Effective Field Theories for Electroweak Interactions in Nuclei

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Winter Workshop on Neutrino-Nucleus Interactions
FNAL - Batavia IL - November 2017

WITH

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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 - PRC(2016)015501 - arXiv:1709.03592 & arXiv:1710.05026

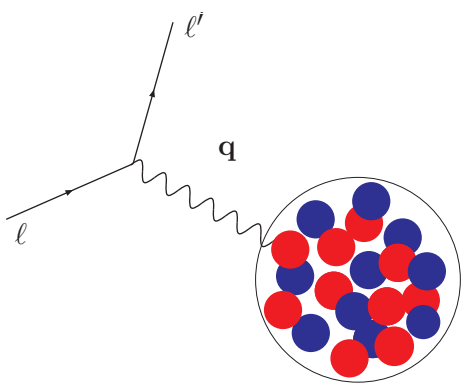
A special request from Andreas S Kronfeld & Maria del Pilar Coloma Escribano

* Cover similar range of topics as in the NuSTEC School *

- two- and three-nucleon pion exchange interactions
- realistic models of two- and three-nucleon interactions
- realistic models of many-body nuclear electroweak currents
- short-range structure of nuclei, nuclear correlations, and quasi-elastic scattering

with emphasis on
how the nuclear-physics concepts are grounded in quantum field theory

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



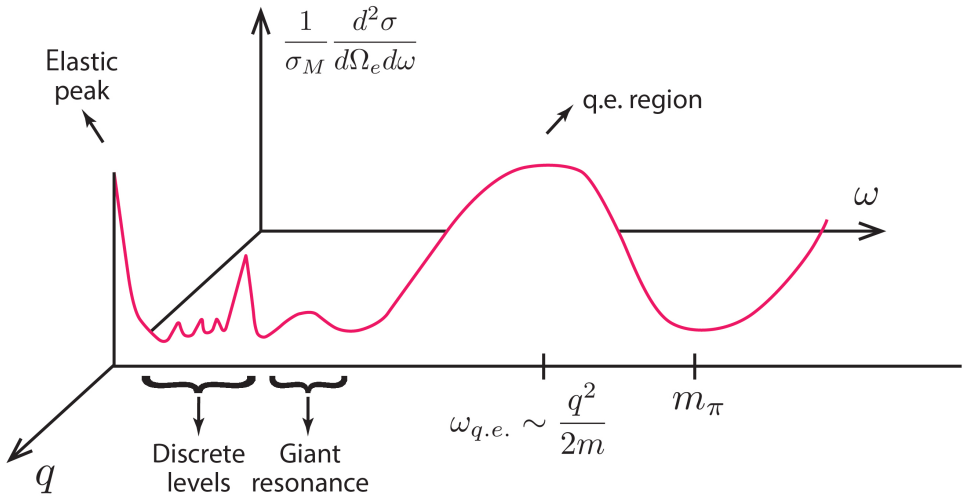
GOAL

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

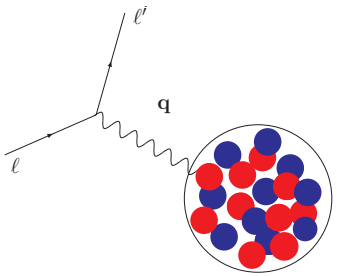
* The *ab initio* Approach*

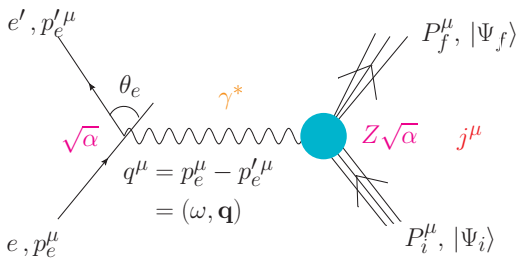
In the *ab initio* Approach one assumes that all nuclear phenomena can be explained in terms of (or emerge from) interactions between nucleons, and interactions between nucleons and external electroweak probes (electrons, photons, neutrinos, DM, ...)

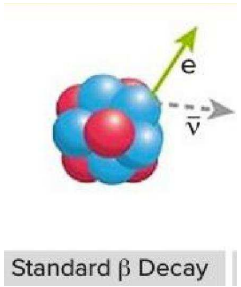
Electroweak Reactions



* $\omega \sim 10^2$ MeV: Accelerator neutrinos
* $\omega \sim 10^1$ MeV: EM decay, β-decay
* $\omega \lesssim 10^1$ MeV: Nuclear Rates for Astrophysics







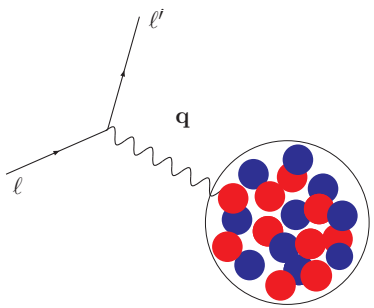
The *ab initio* Approach

The nucleus is made of A interacting nucleons and its energy is

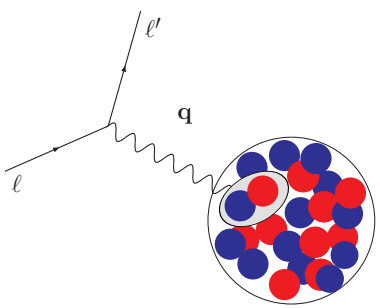
$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

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

1b



2b



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

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

Two-body 2b currents essential to satisfy current conservation

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

* "Longitudinal" component fixed by current conservation
* "Transverse" component "model dependent"

Time-Ordered-Perturbation Theory

The relevant degrees of freedom of nuclear physics are bound states of QCD

* non relativistic nucleons N
* pions π as mediators of the nucleon-nucleon interaction
* non relativistic Delta's Δ with $m_\Delta \sim m_N + 2m_\pi$

Transition amplitude in time-ordered perturbation theory

$$T_{fi} = \langle N'N' \mid H_1 \sum_{n=1}^{\infty} \left(\frac{1}{E_i - H_0 + i\eta} H_1 \right)^{n-1} \mid NN \rangle^*$$

H_0 = free π, N, Δ Hamiltonians
H_1 = interacting π, N, Δ, and external electroweak fields Hamiltonians

$$T_{fi} = \langle N'N' \mid T \mid NN \rangle \propto \upsilon_{ij} \ , \qquad T_{fi} = \langle N'N' \mid T \mid NN; \gamma \rangle \propto (A^0 \rho_{ij}, \mathbf{A} \cdot \mathbf{j}_{ij})$$

$*$ Note no pions in the initial or final states, *i.e.*, pion-production not accounted in the theory

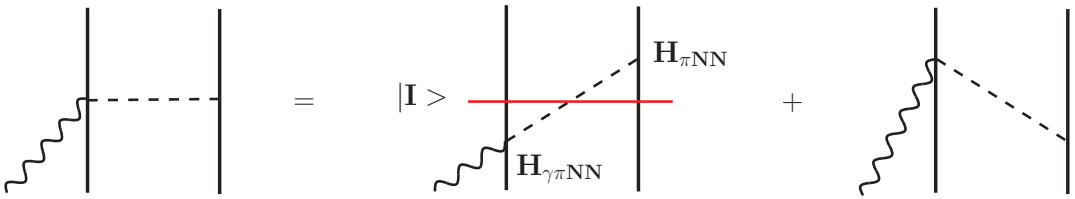
Transition amplitude in time-ordered perturbation theory

Insert complete sets of eigenstates of H_0 between successive terms of H_1

$$T_{fi} = \langle N'N' \mid H_1 \mid NN;\gamma\rangle + \sum_{|I\rangle} \langle N'N' \mid H_1 \mid I\rangle \frac{1}{E_i - E_I} \langle I \mid H_1 \mid NN;\gamma\rangle + \ldots$$

The contributions to the T_{fi} are represented by time ordered diagrams

Example: seagull pion exchange current

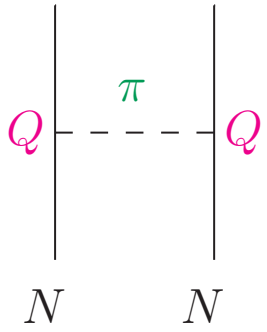


N number of H_1's (vertices) $\rightarrow$ N! time-ordered diagrams

Nuclear Chiral Effective Field Theory (χEFT) approach

S. Weinberg, Phys. Lett. **B251**, 288 (1990); Nucl. Phys. **B363**, 3 (1991); Phys. Lett. **B295**, 114 (1992)

* χEFT is a low-energy ($Q \ll \Lambda_\chi \sim 1$ GeV) approximation of QCD
* It provides effective Lagrangians describing π's, N's, Δ's, ... interactions that are expanded in powers n of a perturbative (small) parameter Q/Λ_χ



$$\mathscr{L}_{eff} = \mathscr{L}^{(0)} + \mathscr{L}^{(1)} + \mathscr{L}^{(2)} + \ldots + \mathscr{L}^{(n)} + \ldots$$

* The coefficients of the expansion, Low Energy Constants (LECs), are unknown and need to be fixed by comparison with exp data, or take them from LQCD
* The systematic expansion in Q naturally has the feature

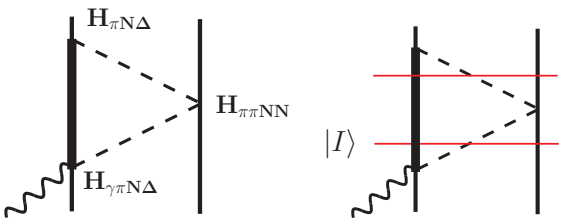
$$\langle \mathscr{O} \rangle_{1-\text{body}} > \langle \mathscr{O} \rangle_{2-\text{body}} > \langle \mathscr{O} \rangle_{3-\text{body}}$$

* A theoretical error due to the truncation of the expansion can be assigned

(Naïve) Power Counting

Each contribution to the T_{fi} scales as

$$\underbrace{\left(\prod_{i=1}^{N} Q^{\alpha_i-\beta_i}\right)}_{H_1\,\text{scaling}} \times \underbrace{Q^{-(N-1)}}_{\text{denominators}} \times \underbrace{Q^{3L}}_{\text{loop integration}}$$



α_i = # of derivatives (momenta) in H_1;
β_i = # of π's;
N = # of vertices; $N-1$ = # of intermediate states;
L = # of loops

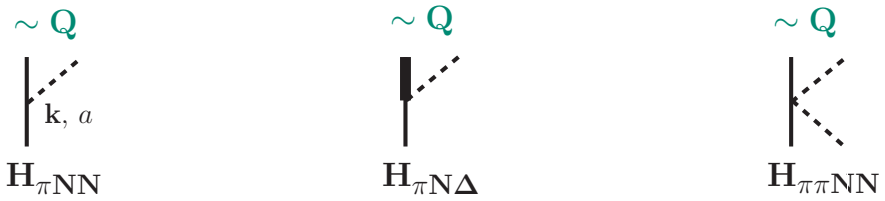
$$H_1 \text{ scaling} \sim \underbrace{Q^1}_{H_{\pi N\Delta}} \times \underbrace{Q^1}_{H_{\pi\pi NN}} \times \underbrace{Q^0}_{H_{\pi\gamma N\Delta}} \times Q^{-2} \sim Q^0$$

$$\text{denominators} \sim \frac{1}{E_i - H_0}|I\rangle \sim \frac{1}{2m_N - (m_\Delta + m_N + \omega_\pi)}|I\rangle = -\frac{1}{m_\Delta - m_N + \omega_\pi}|I\rangle \sim \frac{1}{Q}|I\rangle$$

$$Q^1 = Q^0 \times Q^{-2} \times Q^3$$

* This power counting also follows from considering Feynman diagrams, where loop integrations are in 4D

π, N and Δ Strong Vertices



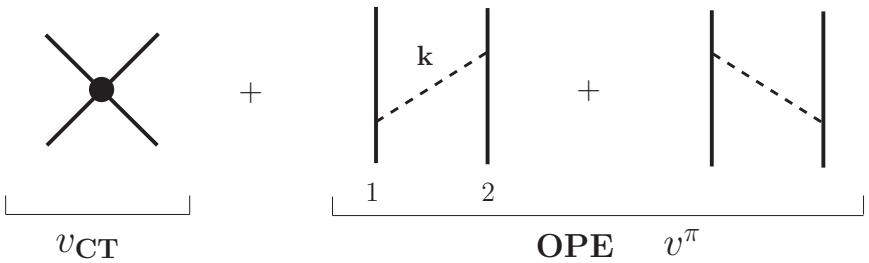
$$H_{\pi NN} = \frac{g_A}{F_\pi} \int \mathrm{d}\mathbf{x} N^\dagger(\mathbf{x}) \left[\boldsymbol{\sigma} \cdot \nabla \pi_a(\mathbf{x})\right] \tau_a N(\mathbf{x}) \quad \longrightarrow \quad V_{\pi NN} = -i \frac{g_A}{F_\pi} \frac{\boldsymbol{\sigma} \cdot \mathbf{k}}{\sqrt{2\,\omega_k}} \tau_a \sim Q^1 \times Q^{-1/2}$$

$$H_{\pi N\Delta} = \frac{h_A}{F_\pi} \int \mathrm{d}\mathbf{x} \Delta^\dagger(\mathbf{x}) \left[\mathbf{S} \cdot \nabla \pi_a(\mathbf{x})\right] T_a N(\mathbf{x}) \quad \longrightarrow \quad V_{\pi N\Delta} = -i \frac{h_A}{F_\pi} \frac{\mathbf{S} \cdot \mathbf{k}}{\sqrt{2\,\omega_k}} T_a \sim Q^1 \times Q^{-1/2}$$

$g_A \simeq 1.27$; $F_\pi \simeq 186$ MeV; $h_A \sim 2.77$ (fixed to the width of the Δ)
are 'known' LECs

$$\begin{aligned} \pi_a(\mathbf{x}) &= \sum_{\mathbf{k}} \frac{1}{\sqrt{2\,\omega_k}} \left[c_{\mathbf{k},a}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{x}} + \mathrm{h.c.}\right] , \\ N(\mathbf{x}) &= \sum_{\mathbf{p},\sigma\tau} b_{\mathbf{p},\sigma\tau}\, \mathrm{e}^{i\mathbf{p}\cdot\mathbf{x}} \chi_{\sigma\tau} , \end{aligned}$$

χEFT nucleon-nucleon potential at LO

$v_{\rm NN}^{\rm LO} =$ 

$\sim \mathbf{Q}^0$

$$T_{fi}^{\rm LO} = \langle N'N' \mid H_{\rm CT,1} \mid NN\rangle + \sum_{|I\rangle} \langle N'N' \mid H_{\pi NN} \mid I\rangle \frac{1}{E_i - E_I} \langle I \mid H_{\pi NN} \mid NN\rangle$$

