Electroweak Properties of Light Nuclei

Saori Pastore

INT-18-1a: Nuclear *ab initio* Theories and Neutrino Physics

Seattle WA - March 2018

Open Questions in Fundamental Symmetries and Neutrino Physics

Majorana Neutrinos, Neutrinos Mass Hierarchy,

CP-Violation in Neutrino Sector, Dark Matter

WITH

Mereghetti & Dekens & Cirigliano & Carlson & Graesser (LANL)

de Vries (Nikhef) & van Kolck (AU+CNRS/IN2P3)

Baroni (USC) & Schiavilla (ODU+JLab) & Gandolfi (LANL) & Piarulli & Pieper & Wiringa (ANL)

Girlanda (Salento U.) & Viviani & Marcucci & Kiewsky (Pisa U.+INFN)

REFERENCES

PRC78(2008)064002 - PRC80(2009)034004 - PRL105(2010)232502 - PRC84(2011)024001 - PRC87(2013)014006 - PRC87(2013)035503 - PRL111(2013)062502 - PRC90(2014)024321 - JPhysG41(2014)123002 - PRC93(2016)01550

*** PRC97(2018)014606 - PRC97(2018)022501 - arXiv:1802.10097 ***

Fundamental Physics Quests: Double Beta Decay

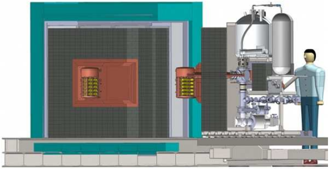
observation of $0\nu\beta\beta$-decay

$\rightarrow$

lepton # $L = l - \bar{l}$ not conserved

$\rightarrow$

implications in
matter-antimatter imbalance

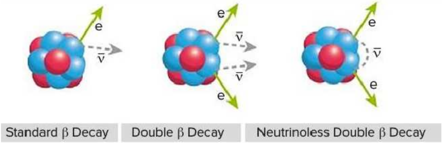


Majorana Demonstrator

$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)

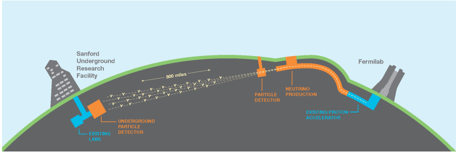
need 1 ton of material to see (if any) ~ 5 decays per year

* Decay Rate $\propto$ (nuclear matrix elements)$^2 \times \langle m_{\beta\beta} \rangle^2$ *

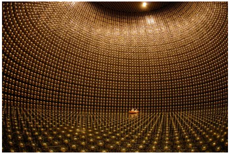


2015 Long Range Plane for Nuclear Physics

Fundamental Physics Quests: Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate

$\rightarrow$

they have tiny masses

$=$

BSM physics

Beyond the Standard Model

Simplified 2 flavors picture:

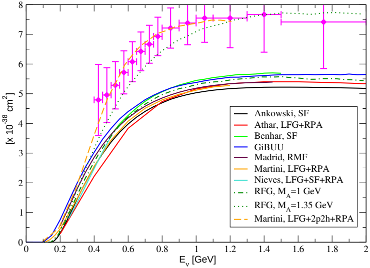
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m^2 L}{2 E_\nu} \right)$$

* Unknown *

ν-mass hierarchy, CP-violation, accurate mixing angles

Neutrino-Nucleus scattering

CCQE on ^{12}C



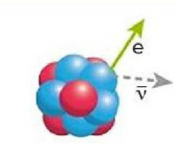
Alvarez-Ruso arXiv:1012.3871

DUNE, MiniBoone, T2K, Minerνa ... active material * ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

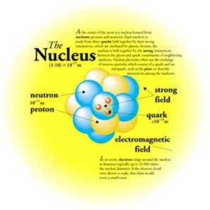
Fundamental Physics Quests rely on Nuclear Physics

* An accurate understanding of nuclear structure and dynamics is required to extract new physics from nuclear effects *

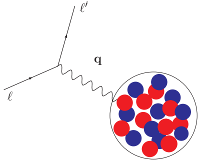
Decays



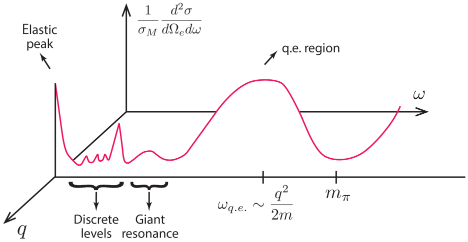
Energies and Structure



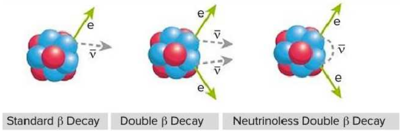
Scattering



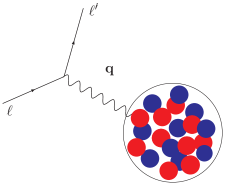
Nuclear Structure and Dynamics



* $\omega \sim$ few MeV, $q \sim 0$: EM decay, β-decay, $\beta\beta$-decays
* $\omega \lesssim$ tens MeV: Nuclear Rates for Astrophysics
* $\omega \sim 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



The Microscopic (or *ab initio*) Description of Nuclei



Develop a comprehensive theory that describes quantitatively and predictably all nuclear structure and reactions

* Accurate understanding of interactions between nucleons, p's and n's
* and between e's, ν's, **DM**, . . . , with nucleons, nucleons-pairs, . . .

