Fundamental Physics with Nuclei

EMMI Workshop and International Workshop XLIX on Gross Properties of Nuclei and Nuclear Excitations

16 January 2023

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https://physics.wustl.edu/quantum-monte-carlo-group

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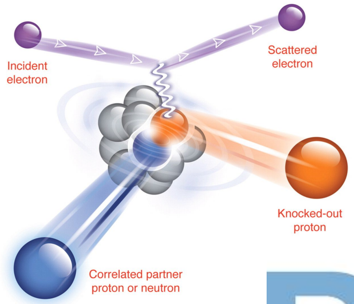
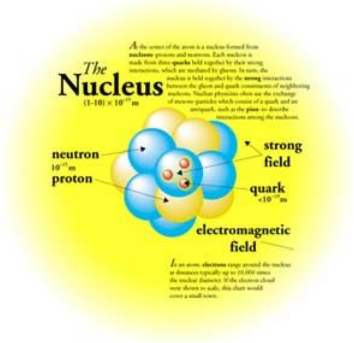
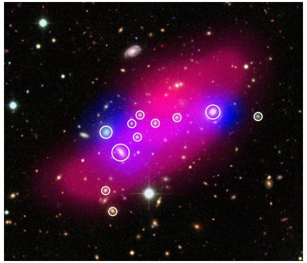
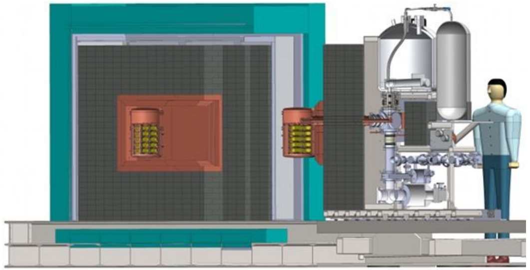
Computational Resources awarded by the DOE ALCC and INCITE programs

Understand Nuclei to Understand the Cosmos



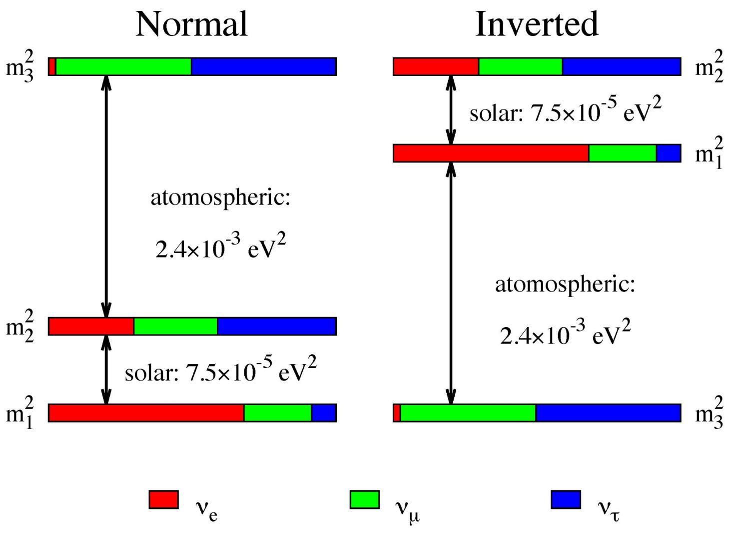



ESA, XMM-Newton, Gastaldello, CFHTL

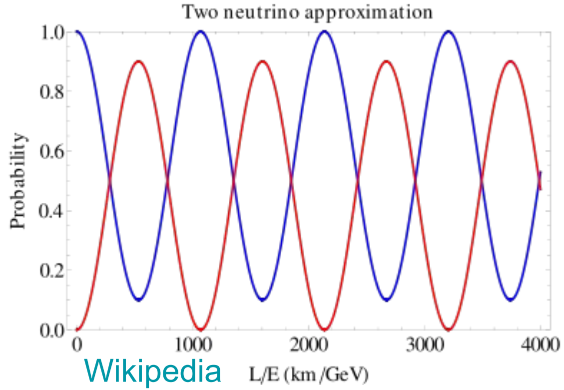


Neutrino Oscillations

Neutrinos oscillate → they have a tiny mass
Beyond the Standard Model physics



J.Phys.G43(2016)030401



Wikipedia

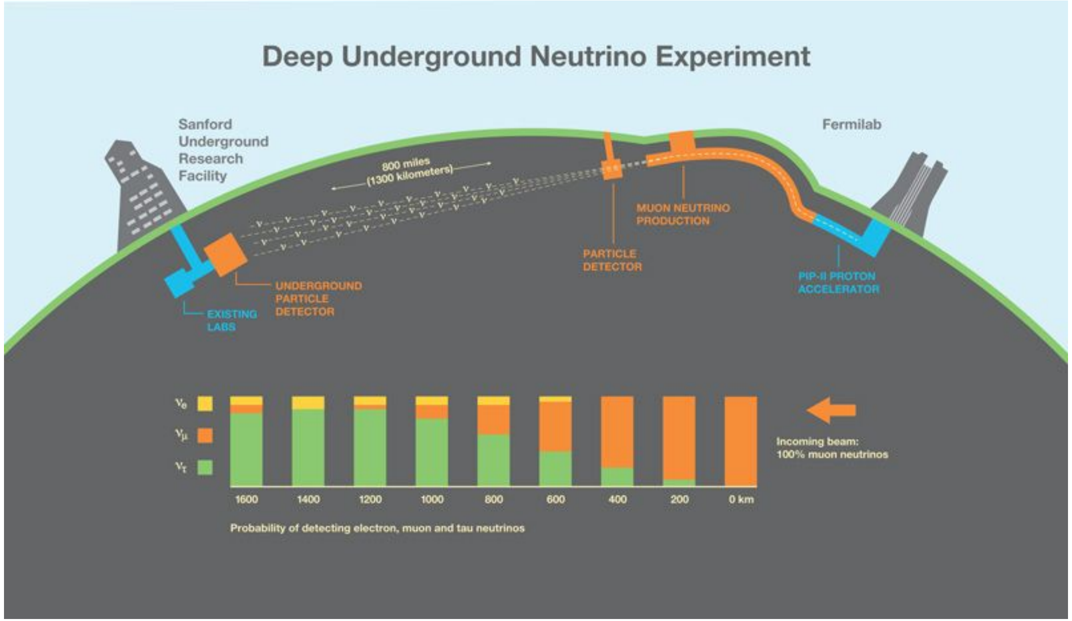
Simplified two-flavour picture

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

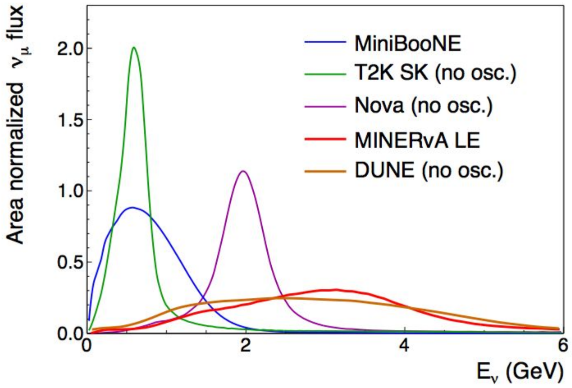
Probability of conversion

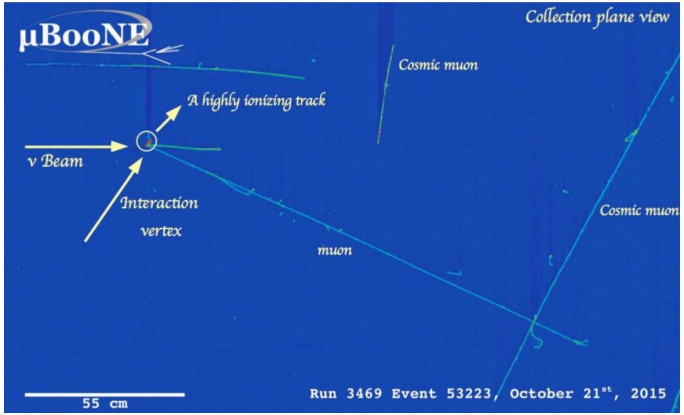
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{2E_\nu}\right)$$

Accelerator Neutrinos' Experiments



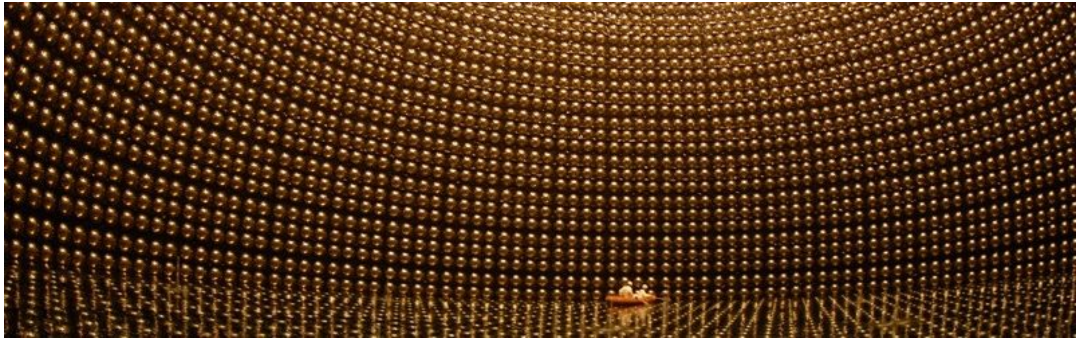
DUNE - Fermilab



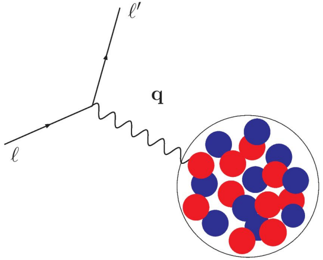


Nuclei for Neutrino Oscillations' Experiments

See Asia and Sonia's talks



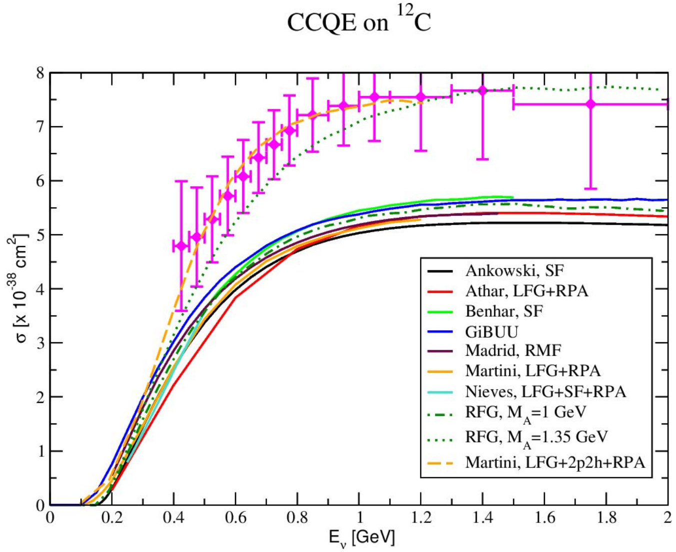
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2_{21} L}{2E_\nu} \right)$$



Nuclei are the active material in the detector. The energy of the incident neutrino is reconstructed from the observed final states using **neutrino event generators** that require **theoretical cross-sections**.

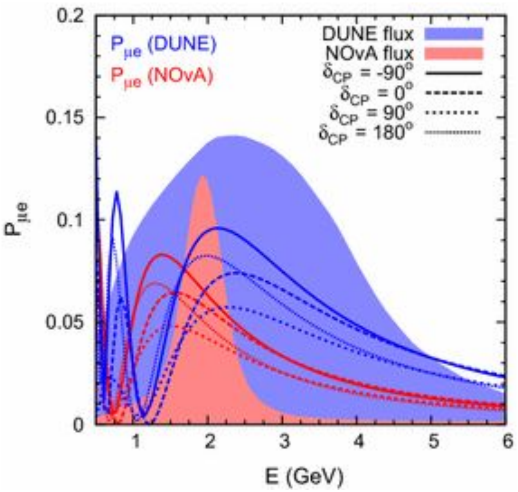
T2K

Neutrino-^{12}C cross section

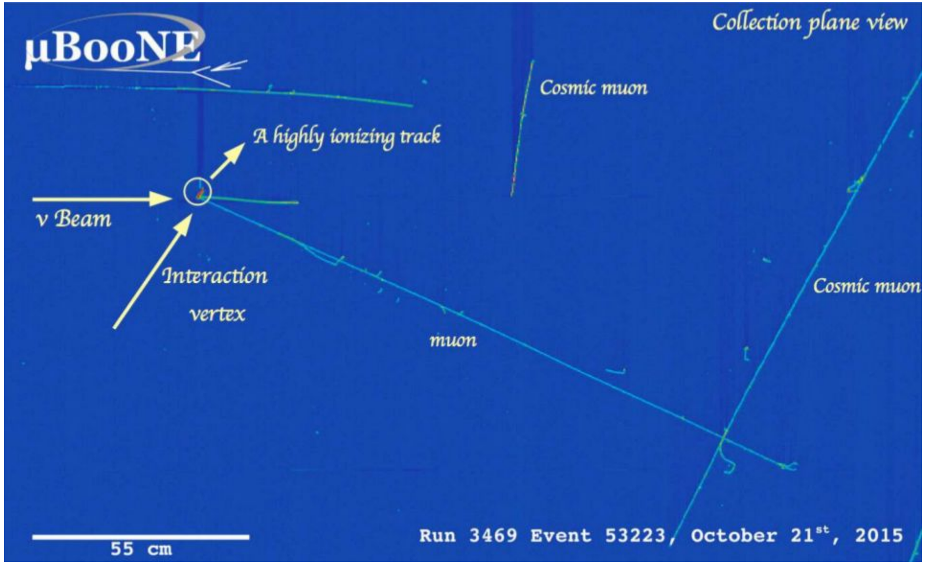


Alvarez-Ruso arXiv:1012.3871

The needs of the experimental programs

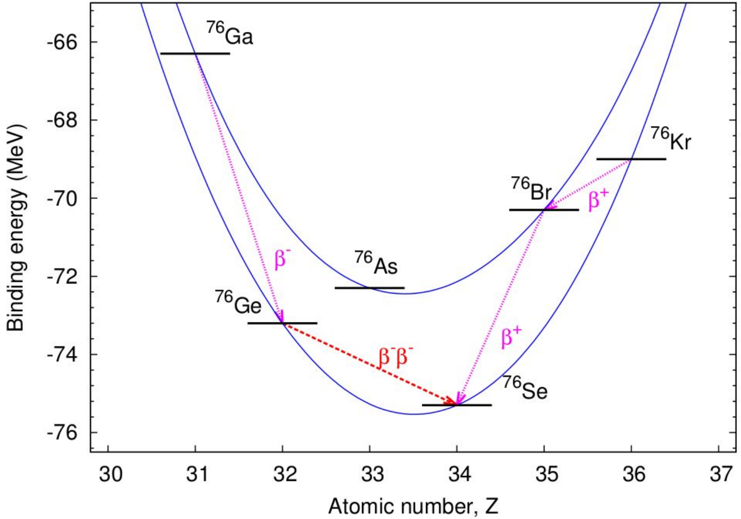


The experimental neutrino program is in need of accurate **theoretical calculations of neutrino-nucleus cross-sections with quantified theoretical errors** to ensure a robust implementation of interaction models in experiments

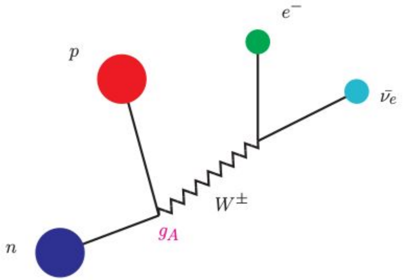


The range of challenges is extreme; ultimately we would like to be able to predict both inclusive and **exclusive cross sections across a wide range of kinematics**.