Leading order nucleon-nucleon potential in χEFT

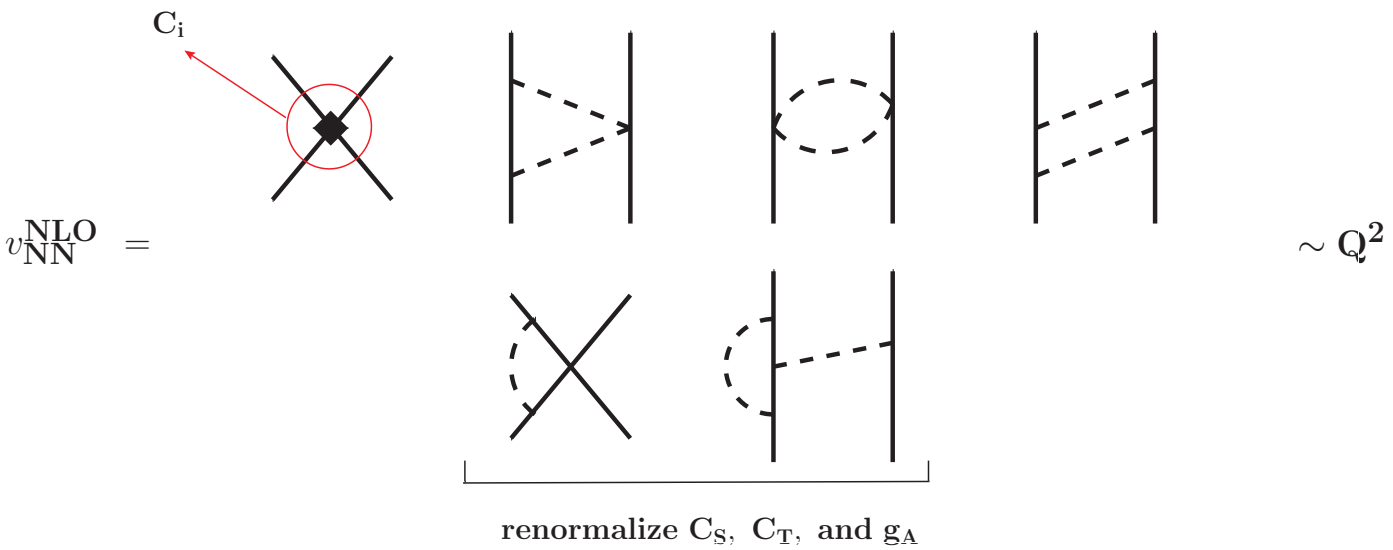
$$v_{\rm NN}^{\rm LO} = v_{\rm CT} + v_\pi = C_S + C_T\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 - \frac{g_A^2}{F_\pi^2} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{k}\, \boldsymbol{\sigma}_2 \cdot \mathbf{k}}{\omega_k^2} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

* Configuration space *

$$v_{12} = \sum_p v_{12}^p(r)\, O_{12}^p; \qquad O_{12} = 1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2, S_{12} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

$$S_{12} = 3\, \boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}}\, \boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}} - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

χEFT nucleon-nucleon potential at NLO (without Δ's)

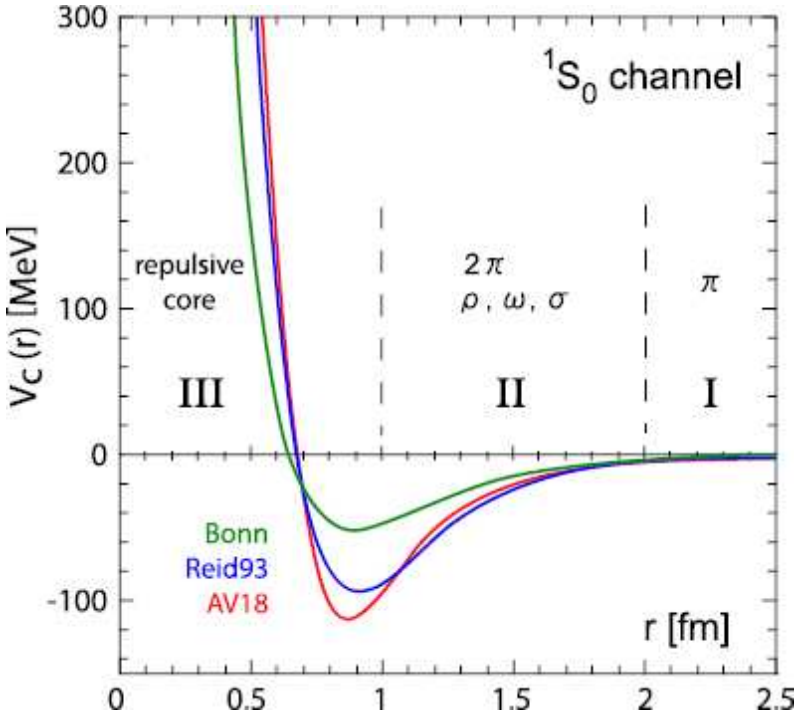


* At NLO there are 7 LEC's, C_i, fixed so as to reproduce nucleon-nucleon scattering data (order of k data)
* C_i's multiply contact terms with 2 derivatives acting on the nucleon fields (∇N)
* Loop-integrals contain ultraviolet divergences reabsorbed into g_A, C_S, C_T, and C_i's (for example, use dimensional regularization)

* Configuration space *

$$v_{12} = \sum_p v_{12}^p(r)\, O_{12}^p; \qquad O_{12} = [1, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, S_{12}, \mathbf{L}\cdot\mathbf{S}] \otimes [1, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$$

Nucleon-nucleon potential

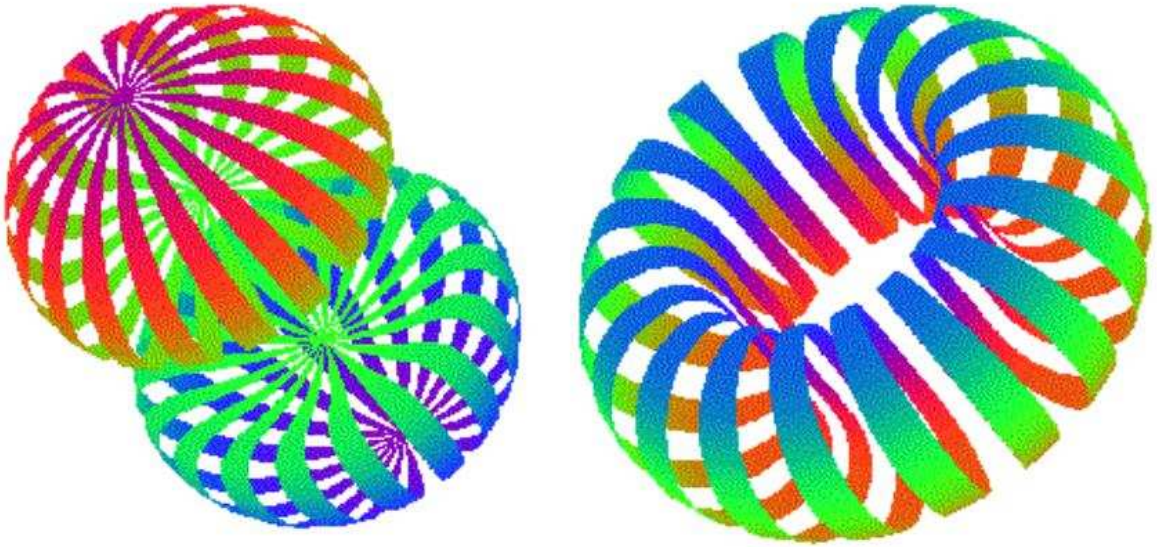


Aoki *et al.* Comput.Sci.Disc.1(2008)015009

CT = Contact Term (short-range);
OPE = One Pion Exchange (range $\sim \frac{1}{m_\pi}$);
TPE = Two Pion Exchange (range $\sim \frac{1}{2m_\pi}$)

Nucleon-Nucleon Potential and the Deuteron

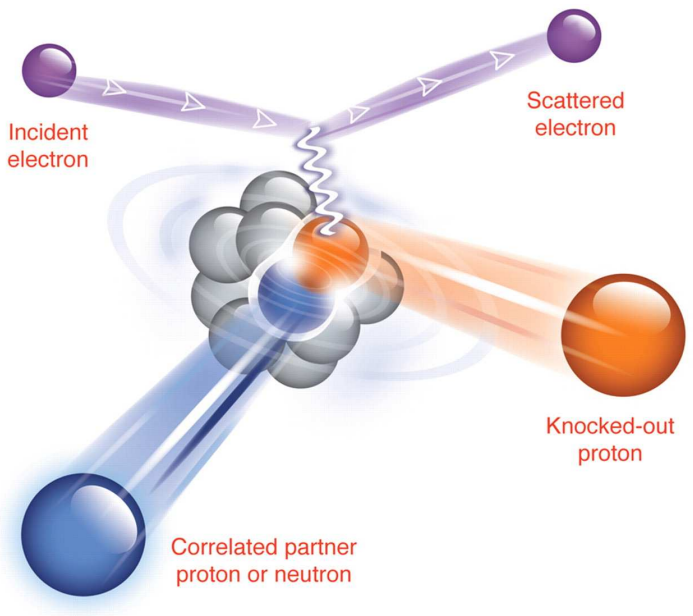
$M = \pm 1$ $M = 0$

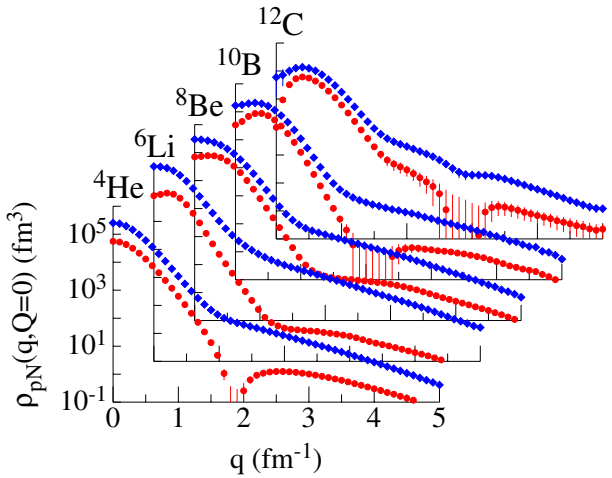


Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

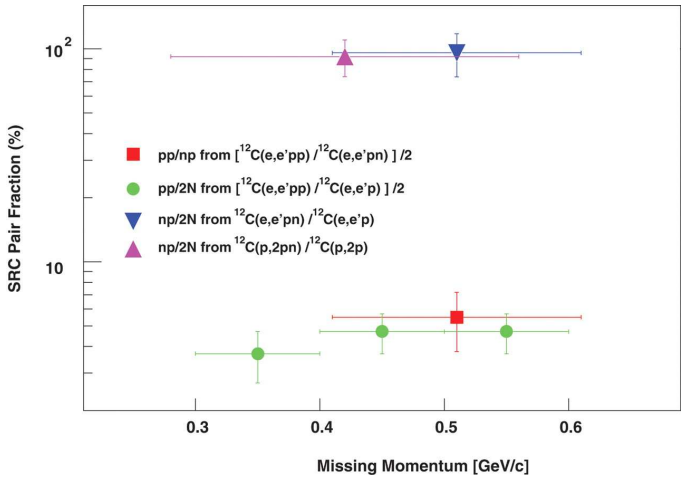
Carlson and Schiavilla Rev.Mod.Phys.70(1998)743

Back-to-back *np* and *pp* Momentum Distributions





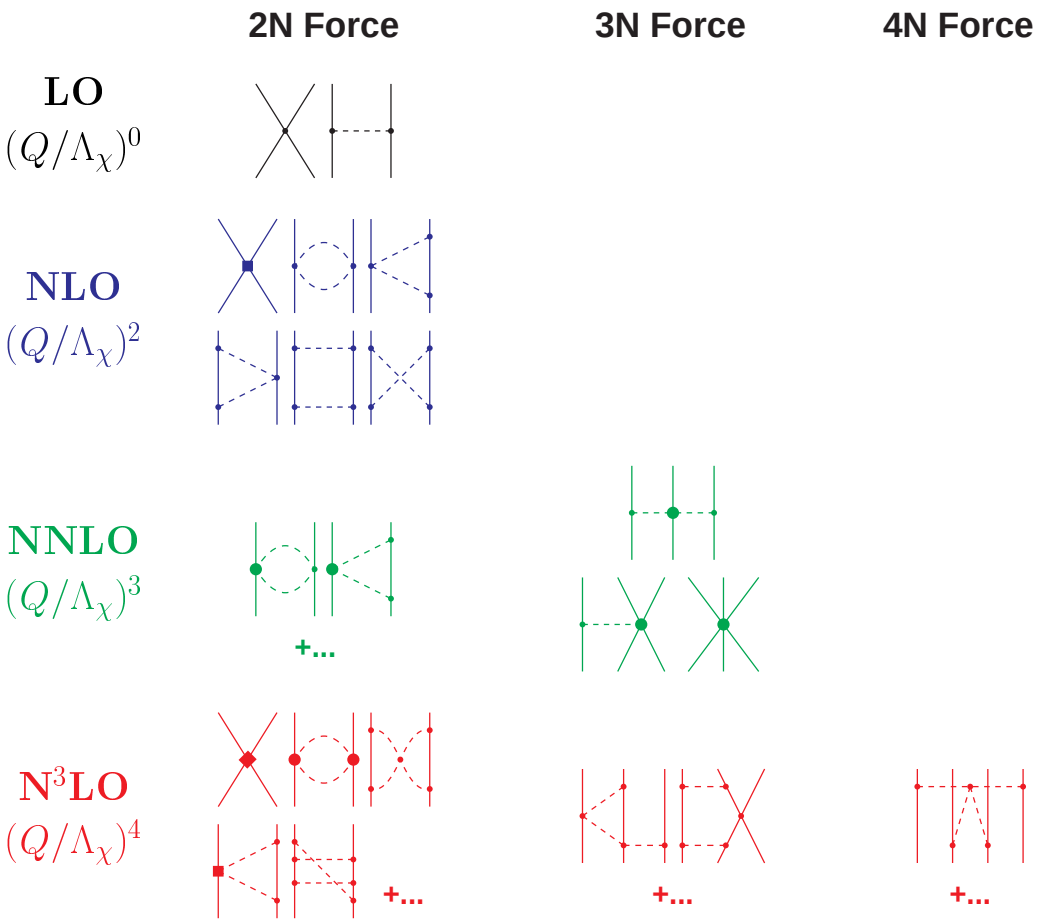
Wiringa *et al.* PRC89(2014)024305



JLab, Subedi *et al.* Science320(2008)1475

Nuclear properties are strongly affected by two-nucleon interactions!