Green's function Monte Carlo Method is a path-integral Monte Carlo Method that solves the many-body problem

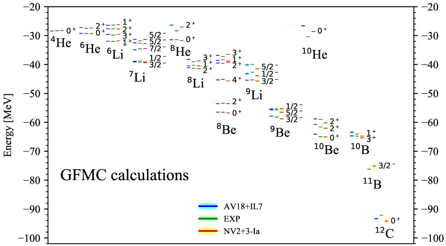
$$H\Psi(\mathbf{r}_1,\mathbf{r}_2,...,\mathbf{r}_A,s_1,s_2,...,s_A,t_1,t_2,...,t_A,) = E\Psi(\mathbf{r}_1,\mathbf{r}_2,...,\mathbf{r}_A,s_1,s_2,...,s_A,t_1,t_2,...,t_A,)$$

Nuclear Interactions

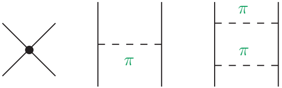
The nucleus is made of A non-relativistic interacting nucleons and its energy is

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

where υ_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD

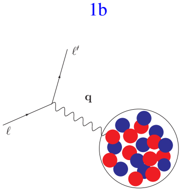


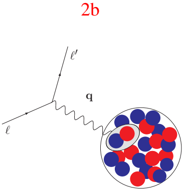
Piarulli *et al.* - PRL120(2018)052503



- * QMC: AV18+UIX / AV18+IL7
  Wiringa+Schiavilla+Pieper *et al.*
- * QMC: NN(N2LO)+3N(N2LO) (π&N)
  Ingo+Lynn *et al.*
- * QMC: NN(N3LO)+3N(N2LO) (π&N&Δ)
  Piarulli *et al.*

Nuclear Currents

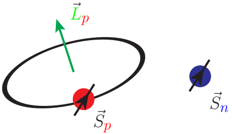




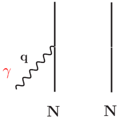
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots ,$$

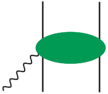
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

* Nuclear currents given by the sum of p's and n's currents, one-body currents (1b)



* plus two-body currents (2b) essential to satisfy current conservation





$+ \; \cdots$

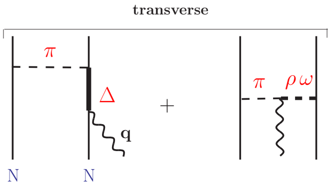
$$\mathbf{q} \cdot \mathbf{j} = \left[H , \rho \right] = \left[t_i + \upsilon_{ij} + V_{ijk} , \rho \right]$$

Electromagnetic Currents from Nuclear Interactions (SNPA currents)

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

1) Longitudinal component fixed by current conservation
2) Plus transverse "phenomenological" terms

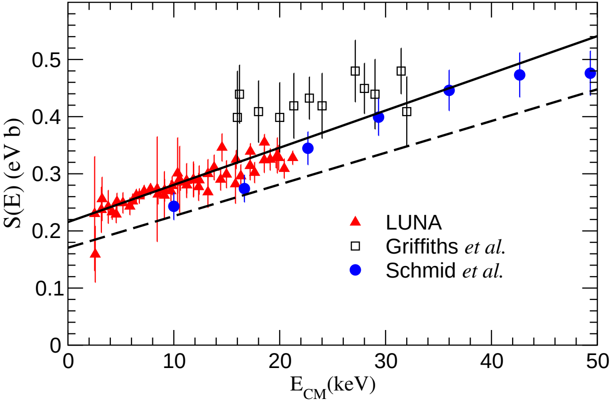
$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \ldots + \mathbf{j}^{(3)}(V)$$



Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla . . .
see, *e.g.*, Marcucci *et al.* PRC**72**(2005)014001 and references therein

Satisfactory description of a variety of nuclear em properties in $A \leq 12$

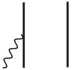
^{2}H(p,γ)^{3}He capture



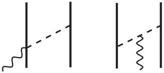
Marcucci *et al.* PRC**72**, 014001 (2005)

Electromagnetic Currents from Chiral Effective Field Theory

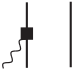
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



NLO : $\mathbf{j}^{(-1)} \sim \mathbf{eQ^{-1}}$

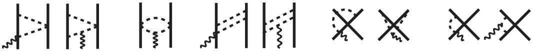


N^{2}LO : $\mathbf{j}^{(-0)} \sim \mathbf{eQ^{0}}$



* 3 unknown Low Energy Constants:
fixed so as to reproduce d, ^3H, and ^{3}He magnetic moments

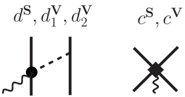
N^{3}LO: $\mathbf{j}^{(1)} \sim \mathbf{eQ}$



unknown LEC′s →

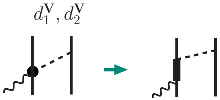
Pastore *et al.* PRC78(2008)064002 & PRC80(2009)034004 & PRC84(2011)024001
* analogue expansion exists for the Axial nuclear current - Baroni *et al.* PRC93 (2016)015501 *

Electromagnetic LECs



d^S, d_1^V, and d_2^V could be determined by $\pi\gamma$-production data on the nucleon

Isovector



$d_2^V = 4\mu^* h_A / 9 m_N (m_\Delta - m_N)$ and
$d_1^V = 0.25 \times d_2^V$
assuming Δ-resonance saturation

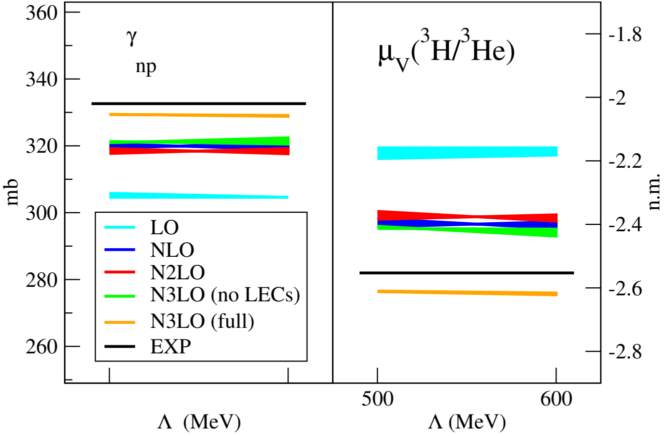
Left with 3 LECs: Fixed in the $A = 2 - 3$ nucleons' sector

* Isoscalar sector:
  * d^S and c^S from EXPT μ_d and $\mu_S(^3\text{H}/^3\text{He})$
* Isovector sector:
  * c^V from EXPT $npd\gamma$ xsec.

    or
  * c^V from EXPT $\mu_V(^3\text{H}/^3\text{He})$ m.m.

