^A \times \frac{A!}{N!Z!}$$

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

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

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

NERSC



ALCF

LANL IC

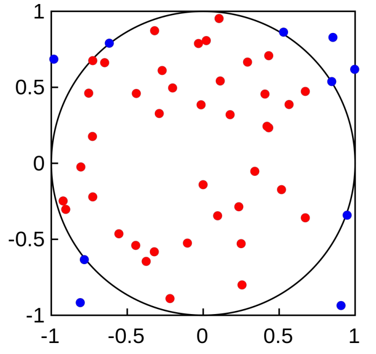
Los Alamos NATIONAL LABORATORY

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%)

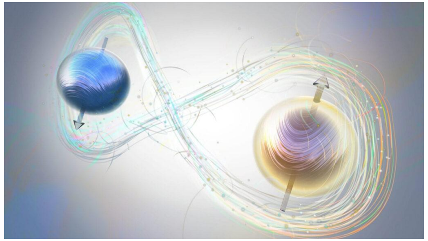
1,000,000 samples = 3.14216 (0.02%)

```
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)
```

Los Alamos NATIONAL LABORATORY

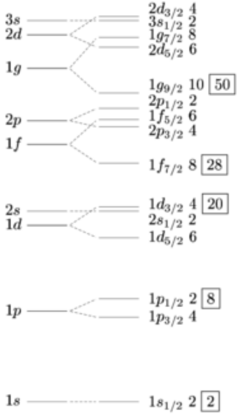
Variational Monte Carlo for correlated Fermions

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



Encodes entanglement between nucleons

Contains the variational parameters

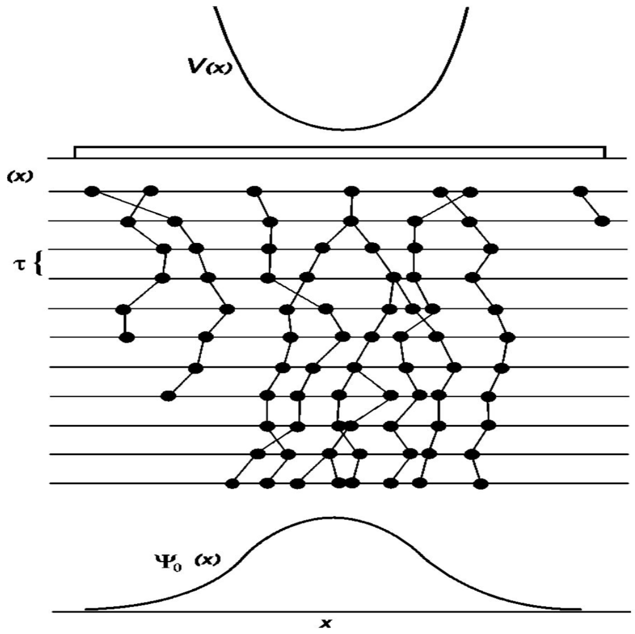


Mean-field description

Encodes long-range structure, quantum numbers

Los Alamos NATIONAL LABORATORY

Green's Function (or Diffusion) Monte Carlo



Can recast the Schrödinger Equation as a Diffusion equation

Sample the path integral with Monte Carlo

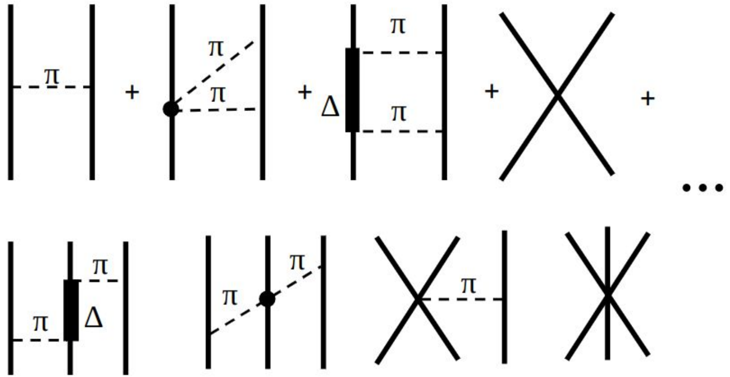
$$\lim_{\tau \to \infty} |\Psi_T\rangle \to c_0 \psi_0$$

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

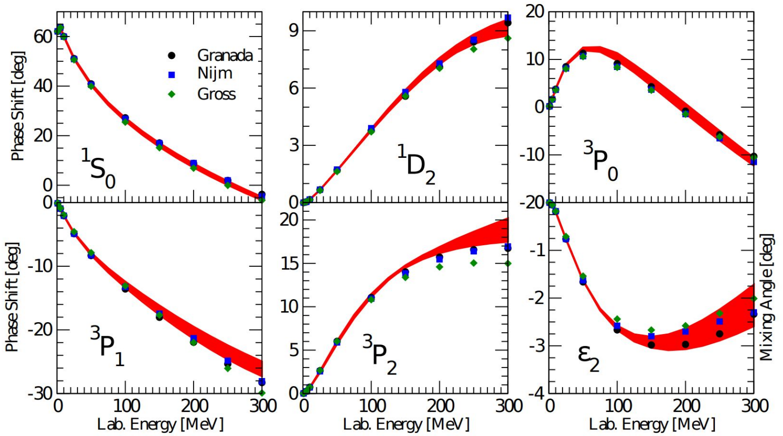
Los Alamos NATIONAL LABORATORY

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)

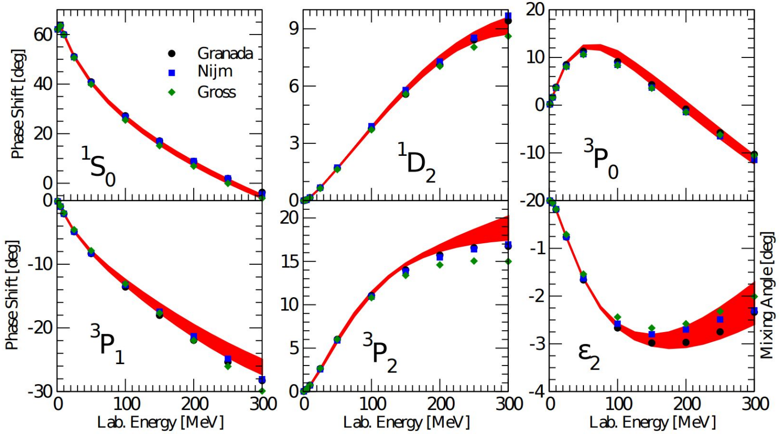
Systematic uncertainty

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)

Los Alamos NATIONAL LABORATORY

Nuclear matrix elements

Use QMC to compute

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

Related to physics quantities of interest

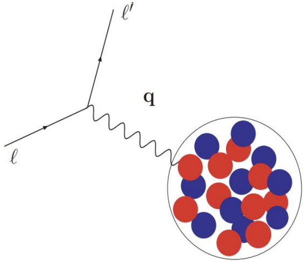
$$|M|^2 \propto \Gamma,\ \tau_{1/2}^{-1},\ d\sigma/d\Omega, \ldots$$

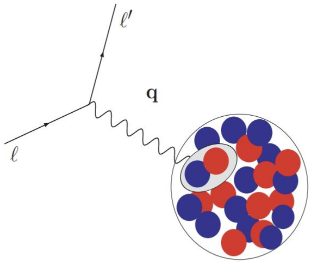
Electroweak charge and current operators

Schematically:

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

External field interacts with single nucleons and correlated pairs of nucleons





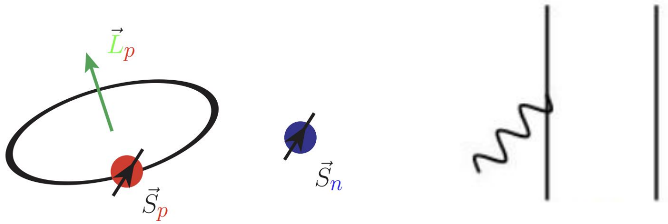
Pastore et al. PRC 80, 034004 (2009), Pastore et al. PRC 84, 024001 (2011), Piarulli et al. PRC 87, 014006 (2013), Schiavilla et al. PRC 99, 034005 (2019), Baroni et al. PRC 93, 049902 (2016), …

Los Alamos NATIONAL LABORATORY

Two-body currents intuition (magnetic moments)

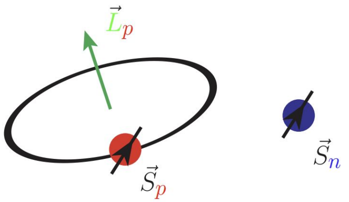
We know that it will arise from charges moving in the system

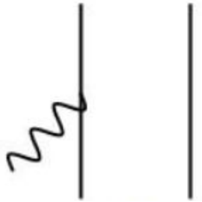
Expect proton orbital, proton spin, and neutron spin contributions



Two-body currents intuition (magnetic moments)

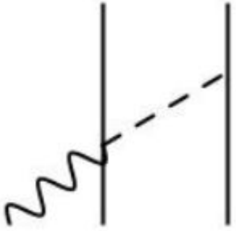
We know that it will arise from charges moving in the system





Expect proton orbital, proton spin, and neutron spin contributions

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



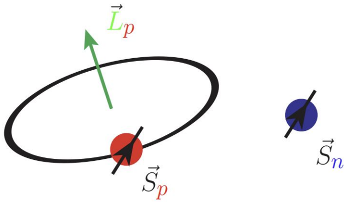
Ex: Pion couplings to an external electromagnetic field

Los Alamos NATIONAL LABORATORY

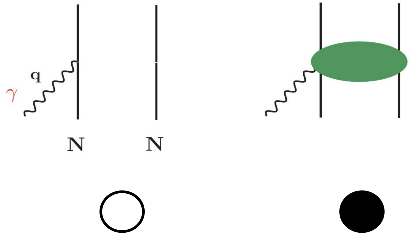
Magnetic moments

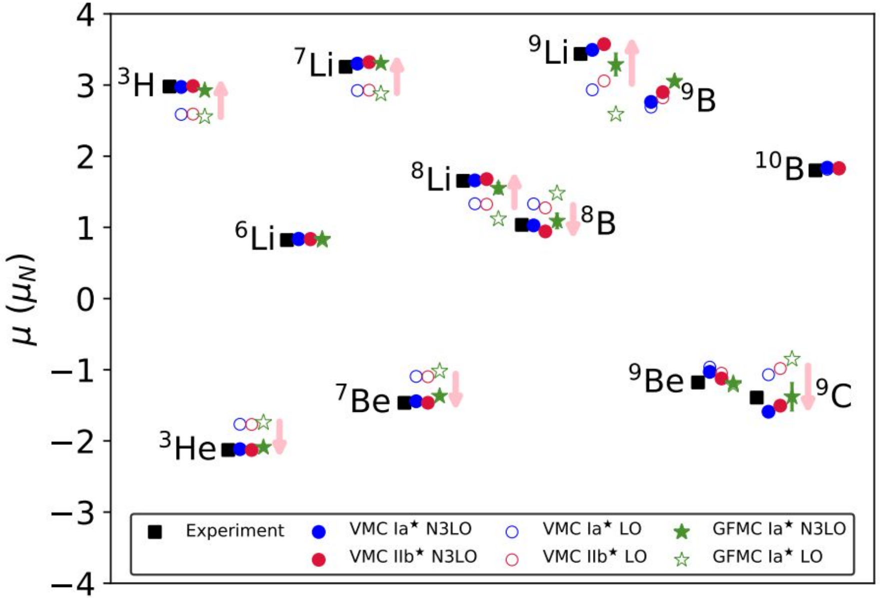
One-body picture:

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



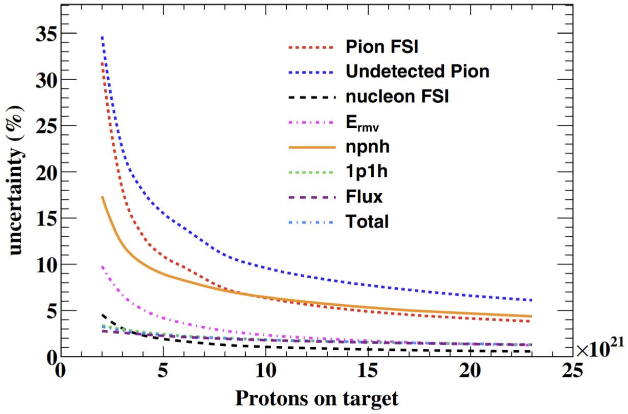
Two-body currents can play a large role (up to ~33%) in describing magnetic dipole moments





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

Importance of two-body physics for neutrino physics



Dolan et al. PRD 105, 032010 (2022)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Two-body physics and beyond mean-field effects are dominant contribution to experimental uncertainty

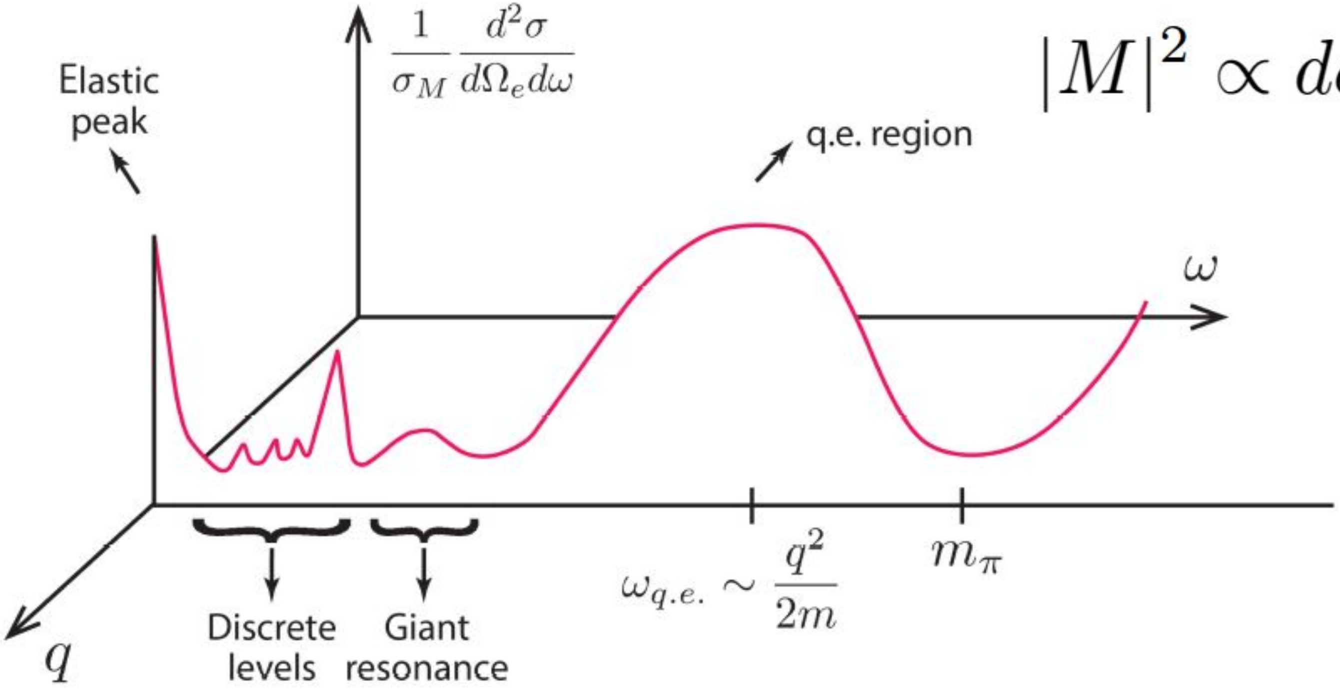
Need to know cross sections at ~100s MeV to GeV energies

Can benchmark models with *electron scattering*

Los Alamos NATIONAL LABORATORY

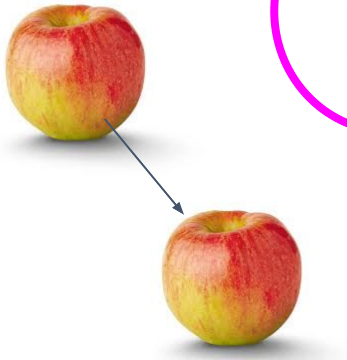
The kinematic regimes of lepton scattering