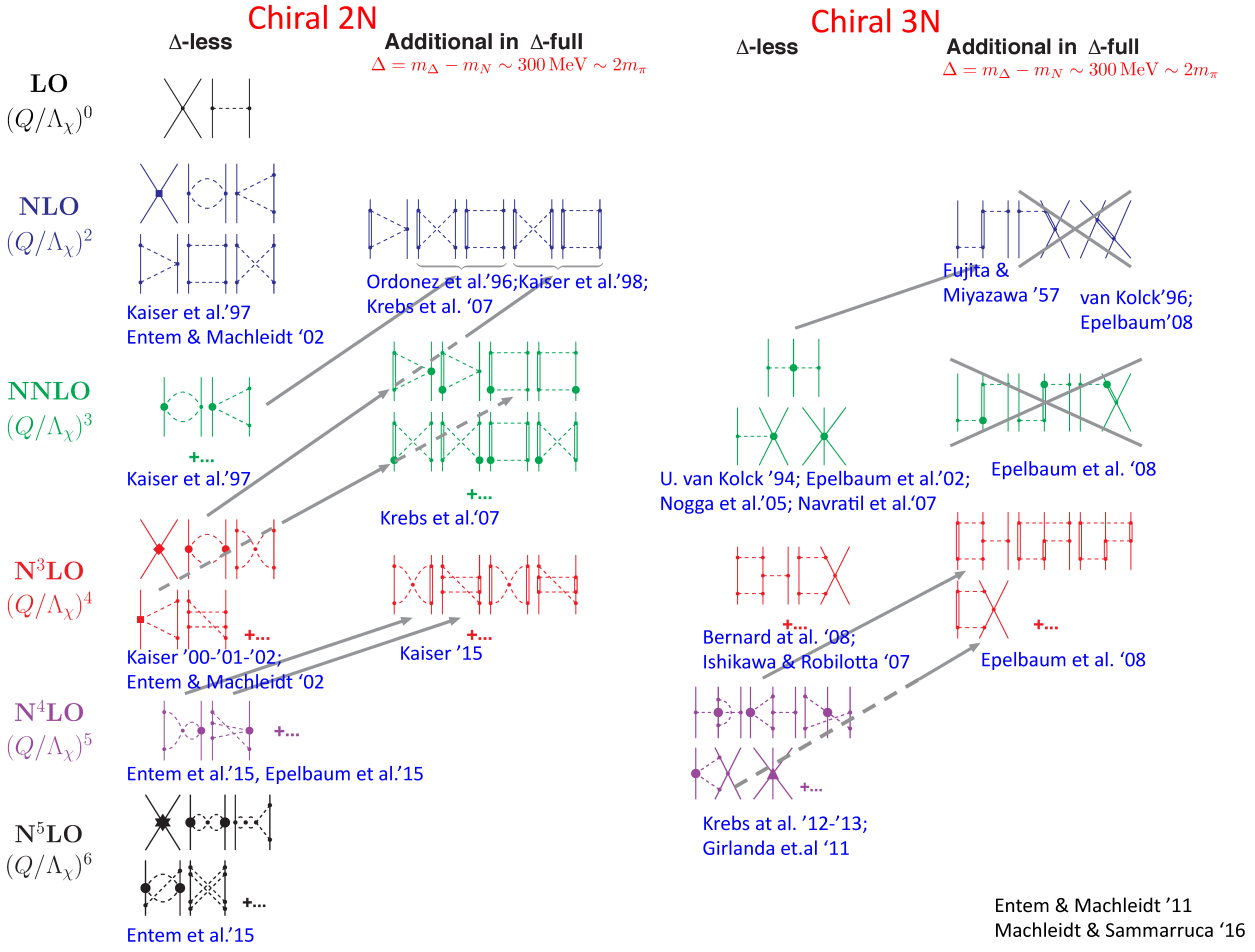
χEFT many-body potential: Hierarchy



Machleidt & Sammarruca - PhysicaScripta91(2016)083007

CT = Contact Term (short-range);
OPE = One Pion Exchange (range $\sim \frac{1}{m_\pi}$);
TPE = Two Pion Exchange (range $\sim \frac{1}{2m_\pi}$)

Nuclear Interactions and the role of the Δ



Courtesy of Maria Piarulli

* N3LO with Δ nucleon-nucleon interaction constructed by Piarulli *et al.* in PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 with $\Delta's$ fits ~ 2000 (~ 3000) data up 125 (200) MeV with χ^2/datum ~ 1;

* N2LO with Δ 3-nucleon force fits ^{3}H binding energy and the *nd* scattering length

“Phenomenological” aka “Conventional” aka “Traditional” aka “Realistic” Two- and Three- Nucleon Potentials

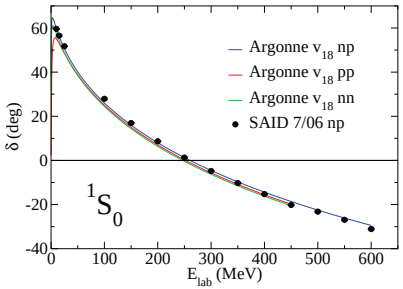
NUCLEAR HAMILTONIAN

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

K_i: Non-relativistic kinetic energy, m_n-m_p effects included

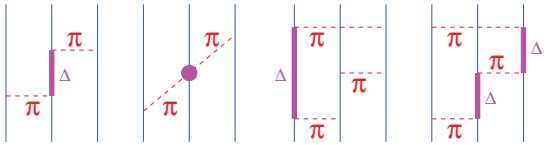
Argonne v18: $v_{ij} = v_{ij}^{\gamma} + v_{ij}^{\pi} + v_{ij}^{I} + v_{ij}^{S} = \sum v_p(r_{ij}) O_{ij}^{p}$

- 18 spin, tensor, spin-orbit, isospin, etc., operators
- full EM and strong CD and CSB terms included
- predominantly local operator structure
- fits Nijmegen PWA93 data with χ^2/d.o.f.=1.1



Wiringa, Stoks, & Schiavilla, PRC **51**, (1995)

Urbana & Illinois: $V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{3\pi} + V_{ijk}^{R}$



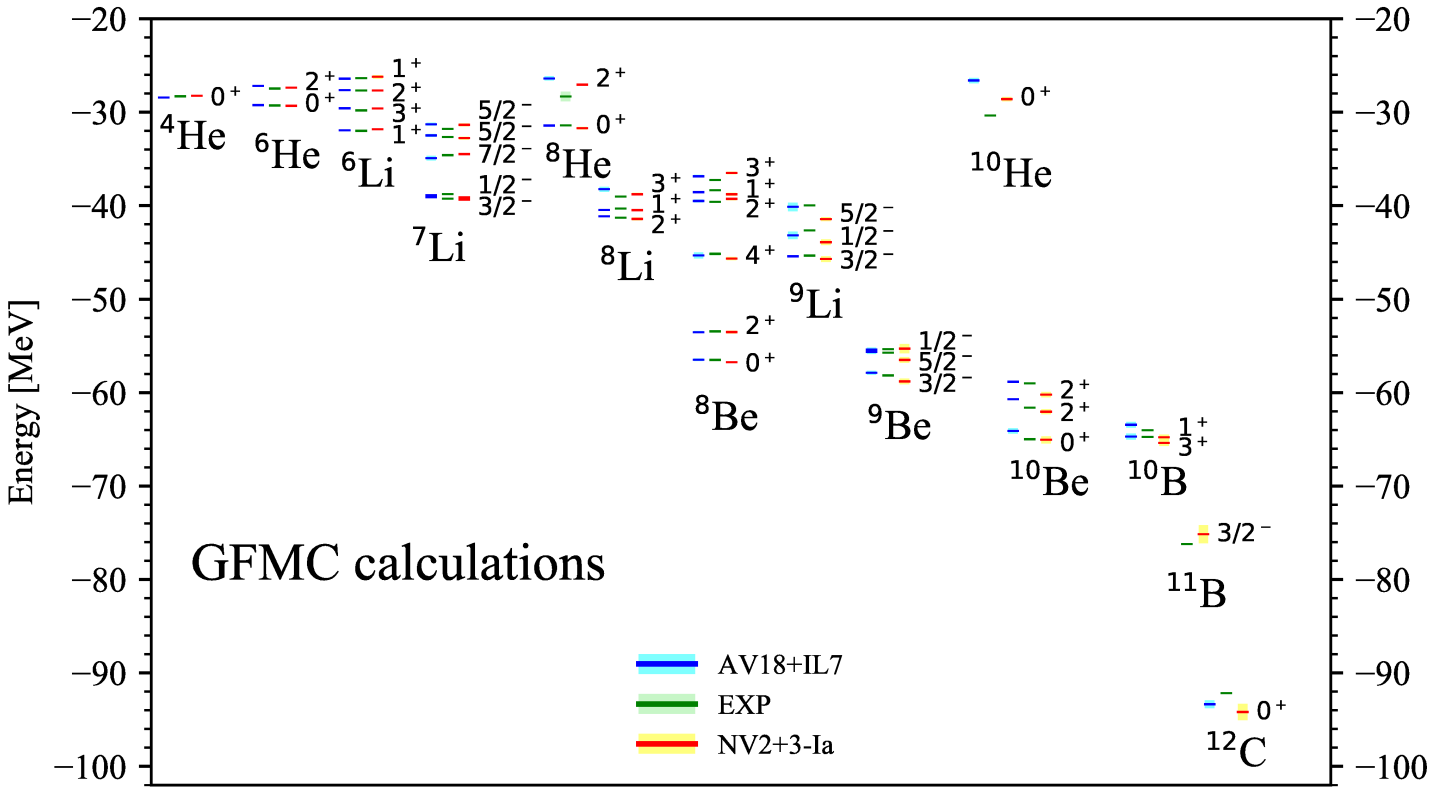
- Urbana has standard 2π P-wave + short-range repulsion for matter saturation
- Illinois adds 2π S-wave + 3π rings to provide extra T=3/2 interaction
- Illinois-7 has four parameters fit to 23 levels in $A \leq$10 nuclei

Pieper, Pandharipande, Wiringa, & Carlson, PRC **64**, 014001 (2001)
Pieper, AIP CP **1011**, 143 (2008)

Courtesy of Bob Wiringa

* AV18 fitted up to 350 MeV, reproduces phase shifts up to $\sim$ 1 GeV *

Spectra of Light Nuclei



M. Piarulli *et al.* - arXiv:1707.02883

* one-pion-exchange physics dominates *
* it is included in both chiral and "conventional" potentials *

Chiral Potentials (Incomplete List of Credits)

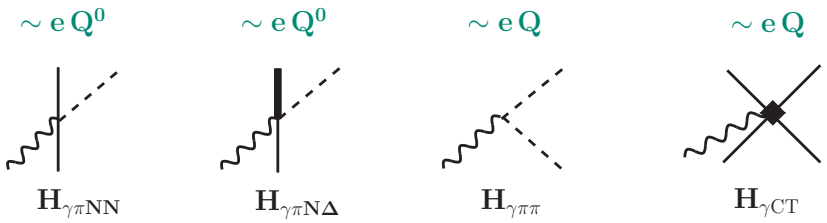
* van Kolck *et al.*; PRL72(1994)1982-PRC53(1996)2086
* Kaiser, Weise *et al.*; NPA625(1997)758-NPA637(1998)395
* Epelbaum, Glöckle, Meissner*; RevModPhys81(2009)1773 and references therein
* Entem and Machleidt*; PhysRept503(2011)1 and references therin

* Chiral Potentials suited for Quantum Monte Carlo calculations *

* Gezerlis *et al.* PRL111(2013)032501-PRC90(2014)054323;
  Lynn *et al.* PRL113(2014)192501
* Piarulli *et al.** PRC91(2015)024003-PRC94(2016)054007-arXiv:1707.02883 (with $\Delta's$)

* Potentials fitted and used in many-body calculations

External Electromagnetic Field



"Minimal" Electromagnetic Vertices

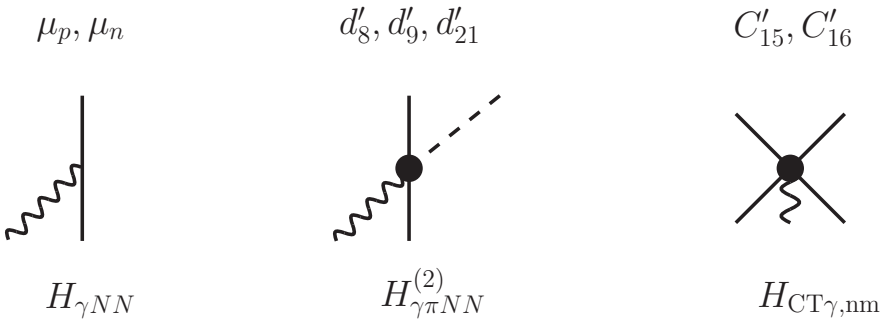
* EM H_1 obtained by minimal substitution in the π- and N-derivative couplings (same as doing $\mathbf{p} \to \mathbf{p} + e\,\mathbf{A}$, minimal coupling)

$$\begin{aligned} \nabla \pi_{\mp}(\mathbf{x}) &\quad \to \quad [\nabla \mp i\,e\mathbf{A}(\mathbf{x})]\,\pi_{\mp}(\mathbf{x}) \\ \nabla N(\mathbf{x}) &\quad \to \quad [\nabla - i\,e\,e_N\mathbf{A}(\mathbf{x})]\,N(\mathbf{x})\ , \qquad e_N = (1+\tau_z)/2 \end{aligned}$$

* same LECs as the Strong Vertices *

* This is equivalent to say that the currents are conserved, *i.e.*, the continuity equation is satisfied

External Electromagnetic Field



"Non-Minimal" Electromagnetic Vertices

* EM H_1 involving the tensor field $F_{\mu\nu} = (\partial_\mu A_\nu - \partial_\nu A_\mu)$

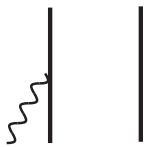
LECs are not constrained by the strong interaction
there are additional LECs fixed to EM observables

* $H_{\gamma NN}$ obtained by non-relativistic reduction of the covariant single nucleon currents constrained to $\mu_p = 2.793$ n.m. and $\mu_n = -1.913$ n.m.
* $H_{\gamma\pi NN}$ involves $\nabla\pi$ and ∇N and 3 new LECs (2 of them are "saturated" by the Δ)
* $H_{CT2\gamma}$ involves 2 new LECs

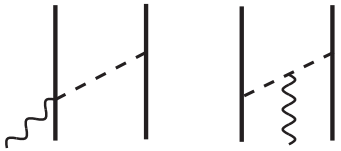
* These are the so called the "transverse" currents

Electromagnetic Currents from Chiral Effective Field Theory

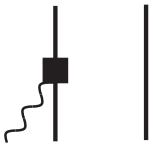
LO : $\mathbf{j}^{(-2)} \sim \mathbf{eQ^{-2}}$



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

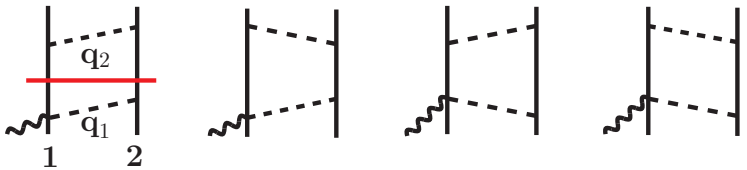
unknown LEC′s →

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 *

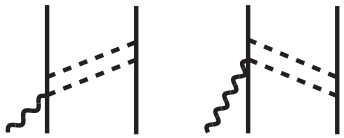
Technicalities I: Reducible Contributions

4 interaction Hamiltonians $\longrightarrow$ 4! time ordered diagrams

Reducible



Irreducible direct



Irreducible crossed

$$|\Psi\rangle \simeq |\phi\rangle + \frac{1}{E_i - H_0} \upsilon^\pi |\phi\rangle + \ldots$$

$$\langle \Psi_f | \mathbf{j} | \Psi_i \rangle \simeq \langle \phi_f | \mathbf{j} | \phi_i \rangle + \langle \phi_f | \upsilon^\pi \frac{1}{E_i - H_0} \mathbf{j} + \text{h.c.} | \phi_i \rangle + \ldots$$

* Need to carefully subtract contributions generated by the iterated solution of the Schrödinger equation