Convergence and cutoff dependence

np capture x-section/ μ_V of $A = 3$ nuclei
bands represent nuclear model dependence [NN(N3LO)+3N(N2LO) – AV18+UIX]



Piarulli *et al.* PRC(2013)014006

Calculations with EM Currents from χEFT with π's and N's

* Park, Min, and Rho *et al.* (1996)

  applications to A=2–4 systems by Song, Lazauskas, Park *at al.* (2009-2011) within the hybrid approach

  ......

  * Based on EM χEFT currents from NPA596(1996)515

* Meissner and Walzl (2001);
  Kölling, Epelbaum, Krebs, and Meissner (2009–2011)

  applications to:
  d and ^{3}He photodisintegration by Rozpedzik *et al.* (2011); e-scattering (2014);
  d magnetic f.f. by Kölling, Epelbaum, Phillips (2012);
  radiative $N-d$ capture by Skibinski *et al.* (2014)

  ......

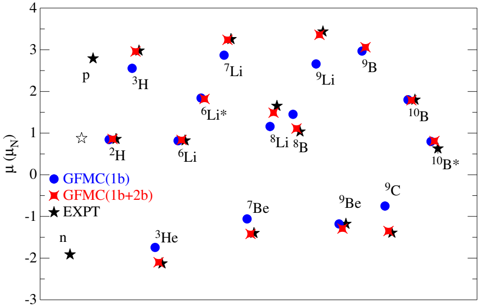
  * Based on EM χEFT currents from PRC80(2009)045502 & PRC84(2011)054008 and consistent χEFT potentials from UT method

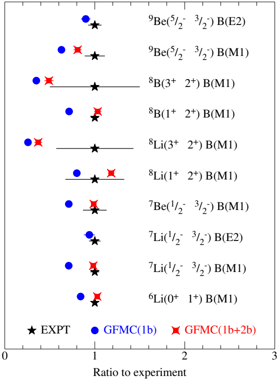
* Phillips (2003-2007)

  applications to deuteron static properties and f.f.'s

  ......

Magnetic Moments and M1 Transitions

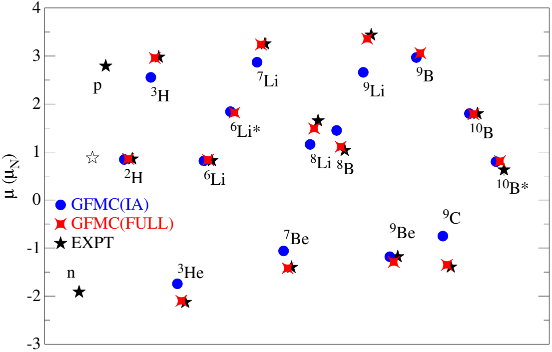




- 2b electromagnetic currents bring the THEORY in agreement with the EXPT
- $\sim 40\%$ 2b-current contribution found in ^{9}C m.m.
- $\sim 60-70\%$ of total 2b-current component is due to one-pion-exchange currents
- $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be

Pastore *et al.* PRC87(2013)035503 & PRC90(2014)024321, Datar *et al.* PRL111(2013)062502

Error Estimate



EE *et al.* error algorithm
Epelbaum, Krebs, and Meissner EPJA51(2015)53

$$\delta^{\mathrm{N3LO}} = \max\Big[Q^4\mu^{\mathrm{LO}},\, Q^3|\mu^{\mathrm{LO}}-\mu^{\mathrm{NLO}}|,\, Q^2|\mu^{\mathrm{NLO}}-\mu^{\mathrm{N2LO}}|,\, Q^1|\mu^{\mathrm{N2LO}}-\mu^{\mathrm{N3LO}}|\Big]$$

$$Q = \max\left[\frac{m_\pi}{\Lambda},\, \frac{p}{\Lambda}\right]$$

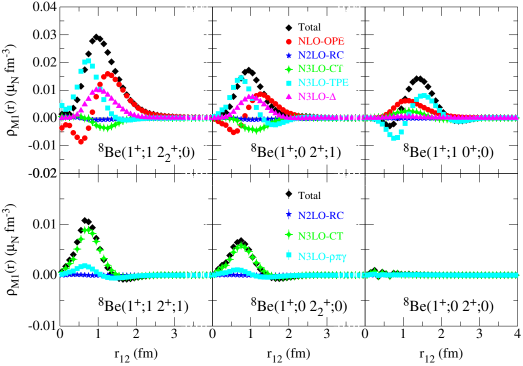
m.m.	THEO	EXP
^{9}C	-1.35(4)(7)	-1.3914(5)
^{9}Li	3.36(4)(8)	3.4391(6)

* 'N3LO-Δ' corrections can be 'large' *

* SNPA and χEFT currents qualitatively in agreement, χEFT isoscalar currents provide better description exp data *

Pastore *et al.* PRC87(2013)035503

Two-body M1 transitions densities

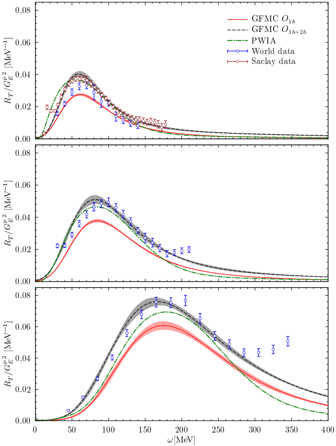


$(J_i, T_i) \rightarrow (J_f, T_f)$	IA	NLO-OPE	N2LO-RC	N3LO-TPE	N3LO-CT	N3LO-Δ	MEC
$(1^+;1) \rightarrow (2_2^+;0)$	2.461 (13)	0.457 (3)	-0.058 (1)	0.095 (2)	-0.035 (3)	0.161 (21)	0.620 (5)

Pastore *et al.* PRC90(2014)024321

Electron Scattering off ^{12}C

Electromagnetic Transverse Responses

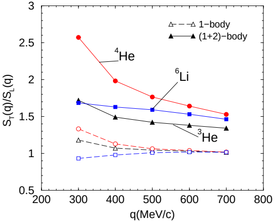


$q = [300 - 750]$ MeV

Lovato *et al.* - PRC91(2015)062501 + arXiv:1605.00248

based on SNPA currents (range up to ~ 1 GeV)