Single and Double Beta Decays



J. Menéndez arXiv:1703.08921v1



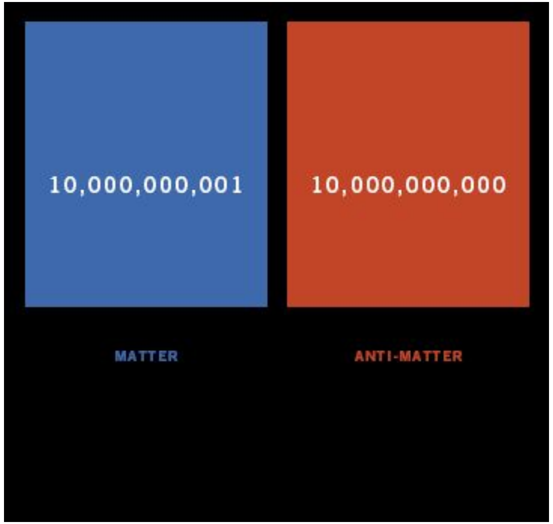
Maria Goeppert-Mayer

Single beta decay $(Z,N) \rightarrow (Z+1, N-1) + e + \bar{\nu}_e$

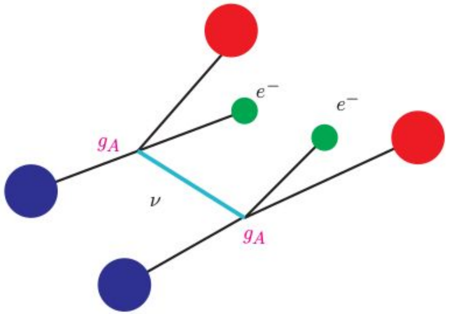
Double beta decay $(Z,N) \rightarrow (Z+2, N-2) + 2e + 2\bar{\nu}_e$

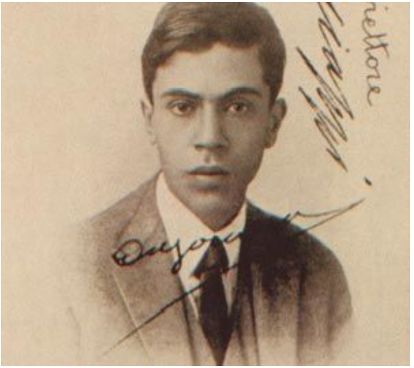
Here the lepton number is conserved

Neutrinoless double beta decay



Hitoshi Murayama

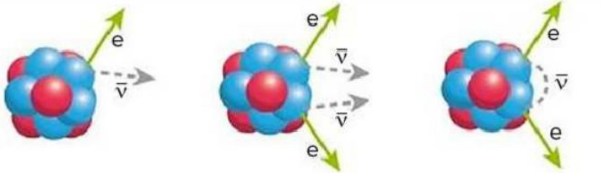




Ettore Majorana

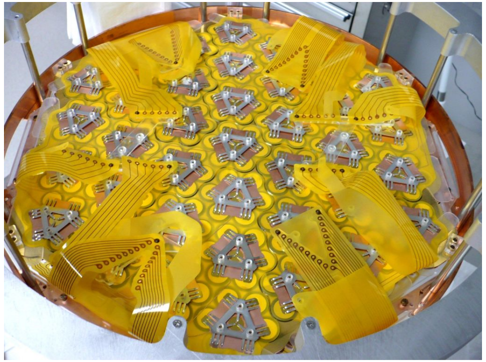
$$(Z,N) \rightarrow (Z+2, N-2) + 2e$$

Here the lepton number is not conserved

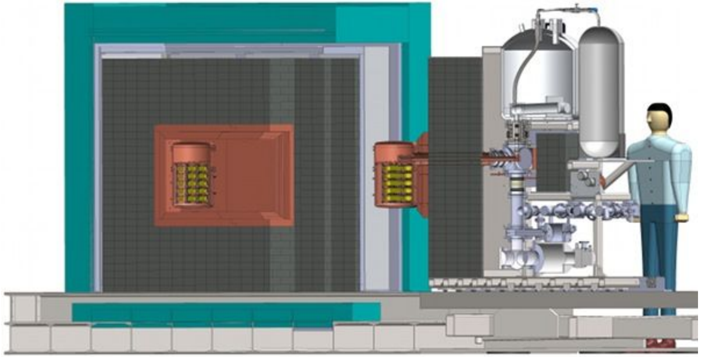


2015 Long Range Plan for Nuclear Physics

Nuclear Physics for Neutrinoless Double Beta Programs



EXO-200 Collaboration



Majorana Demonstrator

Neutrinoless double beta decay half-life $T_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)
1 ton of material is required to see few events per year

Decay Rate $\propto$ (**nuclear matrix element**)^2 x $(m_{\beta\beta})^2$

Beta decay spectrum

See Petr and Doron's talks

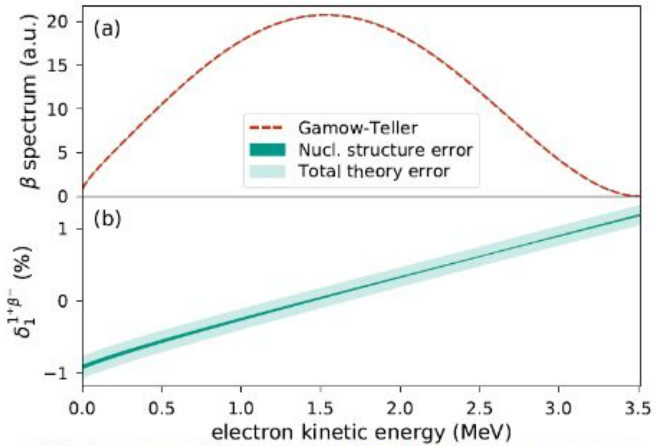
^{6}He Beta decay spectrum for BSM searches with NCSL, He6-CRES, LPC-Caen

NSCL

He6 CRES

lpc caen

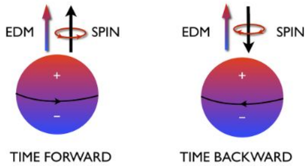
^{6}He beta-decay spectrum from NCSM



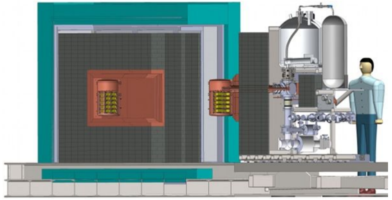
Glick-Magid et al. arXiv:2107.10212

$$\frac{d\Gamma}{d\varepsilon} = \frac{d\Gamma_0}{d\varepsilon} \times (1 + \text{corrections})$$

Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

(ω,q)~0 MeV

ω~few MeVs q~0 MeV

ω~few MeVs q~10^2 MeV

ω~tens of MeVs

ω~10^2 MeV

FRIB

Electromagnetic Decay, Beta Decay, Double Beta Decay & inverse processes

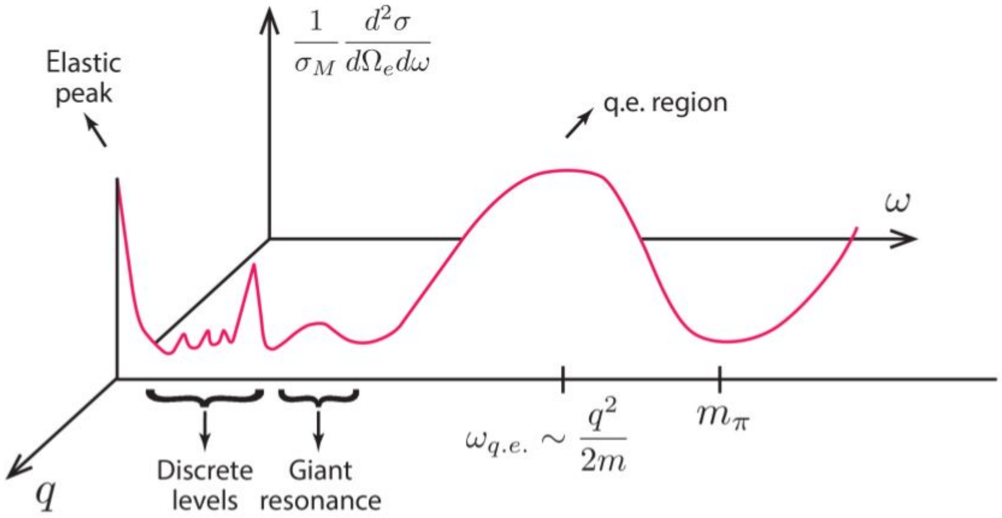
JINA-CEE

Nuclear Rates for Astrophysics

DUNE

Jefferson Lab

Electron-Nucleus Scattering Cross Section



Energy and momentum transferred (ω,q)

Current and planned experimental programs rely on theoretical calculations at different kinematics

Strategy

Validate the Nuclear Model against available data for strong and electroweak observables

- Energy Spectra, Electromagnetic Form Factors, Electromagnetic Moments, ...
- Electromagnetic and Beta decay rates, ...
- Muon Capture Rates, ...
- Electron-Nucleus Scattering Cross Sections, ...

Use attained information to make (accurate) predictions for BSM searches and precision tests

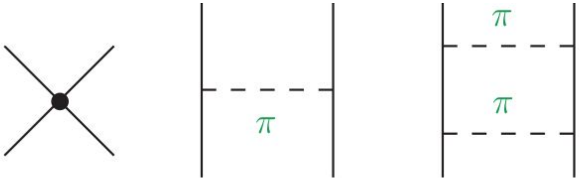
- EDMs, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Many-body Nuclear Interactions

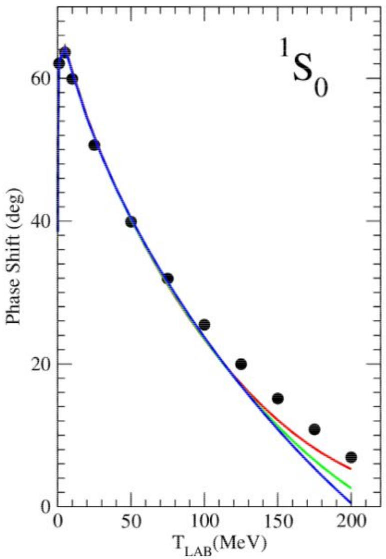
Many-body Nuclear Hamiltonian

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

v_{ij} and V_{ijk} are two- and three-nucleon operators based on experimental data fitting; fitted parameters subsume underlying QCD dynamics



Contact term: short-range
Two-pion range: intermediate-range $r \propto (2\,m_\pi)^{-1}$
One-pion range: long-range $r \propto m_\pi^{-1}$



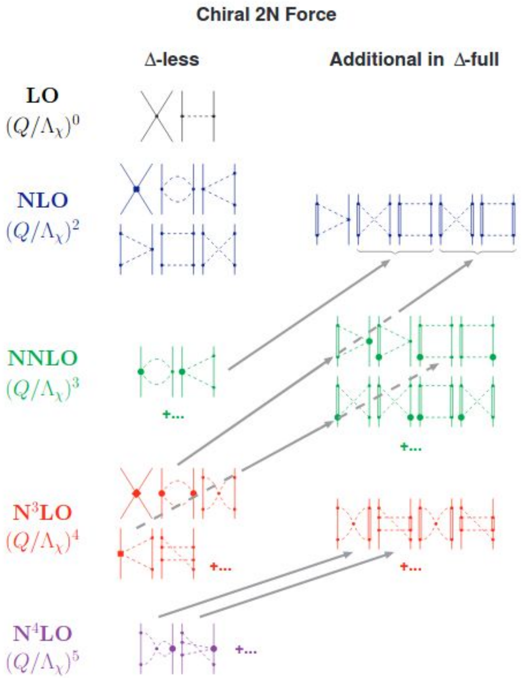
SP et al. PRC80(2009)034004

Hideki Yukawa

AV18+UIX; AV18+IL7
Wiringa, Schiavilla, Pieper *et al*.