Technicalities II: The Cutoff

* χEFT operators have a power law behavior in Q

1. introduce a regulator to kill divergencies at large Q, *e.g.*, $C_\Lambda = e^{-(Q/\Lambda)^n}$
2. pick n large enough so as to not generate spurious contributions

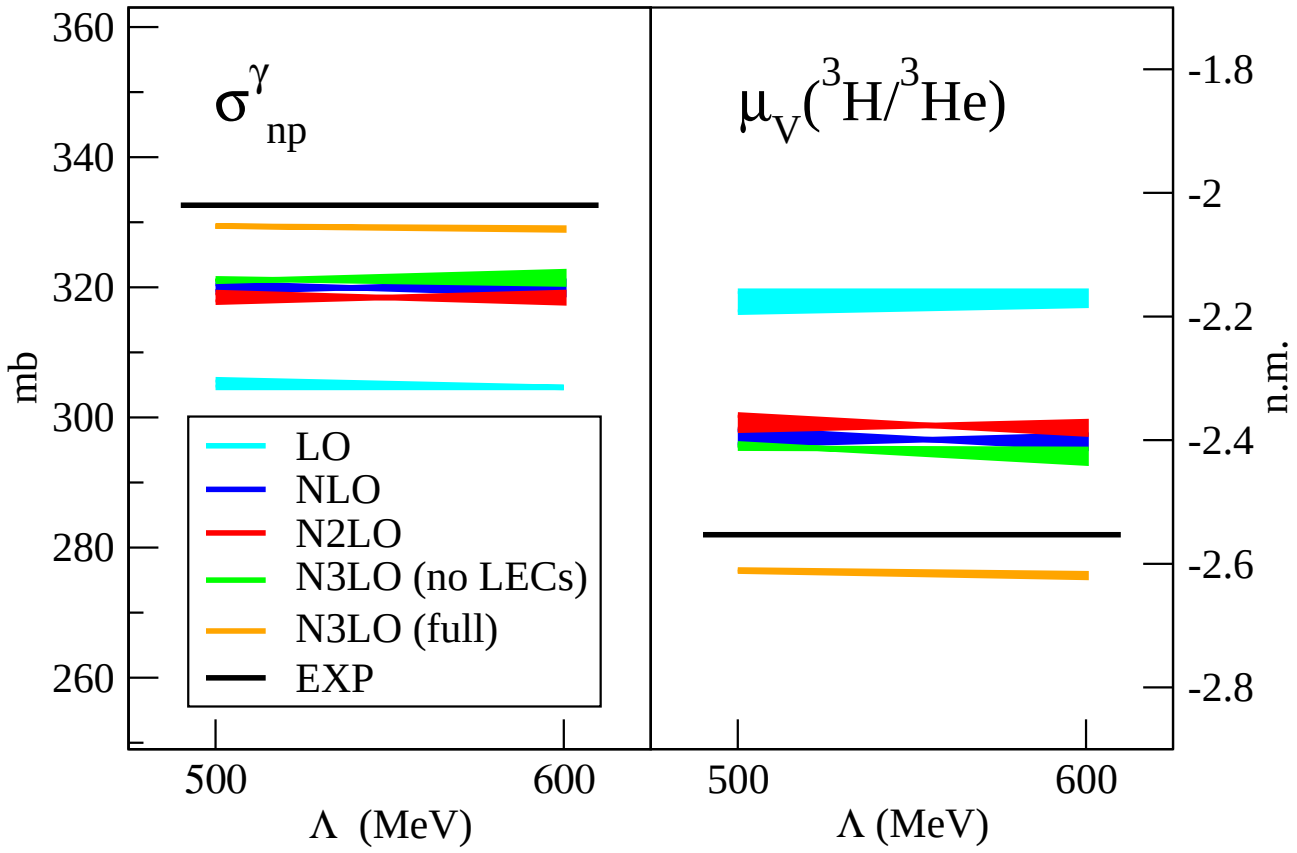
$$C_\Lambda \sim 1 - \left(\frac{Q}{\Lambda}\right)^n + \ldots$$

3. for each cutoff Λ re-fit the LECs
4. ideally, your results should be cutoff-independent

* In r_{ij}-space this corresponds to cutting off the short-range part of the operators that make the matrix elements diverge at $r_{ij} = 0$

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]

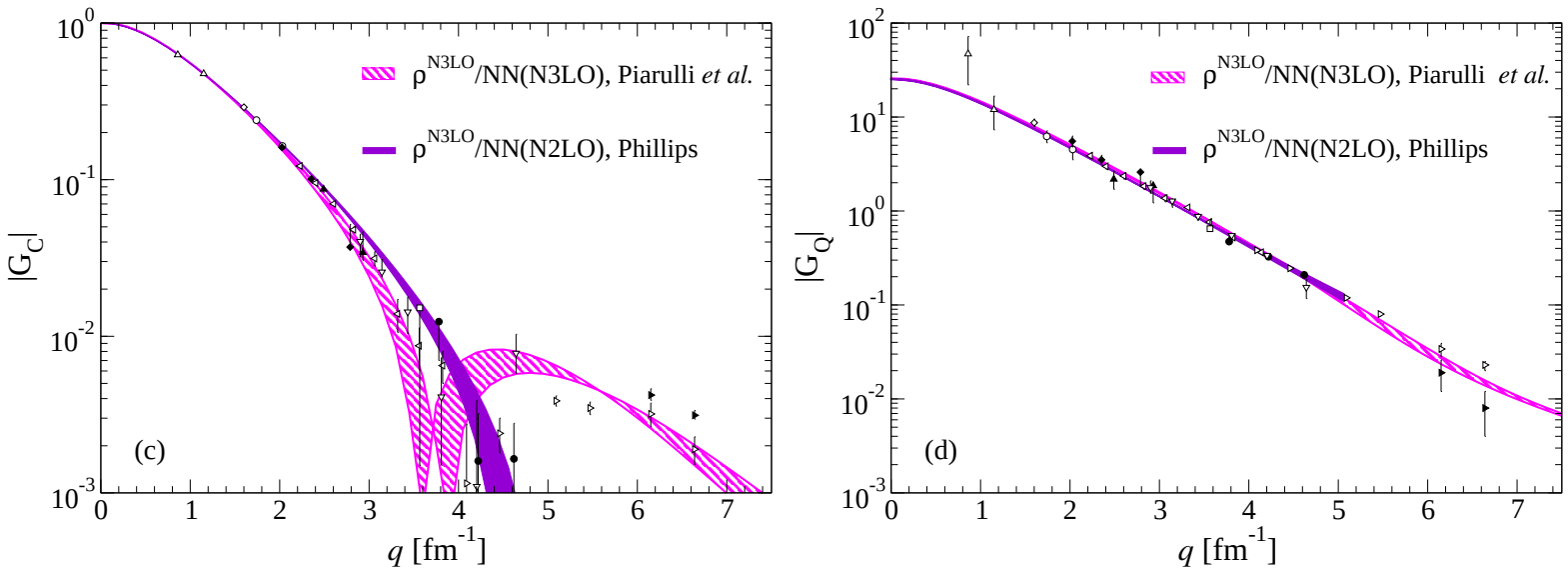


- $npd\gamma$ x-section and $\mu_V(^3H/^3He)$ m.m. are within 1% and 3% of EXPT
- negligible dependence on the cutoff

Piarulli *et al.* PRC87(2013)014006

Predictions with χEFT EM currents for the deuteron Charge and Quadrupole f.f.'s

Bands represent cutoff Λ dependence

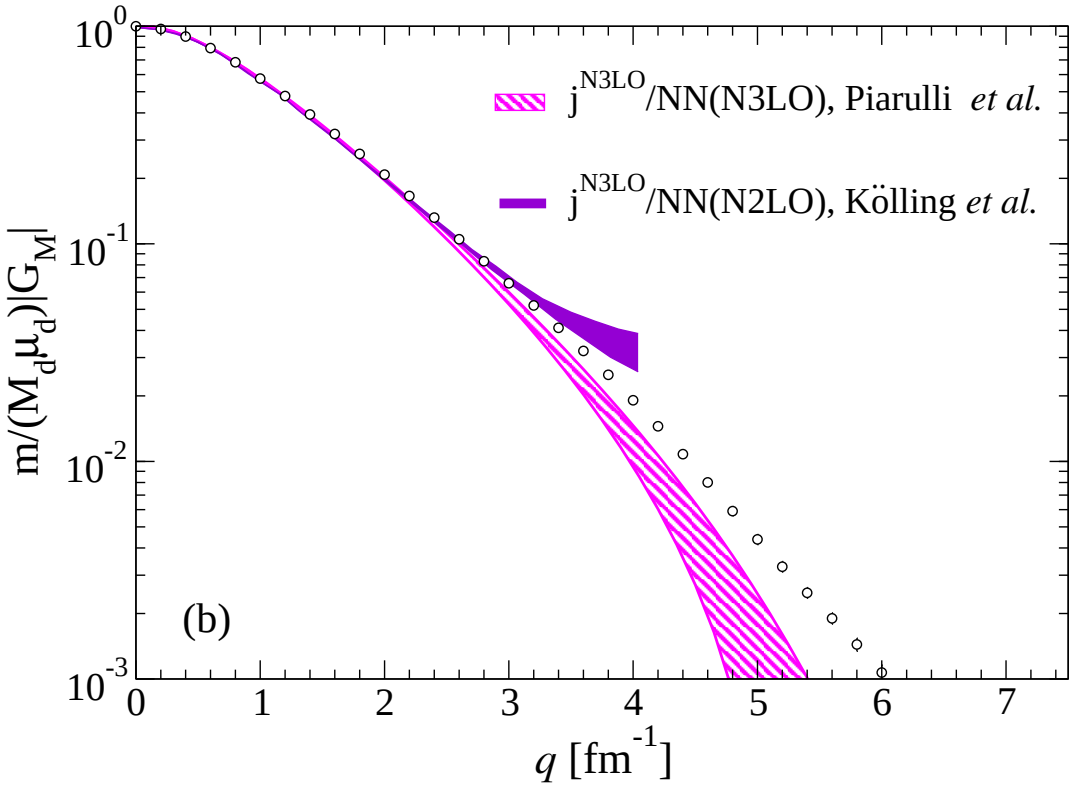


$*$ Calculations include nucleonic form factors taken from EXPT data $*$

J.Phys.G34(2007)365 & PRC87(2013)014006

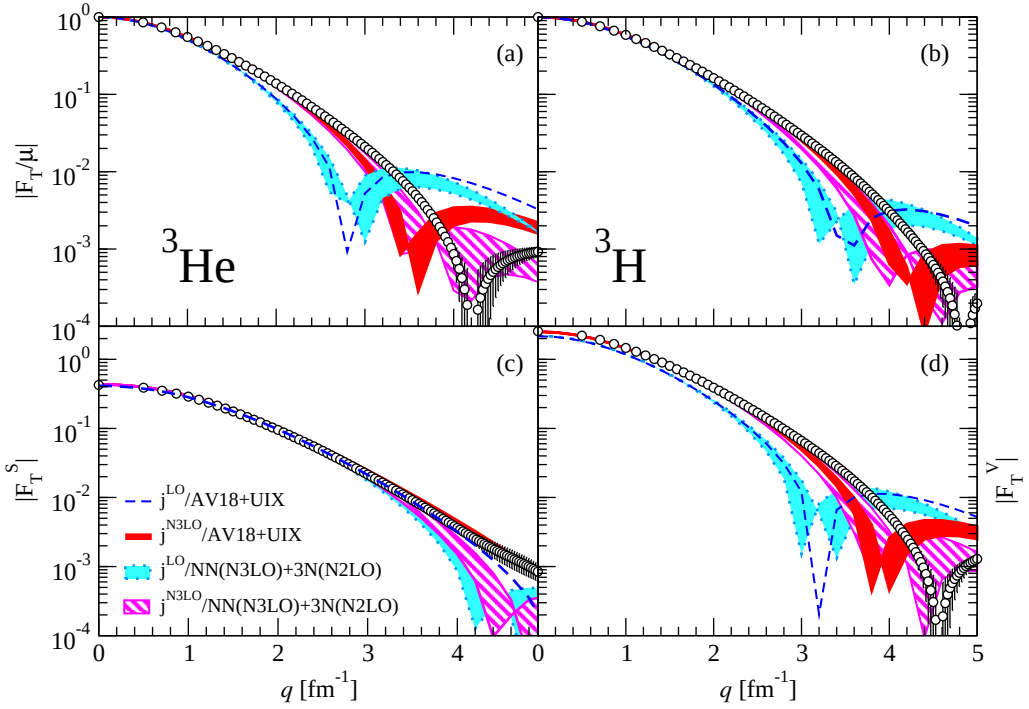
Predictions with χEFT EM currents for the deuteron magnetic f.f.

Bands represent cutoff Λ dependence



PRC86(2012)047001 & PRC87(2013)014006

Predictions with χEFT EM currents for ^{3}He and ^{3}H magnetic f.f.'s



LO/N3LO with AV18+UIX – LO/N3LO with χ-potentials NN(N3LO)+3N(N2LO)

- ^{3}He/^{3}H m.m.'s used to fix EM LECs; $\sim$ 10% correction from two-body currents
- Two-body corrections crucial to improve agreement with EXPT data

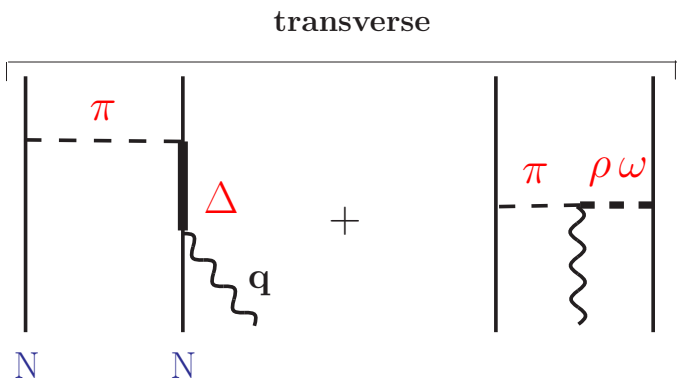
Piarulli *et al.* PRC87(2013)014006

Electromagnetic Currents from Nuclear Interactions aka Standard Nuclear Physics Approach (SNPA) Currents aka Meson Exchange Currents (MEC)

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

1) "Longitudinal" component fixed by current conservation
2) "Plus transverse" component "model dependent"