Sum Rules and Two-body Currents



Carlson *et al.* PRC65(2002)024002

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

- $\mathbf{j} = \mathbf{j}_{1b} + \mathbf{j}_{2b}$

• enhancement of the transverse response is due to interference between 1b and 2b currents AND presence of two-nucleon correlations •

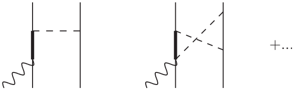
$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle\ > 0$

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

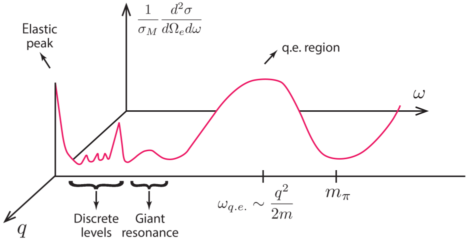
Electron-scattering data are explained when two-body correlations and currents are accounted for!

To do list:

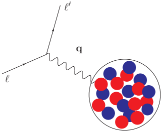
* QMC calculations based on both chiral interactions and chiral currents
* Pions and nucleons d.o.f.'s:
  electromagnetic currents are fully developed
* Pions, nucleons, and deltas d.o.f.'s (interaction by Piarulli *et al.* PRC91(2015)024003-PRC94(2016)054007-PRL120(2018)052503):
  electromagnetic currents up to one loop have been derived in momentum space (Pastore *et al.* PRC78(2008)064002)
  * tree-level fully developed
  * loop need to implement them in r-space & in the codes (on going)

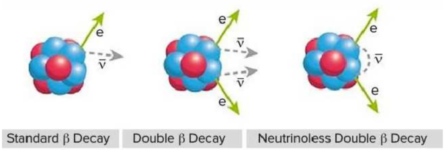


Nuclei and Neutrinos



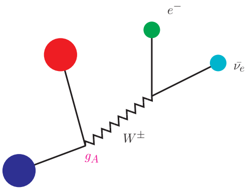
* $\omega \sim$ few MeVs, $q \sim 0$: "g_A-problem" in single beta decays
* Scarce data at moderate values of momentum transfer
* $\omega \sim 10^2$ MeV: ν-A scattering "Anomalies" the QE region





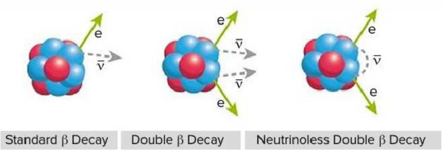
Standard Beta Decay

The "g_A problem"
and
the role of two-body correlations and two-body currents



* Matrix Element $\langle \Psi_f | \mathrm{GT} | \Psi_i \rangle \propto g_A$ and Decay Rates $\propto g_A^2$ *

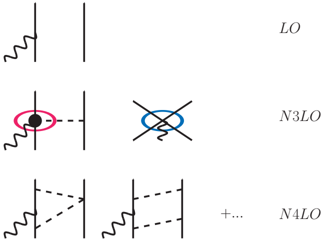
$$(Z, N) \rightarrow (Z+1, N-1) + e + \bar{\nu}_e$$



Nuclear Interactions and Axial Currents

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

so far results are available with AV18+IL7 ($A \leq 10$)
and SNPA or chiral currents (*a.k.a.* hybrid calculations)

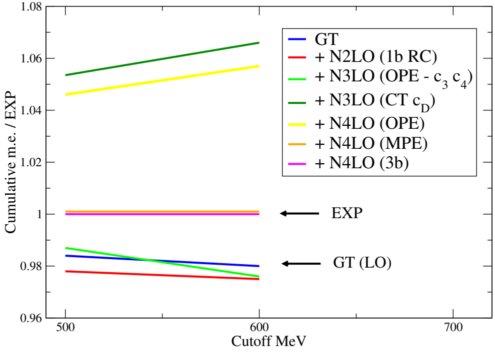


A. Baroni *et al.* PRC93(2016)015501

H. Krebs *et al.* Ann.Phy.378(2017)

- c_3 and c_4 are taken them from Entem and Machleidt PRC68(2003)041001 & Phys.Rep.503(2011)1
- c_D fitted to GT m.e. of tritium Baroni *et al.* PRC94(2016)024003
- cutoffs $\Lambda = 500$ and 600 MeV
- include also N4LO 3b currents (tiny)

Tritium β-decay



* Results based on AV18+UIX and Chiral Currents are qualitatively in agreement
* All contributions "quench" but for the N3LO OPE (tiny due to a cancellation) and CT (fitted)
* They quench too much, and this is compensated by the fitting of c_D to EXP GT
* Use of N4LO 2b loop currents from H. Krebs *et al.* Ann.Phy.378(2017) leads to a reduced value of c_D

* $\sim 2\%$ additive contribution from two-body currents *

A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

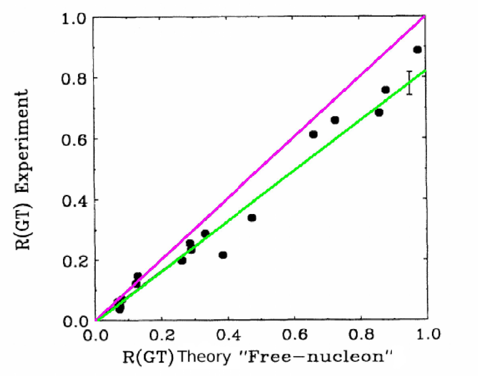
χEFT currents in $A > 3$ systems

$A = 7$ Captures

	gs	ex
LO	2.334	2.150
N2LO	-3.18×10^{-2}	-2.79×10^{-2}
N3LO(OPE)	-2.99×10^{-2}	-2.44×10^{-2}
N3LO(CT)	2.79×10^{-1}	2.36×10^{-1}
N4LO(2b)	-1.61×10^{-1}	-1.33×10^{-1}
N4LO(3b)	-6.59×10^{-3}	-4.86×10^{-3}
TOT(2b+3b)	0.050	0.046