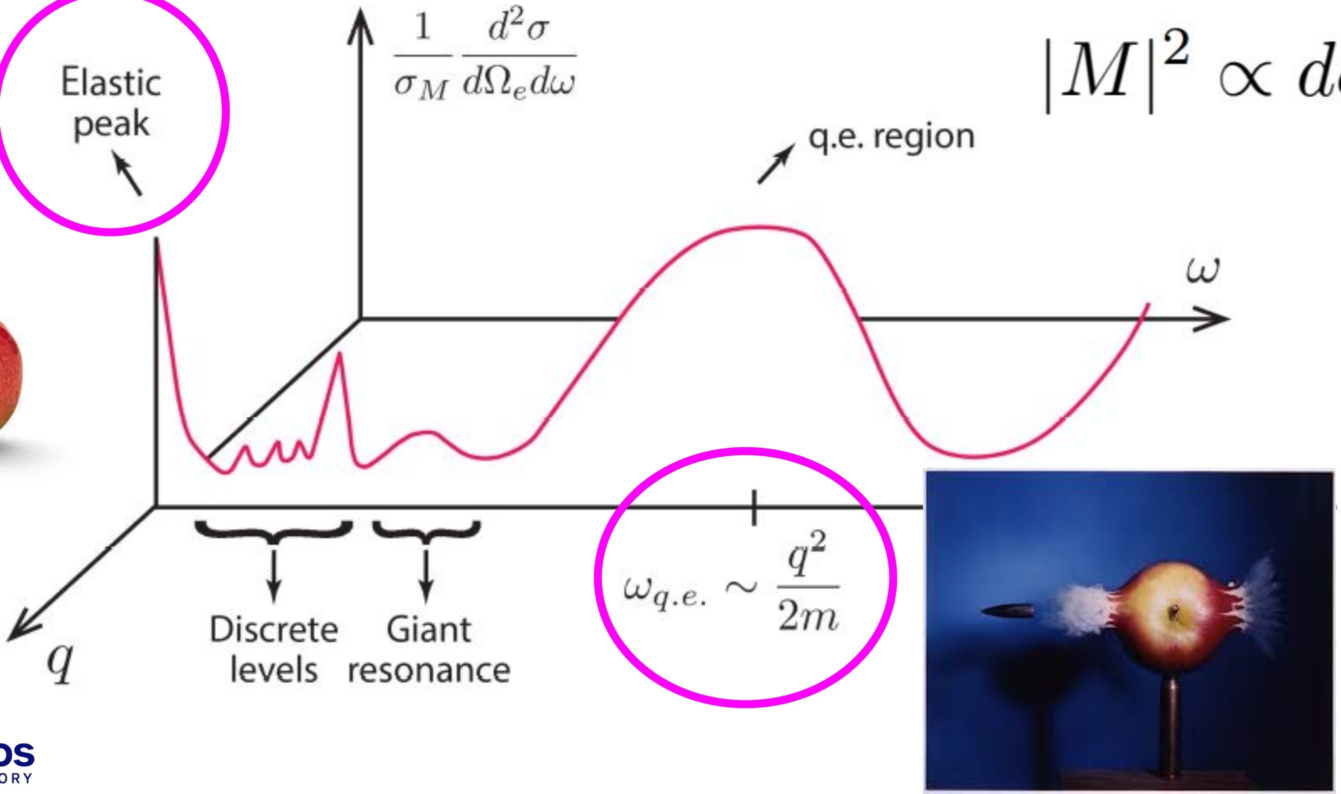
$$|M|^2 \propto d\sigma/d\Omega$$



Los Alamos NATIONAL LABORATORY

The kinematic regimes of lepton scattering

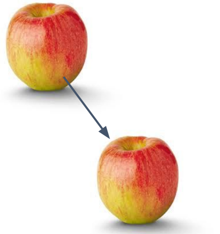


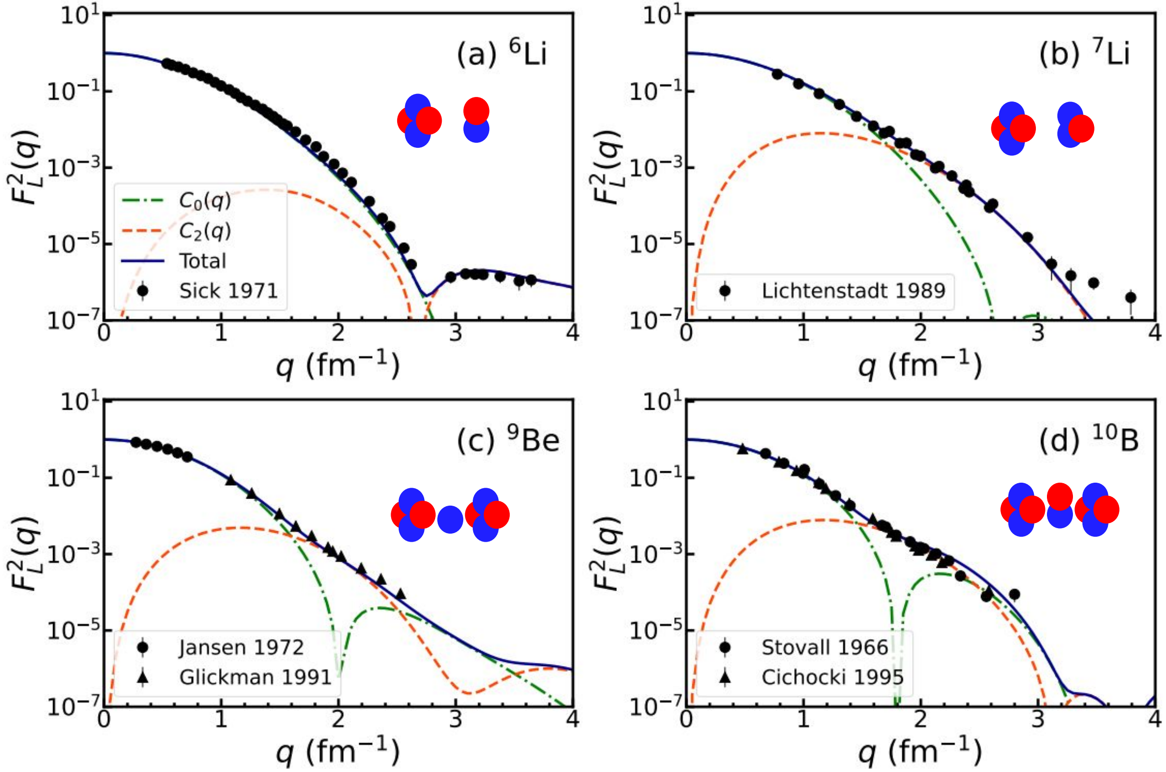


$$|M|^2 \propto d\sigma/d\Omega$$

Los Alamos NATIONAL LABORATORY

Elastic electron scattering form factors





Charge form factor depends on sum of excited “multipolarities”

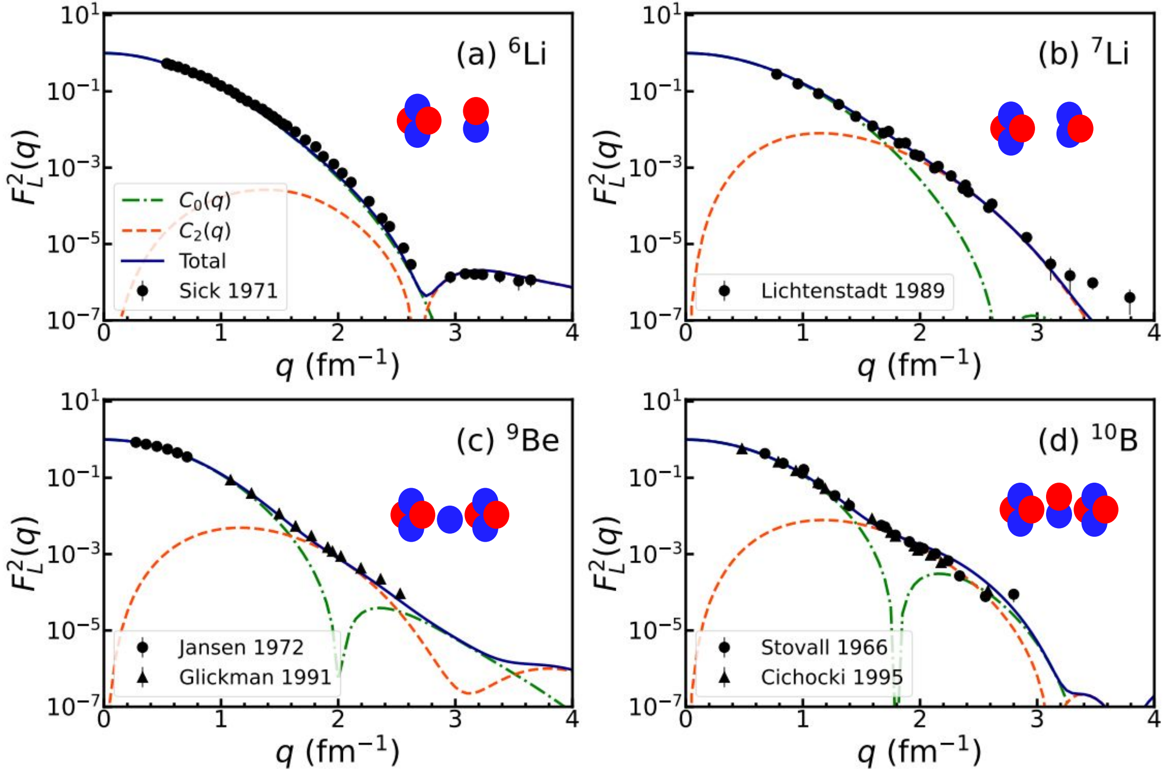
The l=0 term is related to spherically averaged charge density

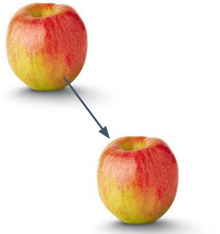
l=2 is sensitive to quadrupole deformation of the nucleus

Los Alamos NATIONAL LABORATORY

King et al. PRC 110, 054325 (2024)

Elastic electron scattering form factors

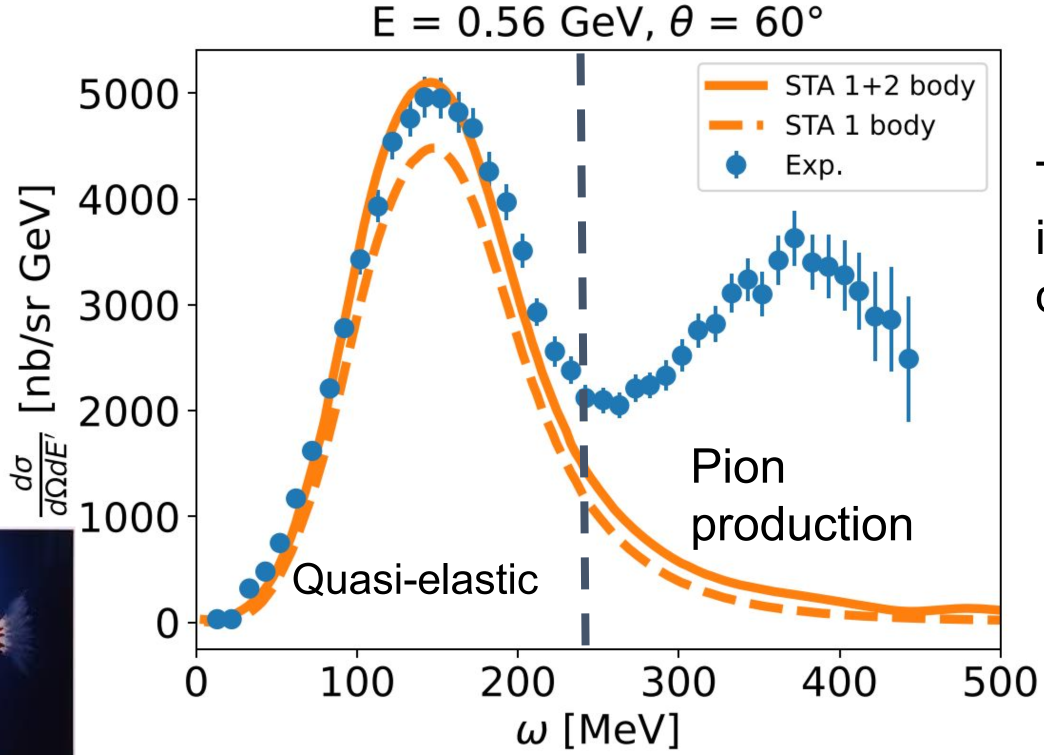




Capturing shape gives insight into the *clustering* and the *nature of the nuclear force*

King et al. PRC 110, 054325 (2024)

Quasi-elastic electron scattering on ^{12}C



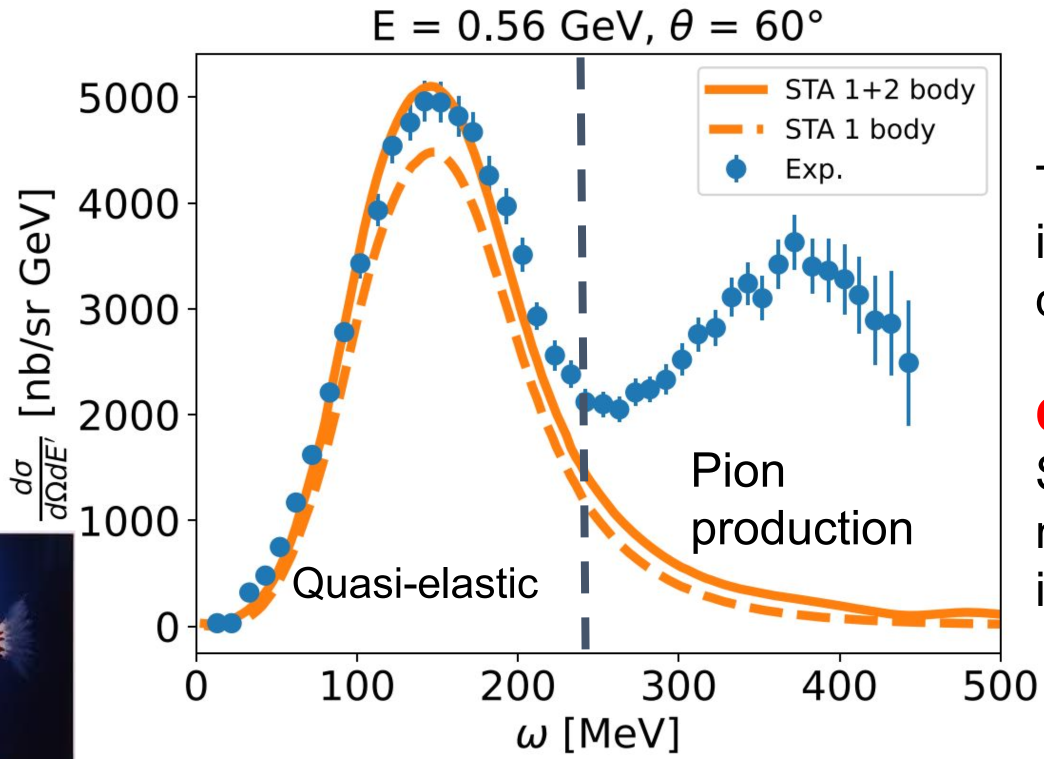
$$\frac{d\sigma}{d\Omega dE'} \propto \sum_i K_i |\langle \Psi | \mathcal{O}_i | \Psi \rangle|^2$$

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

Los Alamos NATIONAL LABORATORY

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

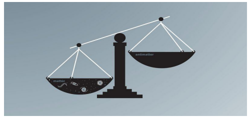
Quasi-elastic electron scattering on ^{12}C