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

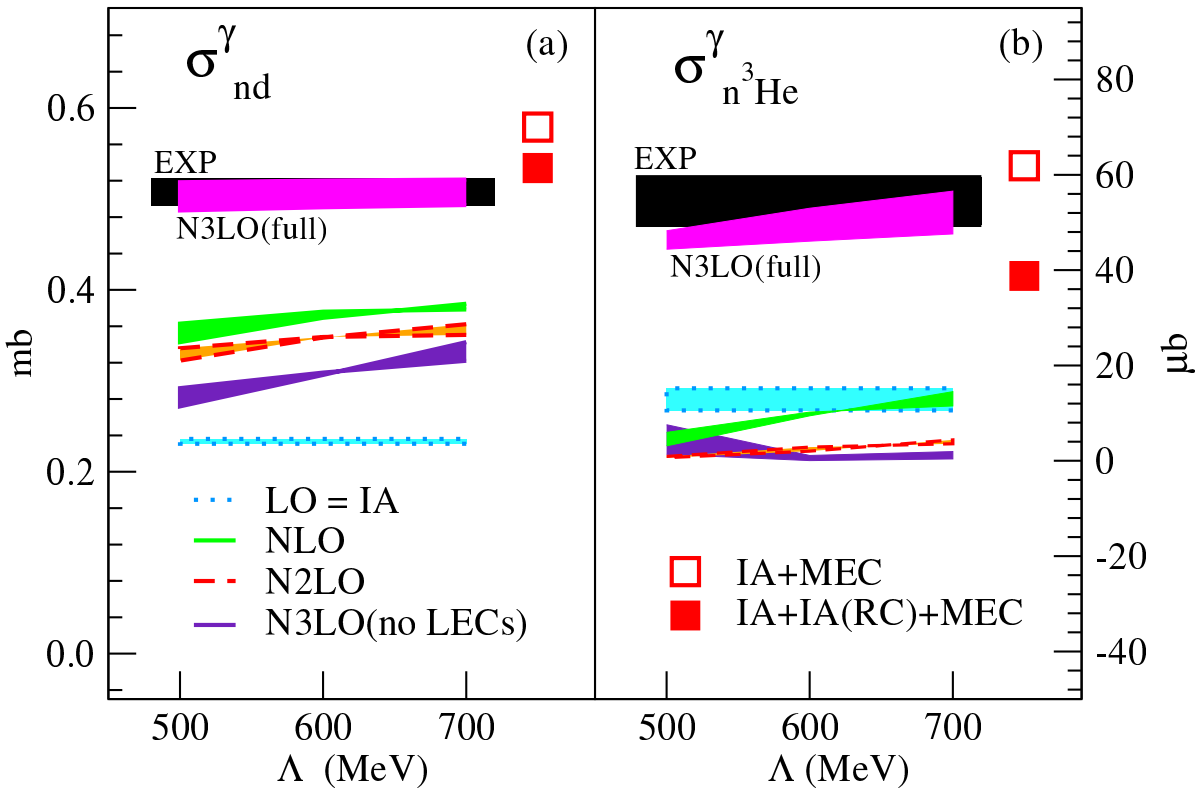


* If v_{ij} = AV18 $\rightarrow \mathbf{j}^{(2)}(v)$ has the same range of applicability ($\sim$ 1 GeV) as the AV18 *

Villars, Myiazawa (40-ies), Chemtob, Riska, Schiavilla ...

see, *e.g.*, Marcucci *et al.* PRC**72**(2005)014001 and references therein

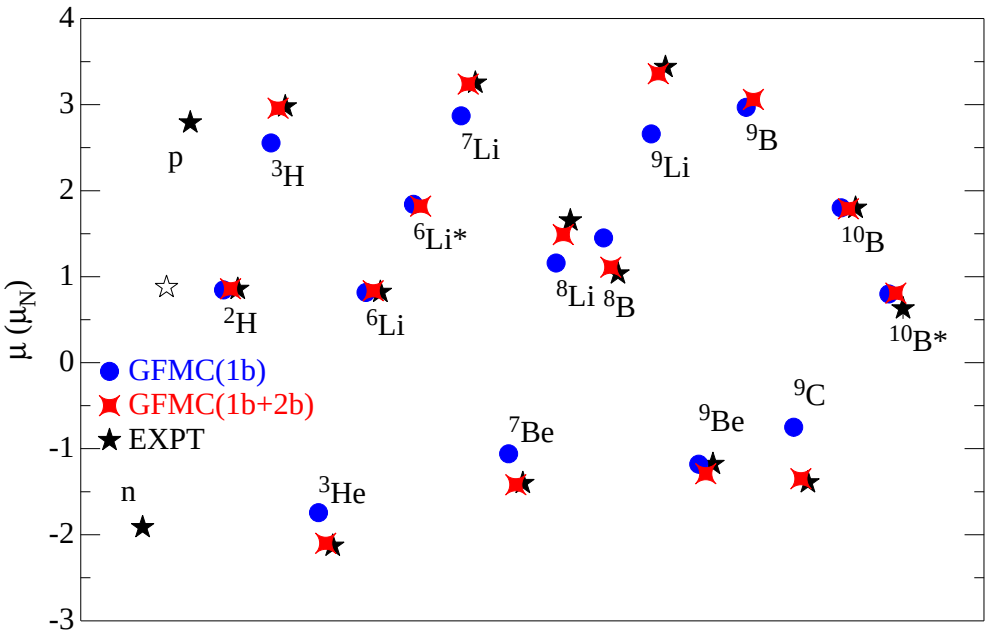
Chiral vs Conventional Approach

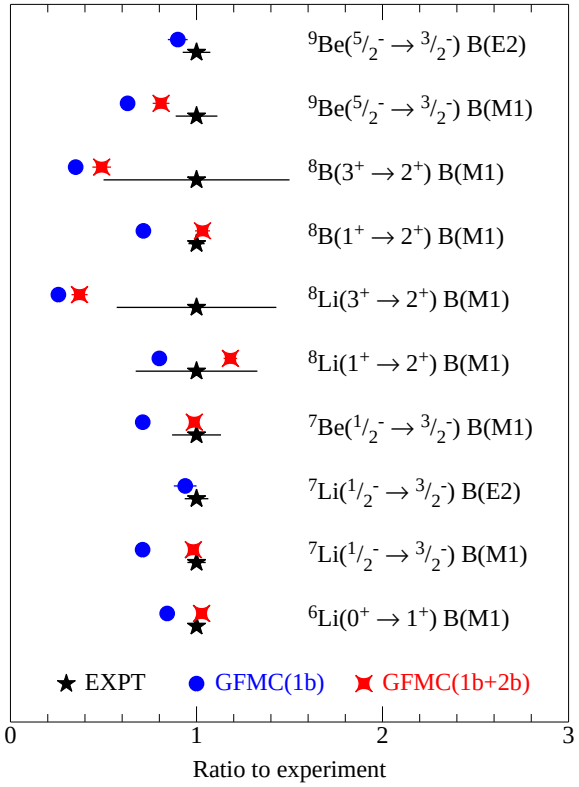


Girlanda *et al.* PRL105(2010)232502

Power Counting doesn't know about suppressions/cancellations at LO

Magnetic Moments and M1 Transitions

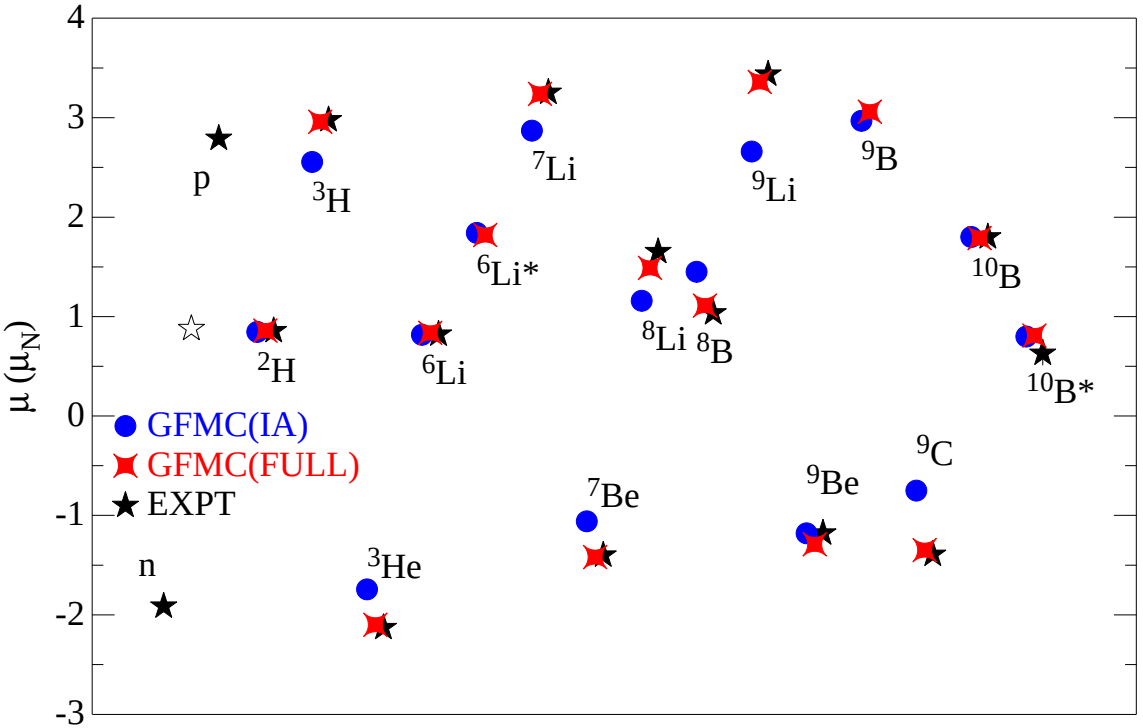




* 2b electromagnetic currents bring the THEORY in agreement with the EXPT
* $\sim 40\%$ 2b-current contribution found in ^{9}C m.m.
* $\sim 60-70\%$ of total 2b-current component is due to one-pion-exchange currents
* $\sim$ 20-30% 2b found in M1 transitions in ^{8}Be

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

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

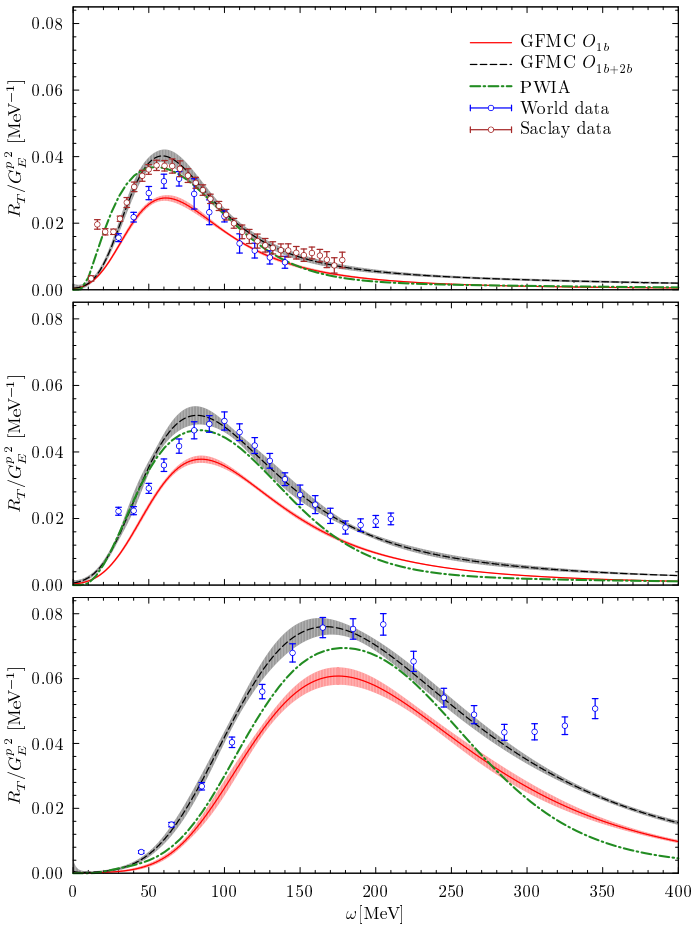
$$Q = \max\left[\frac{m_\pi}{\Lambda}, \frac{p}{\Lambda}\right]$$

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’ *
* “Conventional” and χEFT currents qualitatively in agreement, χEFT isoscalar currents provide better description exp data *
Pastore *et al.* PRC87(2013)035503

Recent Developments on ^{12}C
Quantum Monte Carlo Calculations of Nuclear Responses and Sum Rules

Electromagnetic Transverse Responses



$q = [300 - 750]$ MeV

More by Alessandro Lovato on THUR @ 2:30 pm WH3NE

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

Chiral Electroweak Currents (Incomplete List of Credits)

* Electromagnetic Currents *

* Park, Min, and Rho *et al.* - NPA596(1996)515
  applications to A=2–4 systems including magnetic moments and M1 properties and radiative captures by Song, Lazauskas, Park *at al.*
* Meissner, Kölling, Epelbaum, Krebs *et al.* - PRC80(2009)045502 & PRC84(2011)054008
  applications to A=2–4 systems including d and ^{3}He photodisintegration by Rozpedzik *et al.*; d magnetic f.f. by Kölling, Epelbaum, Phillips; radiative $N-d$ capture by Skibinski *et al.* (2014)
* Phillips

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

* Axial Currents *

* Park, Min, and Rho *et al.* - PhysRept233(1993)341
  applications to A=2–4 systems including μ-capture, pp-fusion, hep ·
* Krebs and Epelbaum *et al.* - AnnalsPhys378(2017)317
* Baroni *et al.* - PRC93(2016)015501
  applications to low-energy neutrino scattering off d and Quantum Monte Carlo calculations of β-decay matrix elements in A=3-10 nuclei

Observations

* Chiral Effective Field Theory *

* Chiral Formulation of Nuclear Physics is extremely successful
* But limited to low-energies
* Inclusion of the Δ possibly allows for applications to higher energies

* "Conventional" Formulation *

* "Conventional" Formulation of Nuclear Physics is extremely successful
* But hard to be systematically improved
* "Conventional" Currents (other names are Meson Exchange Currents, MEC, or Standard Nuclear Physics Approach Currents, SNAP) satisfy the continuity equation (with, *e.g.*, the AV18) by construction (they have the same range of applicability as the AV18, *i.e.* ~ 1 GeV)

Conclusion and Outlook I

* The Microscopic picture of the nucleus based on many-body interactions and electroweak currents successfully explains the data both qualitatively and quantitatively

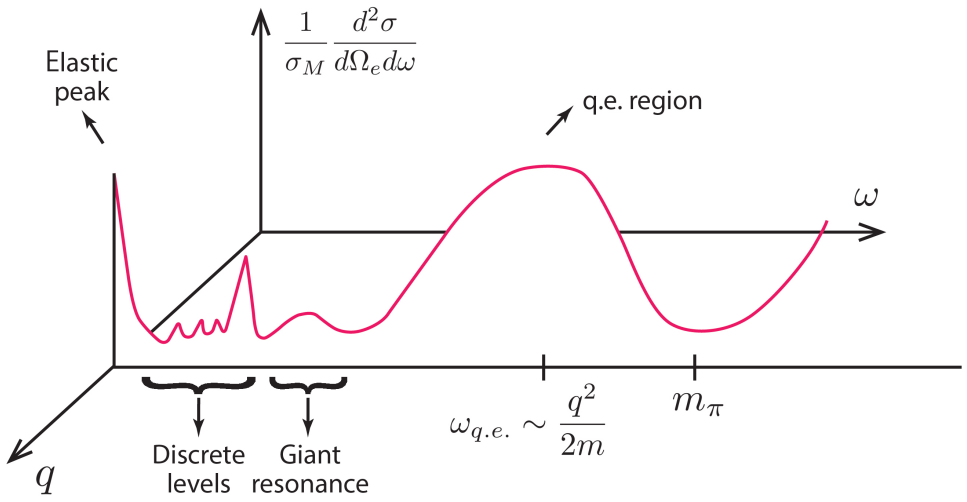
* It explains the spectra and shapes of nuclei