* Large cancellations between CT at N3LO (with c_D fitted) and other 2b currents
* $\lesssim 3\%$ additive contribution from 2b currents in the $A \leq 10$ systems we considered
* this is in agreement with results obtained with "conventional" axial currents

Single β-decay: The "g_A problem"

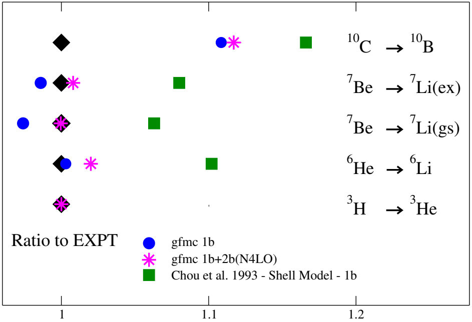


in $3 \leq A \leq 18 \longrightarrow g_A^{\text{eff}} \simeq 0.80\, g_A$

Chou *et al.* PRC47(1993)163

Missing Physics: 1. Correlations and/or 2. Two-body currents

Single Beta Decay Matrix Elements in $A = 6$–10



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

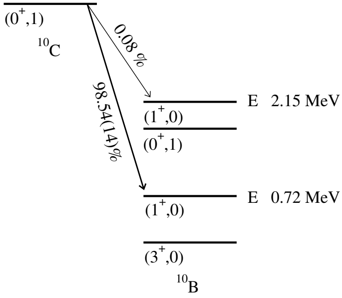
Pastore *et al.* PRC97(2018)022501

A. Baroni *et al.* PRC93(2016)015501 & PRC94(2016)024003

Based on $g_A \sim 1.27$ no quenching factor

$*$ data from TUNL, Suzuki *et al.* PRC67(2003)044302, Chou *et al.* PRC47(1993)163

^{10}B

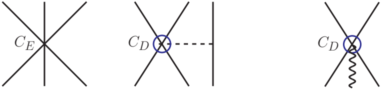


* In ^{10}B, ΔE with same quantum numbers ~ 1.5 MeV
* In $A = 7$, ΔE with same quantum numbers $\gtrsim 10$ MeV

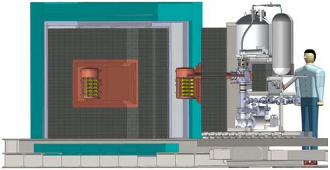
Beta-decay

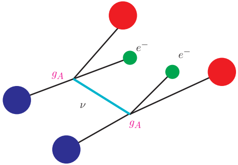
To do list:

* QMC calculations based on both chiral interactions and chiral currents
* In this case c_D enters both the 3b interaction and 2b axial current
    * c_D (and c_E) depend on the fitting strategy, *e.g.*, EXP GT in tritium, EXP B.E. A=3, EXP B.E. A=4, *nd* scattering length, ...
    * c_D (and c_E) depend on the regulator utilized in the fitting procedure
* Pions and nucleons d.o.f.'s:
  axial currents fully developed
* Pions, nucleons, and deltas d.o.f.'s (interaction by Piarulli *et al.* PRC91(2015)024003-PRC94(2016)054007-PRL120(2018)052503):
  axial currents at tree-level fully developed (on going)
* Benchmark with calculations by Gaute, Quaglioni *et al.*



Neutrinoless Double Beta Decay

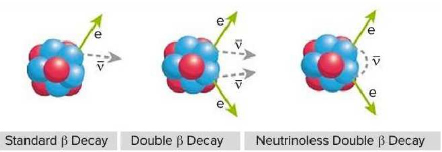




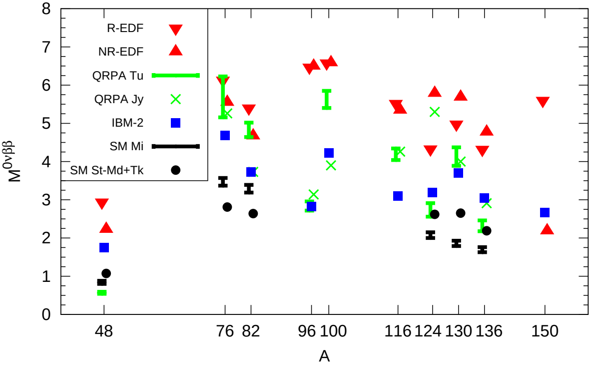
“The average momentum is about 100 MeV, a scale set by the average distance between the two decaying neutrons” cit. Engel&Menéndez

* Decay rate $\propto$ (nuclear matrix elements) $^2 \times \langle m_{\beta\beta} \rangle^2$ *

* Nuclear matrix elements $\propto g_A^2$ and Decay Rates $\propto g_A^4$ *

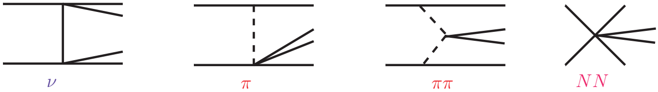


Neutrinoless double beta decay: STATUS



Javier Menendez arXiv:1703.08921 (2017)

Double beta-decay Potentials



$$\upsilon_\nu \sim L_\nu \, \tau_{1,+} \, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi \, \mathbf{q}^2} + \cdots + \upsilon_\nu{}^{\text{N2LO}-\text{loop}*}$$

$$\upsilon_{\pi\pi} \sim L_{\pi\pi} \, \tau_{1,+} \, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q} \, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi \, (\mathbf{q}^2 + m_\pi^2)^2}$$

$$\upsilon_\pi \sim L_\pi \, \tau_{1,+} \, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q} \, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{m_\pi^3 \, (\mathbf{q}^2 + m_\pi^2)}$$

$$\upsilon_{\text{NN}} \sim L_{\text{NN}} \, \tau_{1,+} \, \tau_{2,+} \frac{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{m_\pi^3}$$