chiral πNΔ
N3LO+N2LO Piarulli *et al*. **Norfolk Models**

Norfolk Two- and Three-body Potentials

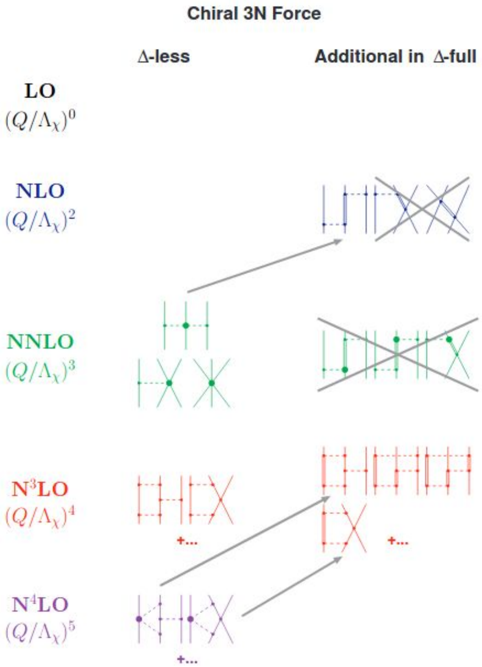


Norfolk Chiral Potentials

NV2+3

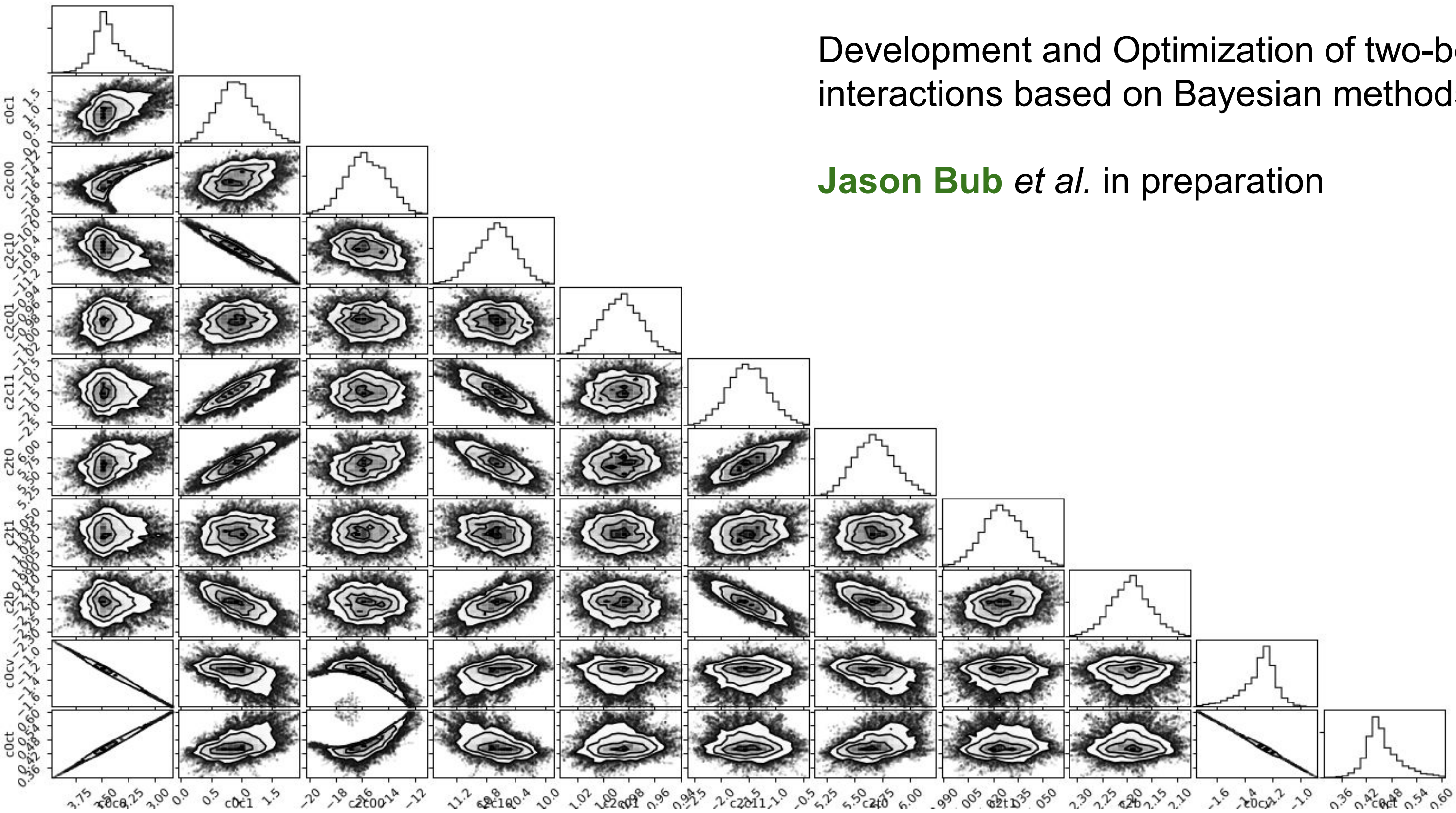
developed in Piarulli *et al*.
PRC91(2015)024003
PRC94(2016)054007

26 LECs fitted to np and pp Granada database (2700-3700 data points; 125-200 MeV) with a chi-square/datum ~1



Figs. credit Entem and Machleidt Phys.Rept.503(2011)1

Optimization of Nuclear Two-body Interactions



Development and Optimization of two-body interactions based on Bayesian methods

Jason Bub *et al.* in preparation

Quantum Monte Carlo Methods

Minimize the expectation value of the nuclear Hamiltonian: H = T + v_{ij} + V_{ijk}

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

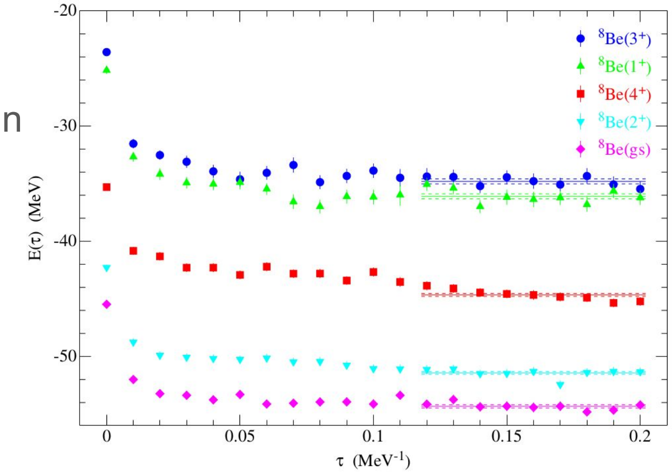
using the trial wave function:

$$|\Psi_V\rangle = \left[\mathcal{S}\prod_{i<j}(1 + U_{ij} + \sum_{k\neq i,j} U_{ijk})\right]\left[\prod_{i<j} f_c(r_{ij})\right]|\Phi_A(JMTT_3)\rangle$$

Further improve the trial wave function by eliminating spurious contaminations via a Green's Function Monte Carlo propagation in imaginary time

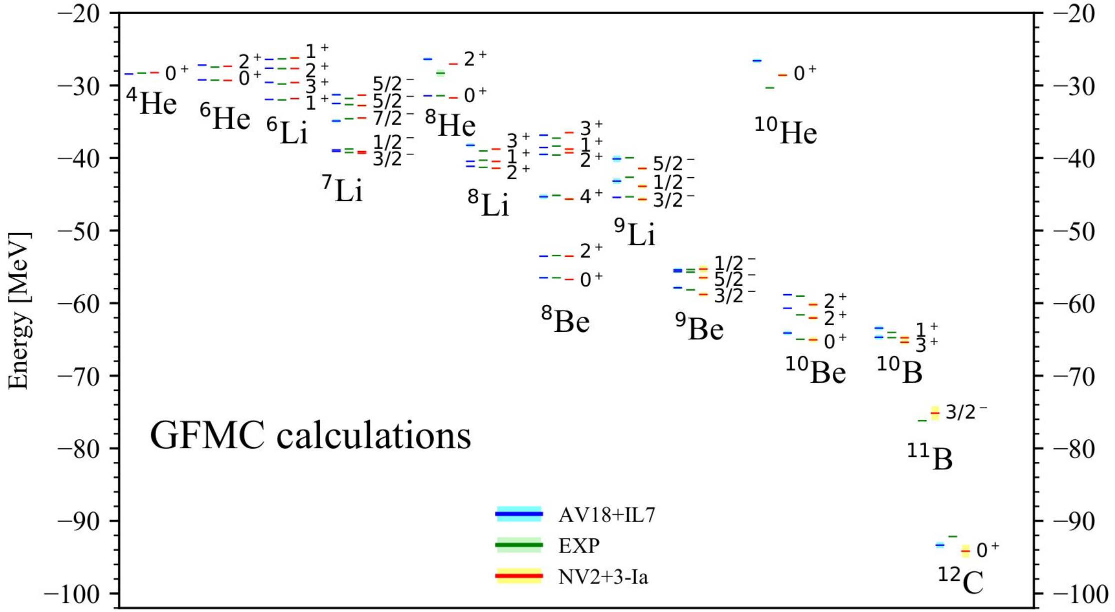
$$\Psi(\tau) = \exp[-(H - E_0)\tau]\Psi_V = \sum_n \exp[-(E_n - E_0)\tau]a_n\psi_n$$

$$\Psi(\tau \to \infty) = a_0\psi_0$$



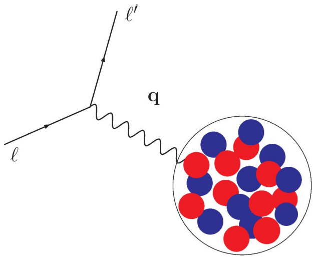
Carlson, Wiringa, Pieper *et al.*

Energies

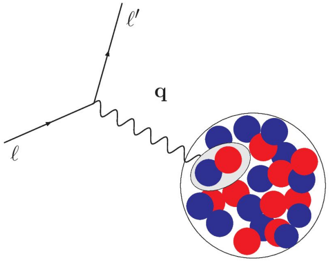


Piarulli *et al.* PRL120(2018)052503

Many-body Nuclear Electroweak Currents



one-body



two-body

Nuclear Charge Operator

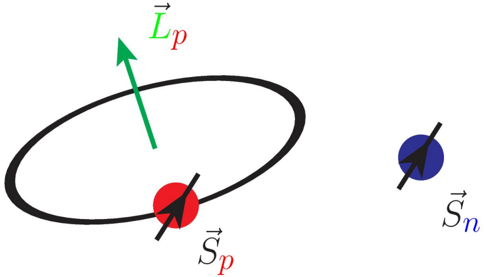
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$

Nuclear (Vector) Current Operator

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

- Two-body currents are a manifestation of two-nucleon correlations
- Electromagnetic two-body currents are required to satisfy current conservation

$$\mathbf{q} \cdot \mathbf{j} = [\, H,\, \rho\,] = [t_i + v_{ij} + V_{ijk},\, \rho\,]$$



Magnetic Moment: Single Particle Picture

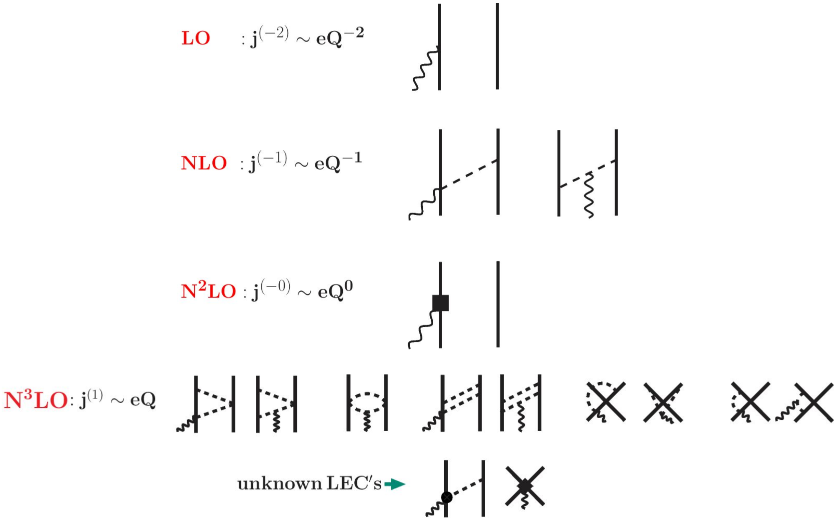
Many-body Currents

- **Meson Exchange Currents** (MEC)

Constrain the MEC current operators by imposing that the current conservation relation is satisfied with the given two-body potential

- **Chiral Effective Field Theory Currents**

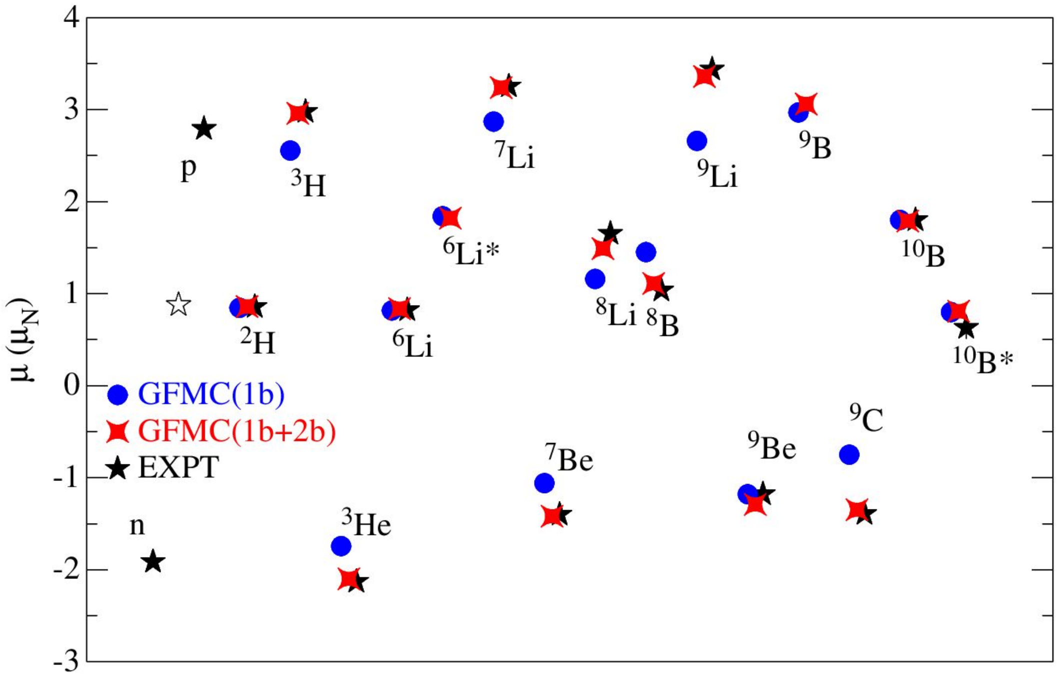
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (**LECs**), need to be **determined by either fits to experimental data or by Lattice QCD calculations**