* It has been validated against electromagnetic observables in a wide range of energies from keV (relevant to astrophysics) to GeV (relevant to accelerator neutrino experiments)

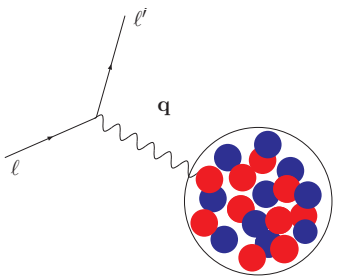
* Two-body physics, correlations and two-body currents, is essential to understand the data both for static nuclear properties (spectra, electromagnetic moments, nuclear form factors) and dynamical properties (transitions in low-lying nuclear states, nuclear responses)

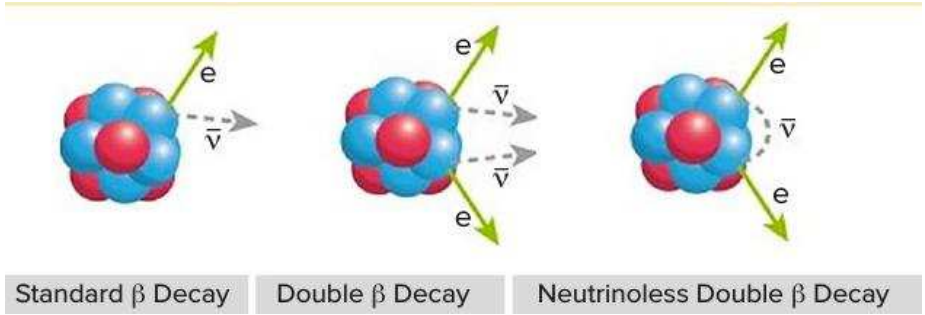
* We want the same coherent picture for interactions with neutrinos *

Nuclei and Neutrinos



* ν-A scattering "Anomalies" the QE region
* "g_A-problem" low-values of momentum/energy transfer
* Scarce data at moderate values of momentum transfer

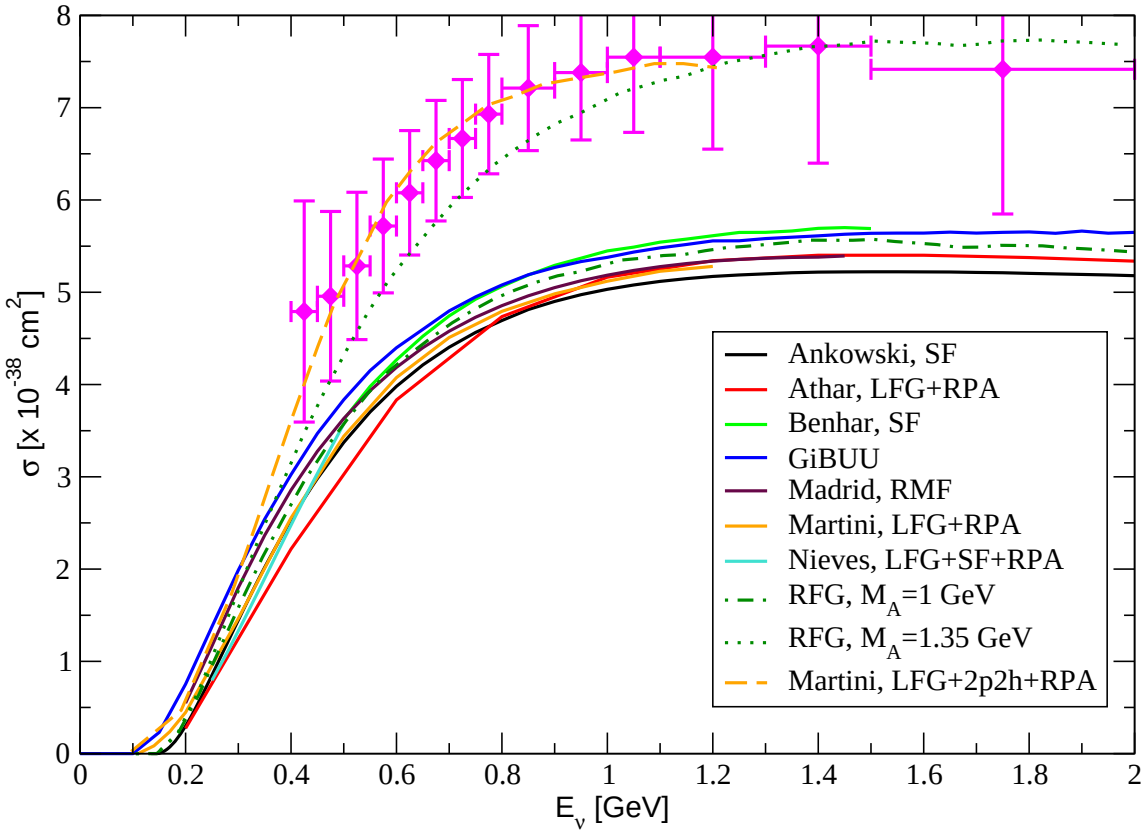




“Anomalies” ∼ GeV

Neutrino-Nucleus scattering

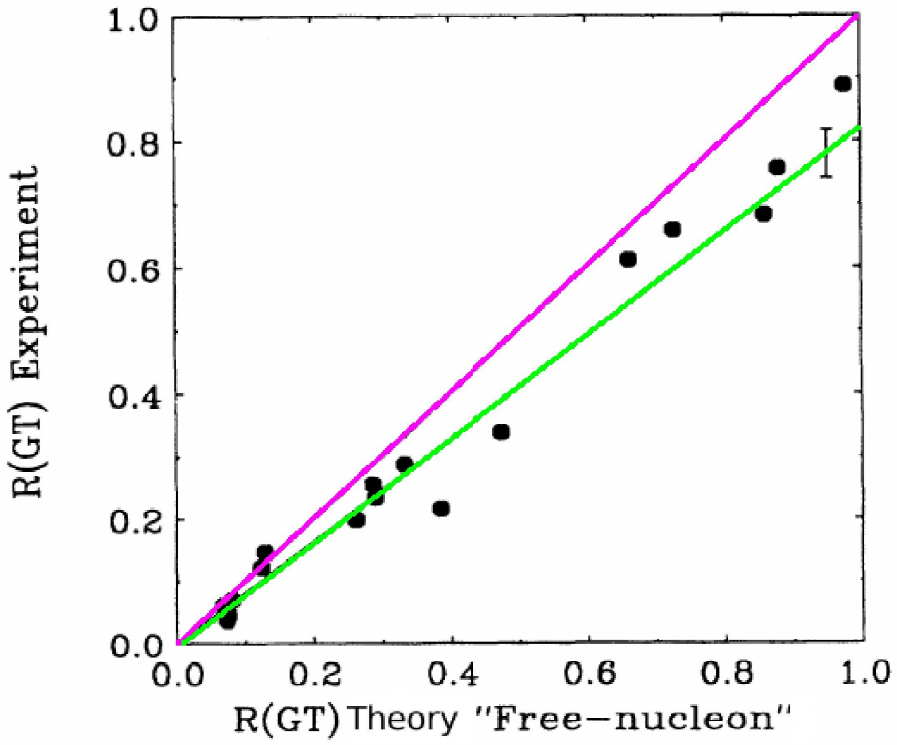
CCQE on ^{12}C



Alvarez-Ruso arXiv:1012.3871

"Anomalies" $q \sim 0$: The "g_A problem"

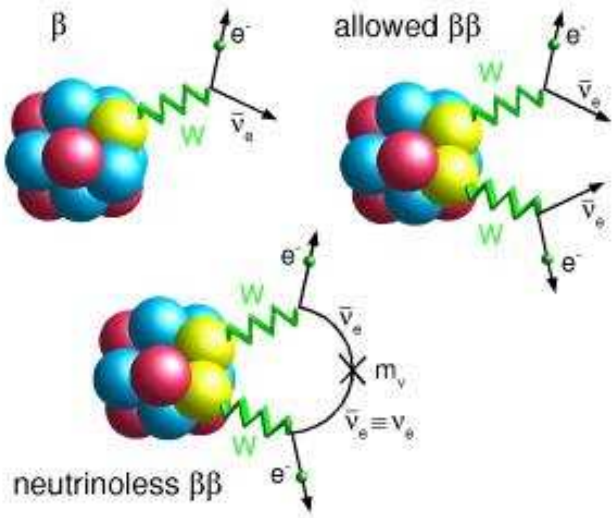
Gamow-Teller Matrix Elements Theory vs Expt



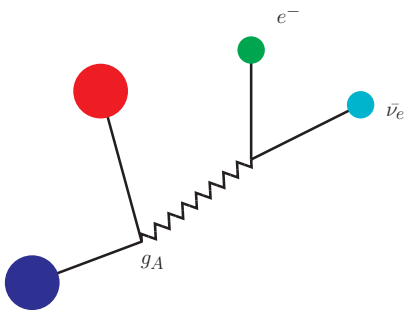
in $3 \leq A \leq 18 \longrightarrow g_A^{\text{eff}} \simeq 0.80\, g_A$

Chou *et al.* PRC47(1993)163

$\beta-$ and $0\nu\beta\beta$-decay



Berna U.

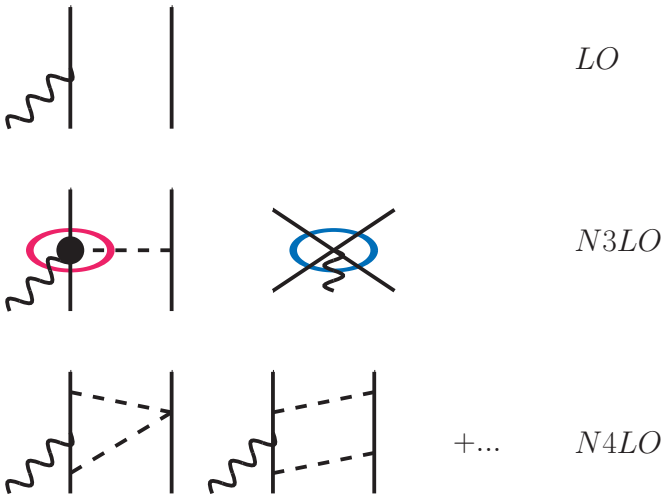


Nuclear Interactions and Axial Currents

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

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

where v_{ij} and V_{ijk} are two- and three-nucleon operators based on EXPT data fitting and fitted parameters subsume underlying QCD;
we use AV18+IL7

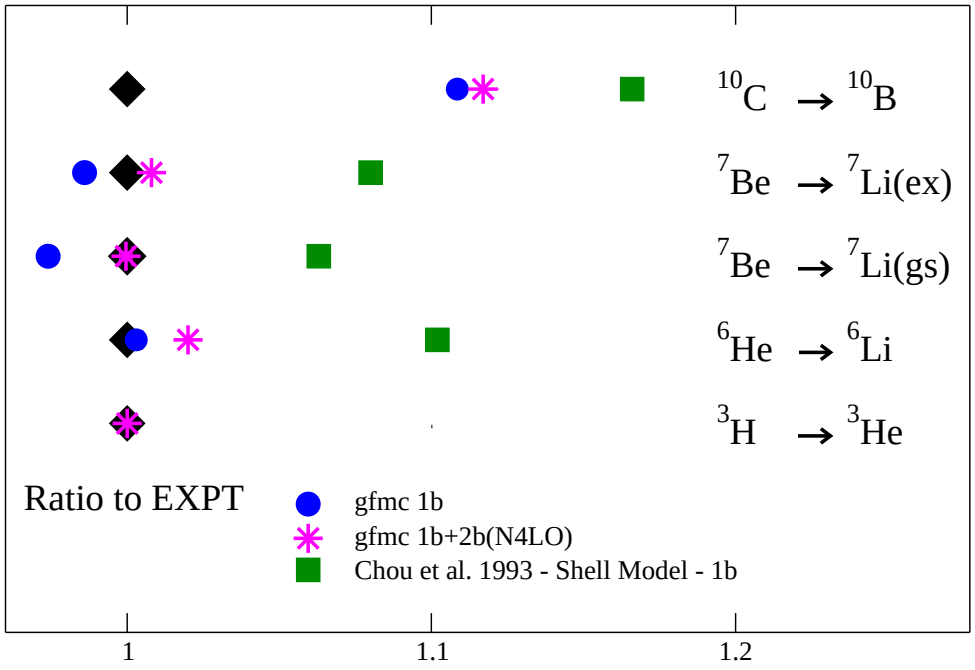


A. Baroni *et al.* PRC93(2016)015501

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 beta-decay Baroni *et al.* PRC94(2016)024003

Single β-decay Matrix Elements in $A = 6$–10



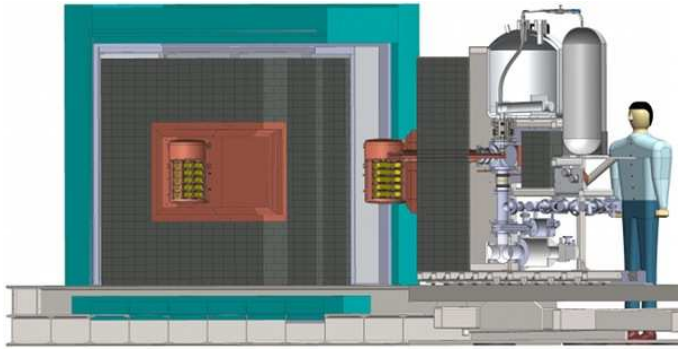
Pastore *et al.* arXiv:1709.03592

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

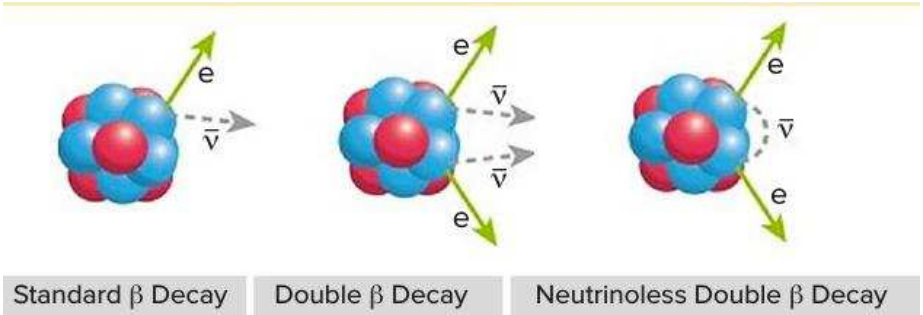
Fundamental Physics Quests: Double Beta Decay

observation of $0\nu\beta\beta$-decay
$\rightarrow$
lepton # $L = l - \bar{l}$ not conserved
$\rightarrow$
implications in
matter-antimatter imbalance