$L_{\pi\pi}$, L_π, L_{NN} encode hadronic and model dependent particle physics

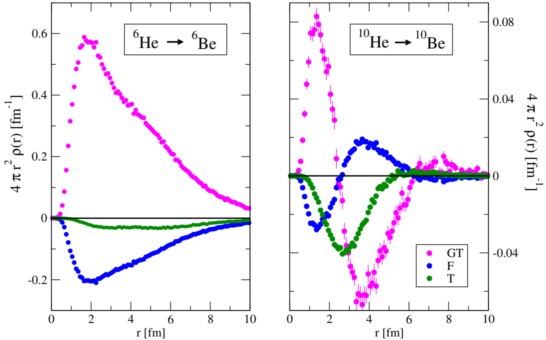
* Cirigliano & Dekens & Mereghetti & Walker-Loud in arXiv:1710.01729

IN COLLABORATION WITH

Emanuele Mereghetti & Wouter Dekens & Cirigliano & Carlson & Wiringa

PRC97(2018)014606

F, GT, and T Transition Densities



* $\Delta T = 0$

^{6}He(1)→^{6}Be(1)
^{8}He(2)→^{8}Be*(2)
^{10}Be(1)→^{10}C(1)

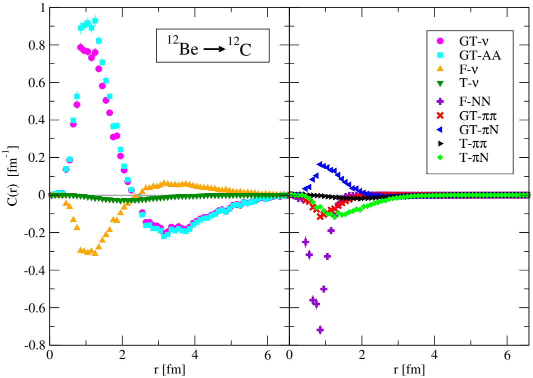
* $\Delta T = 2$

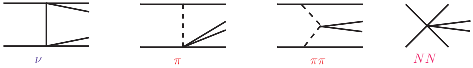
^{8}He(1)→^{8}Be(0)
^{10}He(3)→^{10}Be(1)
^{12}Be(2)→^{12}C(0)

$$\mathrm{F}= \tau_{1,+}\,\tau_{2,+} \;\; ;\mathrm{GT} = \tau_{1,+}\,\tau_{2,+}\,\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \;\; ;\mathrm{T}= \tau_{1,+}\,\tau_{2,+}\,S_{12}$$

PRC97(2018)014606

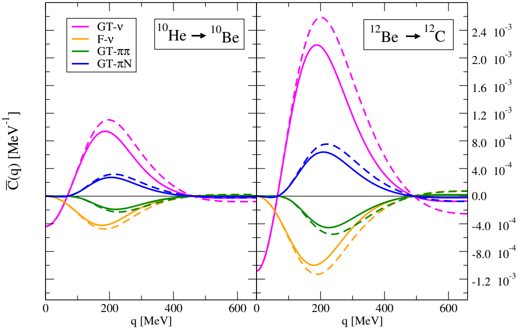
Double beta-decay Matrix Elements





PRC97(2018)014606

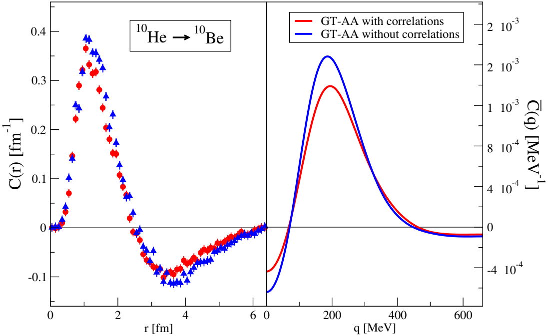
Momentum Dependence and Sensitivity to N2LO effects
i.e., 'dipole' nucleonic form factors and $\upsilon_\nu^{\mathrm{N2LO-loop}}$



* Peaks at ~ 200 MeV
* Form factors on/off $\rightarrow \sim 10\%$ variation same size as $\upsilon_\nu^{\mathrm{N2LO-loop}}$ from Cirigliano *et al.* arXiv:1710.01729
* $A = 10$ highly suppressed w.r.t. $A = 12$ (clusterization matter?)
* $A = 12$ 'most similar' to experimental cases

PRC97(2018)014606

Sensitivity to 'pion-exchange-like' correlations

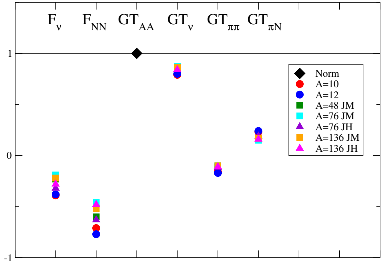


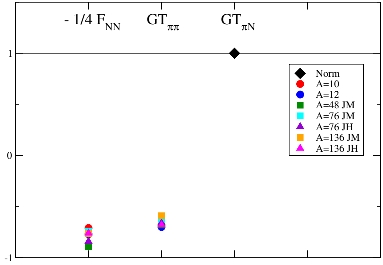
* no 'pion-exchange-like' correlation operators U_{ij}
* yes 'pion-exchange-like' correlation operators U_{ij}
* $\sim$ 10% increase in the matrix elements corresponds to a 'g_A-quenching' of $\sim$ 0.95
* as opposed to $\sim$ 0.83 found in $A = 10$ single beta decay

* Correlations reduce the m.e.'s (also true for μ's and GT's) *

PRC97(2018)014606

Comparison with calculations of larger nuclei





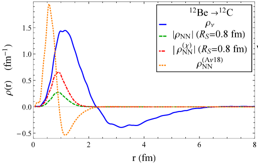
JM = Javier Menendez private communication
JH = Hyvärien *et al.* PRC91(2015)024613

* Relative size of the matrix elements is approximately the same in all nuclei
* Short-range terms approximately the same in all nuclei

PRC97(2018)014606

The contact!

Impact on $0\nu\beta\beta$ nuclear matrix elements



VMC calculation
w. AV18 potential

- assuming $C_1 = C_2$ & extract from AV18

$$M_{F\nu} = 0.191 \quad M_{GT\nu} = 0.400 \quad M_{F,NN} = 0.460$$

$\mathcal{O}(1)$ correction!