Electromagnetic Current Operator

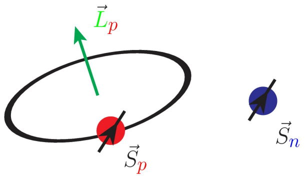
SP *et al.* PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001, PRC87(2013)014006
Park *et al.* NPA596(1996)515, Phillips (2005)
Kölling *et al.* PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Light Nuclei



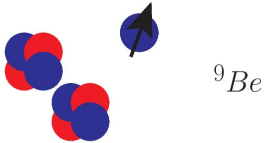
SP *et al*. PRC87(2013)035503

Single particle picture

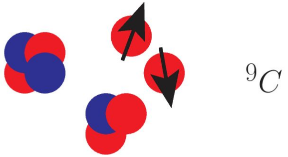


$$\mu_N(1\mathrm{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Small two-body current effects

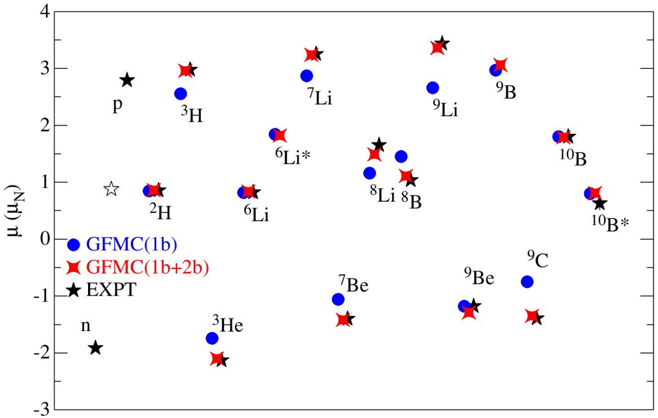


Large two-body current effects



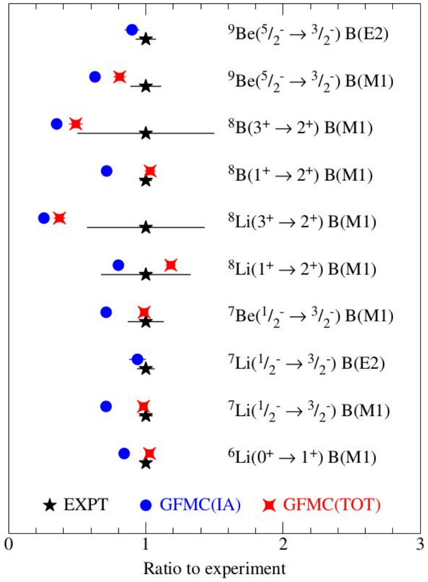
Electromagnetic Observables

Magnetic moments

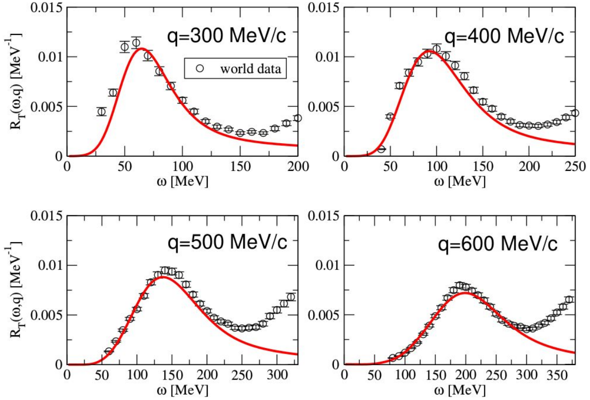


SP *et al*. PRC87(2013)035503, PRC101(2020)044612

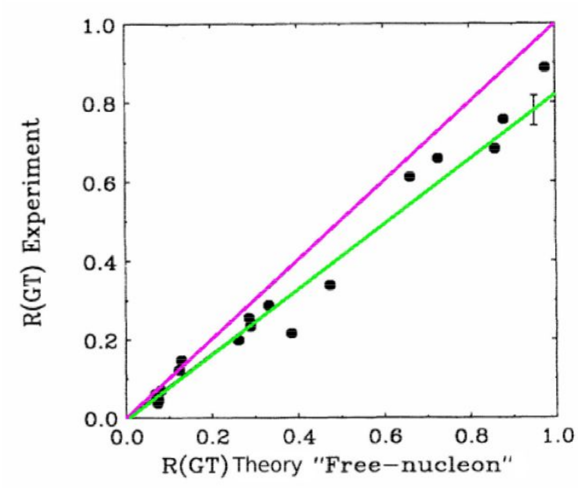
EM decay



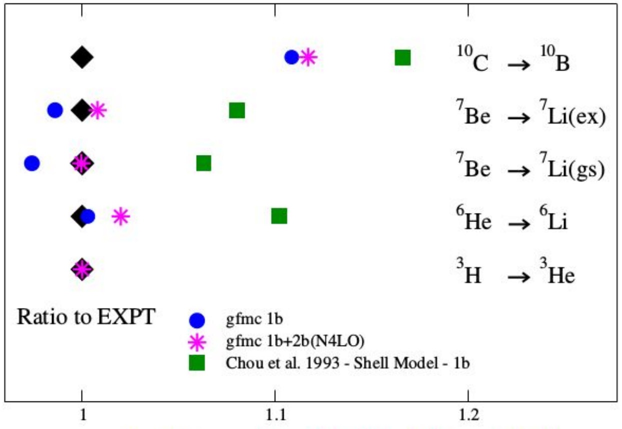
e-^{4}He particle scattering



Beta decay

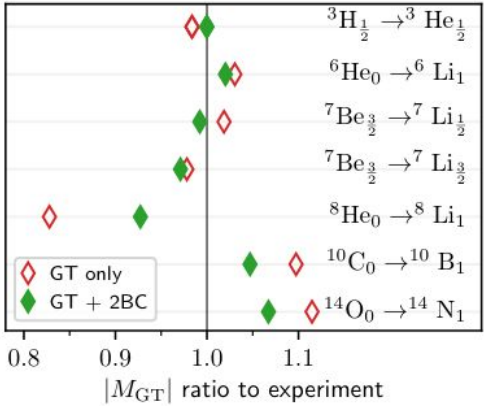


Chou et al. PRC47(1993)163



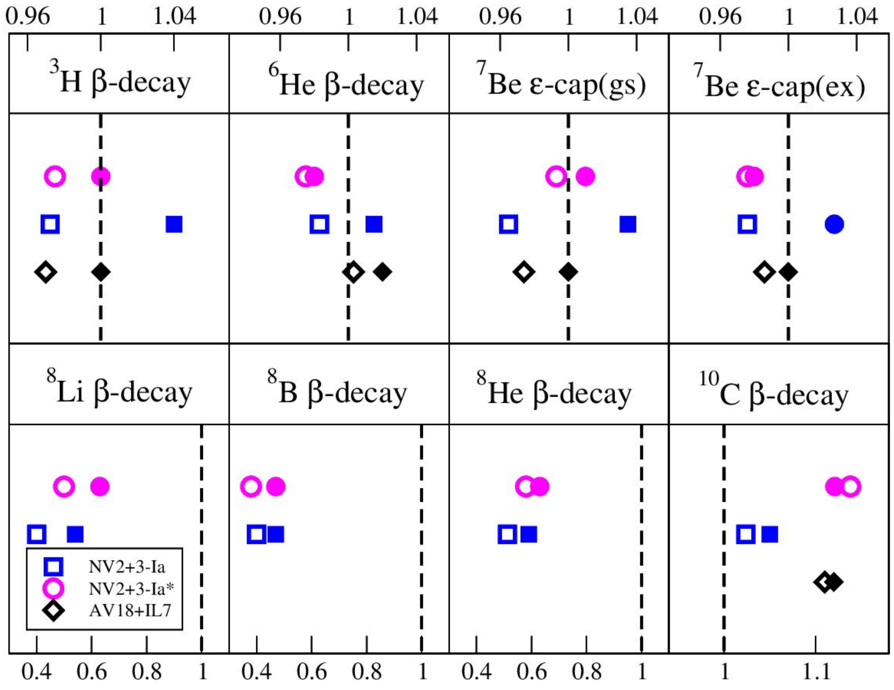
gfmc (1b) and gfmc (1b+2b); shell model (1b)

SP *et al*. PRC97(2018)022501



P. Gysbers *Nature Phys.* 15 (2019)

Beta Decay and Electron Capture in Light Nuclei



Garrett King *et al.* PRC102(2020)025501

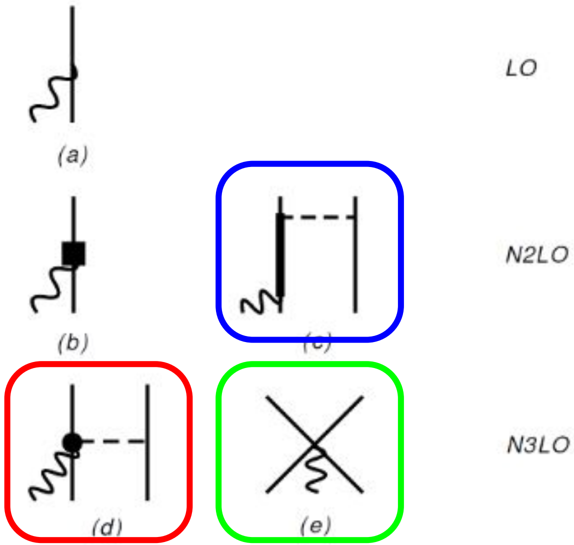
Calculations based on

- chiral interactions and currents
  NV2+3-Ia Norfolk unstarred
  NV2+3-Ia* Norfolk* starred
  Piarulli *et al.* PRL120(2018)052503
  Baroni *et al.* PRC98(2018)044003

- phenomenological **AV18+IL7** potential and chiral axial currents (hybrid calculation)

Two-body currents are small/negligible;
Results for A=6-7 are within 2% of data;
Results for A=8 are off by a 30-40%;
Results for A=10 are affected by the second $J^{\pi}=(1^{+})$ state in ^{10}B

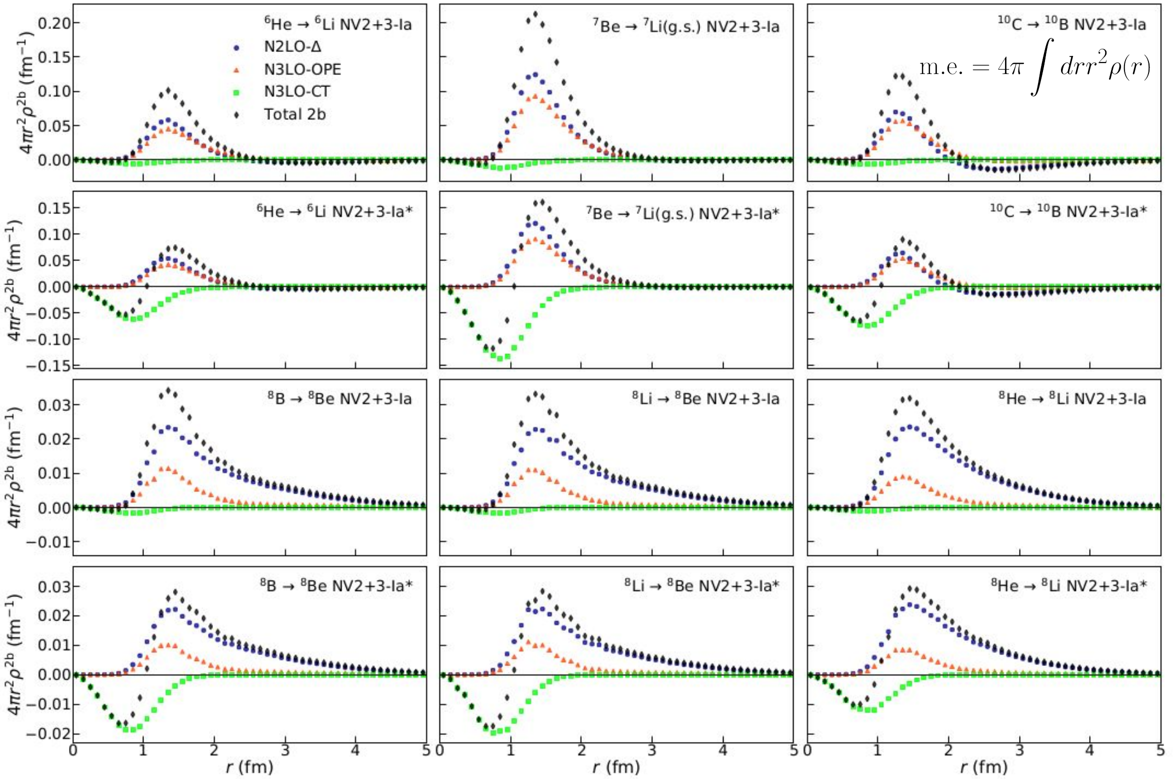
Axial currents with Δ at tree-level



Two body currents of one pion range (red and blue) with c_3 c_4 from Krebs *et al.* Eur.Phys.J.(2007)A32