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

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

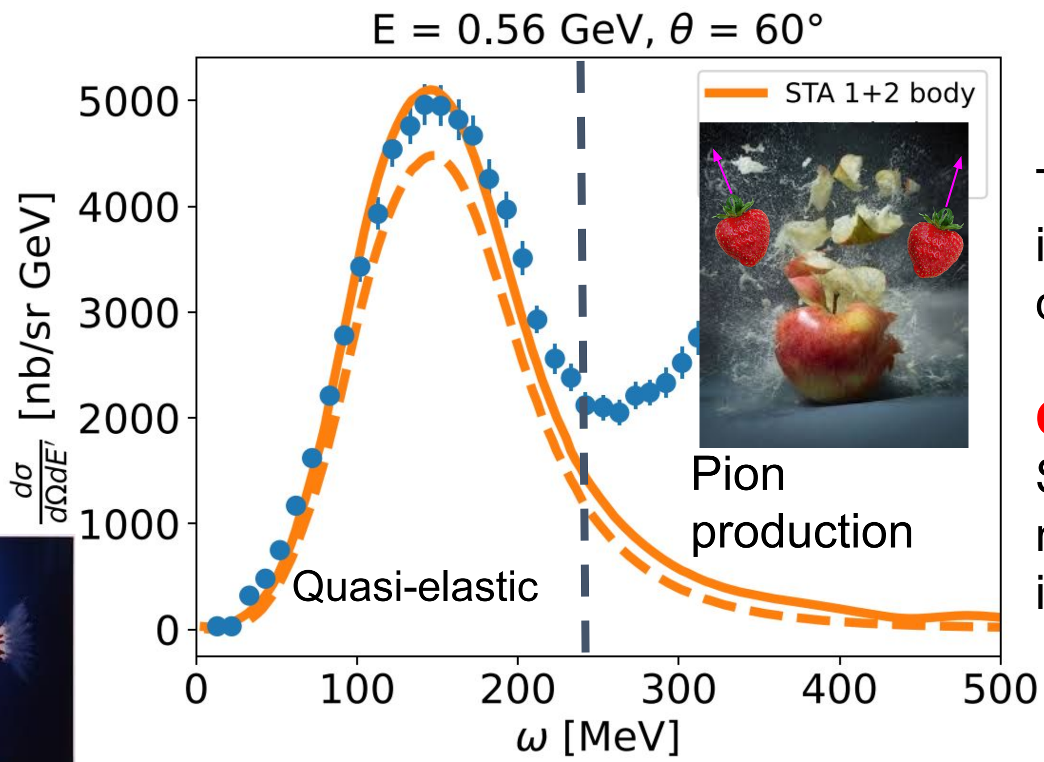


Andreoli, King, et al. PRC 110, 064004 (2024)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Los Alamos NATIONAL LABORATORY

Quasi-elastic electron scattering on ^{12}C



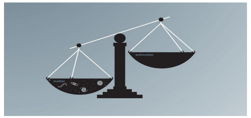
$$\frac{d\sigma}{d\Omega dE'} \propto \sum_i K_i |\langle\Psi|\mathcal{O}_i|\Psi\rangle|^2$$

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)

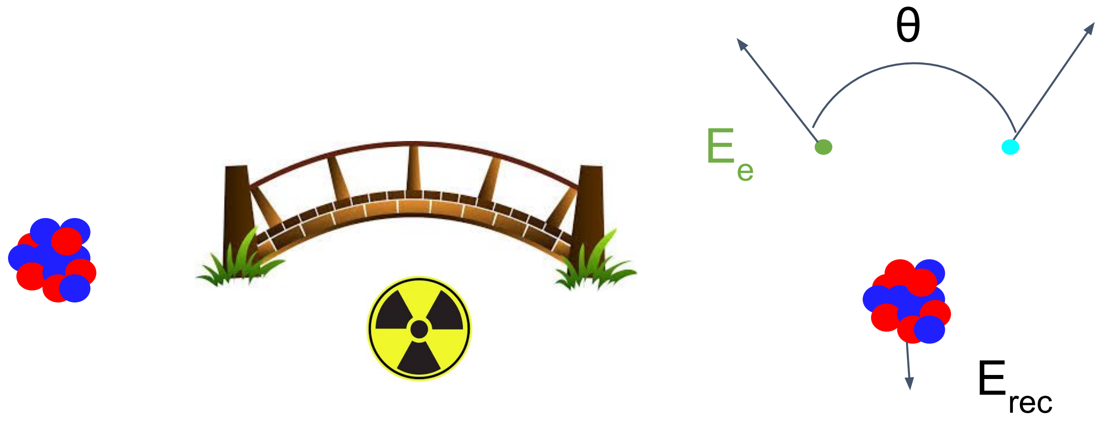
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Los Alamos NATIONAL LABORATORY

Nuclear β-decay

β-decays as a bridge to new physics



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

Los Alamos NATIONAL LABORATORY

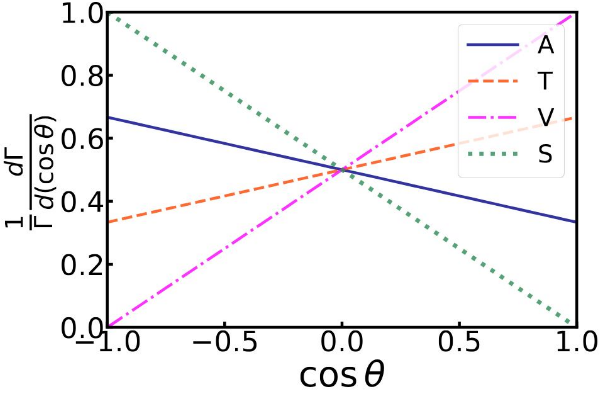
β-decays as a bridge to new physics

Weak currents with different transformation properties prefer different lepton angles

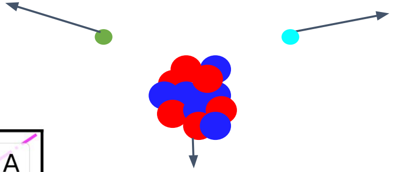
Standard Model is a vector minus axial theory

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

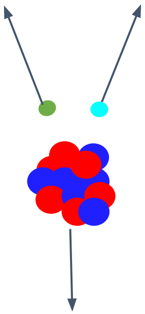
Neutrino mass would remove some phase space for the outgoing electron



θ ~ 180°

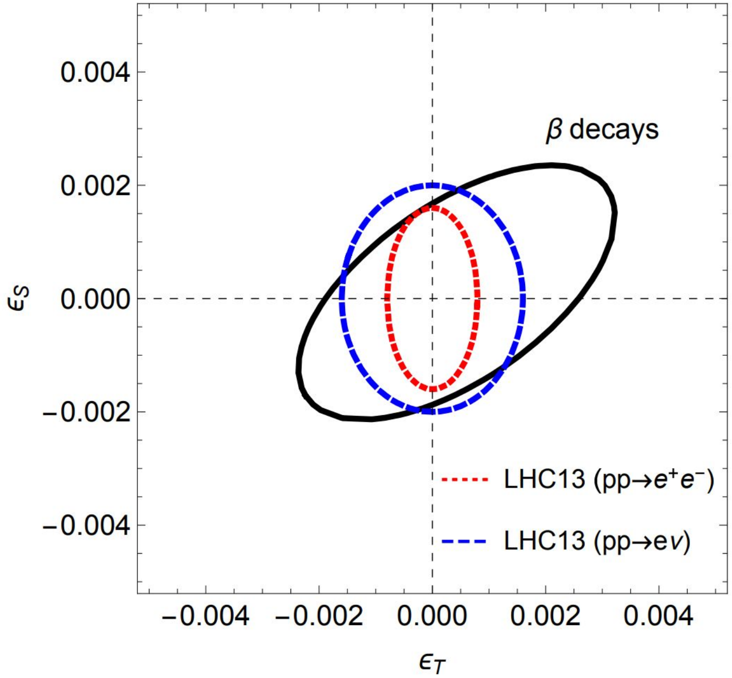


θ ~ 0°



Los Alamos NATIONAL LABORATORY

New physics impact of nuclear β-decays

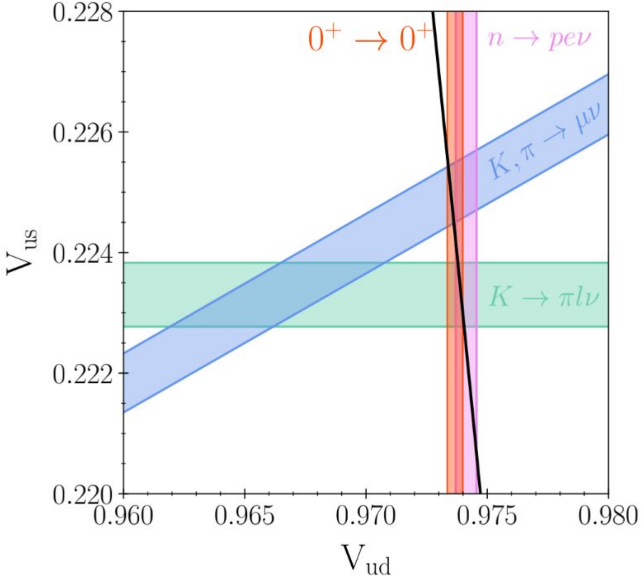


Falkowski et al, JHEP04 (2021) 126

Competitive bounds on BSM currents that complement high-energy searches

Los Alamos NATIONAL LABORATORY

New physics impact of nuclear β-decays



Cirigliano et al., PLB 838 (2023) 137748

Competitive bounds on BSM currents that complement high-energy searches

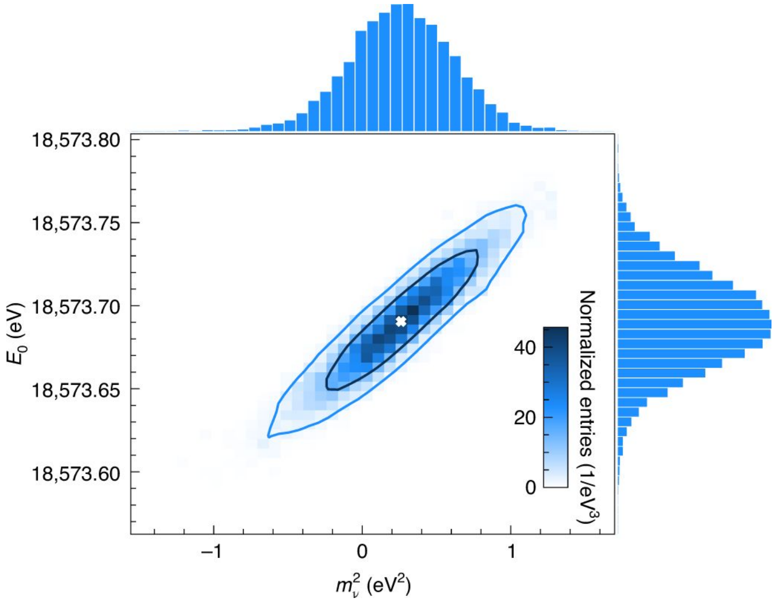
Tests of CKM unitarity

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

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

Los Alamos NATIONAL LABORATORY

New physics impact of nuclear β-decays



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

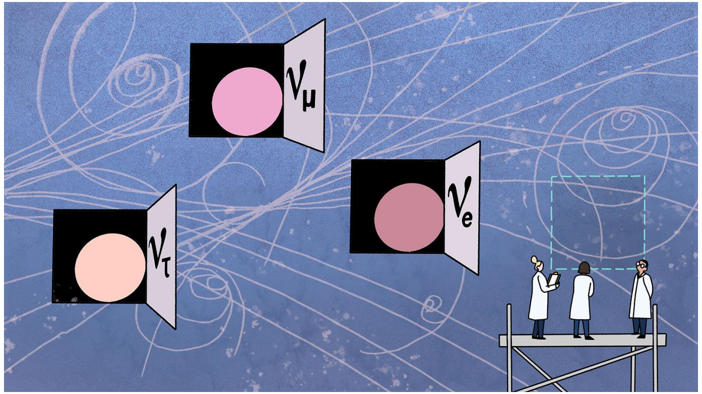
Competitive bounds on BSM currents that complement high-energy searches

Tests of CKM unitarity

Access to the scale of neutrino masses

Los Alamos NATIONAL LABORATORY

New physics impact of nuclear β-decays



Symmetry Magazine / Sandbox Studio, Chicago

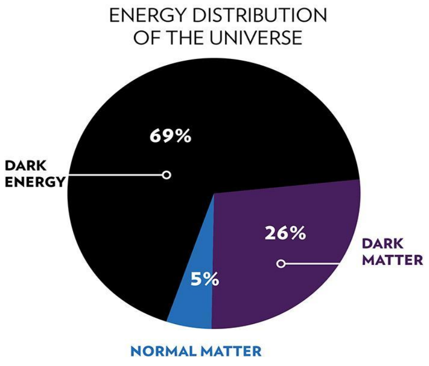
Competitive bounds on BSM currents that complement high-energy searches

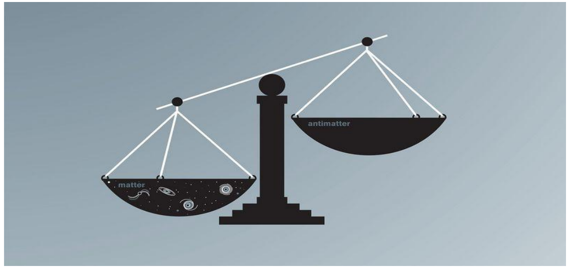
Tests of CKM unitarity

Access to the scale of neutrino masses

Bounds on sterile neutrinos

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

Bounds on sterile neutrinos

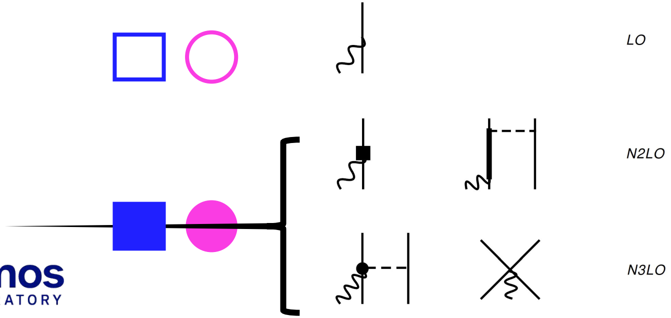
β-decay rates

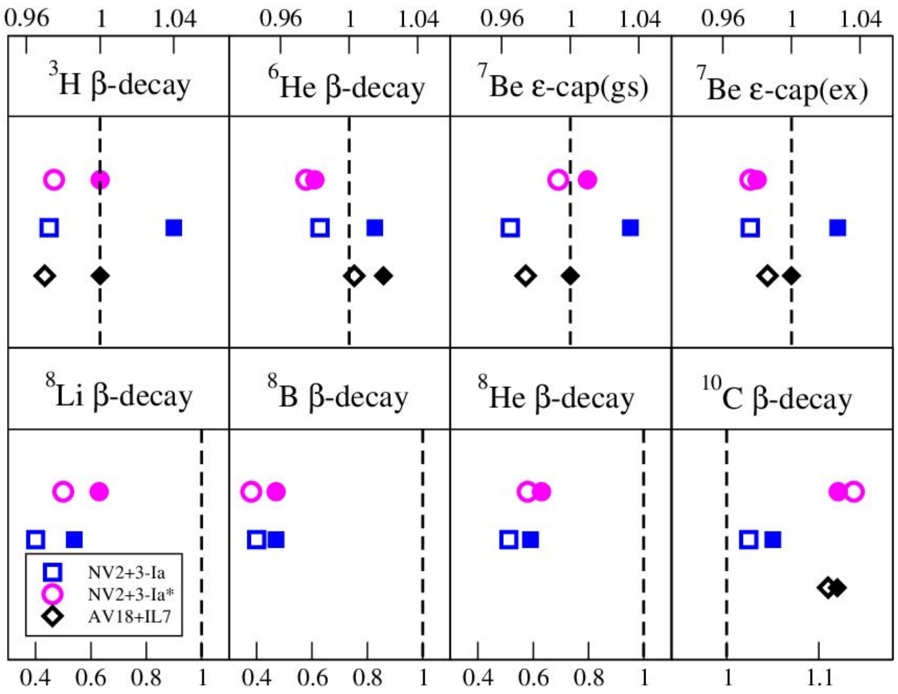
Computed with two models:

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 without recoil:

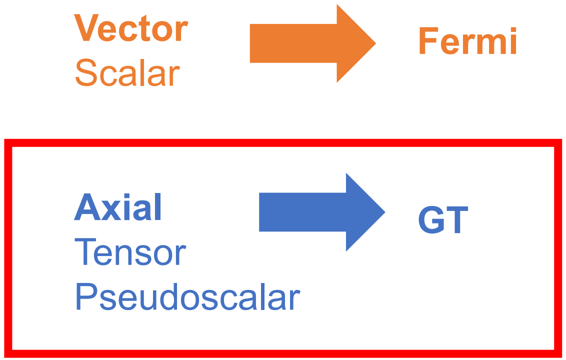
$$\frac{d\Gamma}{dE_e} = |M|^2 G_\beta(E)$$