- need consistent treatment of weak and strong interactions

Courtesy of Emanuele Mereghetti

* renormalization requires to introduce a counter term at leading order

$$\upsilon_\nu = \upsilon_\nu^{\rm LO} + \upsilon_{CT}$$

* υ_{CT} is 'partially' determined by the isospin breaking NN potential ($\propto (\tau_{1,z} + \tau_{2,z})$)

Mereghetti & Dekens & Cirigliano & Graesser & de Vries & van Kolck & Pastore

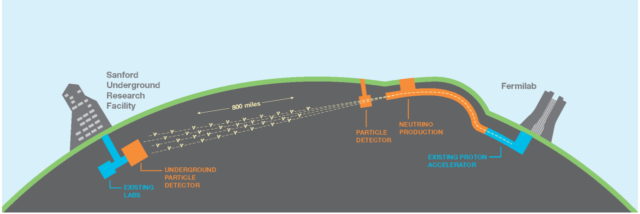
arXiv:1802.10097

$e-A$ and $\nu-A$ Scattering

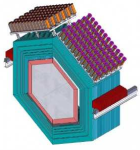
- How do nuclei interact with electrons and neutrinos in the GeV energy regime and how can calculations of these interaction cross sections be improved?

i.e.

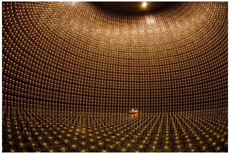
Towards a microscopic description of the ν-A inclusive cross section: The Short-Time-Approximation



LBNF

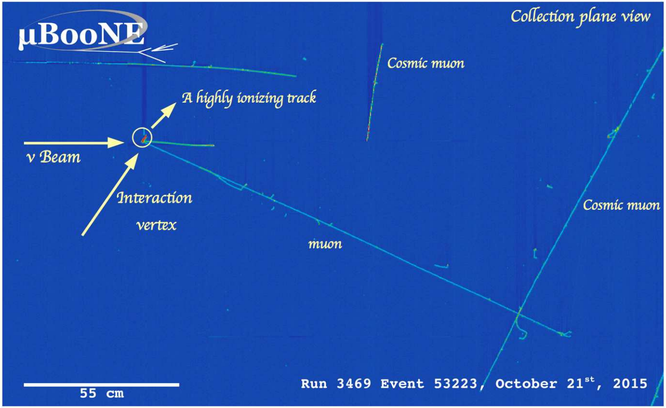


Minerva



T2K

Towards a microscopic description of the ν-nucleus cross section



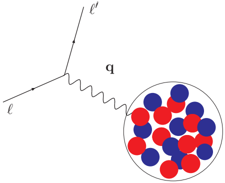
μBoone - ^{40}Ar

Inclusive (e,e') scattering

* ν/e inclusive xsecs are completely specified by the response functions
* Two (five) response functions for (e,e') (ν-A) inclusive xsec

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

Longitudinal response induced by $O_L = \rho$
Transverse response induced by $O_T = \mathbf{j}$



* Sum Rules *

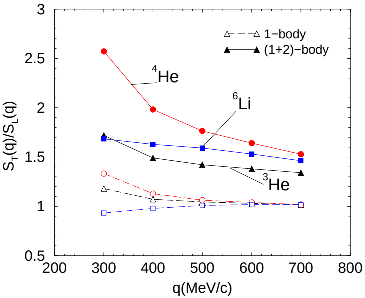
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega) R_\alpha(q,\omega)$$

* Coulomb Sum Rules *

$$S_\alpha(q) = \int_0^\infty d\omega\, R_\alpha(q,\omega) \propto \langle 0|O_\alpha^\dagger(\mathbf{q}) O_\alpha(\mathbf{q})|0\rangle$$

Sum Rules and Two-body Currents: Excess Transverse Strength

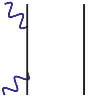


Carlson *et al.* PRC65(2002)024002

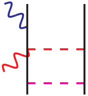
$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\,\mathbf{j}|0\rangle$$
$$\propto \langle 0|\mathbf{j}_{1b}{}^\dagger\,\mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\,\mathbf{j}_{2b}|0\rangle + \dots$$

- $\mathbf{j} = \mathbf{j}_{1b} + \mathbf{j}_{2b}$

• enhancement of the transverse response is due to interference between 1b and 2b currents AND presence of two-nucleon correlations •



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

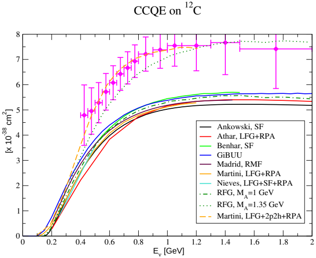


$\langle \mathbf{j}^\dagger_{1b}\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle\ > 0$

Electron-scattering data are explained when two-body correlations and currents are accounted for!

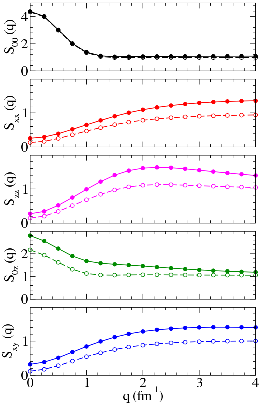
Recent Developments on ^{12}C

Charge-Current Cross Section



Alvarez-Ruso arXiv:1012.3871

Weak Responses



$q = [300 - 750]$ MeV

Lovato *et al.* PRC91(2015)062501 + arXiv:1605.00248

$\sim$ 100 million core hours

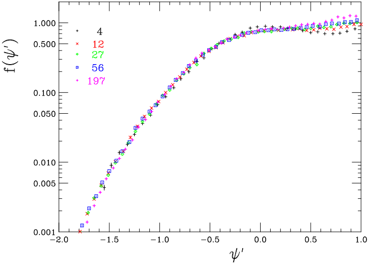
CHALLENGE:

How do we describe electroweak-scattering off $A > 12$ nuclei without loosing two-body physics?