Contact current involves the LEC c_D

Axial Two-body Transition Density



Garrett King *et al.* PRC102(2020)025501

NV2+3-Ia ; NV2+3-Ia*

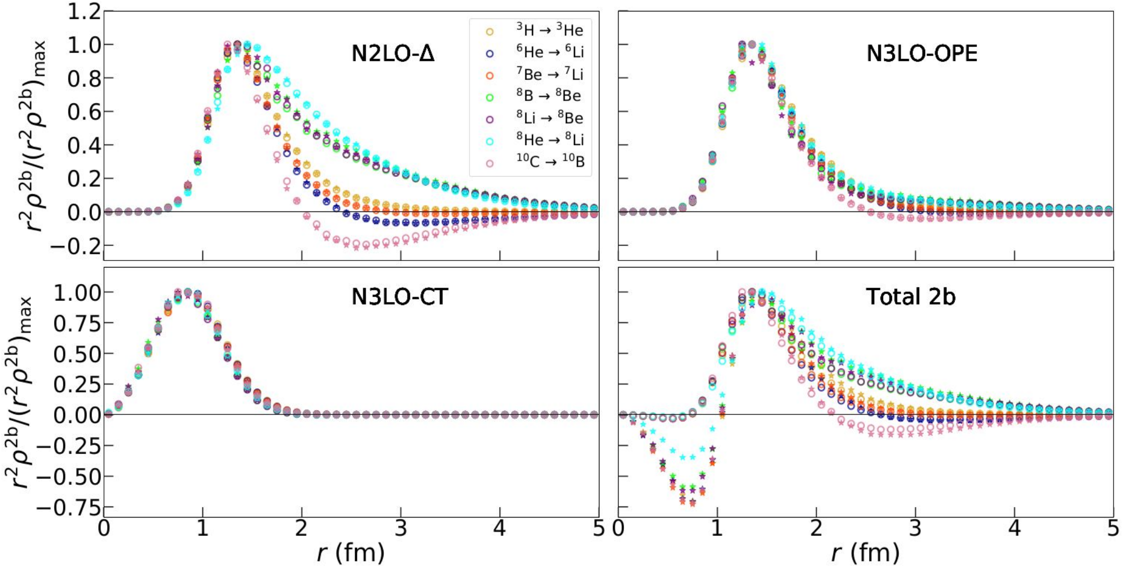
enhanced contribution from contact current in the starred model gives rise to nodes in the two-body transition density

Two-body axial currents

long-range at N2LO and N3LO

contact current at N3LO

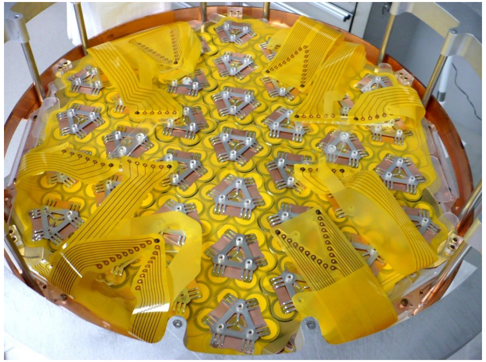
Scaling & Universality of Short-Range Dynamics



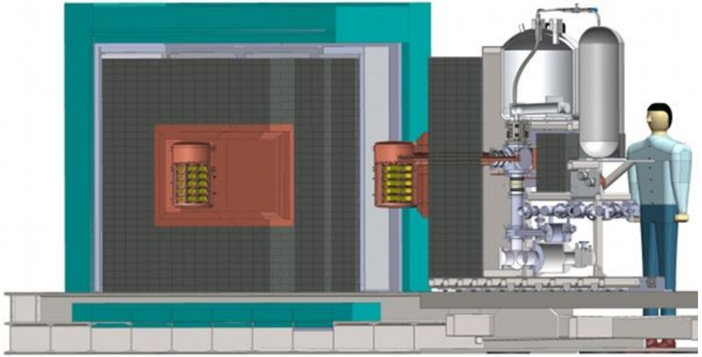
Garrett King *et al.* PRC102(2020)025501

NV2+3-Ia empty circles; NV2+3-Ia* stars
Different colors refer to different transitions

Nuclear Physics for Neutrinoless Double Beta Programs



EXO-200 Collaboration

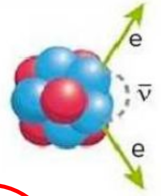


Majorana Demonstrator

Neutrinoless double beta decay half-life $T_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)
1 ton of material is required to see few events per year

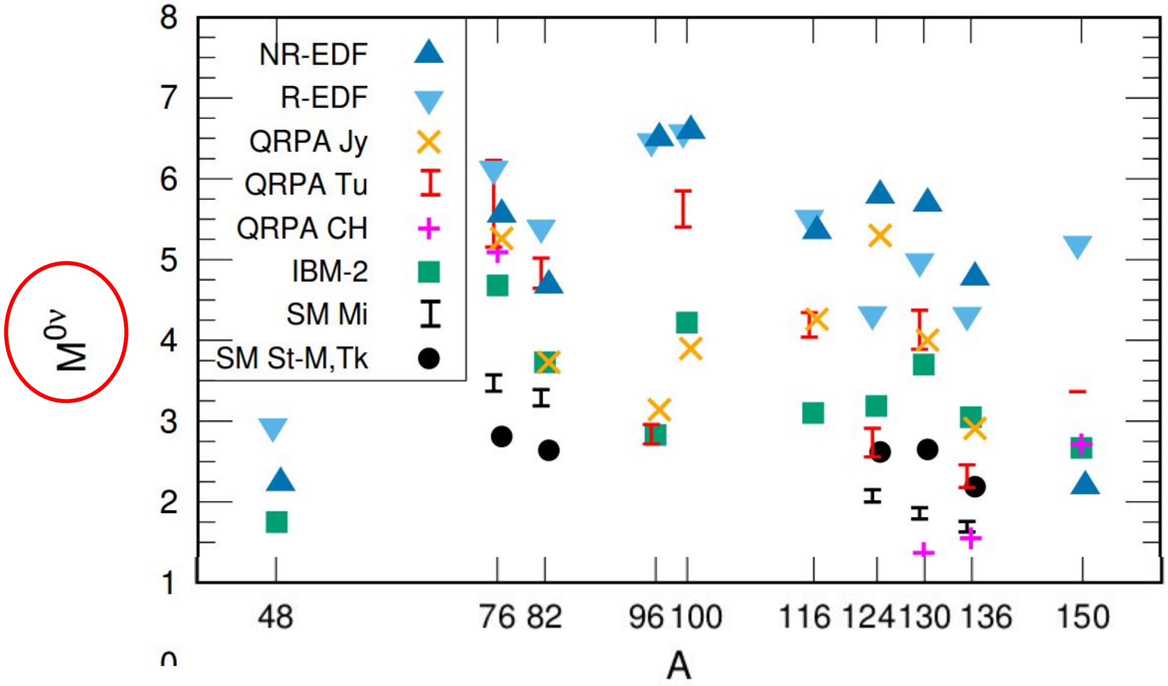
Decay Rate $\propto$ (**nuclear matrix element**)^2 x $(m_{\beta\beta})^2$

Neutrinoless Double Beta Decay

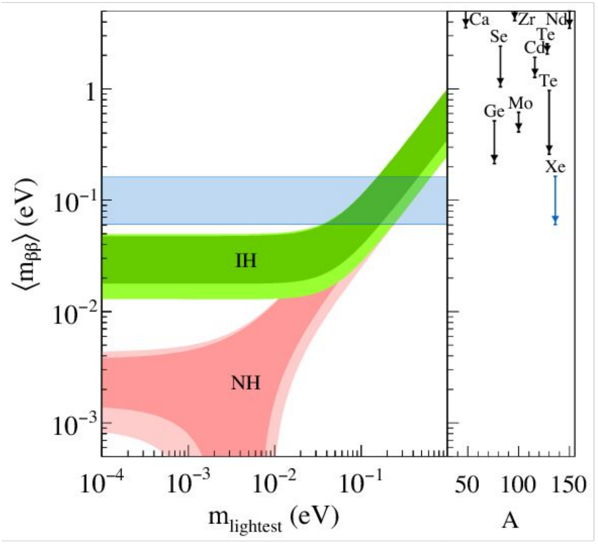


$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

$$(Z,N) \rightarrow (Z+2, N-2) + 2e$$



Engel & Menendez Rep.Progr.Phys80(2017)046301



Partial muon capture rates: VMC calculations

$\Gamma_{VMC}(\text{avg.}) = 1495\ s^{-1} \pm 19\ s^{-1}$

$\Gamma_{expt} = 1496.0\ s^{-1} \pm 4.0\ s^{-1}$

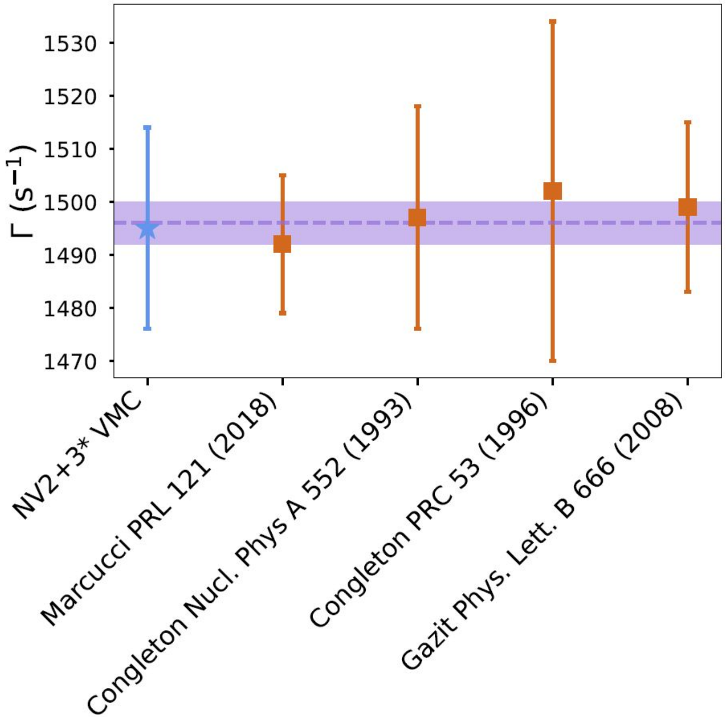
Ackerbauer *et al.* PLB417, 224(1998)

Momentum transfer **q~ 100 MeV**

Two-body correction is ~8% of total rate on average for A=3

Garrett King *et al.* PRC2022

$^{3}\mathrm{He}(1/2^{+};1/2) \rightarrow ^{3}\mathrm{H}(1/2^{+};1/2)$



Partial muon capture rates: VMC calculations

$\Gamma_{VMC}(\text{avg.}) = 1235\ s^{-1} \pm 101\ s^{-1}$

$\Gamma_{GFMC}(\text{IIa}^*) = 1171\ s^{-1} \pm 164\ s^{-1}$

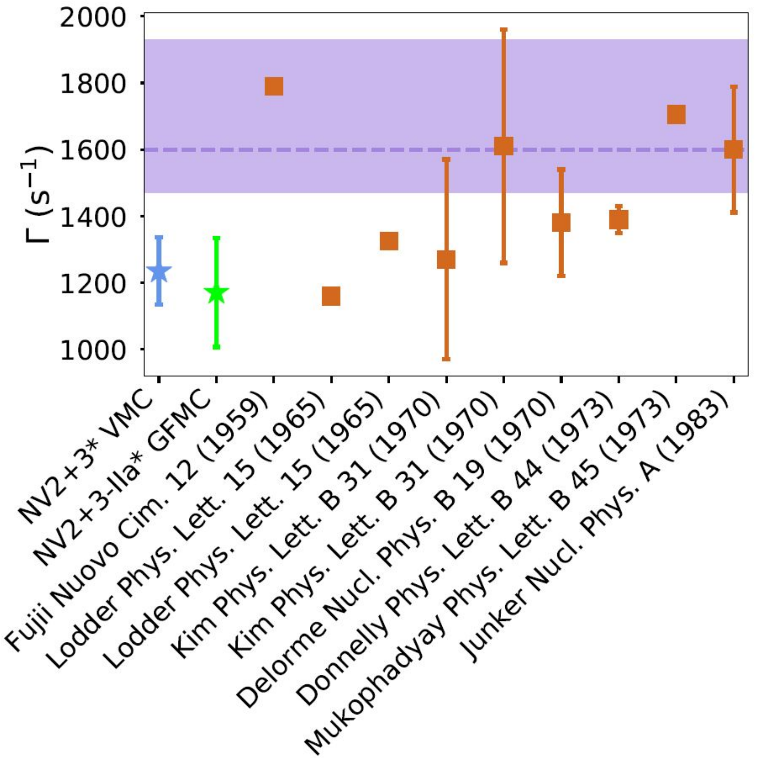
$\Gamma_{expt} = 1600\ s^{-1}\ +330/-129\ s^{-1}$

Deutsch *et al.* PLB26(1968)315

Garrett King *et al.* PRC2022

FRIB: extraction of the Gamow-Teller strength
A=11, A=12 PRC2022 J. Schmitt et al.