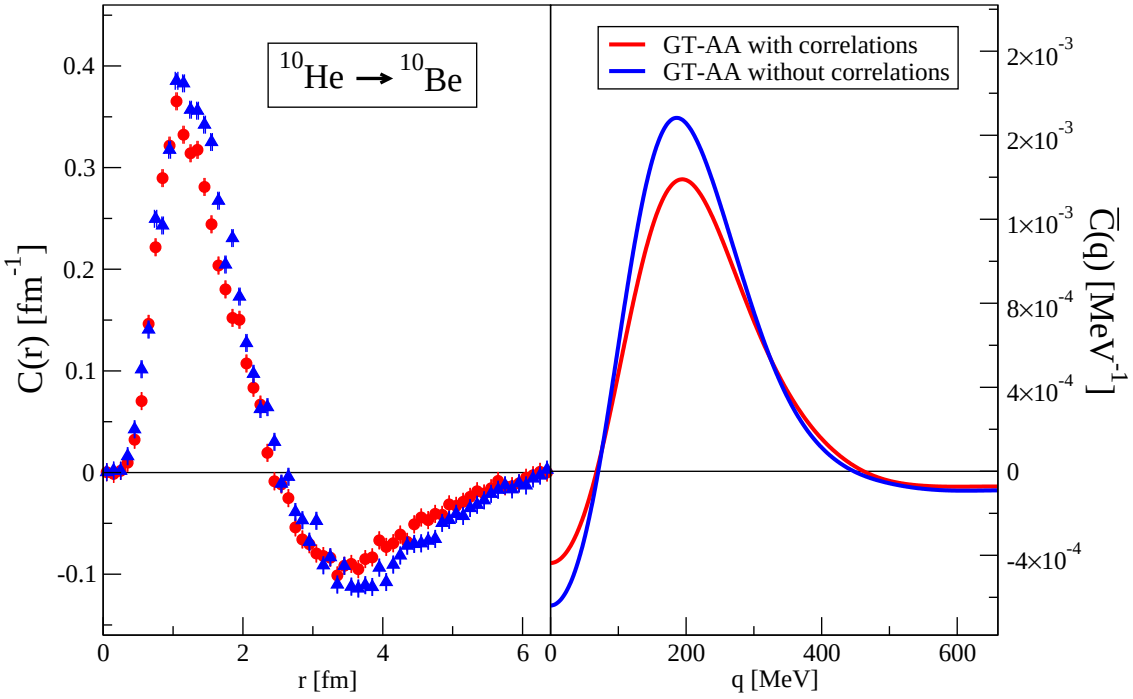
Majorana Demonstrator

* detectors' active material ^{76}Ge *
$0\nu\beta\beta$-decay $\tau_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)
1 ton of material to see (if any) ~ 5 decays per year
* also, if nuclear m.e.'s are known, absolute ν-masses can be extracted *



2015 Long Range Plane for Nuclear Physics

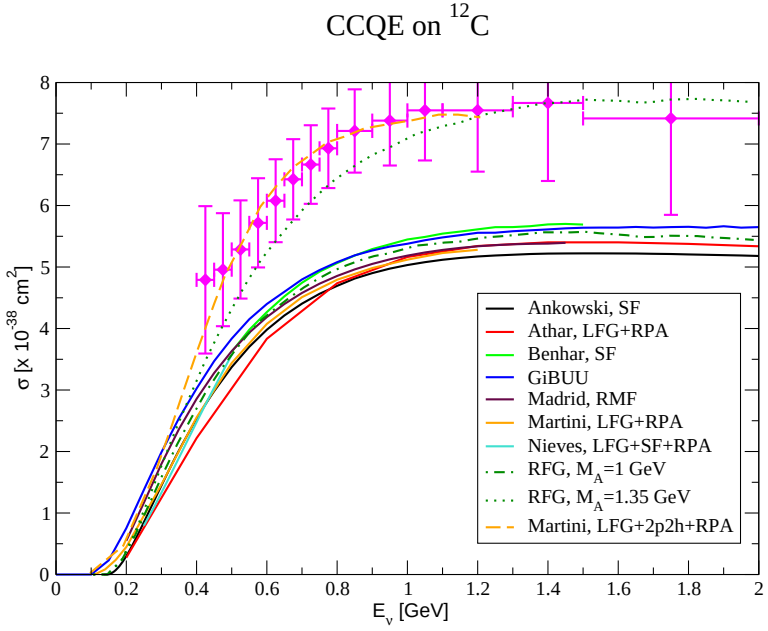
Momentum Dependence



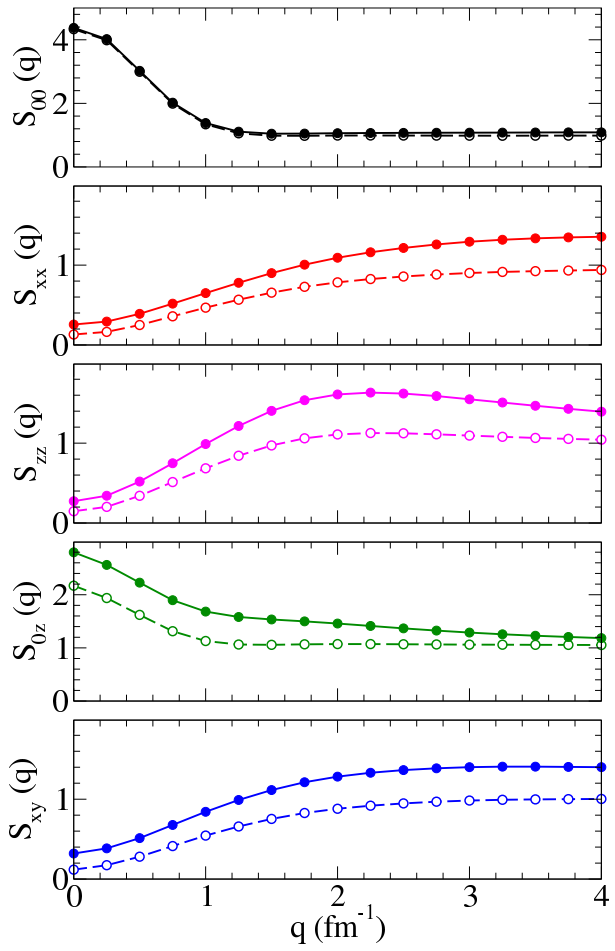
* Peaks at ~ 200 MeV
* no 'pion-exchange-like' correlation operators U_{ij}
* yes 'pion-exchange-like' correlation operators U_{ij}
* $\sim 10\%$ increase in the matrix elements corresponds to a 'g_A-quenching' of ~ 0.95
* as opposed to ~ 0.83 found in $A = 10$ single beta decay

Pastore, Mereghetti, Dekens, Carlson, Cirigliano, Wiringa arXiv:1710.05026

Recent Developments on ^{12}C: Weak Responses



Alvarez-Ruso arXiv:1012.3871



$q = [300 - 750]$ MeV

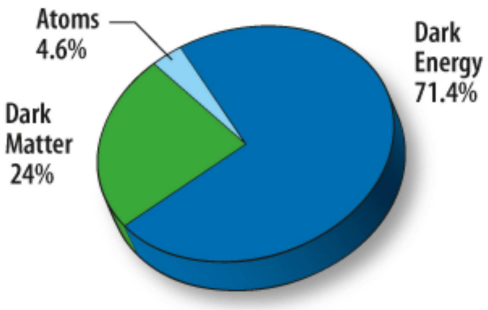
Lovato, Gandolfi *et al.* - PRL112(2014)182502

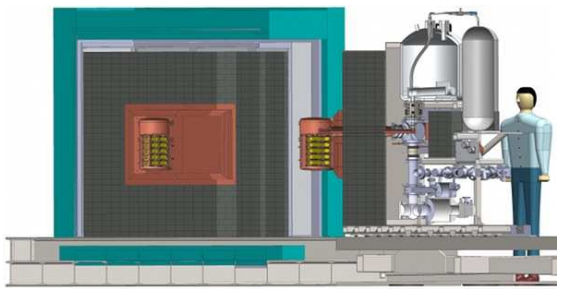
More by Alessandro Lovato on THUR @ 2:30 pm WH3NE

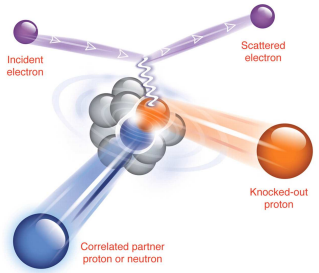
Conclusion and Outlook II

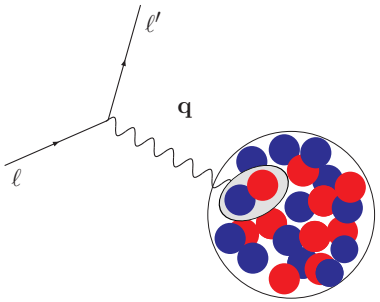
* We are constructing a coherent picture of neutrino-nucleus interactions spanning wide rage of energy and momenta
* Many-body correlations contribute to explain the "g_A-problem"
* Studies on neutrinoless double beta decay indicate a less severe "g_A-problem" at moderate values of momentum transfer
* Two-body physics, correlations and two-body currents, play a crucial role in the explanation of electromagnetic responses of nuclei
* Microscopic Calculations of weak response indicate that two-body physics important in electroweak responses More by Alessandro Lovato on THUR @ 2:00 pm
* We are addressing how to retain two-body physics in approximated Microscopic calculations of responses in $A > 12$ nuclei
* Benchmark with existing exact calculations by Lovato *et al.* is excellent
* All this work impacts on Fundamental Physics Quests! *

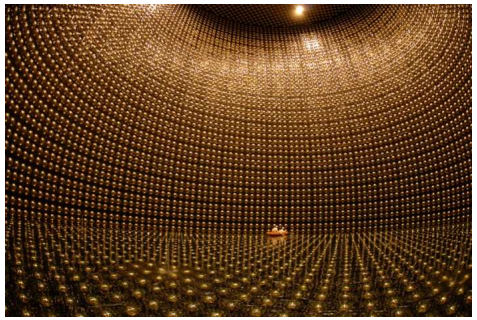
Outlook

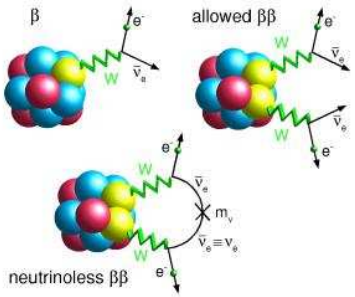


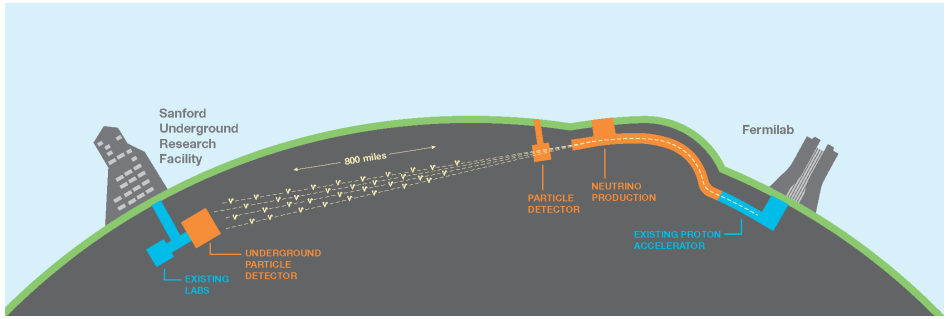


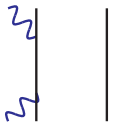




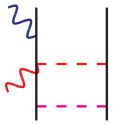






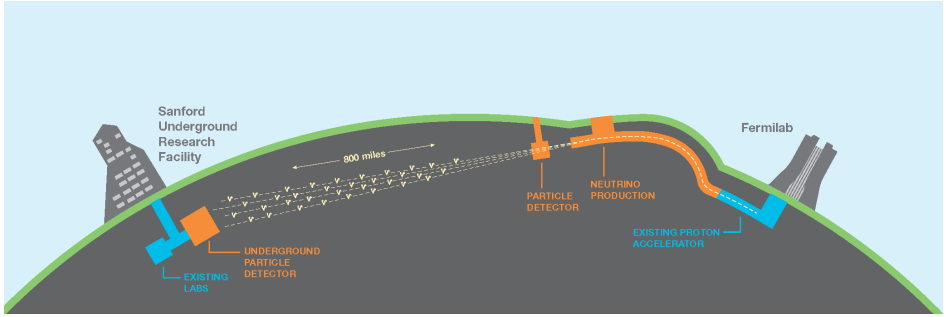


$$\langle \mathbf{j}_{1b}^{\dagger} \ \mathbf{j}_{1b} \rangle \ > 0$$

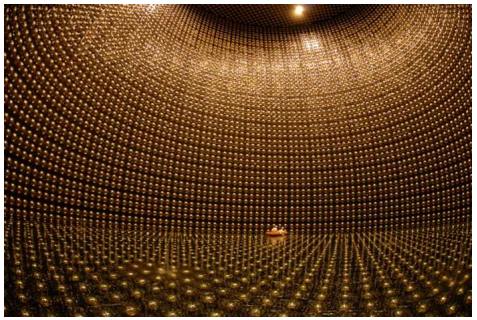


$$\langle \mathbf{j}_{1b}^{\dagger} \ \mathbf{j}_{2b} \ v_{\pi} \rangle \propto \langle v_{\pi}^{2} \rangle \ > 0$$

Fundamental Physics Quests: Accelerator Neutrinos



LBNF



T2K

neutrinos oscillate

$\rightarrow$

they have tiny masses

=

BSM physics

Beyond the Standard Model

Simplified 2 flavors picture:

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

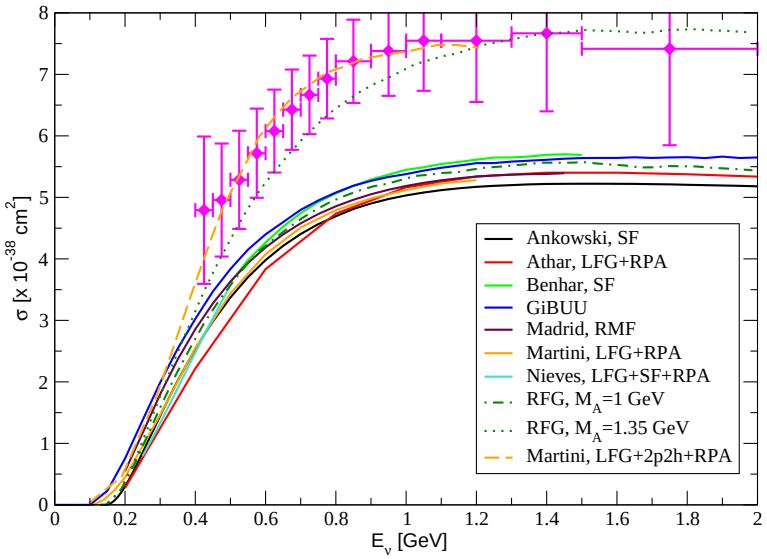
* Unknown *

ν-mass hierarchy, CP-violation,

accurate mixing angles

Neutrino-Nucleus scattering

CCQE on ^{12}C



Alvarez-Ruso arXiv:1012.3871

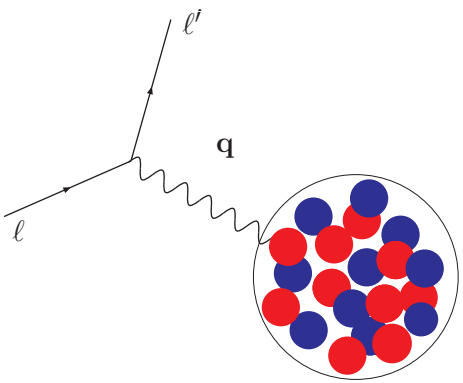
DUNE, MiniBoone, T2K, Minerνa ... active material * ^{12}C, ^{40}Ar, ^{16}O, ^{56}Fe, ... *