Scaling properties of the Response Functions

Inclusive xsec depends on a single (scaling) function of ω and q

Scaling 2$^{\text{nd}}$ kind: independence form A



Donnelly and Sick - PRC60(1999)065502

1. Rely on observed scaling properties of inclusive xsecs, universal behavior of nucleon/A momentum distributions, and exhibited locality of nuclear properties to build approximate response functions for $A > 12$ nuclei
2. From exact *ab initio* calculations we know that two-body correlations and two-body currents are crucial
3. Build a model that retains two-body physics

Factorization: Short-Time Approximation

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

$$R_{\alpha}(q,\omega) = \int dt \langle\, 0|O^{\dagger}_{\alpha}(\mathbf{q})\, e^{i(H-\omega)t}\, O_{\alpha}(\mathbf{q})|0\,\rangle$$

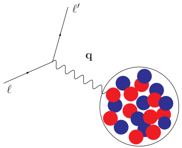
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_{i} t_i + \sum_{i<j} v_{ij}$$

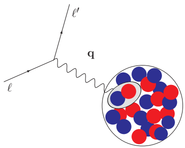
and

$$O^{\dagger}_{i}P(t)O_{i} + O^{\dagger}_{i}P(t)O_{j} + O^{\dagger}_{i}P(t)O_{ij} + O^{\dagger}_{ij}P(t)O_{ij}$$

1b



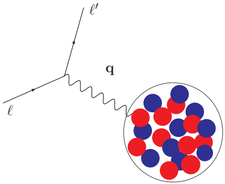
2b



Factorization I: The Plane Wave Impulse Approximation (PWIA)

In PWIA:

Response functions given by incoherent scattering off single nucleons that propagate freely in the final state (plane waves)

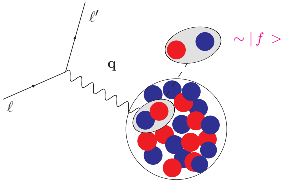


$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right)\langle 0|O^\dagger_\alpha(\mathbf{q})|f\rangle\langle f|O_\alpha(\mathbf{q})|0\rangle$$

$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) = 1\text{b}$$

$$|f\rangle \sim e^{i(\mathbf{k}+\mathbf{q})\cdot\mathbf{r}} = \text{free single nucleon w.f.}$$

Factorization II: The Short-Time Approximation (STA)



In STA:

Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons

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

$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) = 1\mathrm{b} + 2\mathrm{b}$$

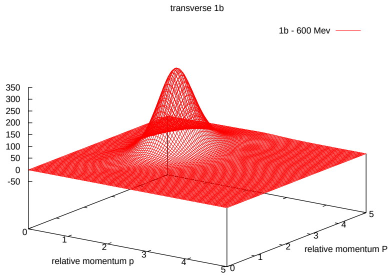
$$|f\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \text{correlated two} - \text{nucleon w.f.}$$

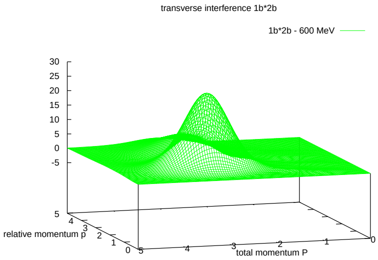
* We retain two-body physics consistently in the nuclear interactions and electroweak currents

* $R_\alpha(q,\omega)$ requires only direct calculation of g.s. $|0\rangle$ w.f.'s *

* STA can be implemented to accommodate for more two-body physics, *e.g.*, pion-production induced by e and ν

The Short-Time Approximation



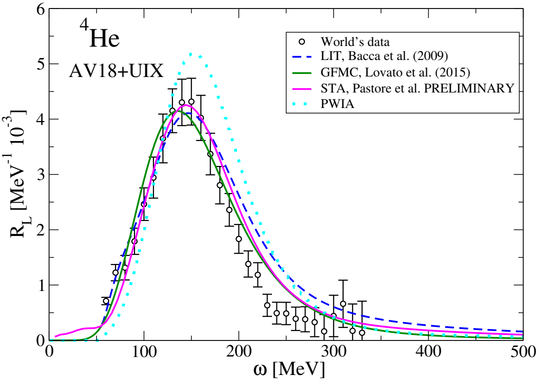


$$R_\alpha(q,\omega) \quad \sim \int \delta\left(\omega + E_0 - E_f\right) d\Omega_P \, d\Omega_p \, dP \, dp \left[p^2 P^2 \langle 0|O_\alpha^\dagger(\mathbf{q})|\mathbf{p},\mathbf{P}\rangle\langle \mathbf{p},\mathbf{P}|O_\alpha(\mathbf{q})|0\rangle\right]$$

300 core hours with 1b + 2b for ^4He

Preliminary results

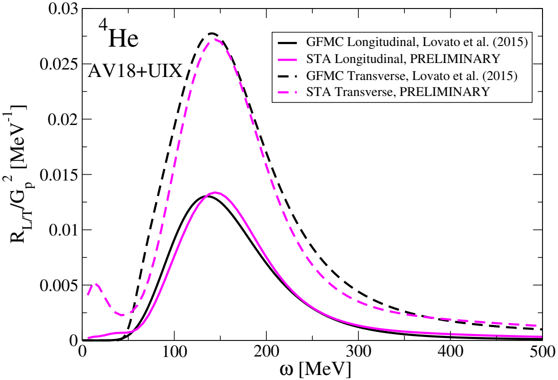
The Short-Time Approximation



Longitudinal Response function at $q = 500$ MeV

Preliminary results

The Short-Time Approximation



Longitudinal vs Transverse Response Function at $q = 500$ MeV

Preliminary results

Current Results

Two-nucleon correlations and two-body electroweak currents
are crucial to explain available experimental data of both static (ground state properties) and dynamical (cross sections and rates) nuclear observables

* Two-body currents can give $\sim 30-40\%$ contributions and improve on theory/EXPT agreement

* Calculations of $\beta-$ and $\beta\beta-$decay m.e.'s in $A \leq 12$ indicate two-body physics (currents and correlations) is required

* Short-Time-Approximation to evaluate υ-A scattering in $A > 12$ nuclei is in excellent agreement with exact calculations and data

* We are developing a coherent picture for neutrino-nucleus interactions *