New physics can distort this:

$$\frac{d\Gamma}{dE_e} = \frac{d\Gamma_0}{dE_e}\left[1 + \Delta(E_e)\right]$$

Similar distortions can be generated when accounting for nuclear recoil

Performed calculation with recoil corrections and two-body physics effects



Los Alamos NATIONAL LABORATORY

^{6}He β-decay spectrum: Multipoles

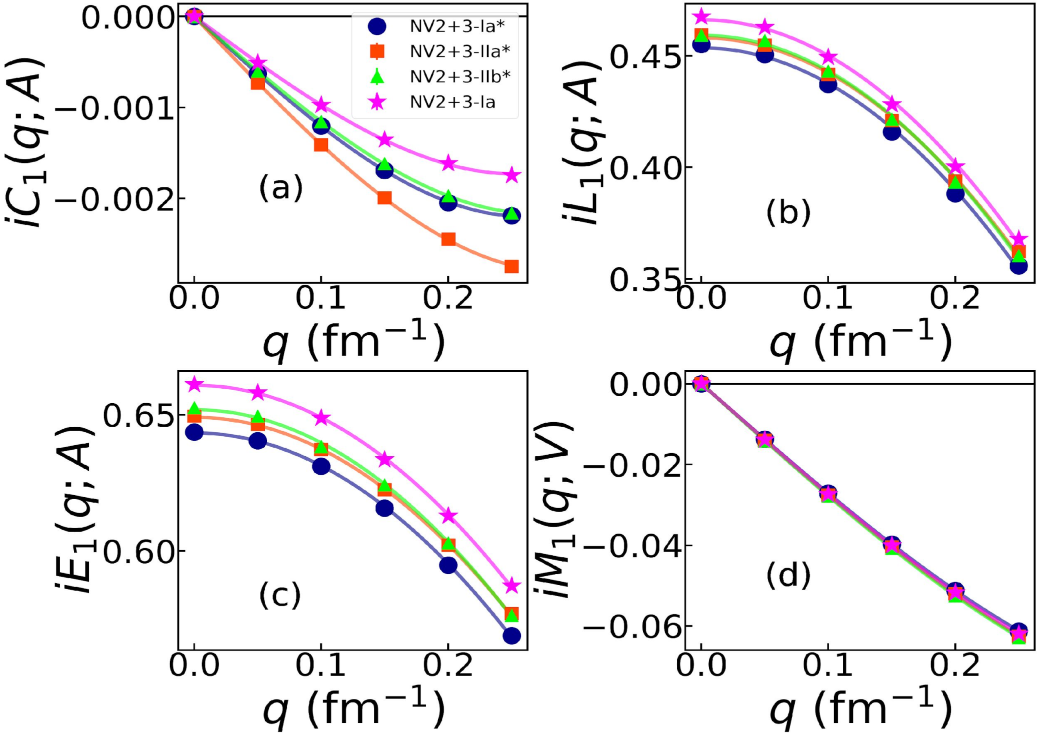
Distortion term is a function of four nuclear matrix elements:

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

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

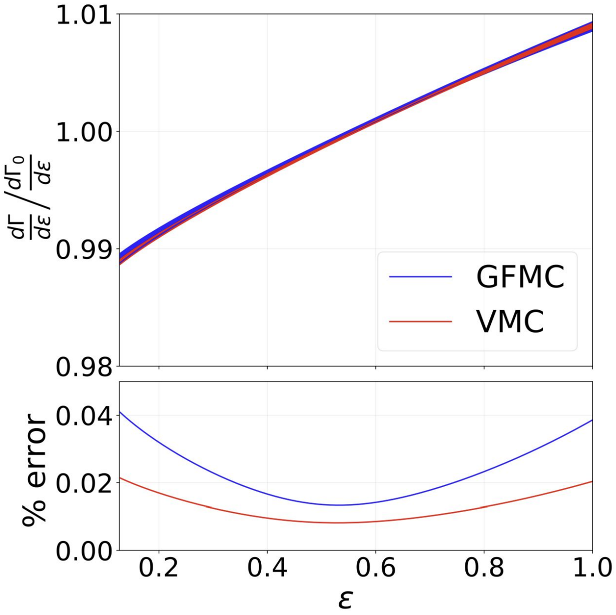
$$E_1(q;A) = -\frac{i}{\sqrt{2\pi}}\langle{}^6\mathrm{Li},10|\hat{\mathbf{z}}\cdot\mathbf{j}_+^\dagger(q\hat{\mathbf{x}};A)|{}^6\mathrm{He},00\rangle$$

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



King et al. PRC 107, 015503 (2023)

^{6}He β-decay spectrum: 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

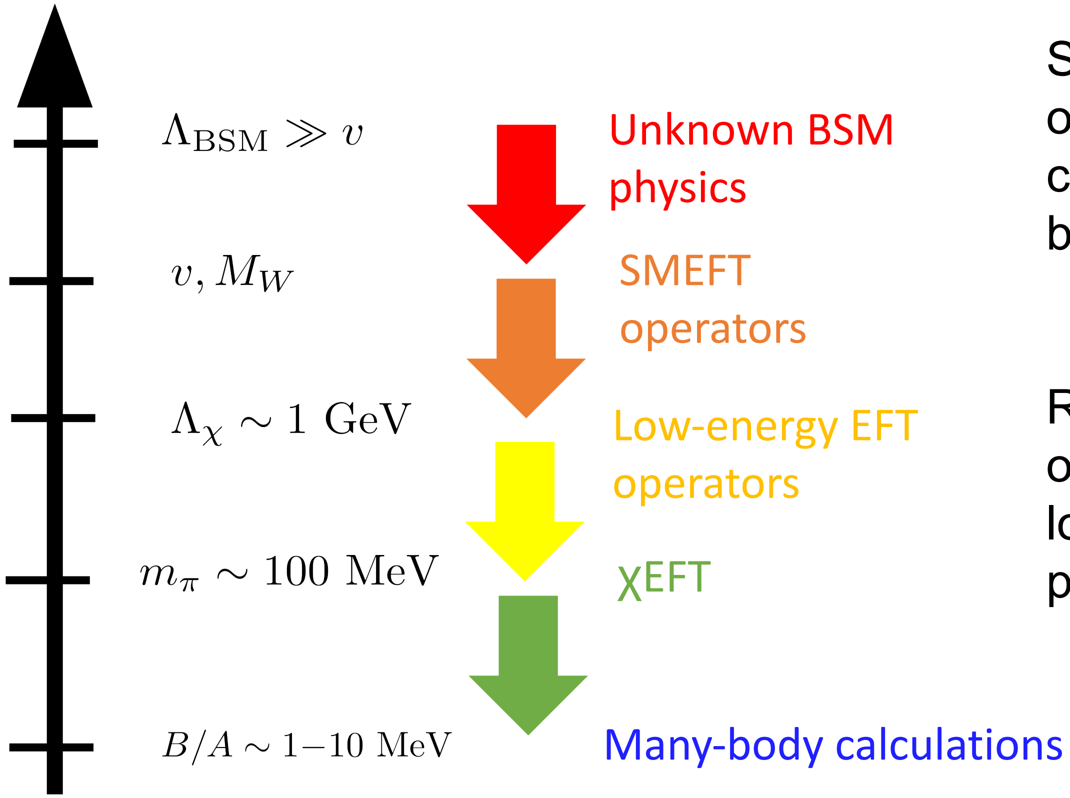
[Kanafani et al. PRC 106, 045502 (2022)]

King et al. PRC 107, 015503 (2023)

Los Alamos NATIONAL LABORATORY

FRIB

^{6}He β-decay spectrum: SMEFT



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

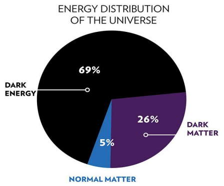
Run the coupling and obtain operators at the low-energy nuclear physics scale

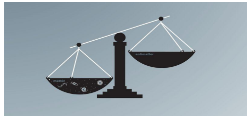
^{6}He β-decay spectrum: Probing new forces

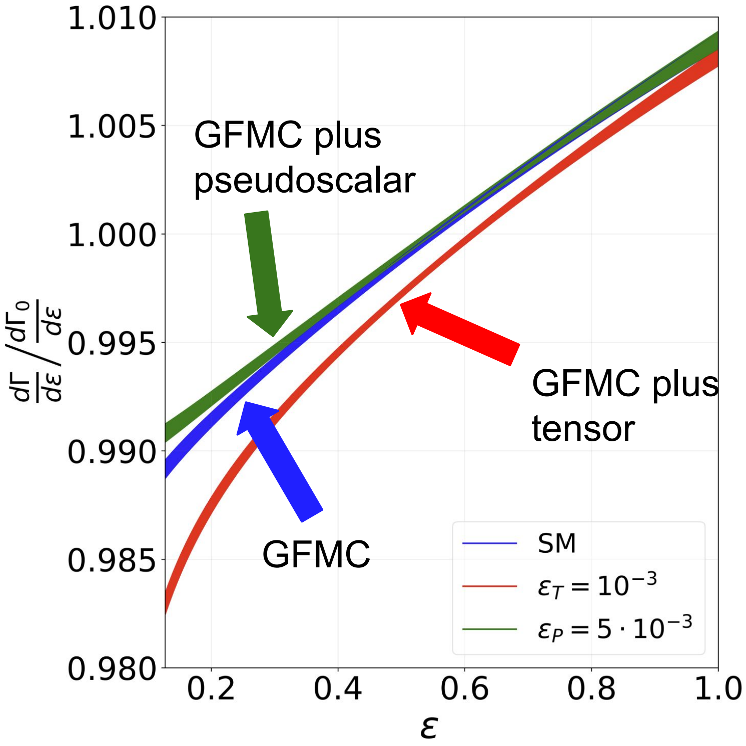
Included transition operators associated with new physics

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

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





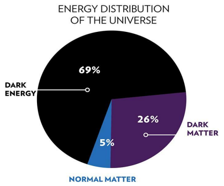


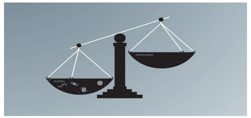
King et al. PRC 107, 015503 (2023)

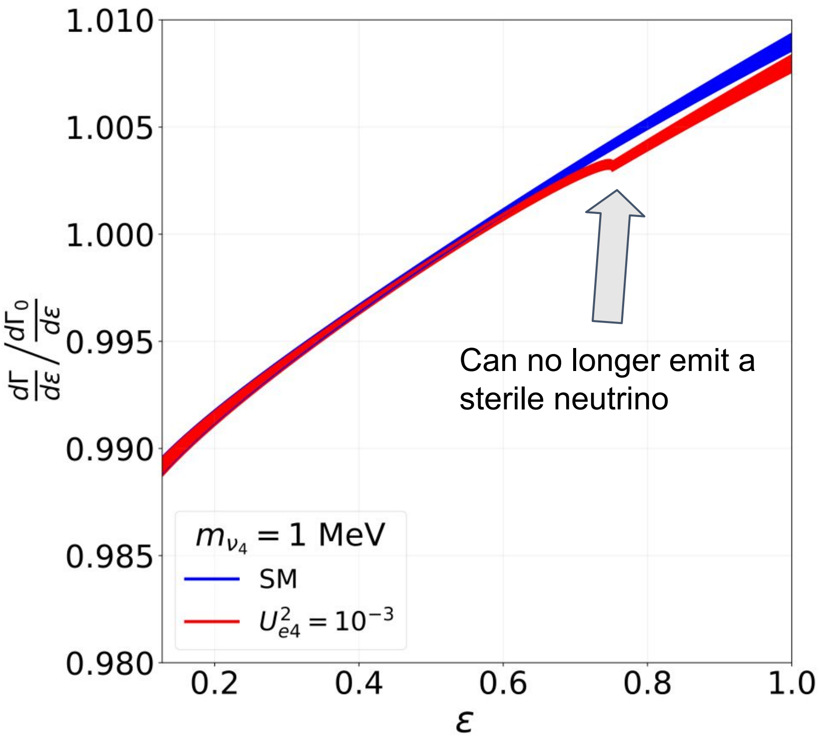
^{6}He β-decay spectrum: Probing neutrino physics

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







King et al. PRC 107, 015503 (2023)

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

Under good isospin $$M_F = \langle T T_z \pm 1 | T_\pm | T T_z \rangle = \sqrt{(T \mp T_z)(T \pm T_z + 1)}$$

For T=1 triplets $$M_F = \sqrt{2}$$

"ft" value should also be constant $$ft = \frac{K}{2 G_F^2 V_{ud}^2}$$

Hardy and Towner PRC 102, 045501 (2020)

Los Alamos NATIONAL LABORATORY

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

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

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

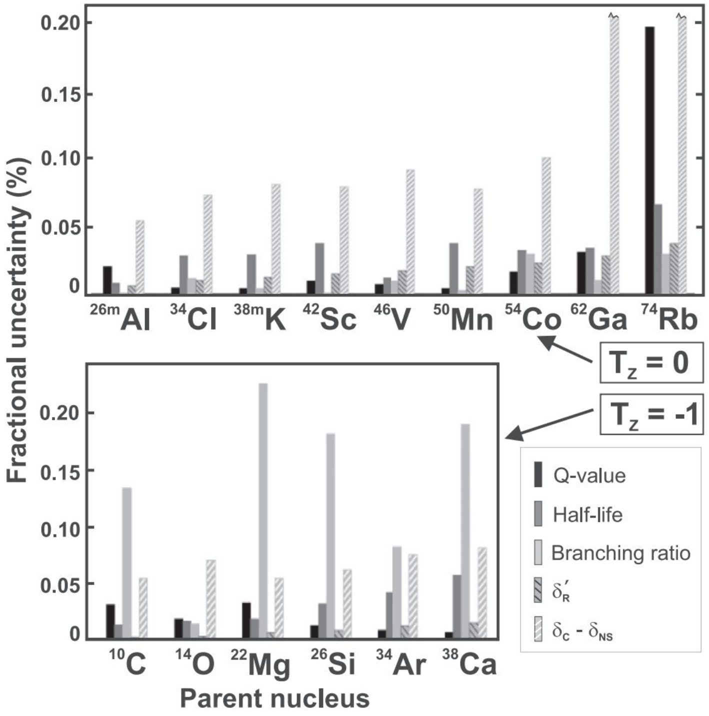
Los Alamos NATIONAL LABORATORY

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

Corrections must be accounted for in real decay

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

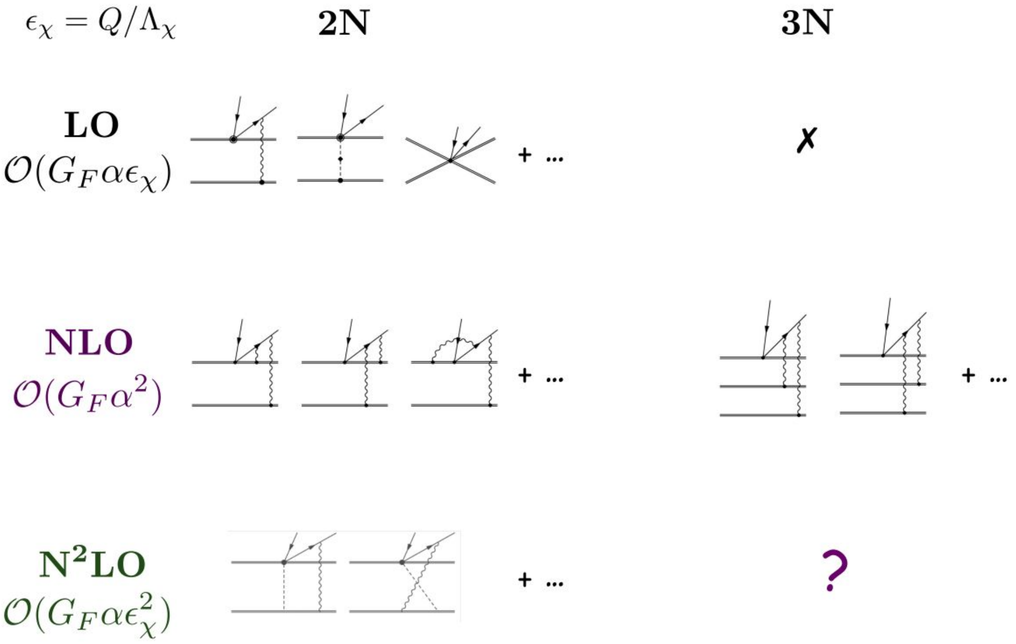
Dominant uncertainty is nuclear theory



Hardy and Towner PRC 102, 045501 (2020)