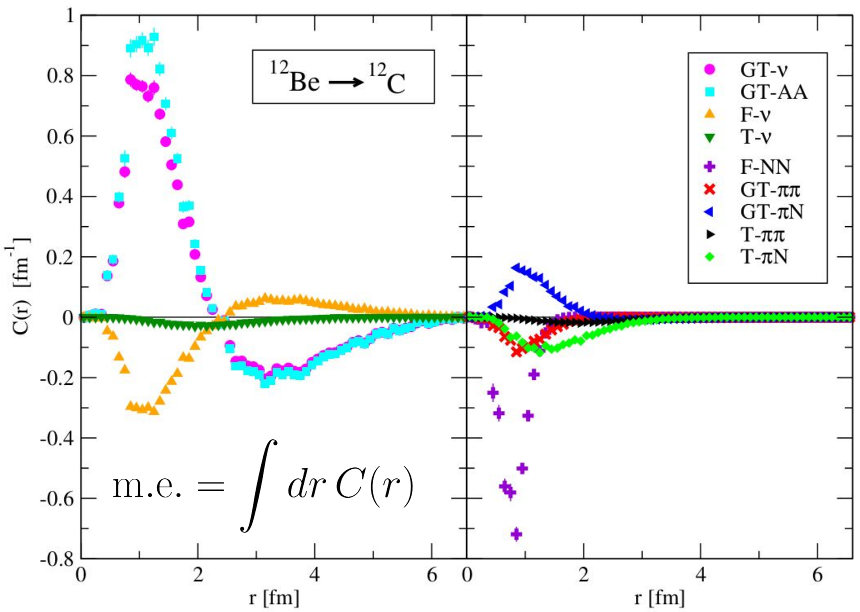
$^6\text{Li}(1^+;0) \rightarrow ^6\text{He}(0^+;1)$



Neutrinoless Double Beta Decay Matrix Elements

Long-range

One-pion & short range

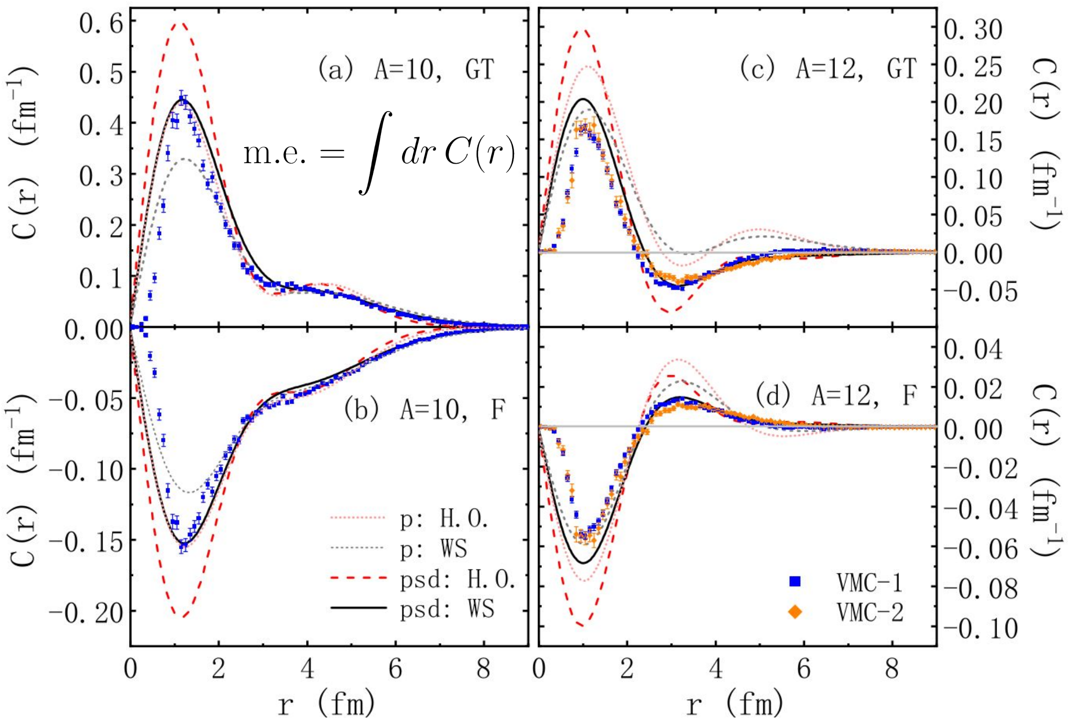


SP *et al.* PRC97(2018)014606

Cirigliano Dekens DeVries Graesser Mereghetti *et al.*
PLB769(2017)460, JHEP12(2017)082, PRC97(2018)065501

- Leading operators in neutrinoless double beta decay are two-body operators
- These observables are particularly sensitive to short-range and two-body physics
- Transition densities calculated in momentum space indicate that the momentum transfer in this process is of the order of **q ~ 200 MeV**

Comparison with Shell-Model Calculations

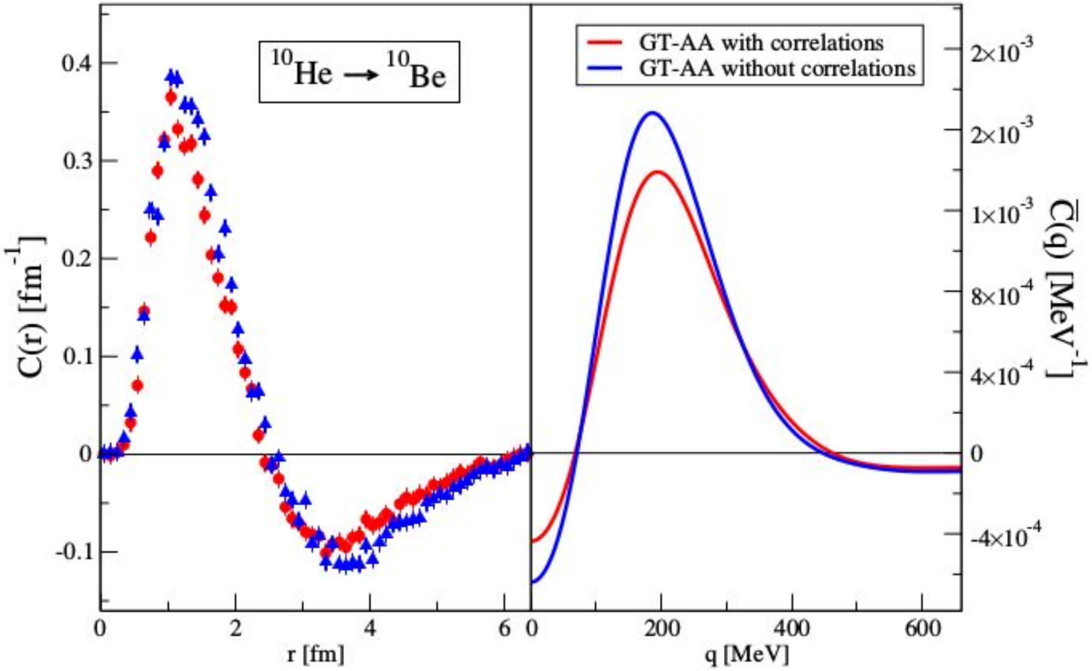


X. Wang *et al.* PLB798(2019)134974

Closer agreement between Shell-Model calculations with Variational Monte Carlo results is reached by

- Increasing the size of the model space
- Wood-Saxon single particle wave functions are superion in describing the tails of the densities wrt harmonic oscillator wave functions
- Phenomenological Short-Range-Correlations functions further improve the agreement

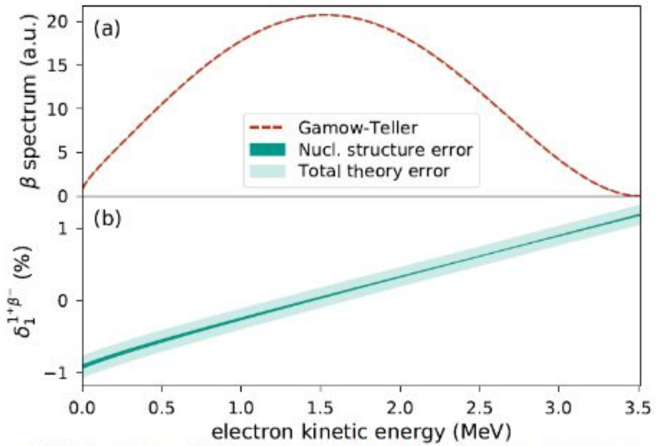
Correlations in neutrinoless double beta decay ME



Beta decay spectrum

^{6}He Beta decay spectrum for BSM searches with NCSL, He6-CRES, LPC-Caen

^{6}He beta-decay spectrum from NCSM



Glick-Magid et al. arXiv:2107.10212

$$\frac{d\Gamma}{d\varepsilon} = \frac{d\Gamma_0}{d\varepsilon} \times (1 + \mathrm{corrections})$$

^{6}He Beta Decay Spectrum

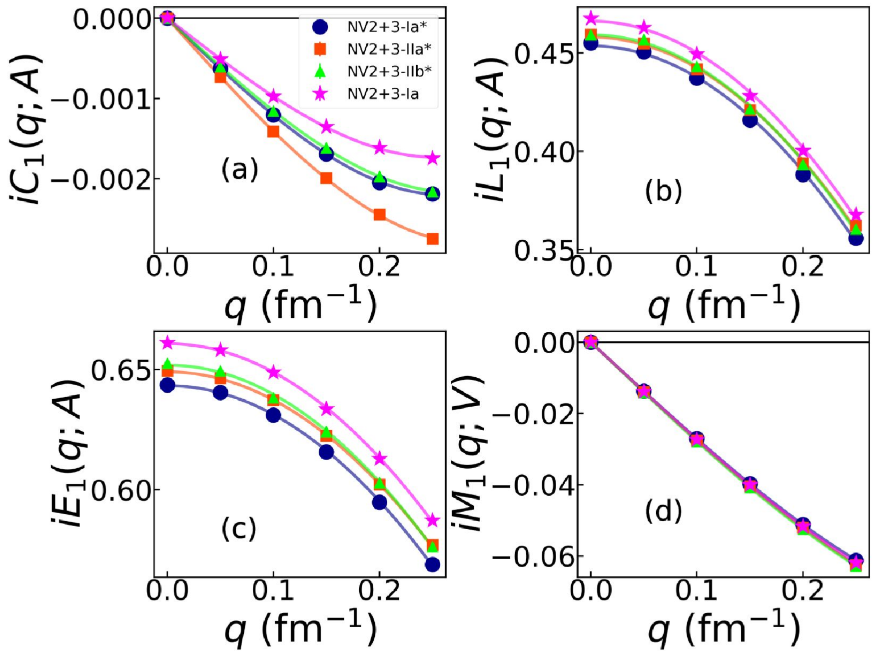
$$d\Gamma = \frac{2\pi}{2J_i+1} \sum_{s_e, s_\nu} \sum_{M_i, M_f} |\langle f|H_W|i\rangle|^2 \delta(\Delta E) \frac{d^3k_e}{(2\pi)^3} \frac{d^3k_\nu}{(2\pi)^3}$$

Multipoles

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

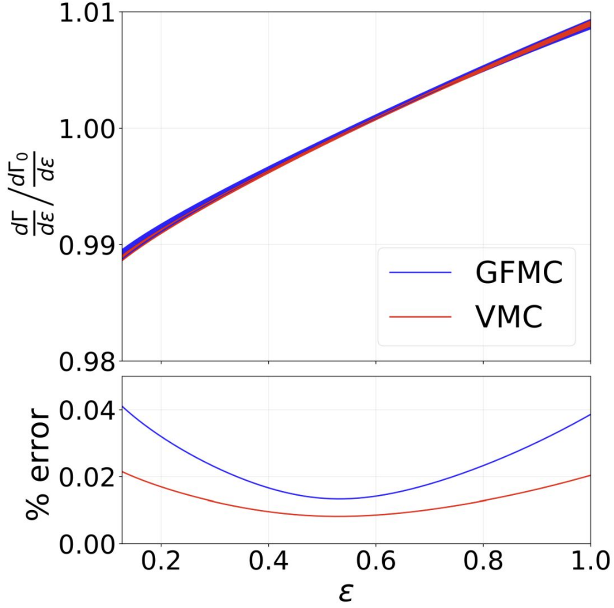
$$\begin{aligned}
C_1(q;A) &= -i\frac{qr_\pi}{3}\left(C_1^{(1)}(A) - \frac{(qr_\pi)^2}{10}C_1^{(3)}(A) + \mathcal{O}\left((qr_\pi)^4\right)\right) \\
L_1(q;A) &= -\frac{i}{3}\left(L_1^{(0)}(A) - \frac{(qr_\pi)^2}{10}L_1^{(2)}(A) + \mathcal{O}\left((qr_\pi)^4\right)\right) \\
M_1(q;V) &= -i\frac{qr_\pi}{3}\left(M_1^{(1)}(V)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

Beta Decay Spectrum



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

Standard Model spectrum for ^{6}He



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

τ_{GFMC} = 808 +/- 24 ms

$\tau_{Expt.}$ = 807.25 +/- 0.16 +/- 0.11 ms

Garrett King et al. PRC Editors' suggestion (2023)

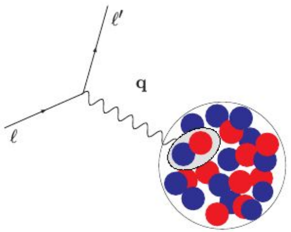
Lepton-Nucleus scattering: Inclusive Processes

Electromagnetic Nuclear Response Functions

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Longitudinal response induced by the charge operator $O_L = \rho$
Transverse response induced by the current operator $O_T = \boldsymbol{j}$
5 Responses in neutrino-nucleus scattering

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)\right]$$

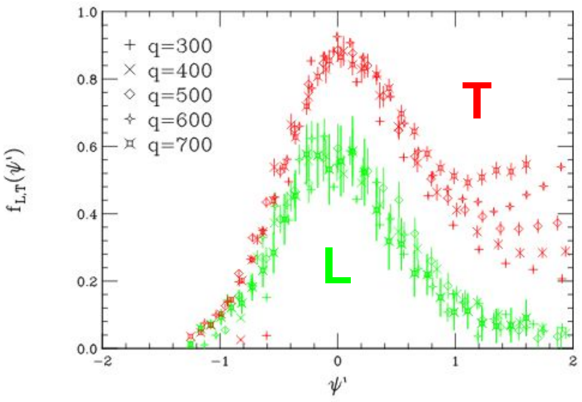


For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

Lepton-Nucleus scattering: Data

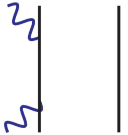
Transverse Sum Rule

$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\ \mathbf{j}|0\rangle \propto \langle 0|\mathbf{j}_{1b}{}^\dagger\ \mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\ \mathbf{j}_{2b}|0\rangle + \ldots$$



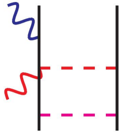
^{4}He Electromagnetic Data
Carlson *et al.* PRC65(2002)024002

Observed transverse enhancement explained by the combined effect of two-body correlations and currents in the interference term



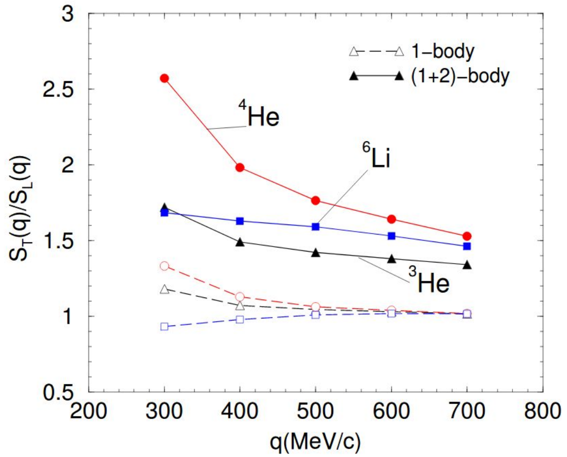
$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle\ > 0$