EFT approach to radiative corrections

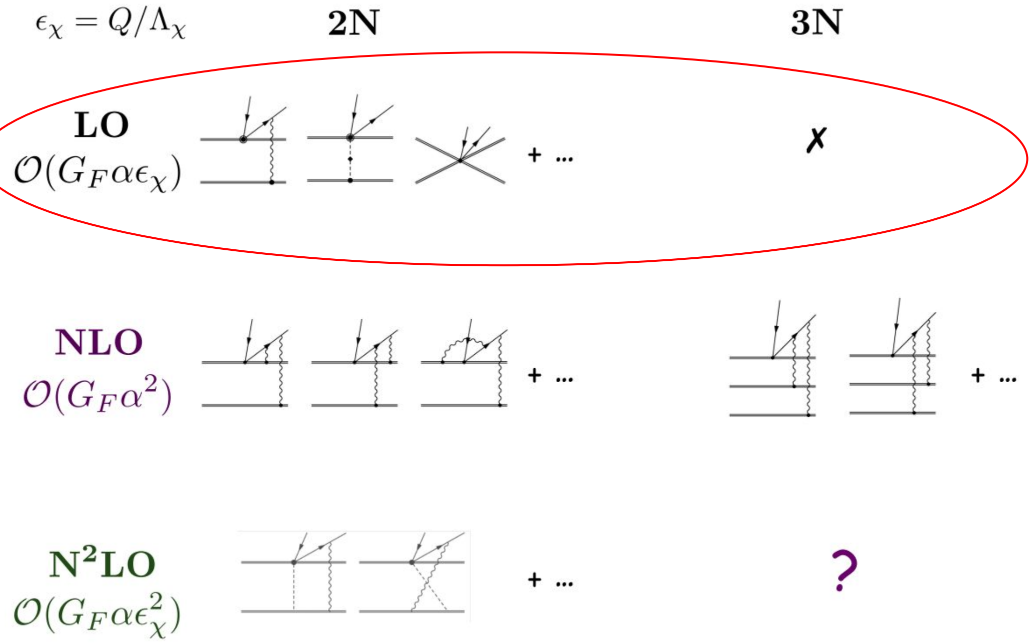
Cirigliano,
Dekens,
Hoferichter,
Mereghetti,
Tomalak, + …



Cirigliano et al. PRL 133, 211801 (2024)

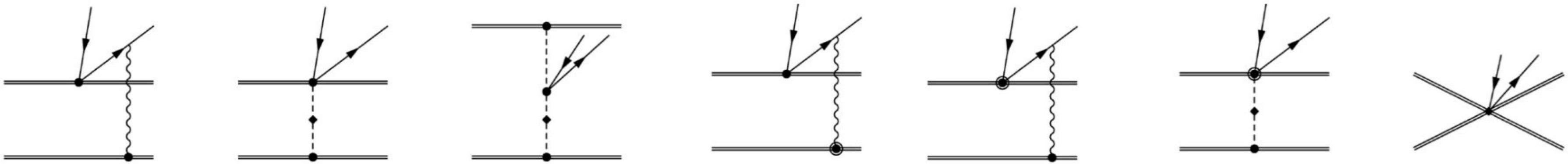
EFT approach to radiative corrections

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



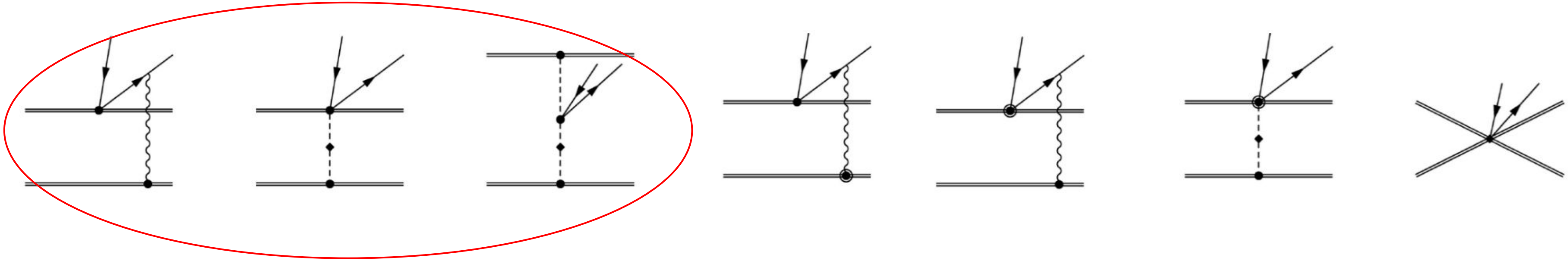
Cirigliano et al. PRL 133, 211801 (2024)

EFT approach to radiative corrections



Cirigliano et al. PRC 110, 055502 (2024)
Cirigliano et al. PRL 133, 211801 (2024)

EFT approach to radiative corrections

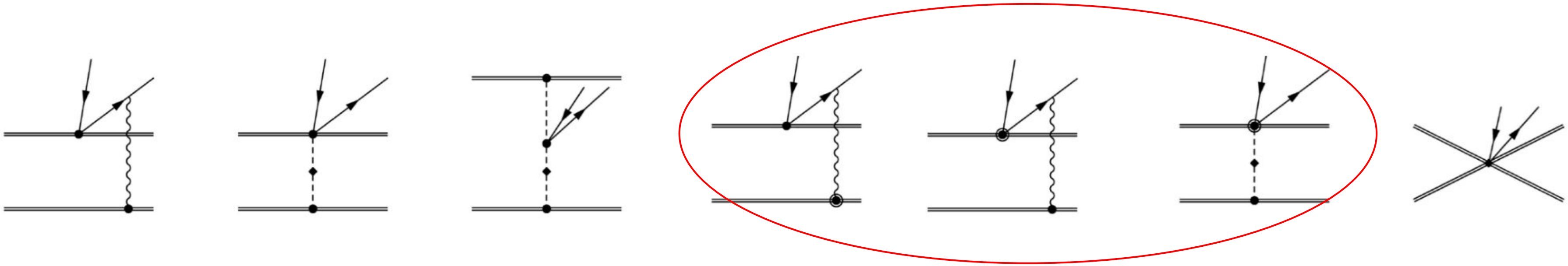


Energy-dependent terms, proportional to the external momentum

Grows with the size of the system

Cirigliano et al. PRC 110, 055502 (2024)
Cirigliano et al. PRL 133, 211801 (2024)

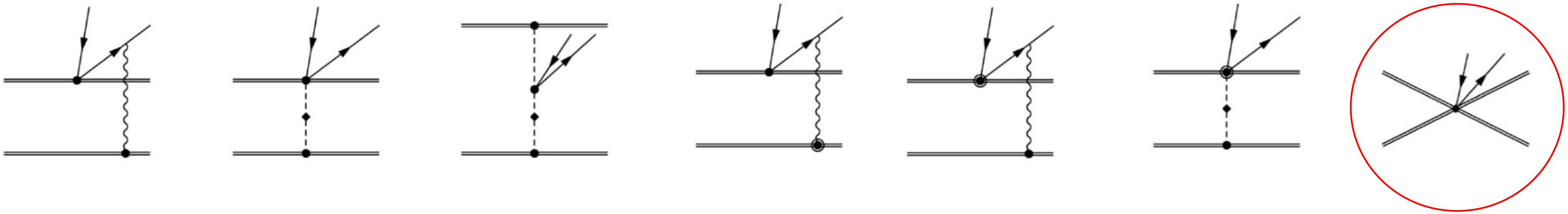
EFT approach to radiative corrections



Energy-independent terms arising from magnetic moment and recoil effects

Cirigliano et al. PRC 110, 055502 (2024)
Cirigliano et al. PRL 133, 211801 (2024)

EFT approach to radiative corrections



Absorbs the cutoff dependence of the long-range terms

Introduces two unknown parameters that must be fit or modelled

LEC is taken as an uncertainty in individual calculations

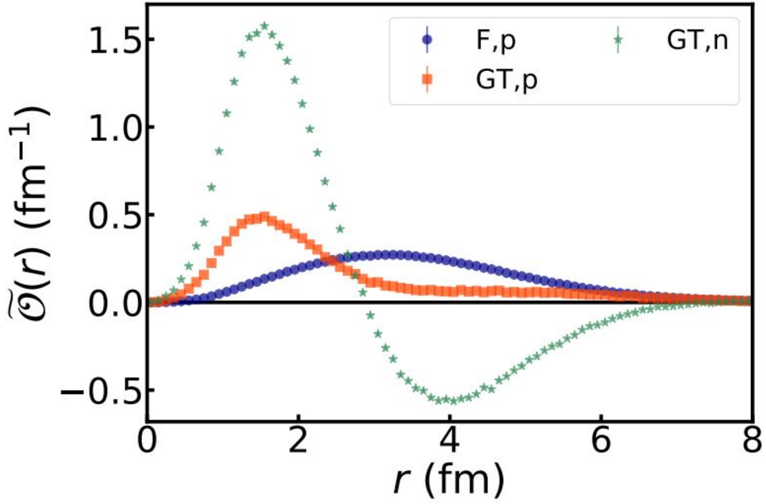
Cirigliano et al. PRC 110, 055502 (2024)
Cirigliano et al. PRL 133, 211801 (2024)

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

In an effective field theory approach:

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

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



King et al., arXiv:2509.07310v1

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

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

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

Los Alamos NATIONAL LABORATORY

Outlook: Benchmark QMC + Coupled-cluster

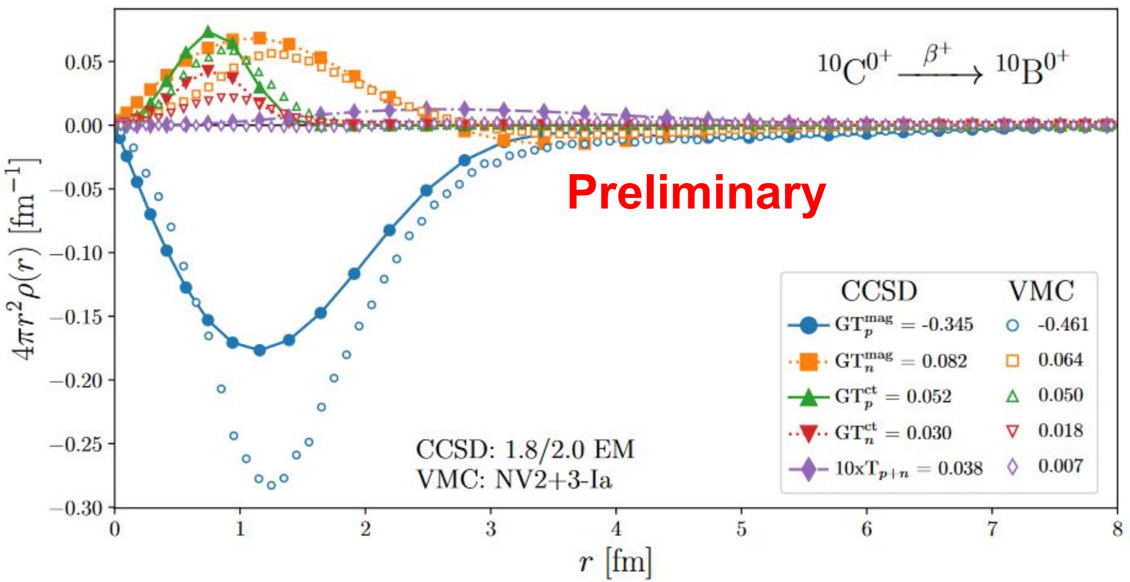


Figure courtesy of Sam Novario

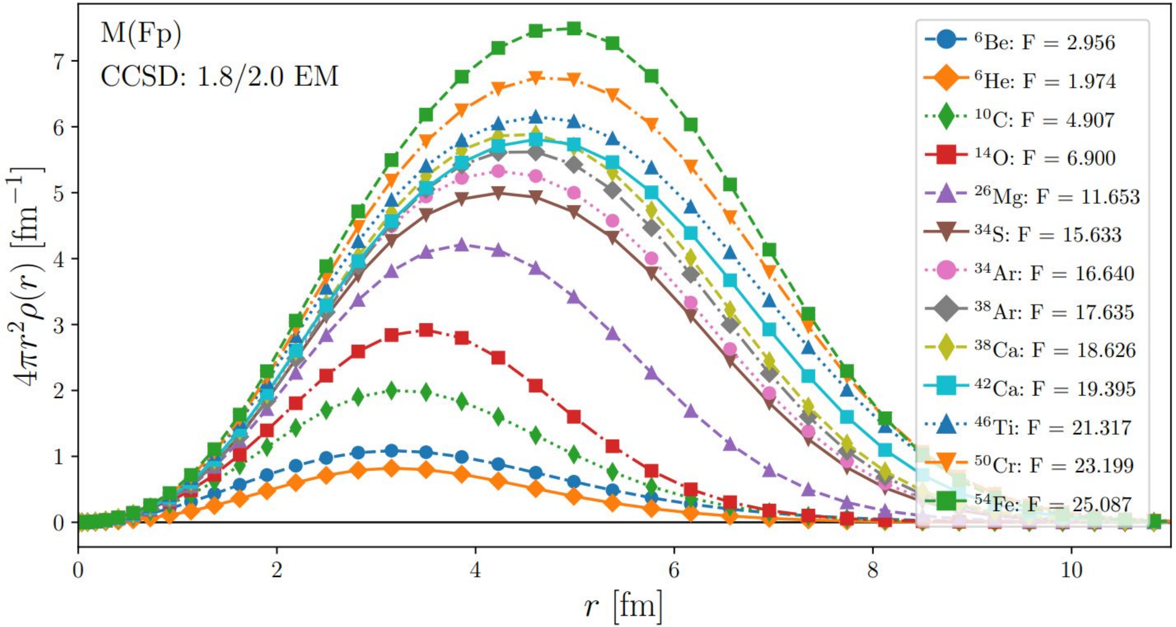
Benchmarking different models, methods in first step toward global analysis

Qualitative agreement, but further analysis necessary

Los Alamos NATIONAL LABORATORY

Outlook: Global analysis Coupled-cluster

Preliminary

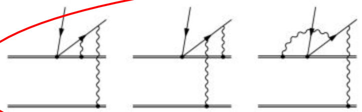
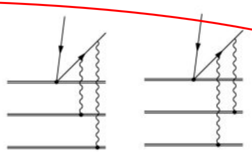
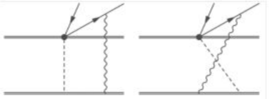


S. J. Novario, "Nuclear-Structure Corrections in Superallowed Beta Decay" (2025)

Los Alamos NATIONAL LABORATORY

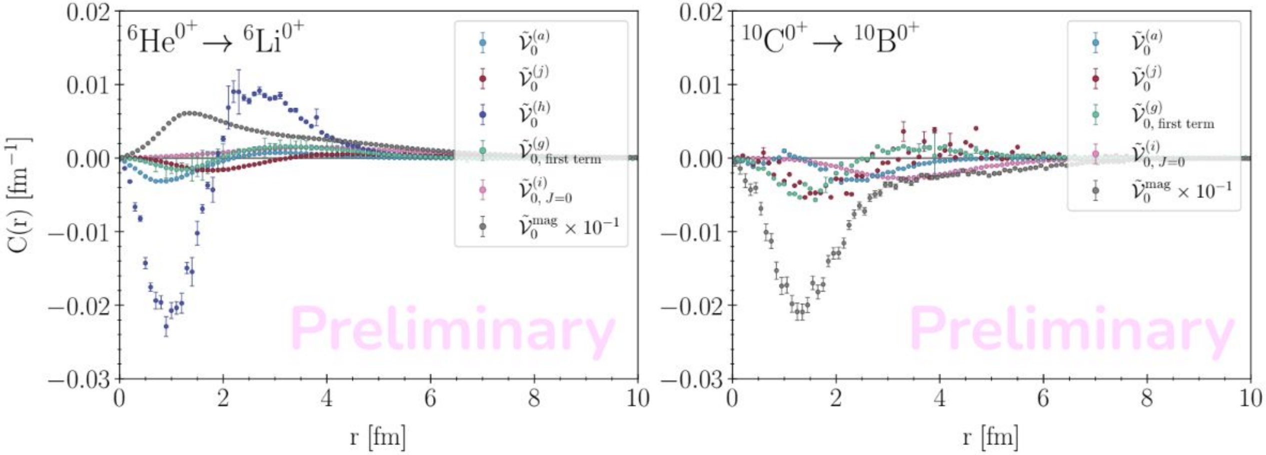
Outlook: Higher-order EFT operators

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

$\epsilon_\chi = Q/\Lambda_\chi$	2N	3N
LO $\mathcal{O}(G_F \alpha \epsilon_\chi)$	 + …	✗
NLO $\mathcal{O}(G_F \alpha^2)$	 + …	 + …
N²LO $\mathcal{O}(G_F \alpha \epsilon_\chi^2)$	 + …	?

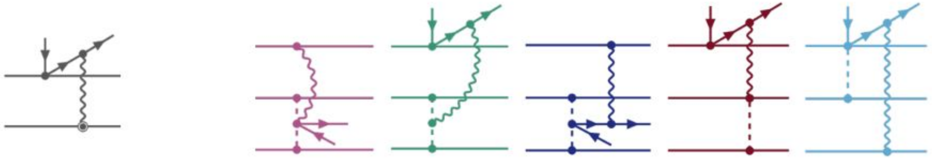
Outlook: Higher-order EFT operators

G. Chambers-Wall



Preliminary calculation of NLO contributions

~5% corrections to LO two-body from NLO



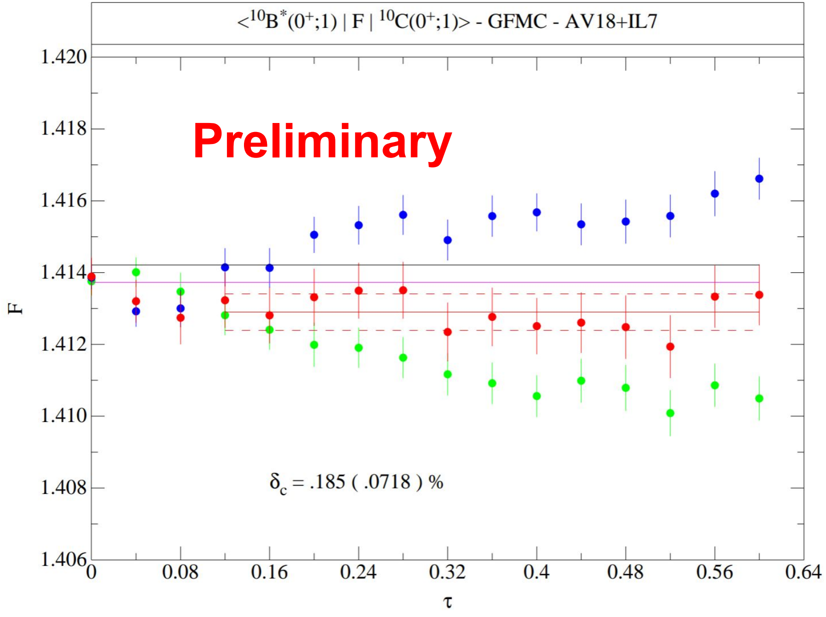
Future directions

Isospin breaking corrections with GFMC

Fermi matrix element evaluated using wave functions with isospin breaking correlations

AV18+IL7 results consistent with shell model with ~2.6 times smaller error bar

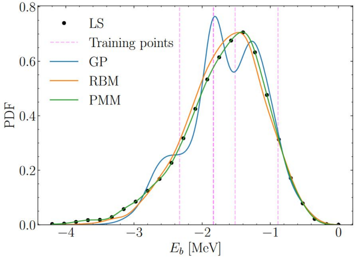
Chiral interaction predicts ~1.4 times larger correction that AV18+IL7, ~1.3 times smaller error than shell model



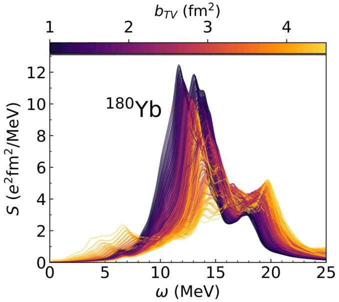
Los Alamos NATIONAL LABORATORY

with Piarulli, Lovato, Wiringa

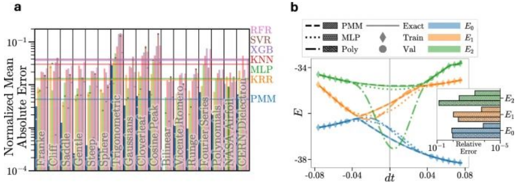
Quantifying uncertainties to connect with precision



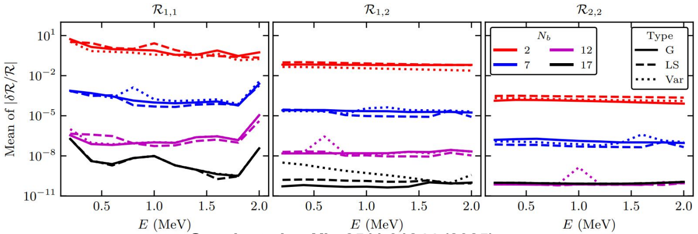
Somasundaram et al. PLB 866, 139558 (2025)



Jin et al. arXiv:2511.01844



Cook et al. Nature Communications 16, 5929 (2025)



Gnech et al. arXiv:2511.01844 (2025)

Bayesian UQ requires sampling many times from parameter space

QMC calculations are costly, sampling is computationally prohibitive

Emulators replace full-order model with low-order approximation

Los Alamos NATIONAL LABORATORY

Pushing to Heavier nuclei with Auxiliary Field Diffusion Monte Carlo (AFDMC)

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

Advantage of a polynomial scaling with A

Technically more complicated to operate on wave function

Cost is a simpler correlation structure in the wave function

Los Alamos NATIONAL LABORATORY

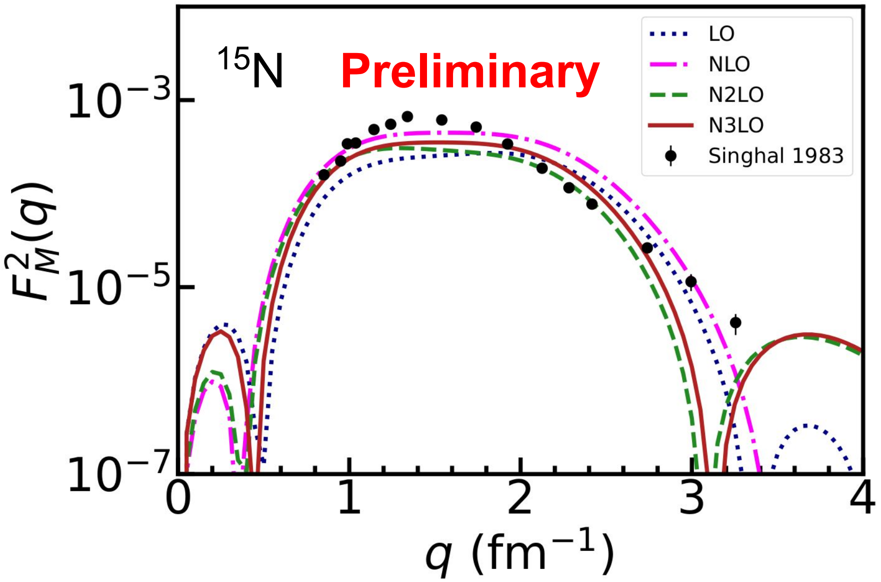
Lonardoni *et al.*, PRC 97, 044318 (2018)

Quasi-elastic neutrino scattering with AFDMC

QMC quasi-elastic responses so far for scattering on A ≤ 12 nuclei

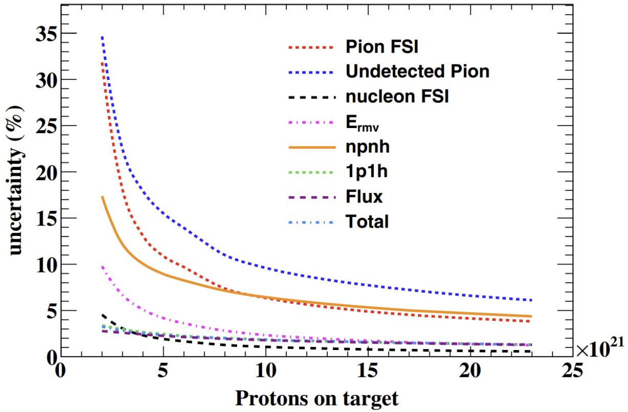
AFDMC basis would allow the study of heavier nuclei

Present: Elastic scattering using the AFDMC basis



In collaboration with: Carlson, Gandolfi, Martin, Tews

Quasi-elastic neutrino scattering outlook

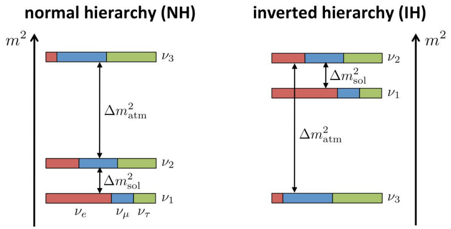


Dolan et al. PRD 105, 032010 (2022)

AFDMC allows for consistent treatment of two-body currents in heavy nuclei

Two-body current processes represent one of the largest systematic uncertainties for DUNE experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Information from DUNE complementary to neutrinoless double beta decay and neutrino mass efforts at UW

Los Alamos NATIONAL LABORATORY

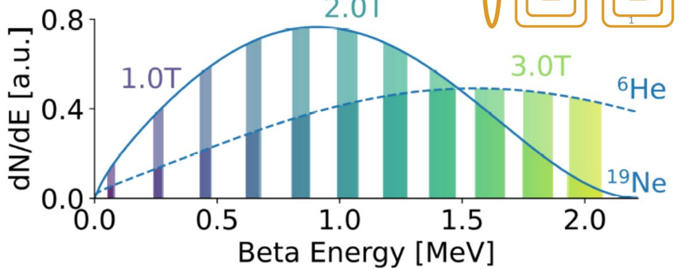
Beta decay spectra

Spectra of nuclei heavier than ^{6}He also important for BSM physics

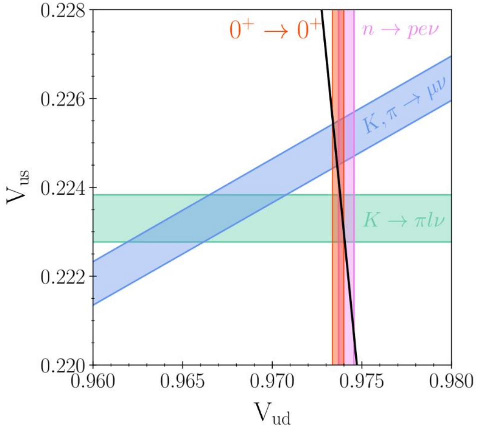
^{19}Ne important for the ^{6}He-CRES experiment

Recoil spectra up to A = 41 important for constraining V_{ud}

AFDMC makes these cases accessible



Byron et al., PRL 131, 082502 (2023)



Cirigliano et al., PLB 838 (2023) 137748

What will this require?

Better understanding of model dependence in nuclear interaction (supported by EFT expertise at UW)

Identifying impactful beta decay spectra (UW and INT collaboration)

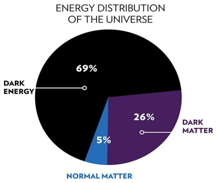
Computational resources (UW Research Computing and external)

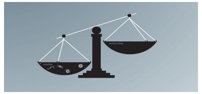
Conclusions

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

Future directions will help bridge precision searches and nuclear physics





QMC @

CENPA Center for Experimental Nuclear Physics and Astrophysics UNIVERSITY of WASHINGTON

FRIB GANIL GSI RIKEN ISOLDE TRIUMF

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

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

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

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

Optimize when you minimize:

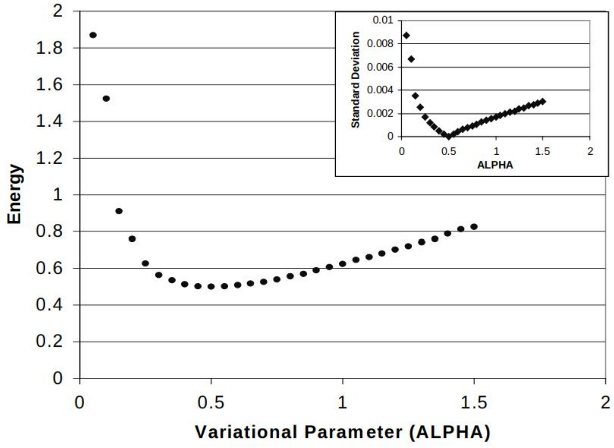
$$E_V = \frac{\langle\Psi_V|H|\Psi_V\rangle}{\langle\Psi_V|\Psi_V\rangle} \geq E_0$$

Los Alamos NATIONAL LABORATORY

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

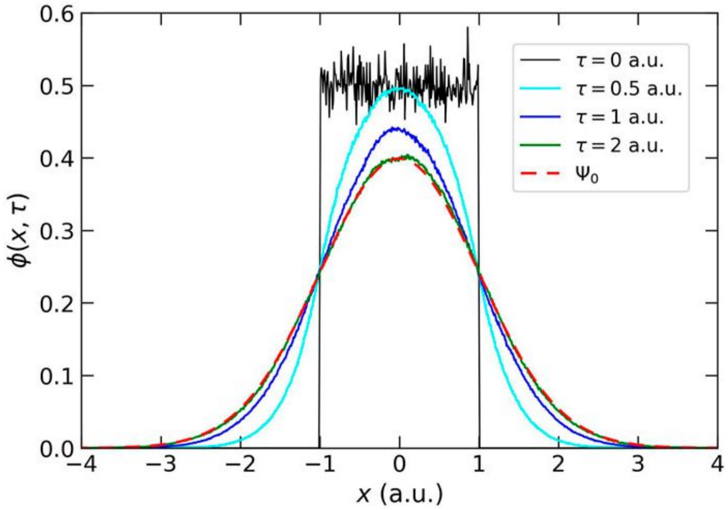
Solution: $$|\Psi(\tau)\rangle = e^{-(H-E_T)\tau}|\Psi(0)\rangle$$

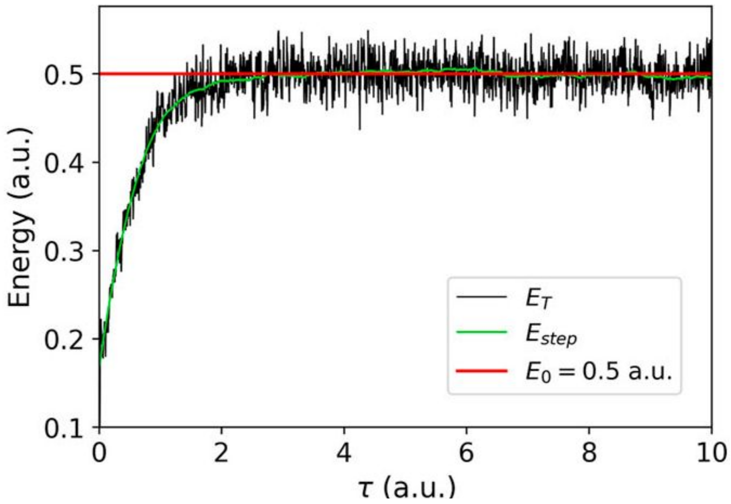
Recall $|\Psi(0)\rangle = \sum_i c_i |\psi_i\rangle$ and note $e^{-(H-E_0)\tau}|\Psi(0)\rangle = c_0\psi_0 + \sum_i e^{-\alpha_i\tau}c_i|\psi_i\rangle\,;\ \alpha_i > 0$