Leading one-body term



$\langle \mathbf{j}^\dagger_{1b}\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle\ > 0$

Interference term

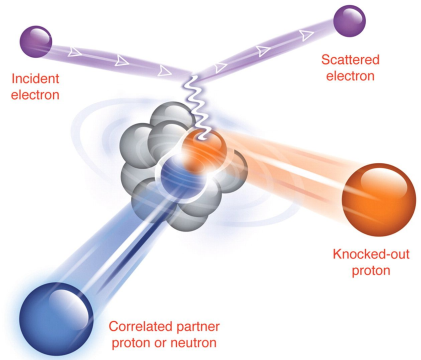


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

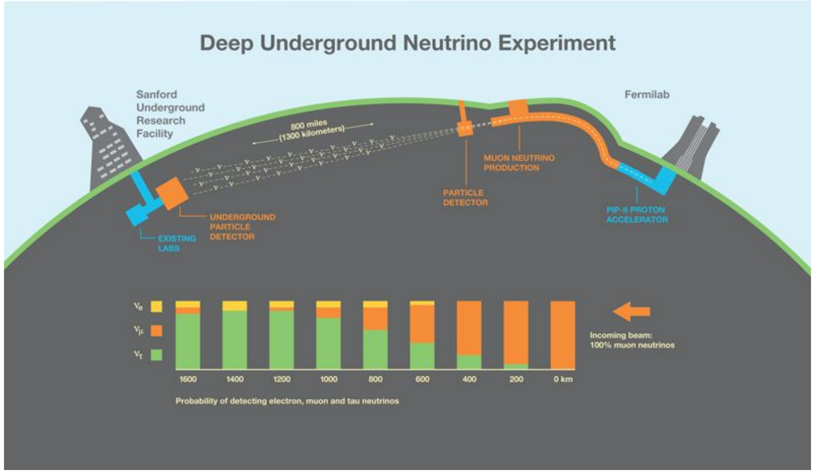
Beyond Inclusive: Short-Time-Approximation

Short-Time-Approximation Goals:

- Describe electroweak scattering from A > 12 without losing two-body physics
- Account for exclusive processes
- Incorporate relativistic effects



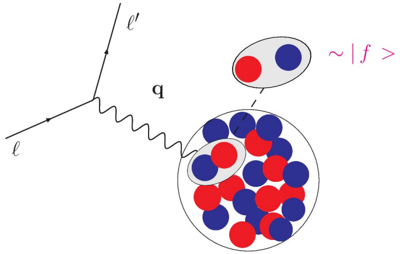
Subedi et al. Science320(2008)1475



Stanford Lab article

e4u collaboration

Short-Time-Approximation



Short-Time-Approximation:

- Based on Factorization
- **Retains two-body physics**
- Response functions are given by the **scattering from pairs of fully interacting nucleons** that propagate into a correlated pair of nucleons
- Allows to retain both two-body correlations and currents at the vertex
- Provides “more” exclusive information in terms of nucleon-pair kinematics via the Response Densities

Response Functions ∝ Cross Sections

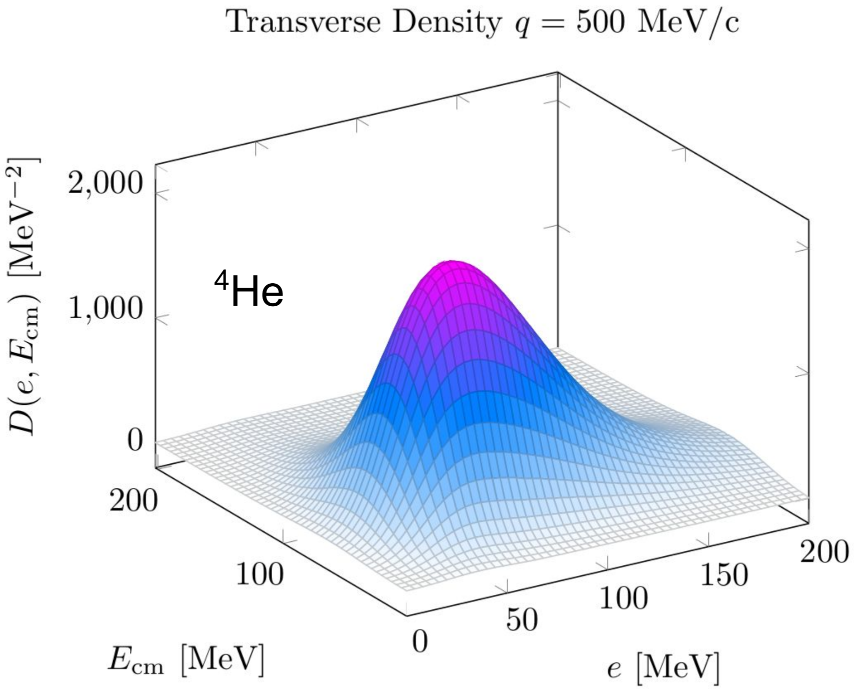
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response ***Densities***

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right)\, dP'\, dp' \mathcal{D}(p', P'; q)$$

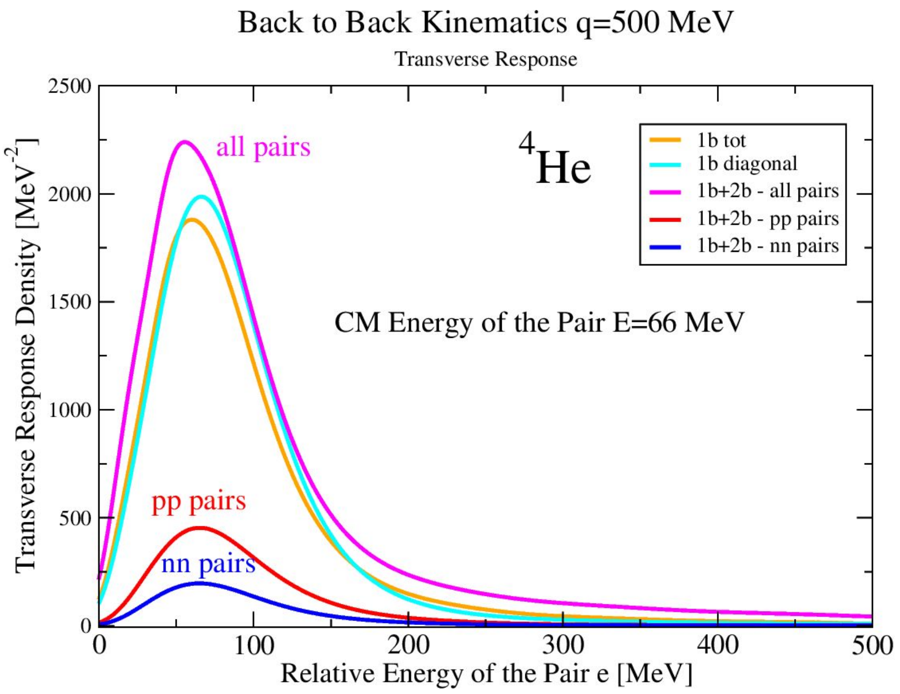
P’ and *p’* are the CM and relative momenta of the struck nucleon pair

Transverse Response Density: e-^{4}He scattering



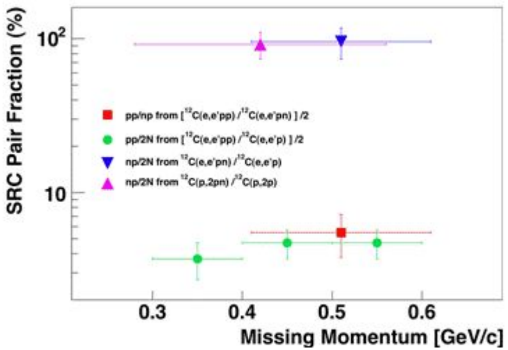
SP *et al.* PRC101(2020)044612

e-^{4}He scattering in the back-to-back kinematic



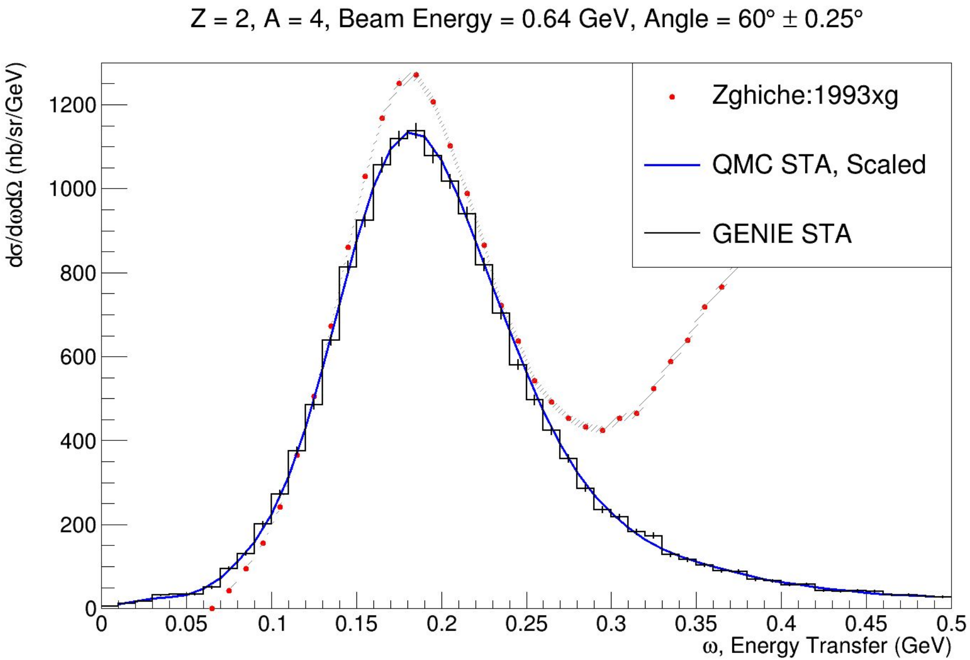
SP *et al.* PRC101(2020)044612

- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot



Subedi et al. Science320(2008)1475

GENIE validation using e-scattering

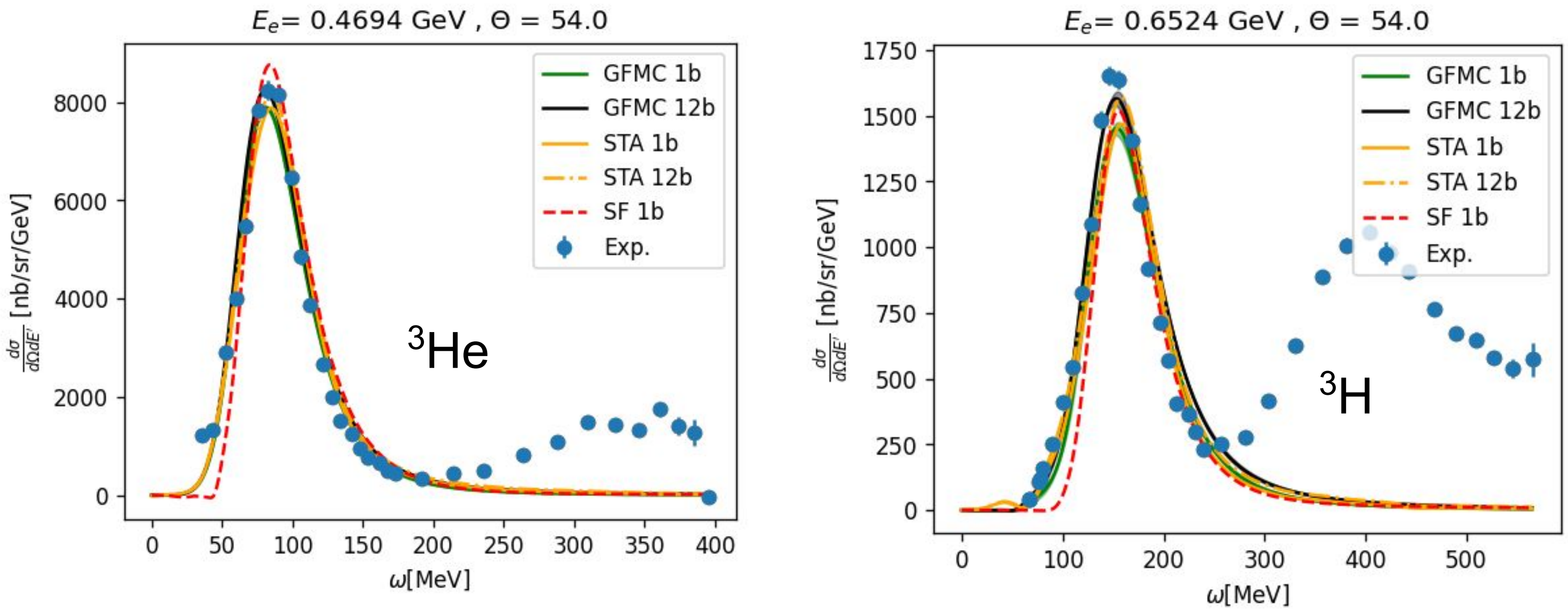


Barrow, Gardiner, SP *et al.* PRD 103 (2021) 5, 052001

- STA responses used to build the cross sections
- Cross sections are used to generate events in GENIE (a Monte Carlo neutrino event generator)
- Here, we use electromagnetic processes (for which data are available) to validate the generator