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

Los Alamos NATIONAL LABORATORY

Green’s function Monte Carlo: 1D example





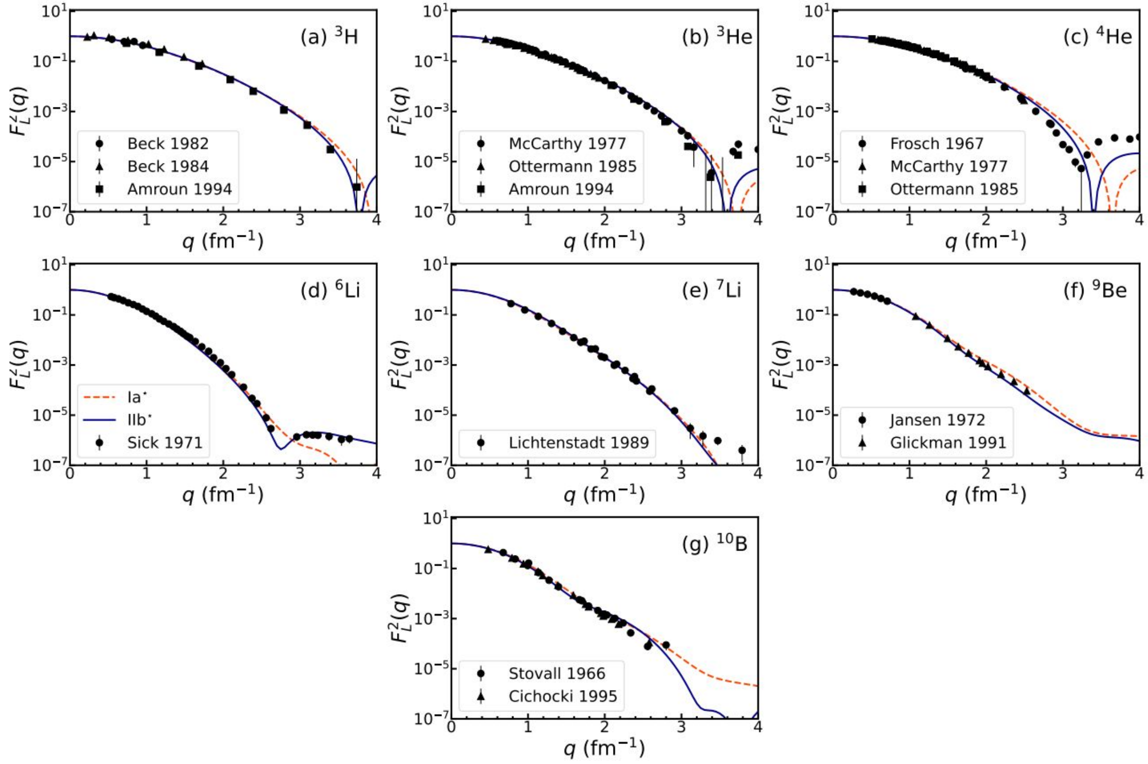
$$G(\mathbf{R}', \mathbf{R}) = \langle \mathbf{R}' | e^{-(H - E_0)\Delta\tau} | \mathbf{R} \rangle$$

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

Los Alamos NATIONAL LABORATORY

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

Model variation of charge form factors

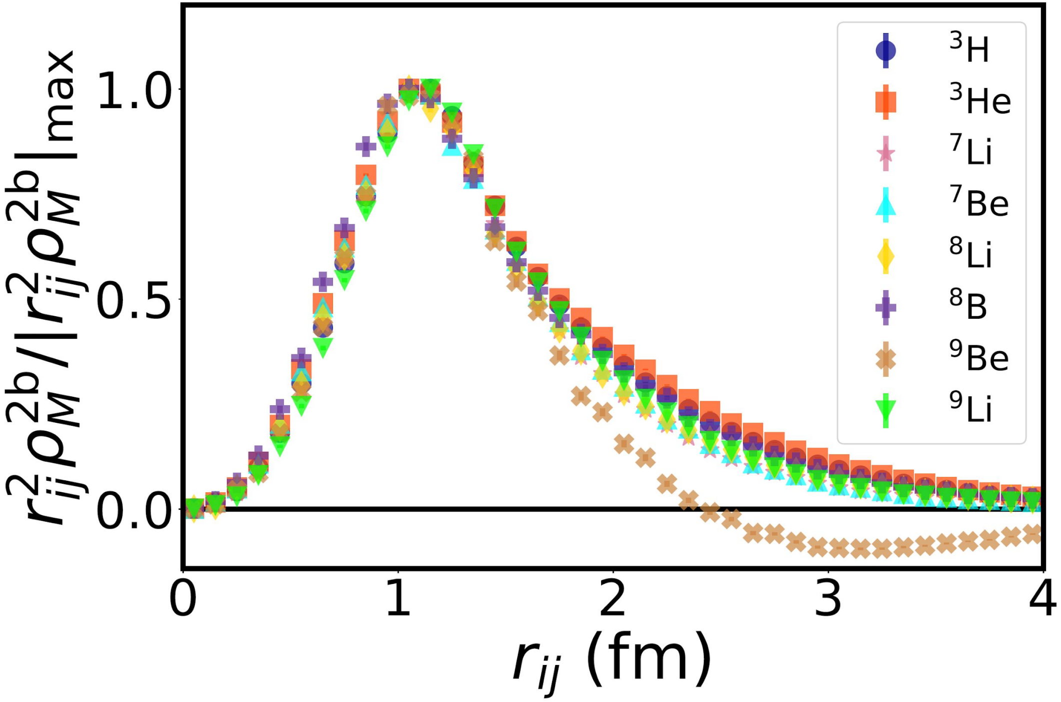


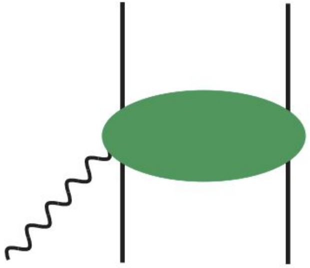
Los Alamos NATIONAL LABORATORY

King et al. PRC 110, 054325 (2024)

Universality in magnetic densities

NV2+3-IIb*





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

Los Alamos NATIONAL LABORATORY

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

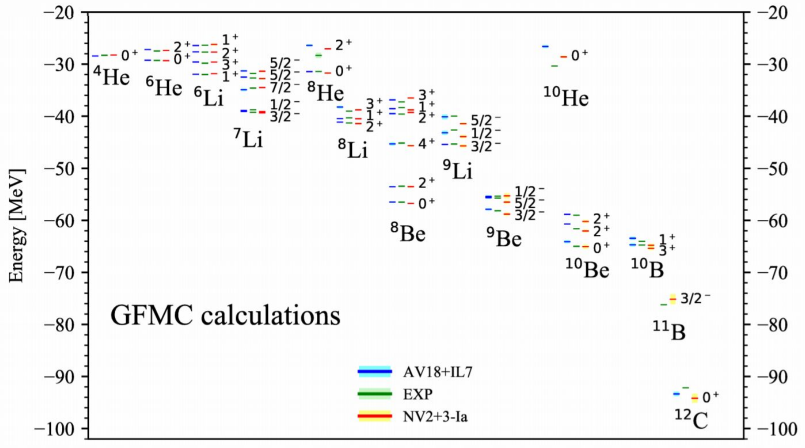
The Norfolk (NV2+3) interactions

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

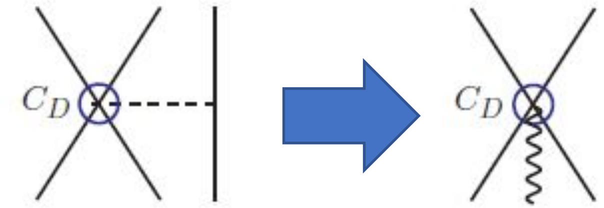
$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

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



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

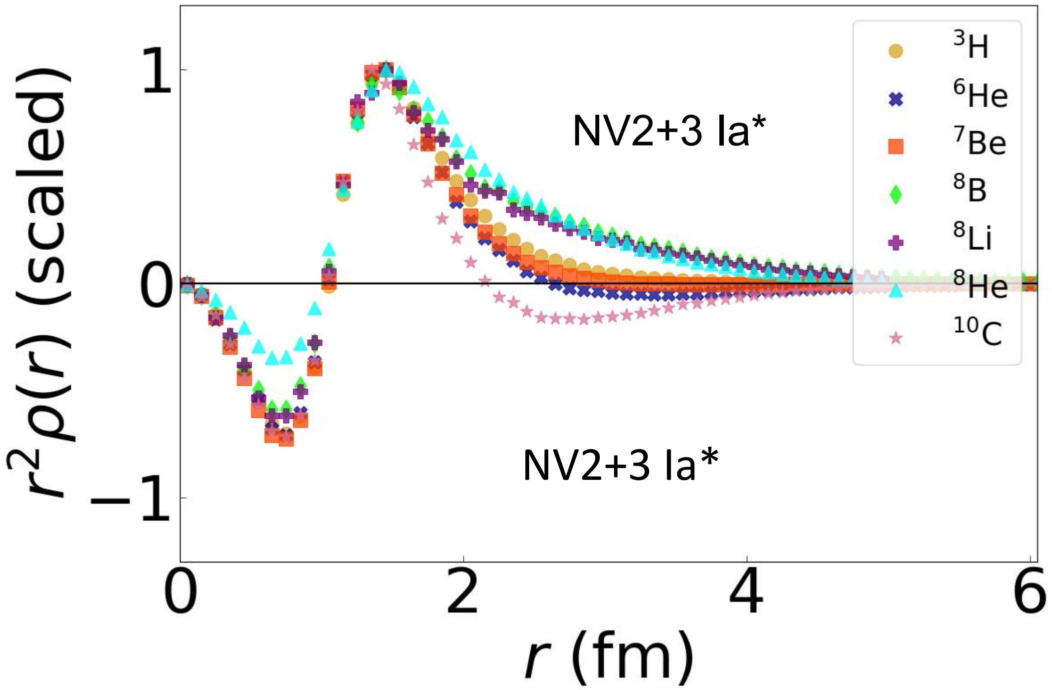
$$z_0 \propto (c_D + \text{ known LECs})$$

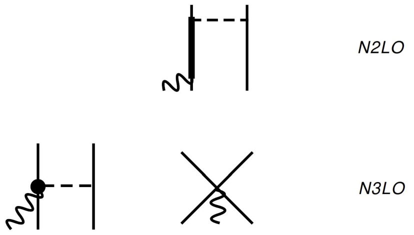
Specific parameter in the three-nucleon force is ***connected to*** a parameter in the two-body weak transition operator

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

Gardestig and Phillips PRL 96, 232301 (2006)

Scaled total two-body transition densities

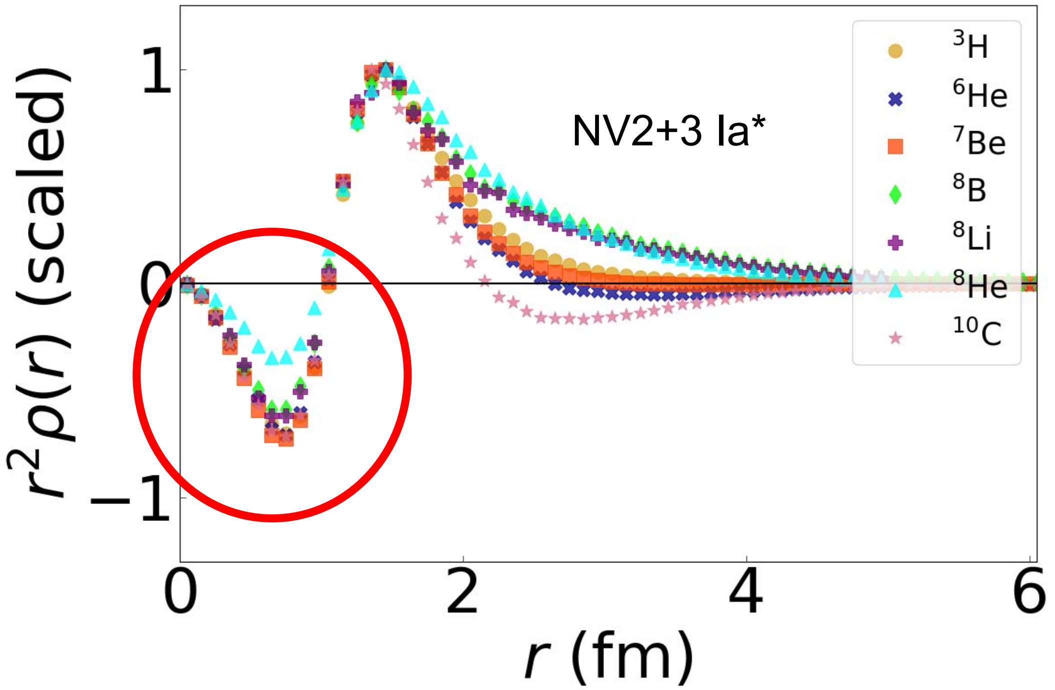


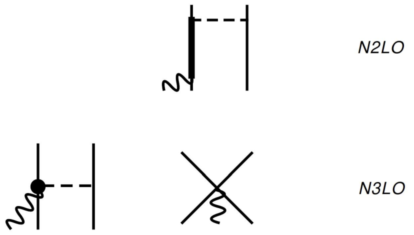


$$M_{\rm GT}^{\rm 2b} = \int dr_{ij} 4\pi r_{ij}^2 \rho_{\rm GT}^{\rm 2b}(r_{ij})$$

King et al. PRC 121, 025501 (2020)

Scaled total two-body transition densities



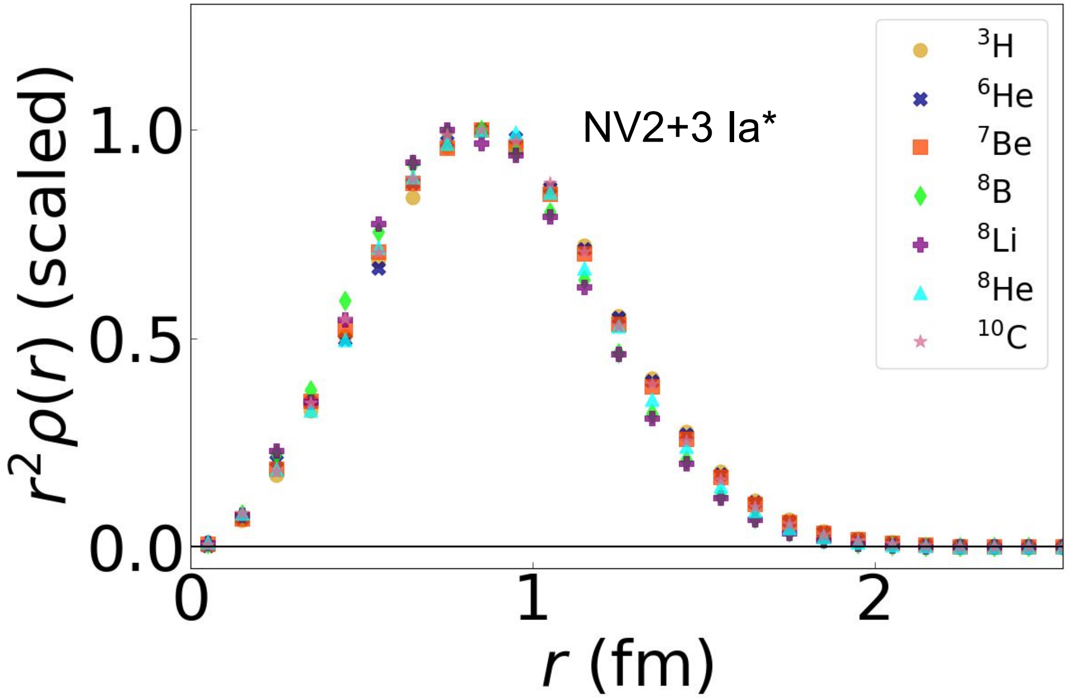


We can isolate the short-range contact piece

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

King et al. PRC 121, 025501 (2020)

Scaled contact two-body transition densities

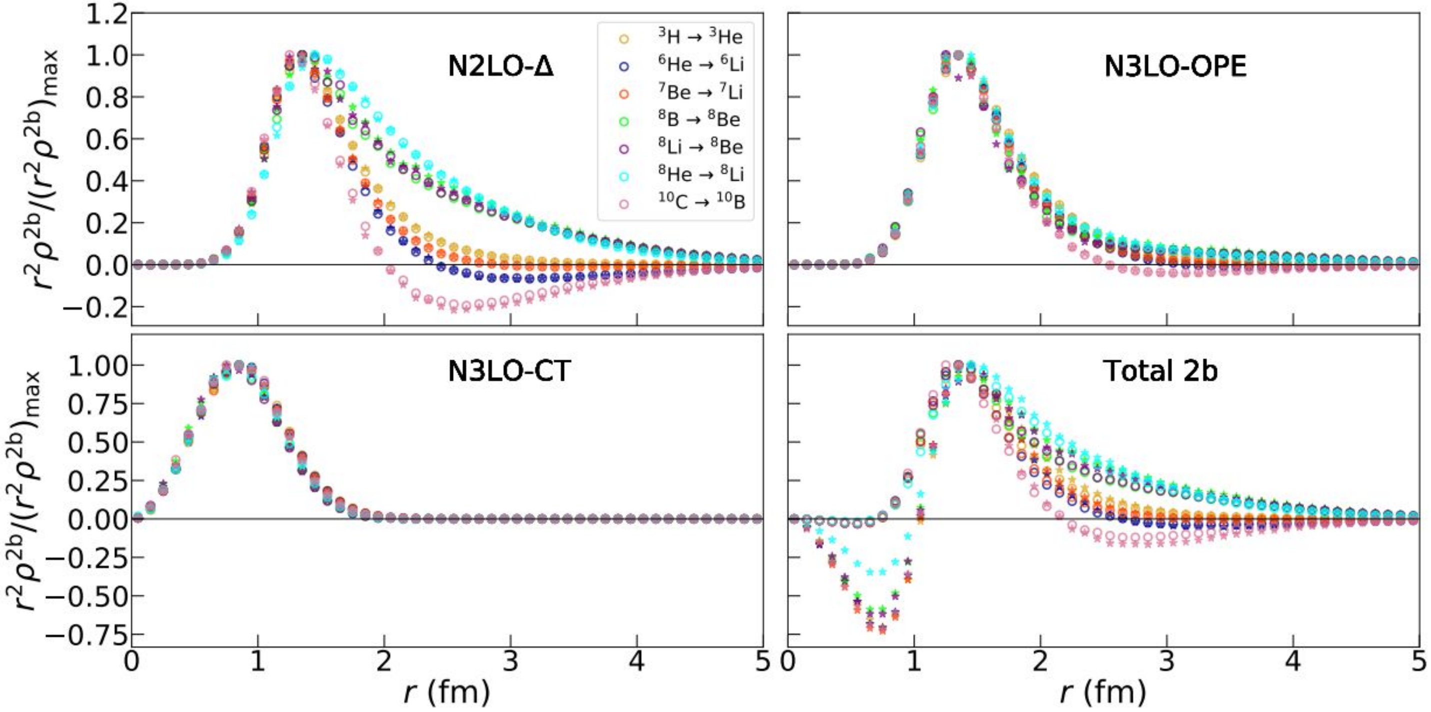


$$M_{\rm GT}^{\rm CT} = \int dr_{ij} 4\pi r_{ij}^2 \rho_{\rm GT}^{\rm CT}(r_{ij})$$

Los Alamos NATIONAL LABORATORY

King et al. PRC 121, 025501 (2020)

Universal behavior in GT densities



King et al. PRC 121, 025501 (2020)

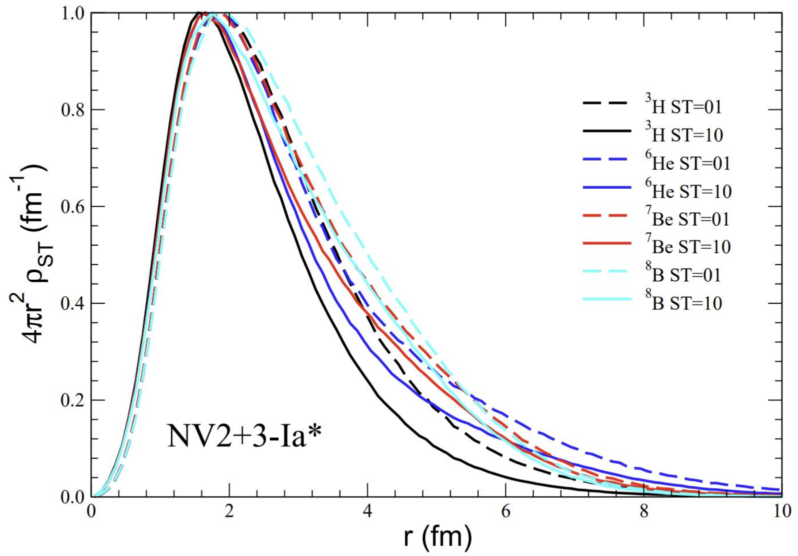
Los Alamos NATIONAL LABORATORY

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

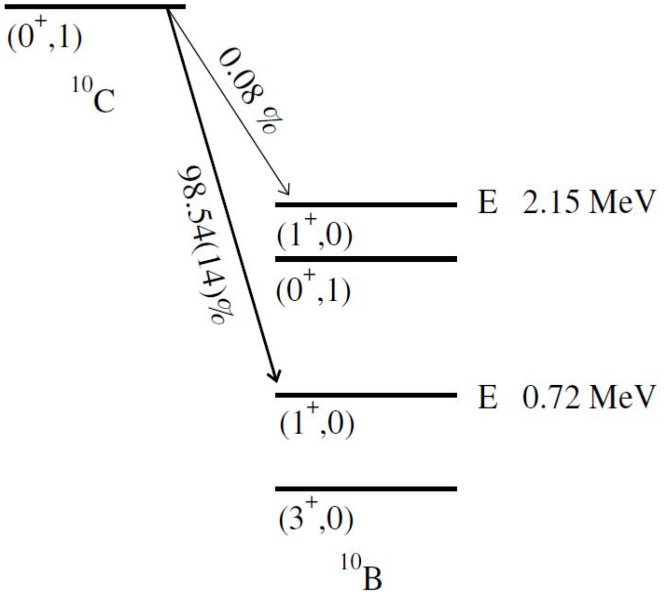


$$N_{ST} = \int dr_{ij} 4\pi r_{ij}^2 \rho_M^{2b}(r_{ij})$$

Los Alamos NATIONAL LABORATORY

King et al. PRC 121, 025501 (2020)

^{10}B β-decay



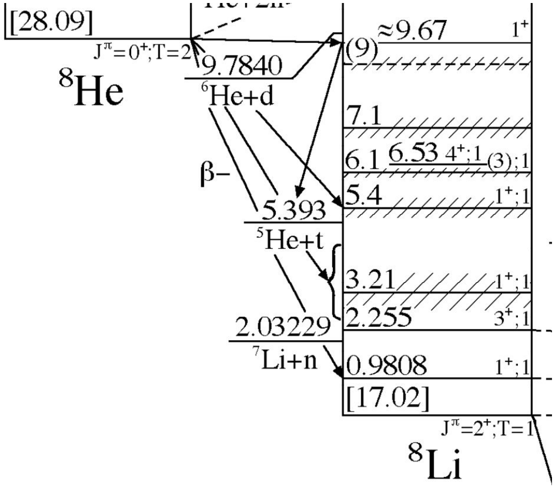
https://nucldata.tunl.duke.edu/

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



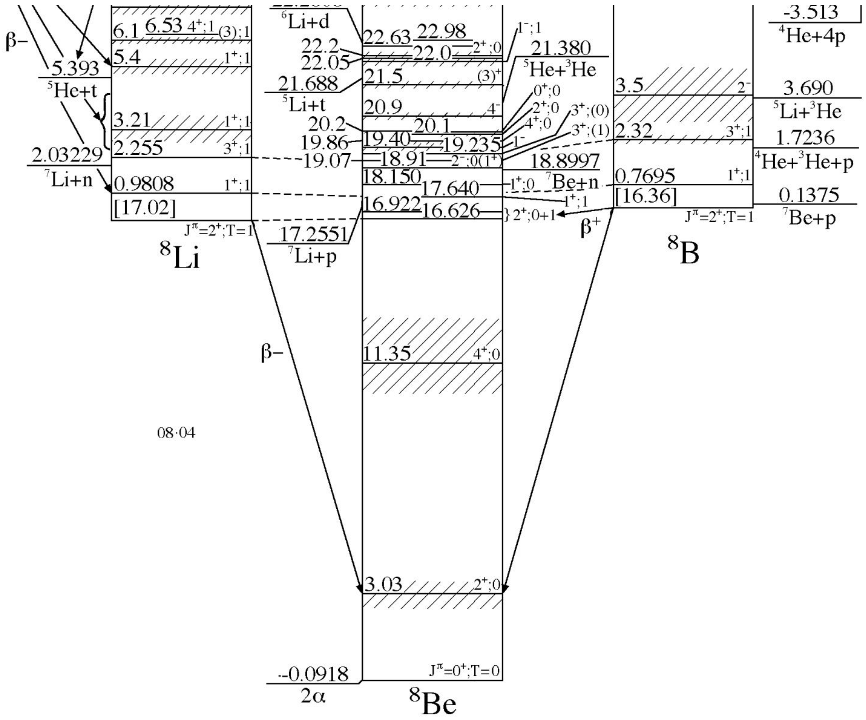
https://nucldata.tunl.duke.edu/

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)]**:

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

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

Los Alamos NATIONAL LABORATORY

Cross section

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

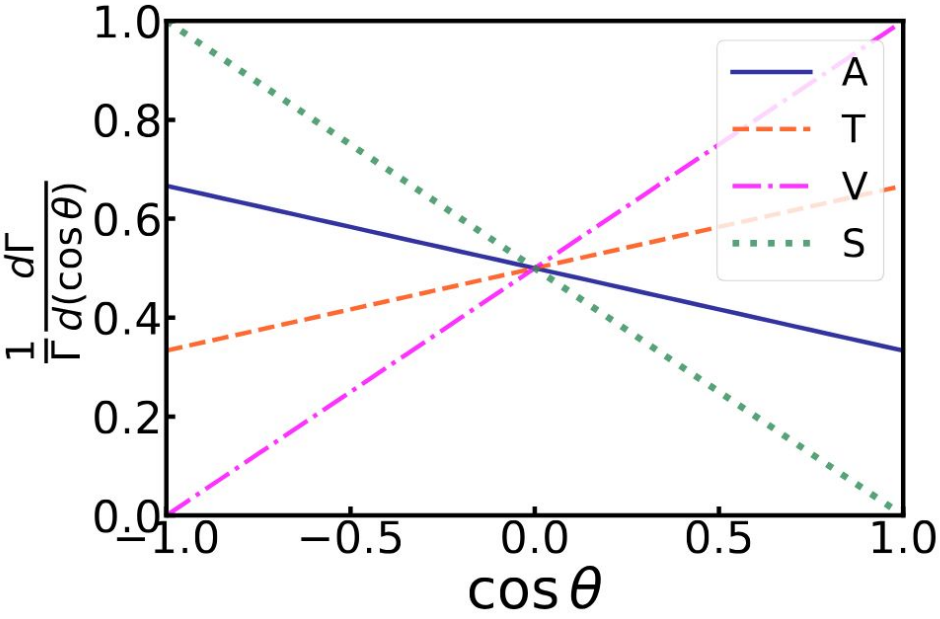
In elastic scattering:

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

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

Los Alamos NATIONAL LABORATORY

BSM current effects on decay correlations

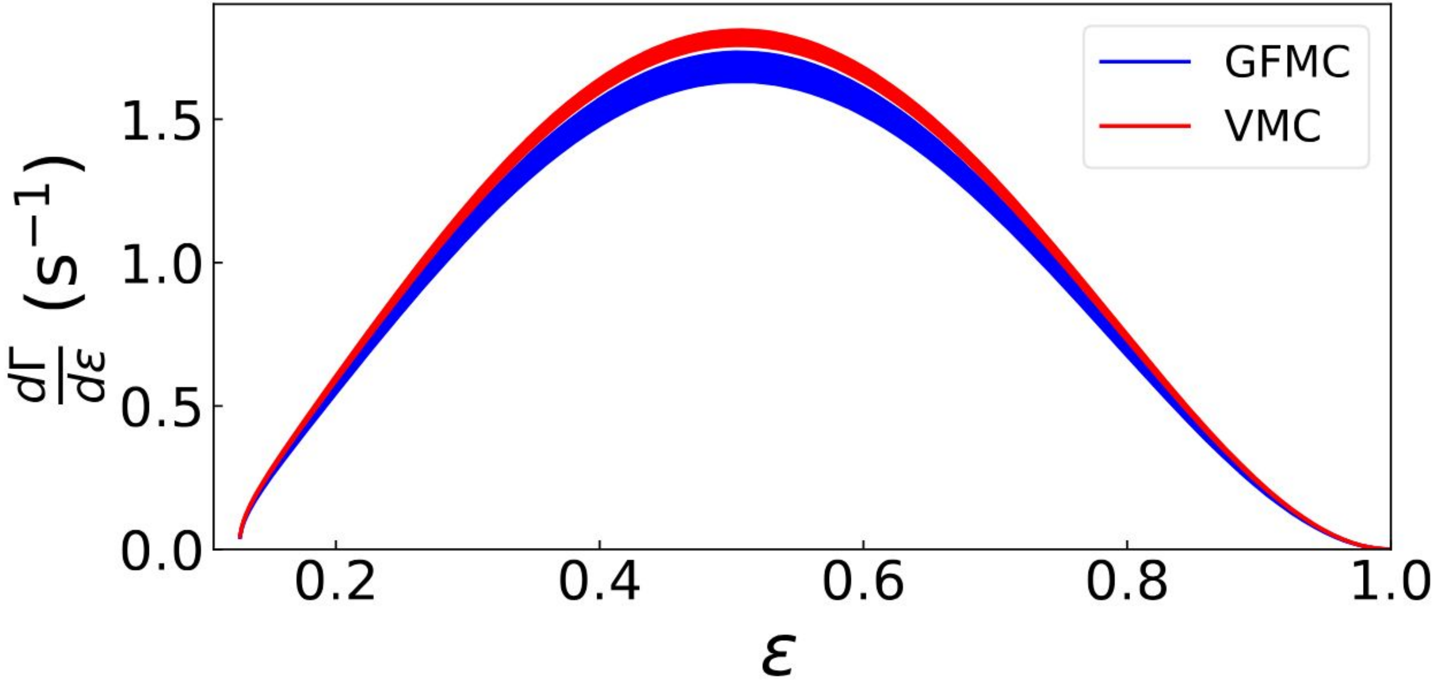


Axial, tensor, vector, and scalar currents preferentially emit electrons at certain angles

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

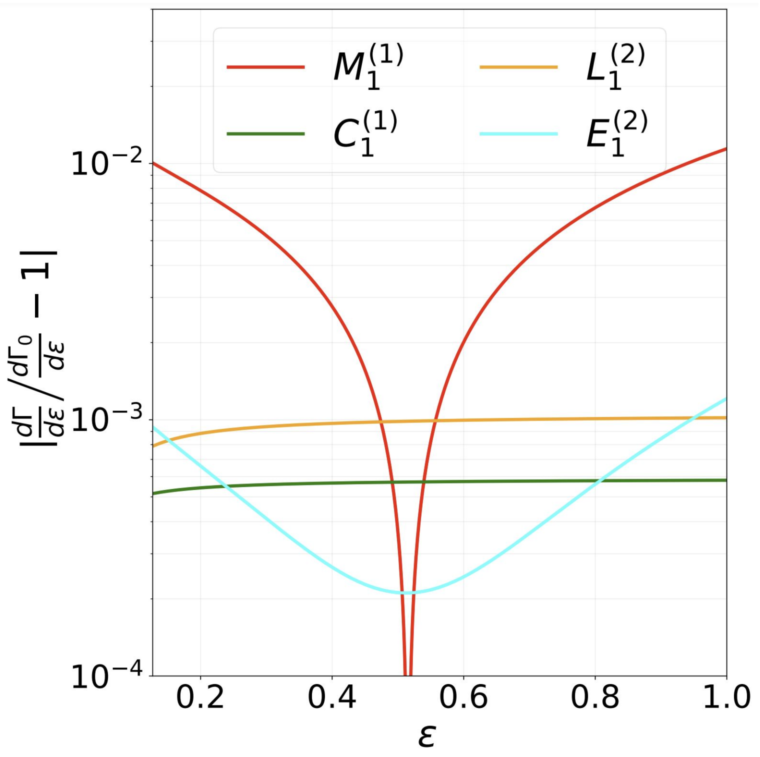
Tensor operator flips electron chirality -> interference at low energy, coherently sums with axial at large energy

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



King et al. PRC 107, 015503 (2023)

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



King et al. PRC 107, 015503 (2023)