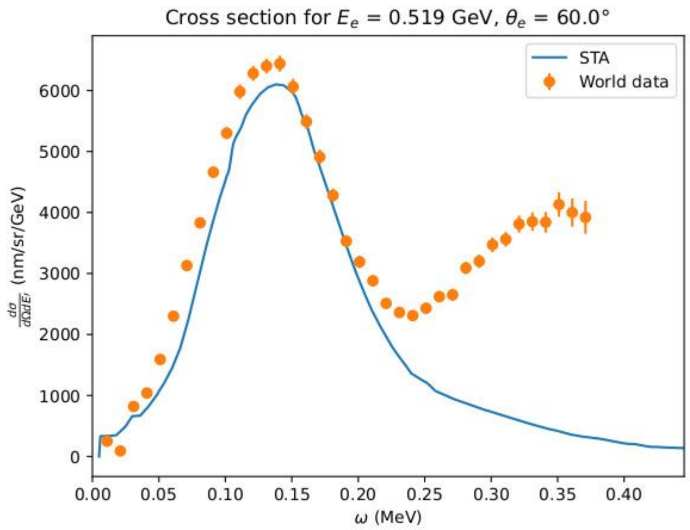
$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)\right]$$

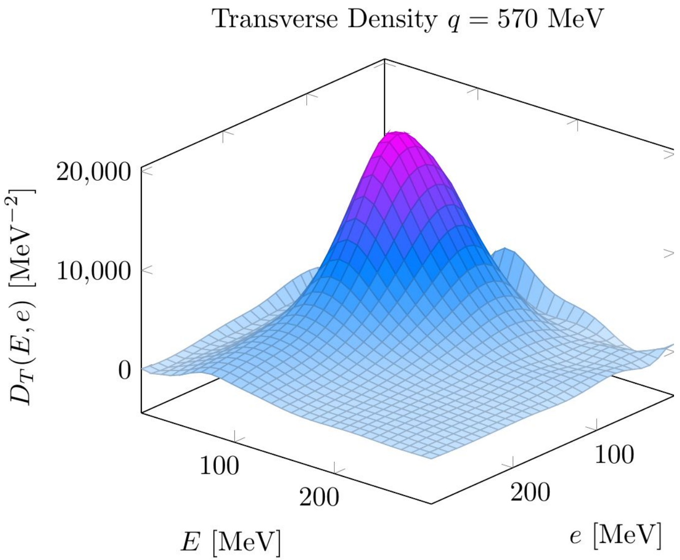
GFMC SF STA: Benchmark & error estimate



Lorenzo Andreoli, *et al.* PRC 2021

STA for Carbon 12: Preliminary results

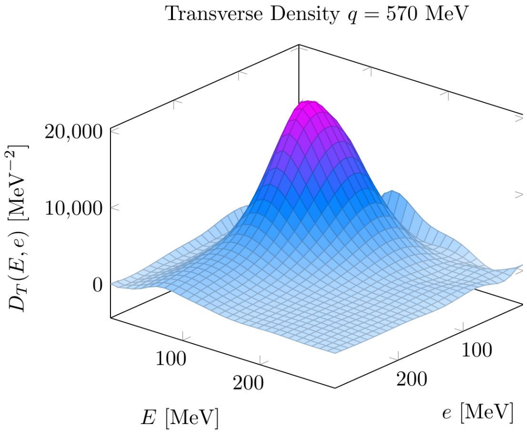


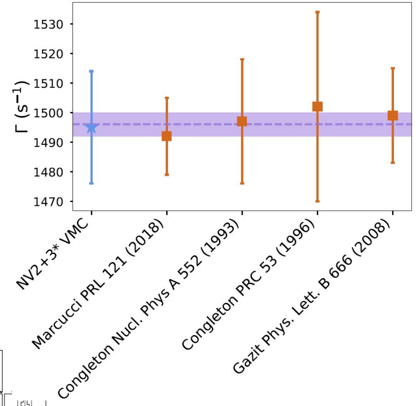


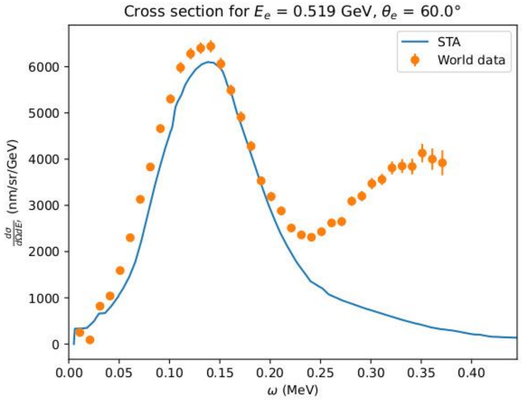
Lorenzo Andreoli *et al.* in preparation

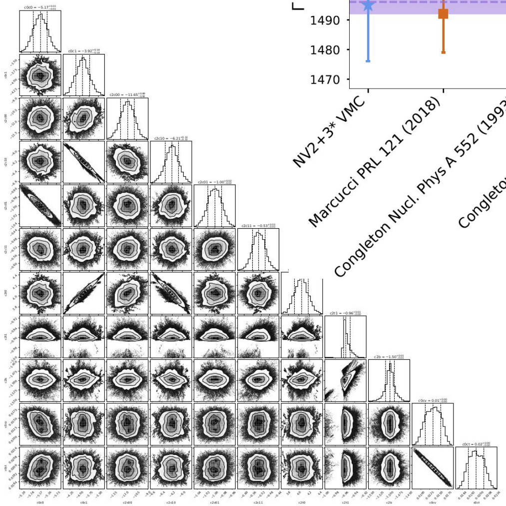
Summary

Ab initio calculations of light nuclei yield a picture of nuclear structure and dynamics where many-body effects play an essential role to explain available data.









Close **collaborations** between **NP**, **LQCD**, **Pheno**, **Hep**, **Comp**, **Expt**, …
are required to progress
e.g., NP is represented in the Snowmass process

It's a very exciting time!

Collaborators

WashU: **Andreoli Bub King Piarulli**
LANL: Baroni Carlson Cirigliano Gandolfi Hayes Mereghetti
JLab+ODU: Schiavilla
ANL: Lovato Rocco Wiringa
UCSD/UW: Dekens
Pisa U/INFN: Kievsky Marcucci Viviani
Salento U: Girlanda
Huzhou U: Dong Wang
Fermilab: Gardiner Betancourt
MIT: Barrow

Washington University in St. Louis
Arts & Sciences

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

Los Alamos NATIONAL LABORATORY EST. 1943

Argonne NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

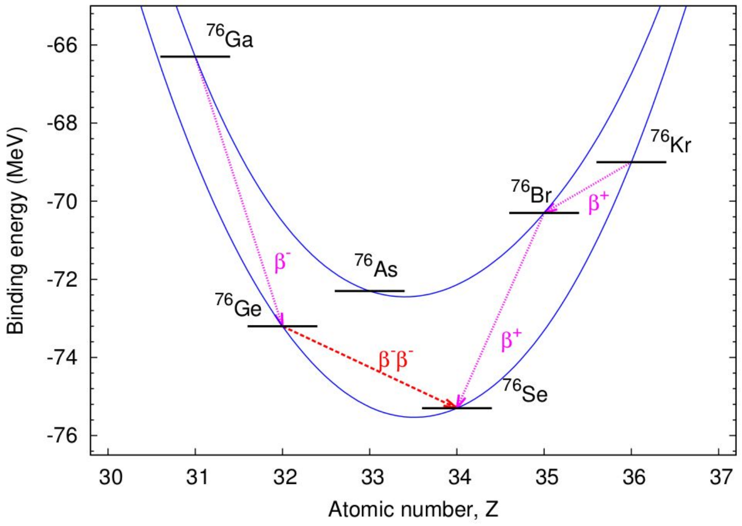
McDonnell Center for the Space Sciences

Fermilab

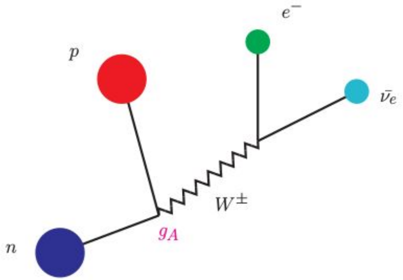
Quantum Monte Carlo group

webpage: Quantum Monte Carlo group

Single and Double Beta Decays



J. Menéndez arXiv:1703.08921v1



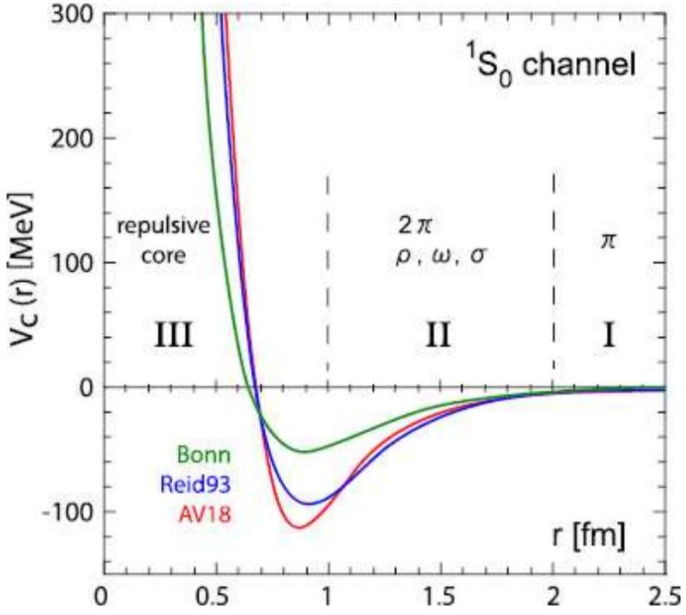
Maria Goeppert-Mayer

Single beta decay $(Z, N) \rightarrow (Z+1, N-1) + e + \bar{\nu}_e$

Double beta decay $(Z, N) \rightarrow (Z+2, N-2) + 2e + 2\bar{\nu}_e$

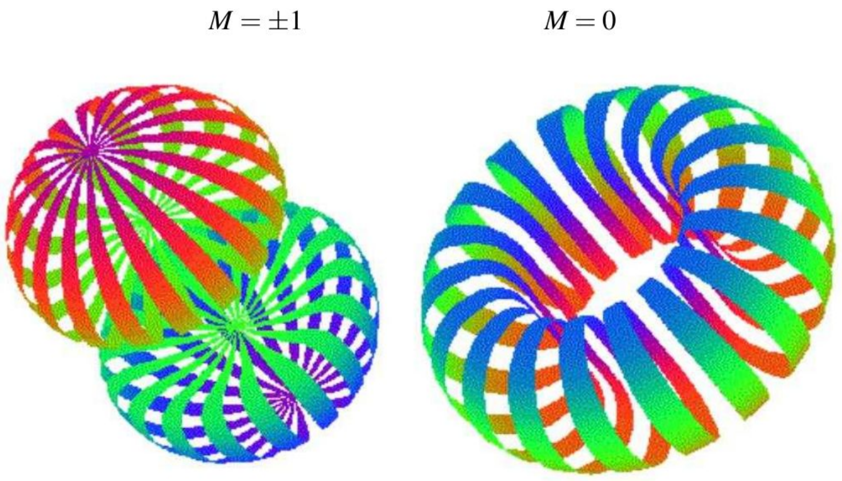
Here the lepton number is conserved

Nucleon-Nucleon Potential



Aoki *et al.* Comput.Sci.Disc.1(2008)015009

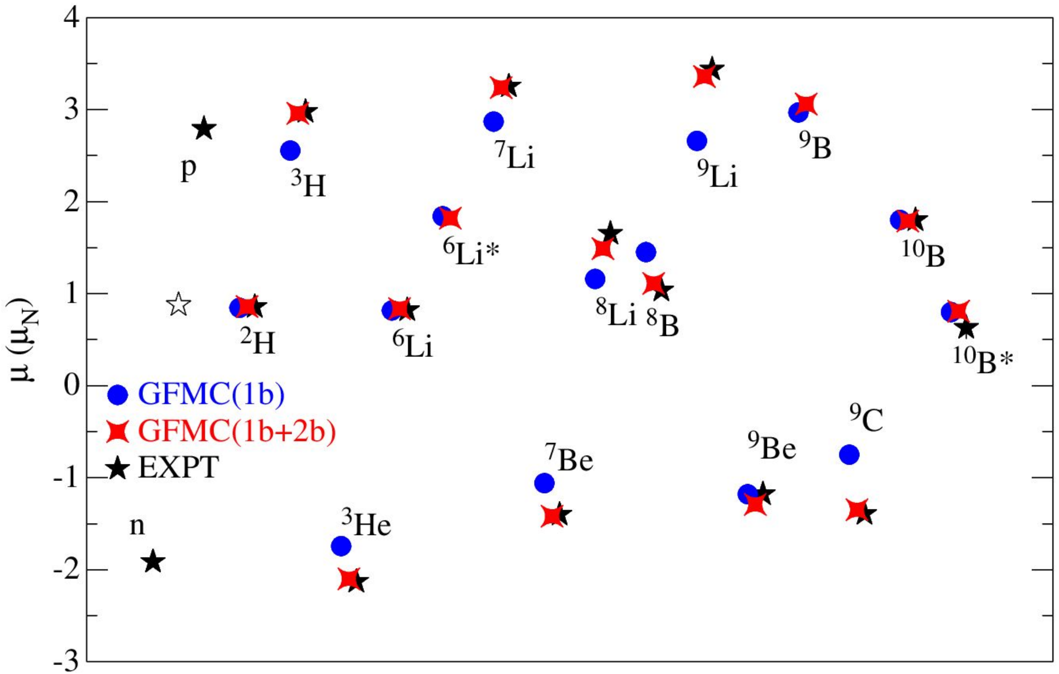
The Deuteron



Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

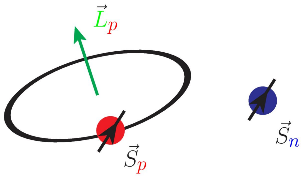
Carlson and Schiavilla Rev.Mod.Phys.70(1998)743

Magnetic Moments of Light Nuclei



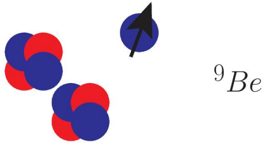
SP *et al*. PRC87(2013)035503

Single particle picture

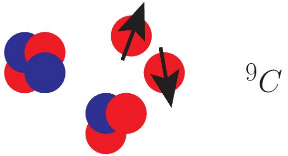


$$\mu_N(1\text{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i(1-\tau_{i,z})/2]$$

Small two-body current effects



Large two-body current effects



Correlations in neutrinoless double beta decay ME