Inclusive (e,e') scattering: Intro to Short-Time-Approximation

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

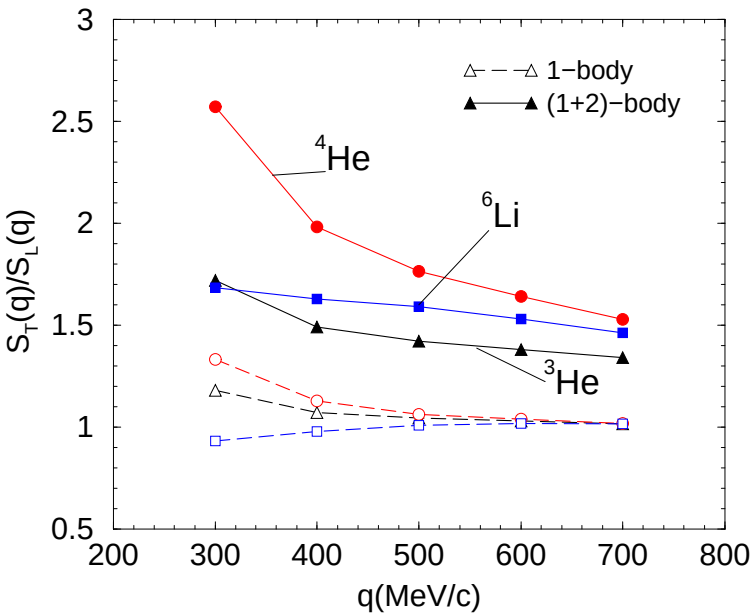
Exploit integral properties of the response functions + closure to avoid explicit calculation of the final states

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

* 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

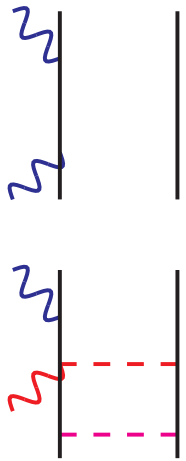


Carlson *et al.* PRC65(2002)024002

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

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

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



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

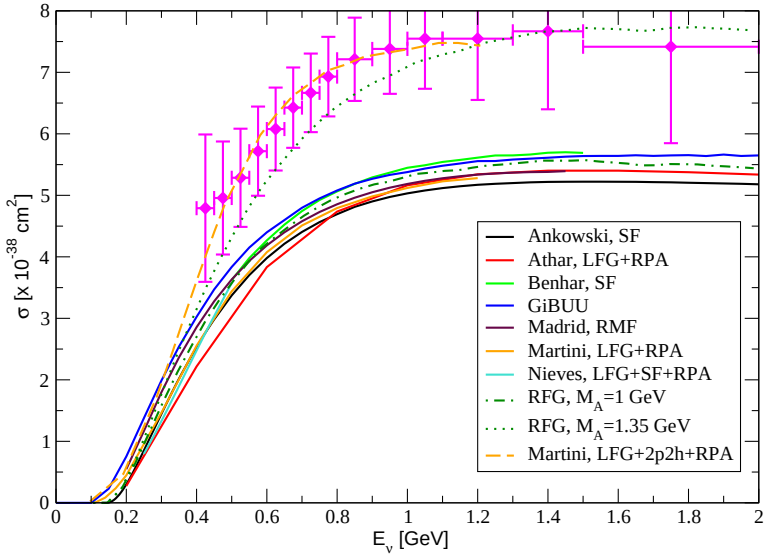
$$\langle \mathbf{j}_{1b}^\dagger\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle > 0$$

Carlson at latest INT neutrino workshop Dec. 2016

Recent Developments on ^{12}C
Quantum Monte Carlo Calculations of Nuclear Responses and Sum Rules

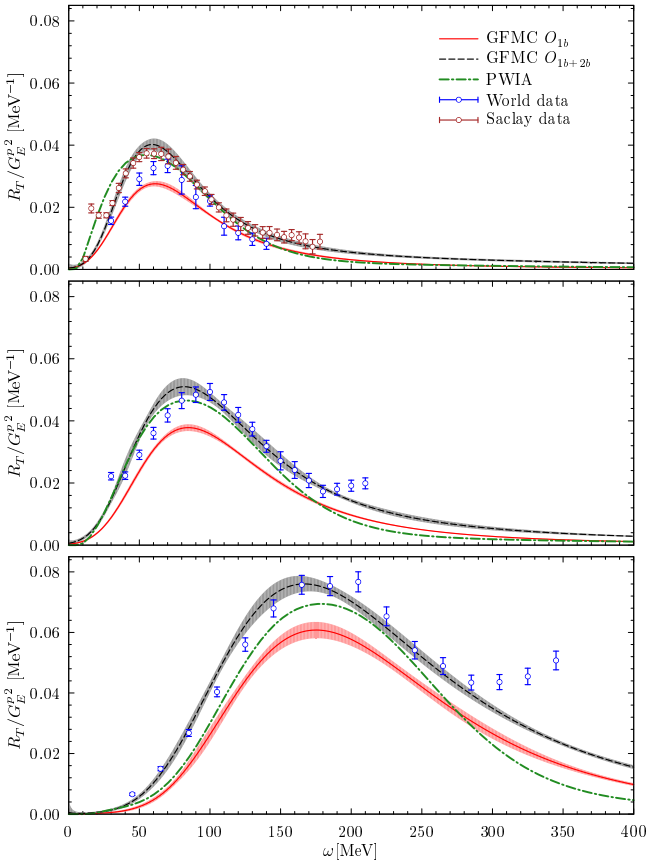
Charge-Current Cross Section

CCQE on ^{12}C



Alvarez-Ruso arXiv:1012.3871

Electromagnetic Transverse 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?

Factorization: Short-Time Approximation

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

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

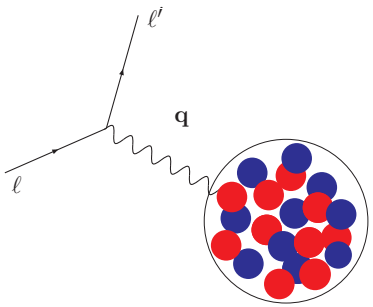
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

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

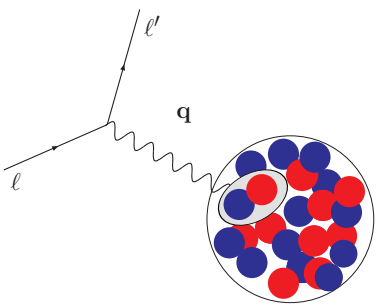
and

$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b



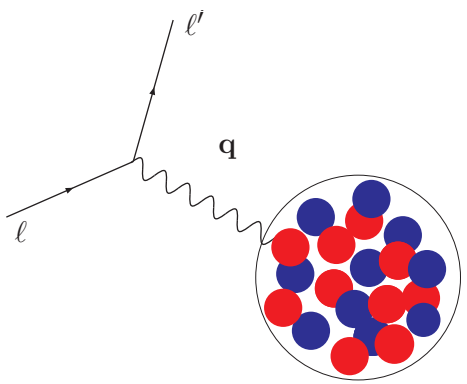
2b



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)



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

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

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

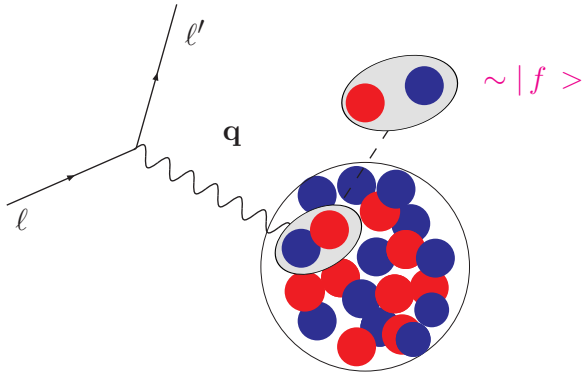
* PWIA Longitudinal Response in terms of the p-momentum distribution $n_p(\mathbf{k})$ *

$$R_L^{\text{PWIA}}(q,\omega) = \int d\mathbf{k}\, n_p(\mathbf{k})\delta\left(\omega - \frac{(\mathbf{k}+\mathbf{q})^2}{2m_N} + \frac{\mathbf{k}^2}{2m_N}\right)$$

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



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

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

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

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

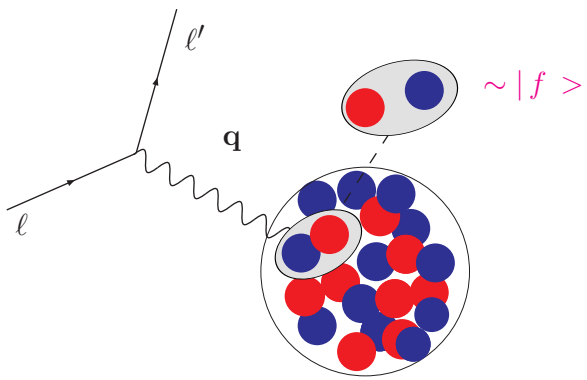
* $R_\alpha(q,\omega)$ requires only direct calculation of g.s. $|0\rangle$ w.f.'s *

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

The Short-Time Approximation

In STA:

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



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

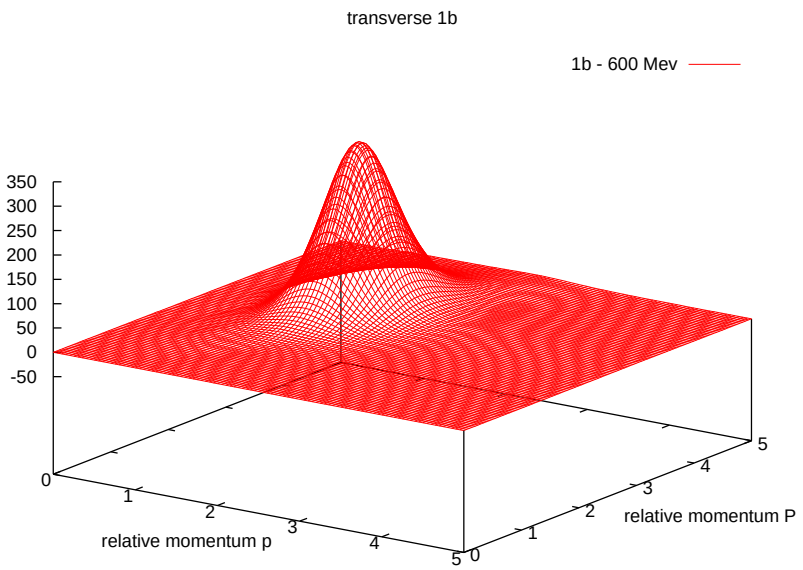
$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) = 1\text{b} + 2\text{b}$$

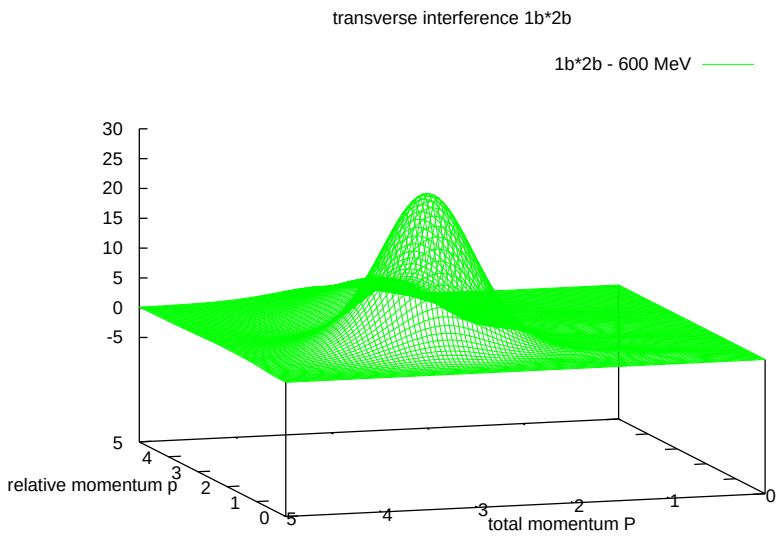
$|f\rangle$ is a function of $\mathbf{p}$ and $\mathbf{P}$ e.g. for free propagator $\sim e^{i\mathbf{p}\cdot\mathbf{r}} e^{i\mathbf{P}\cdot\mathbf{R}}$

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

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

The Short-Time Approximation

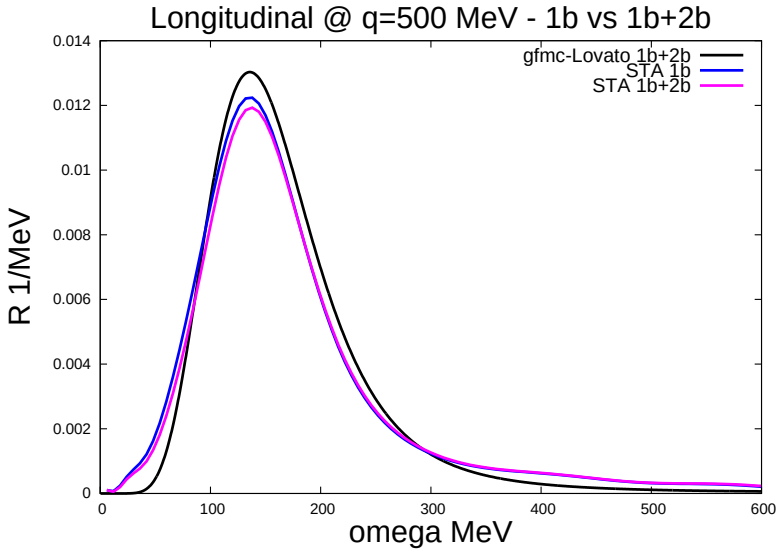


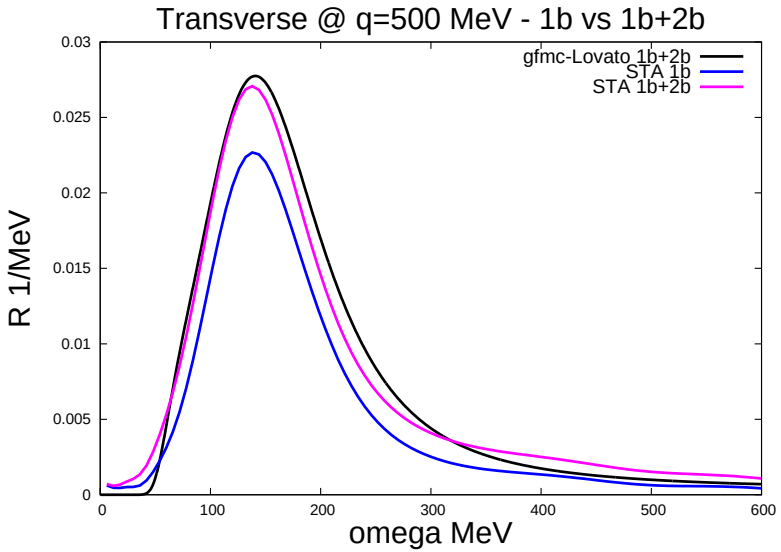


300 core hours with 1b + 2b for ^4He

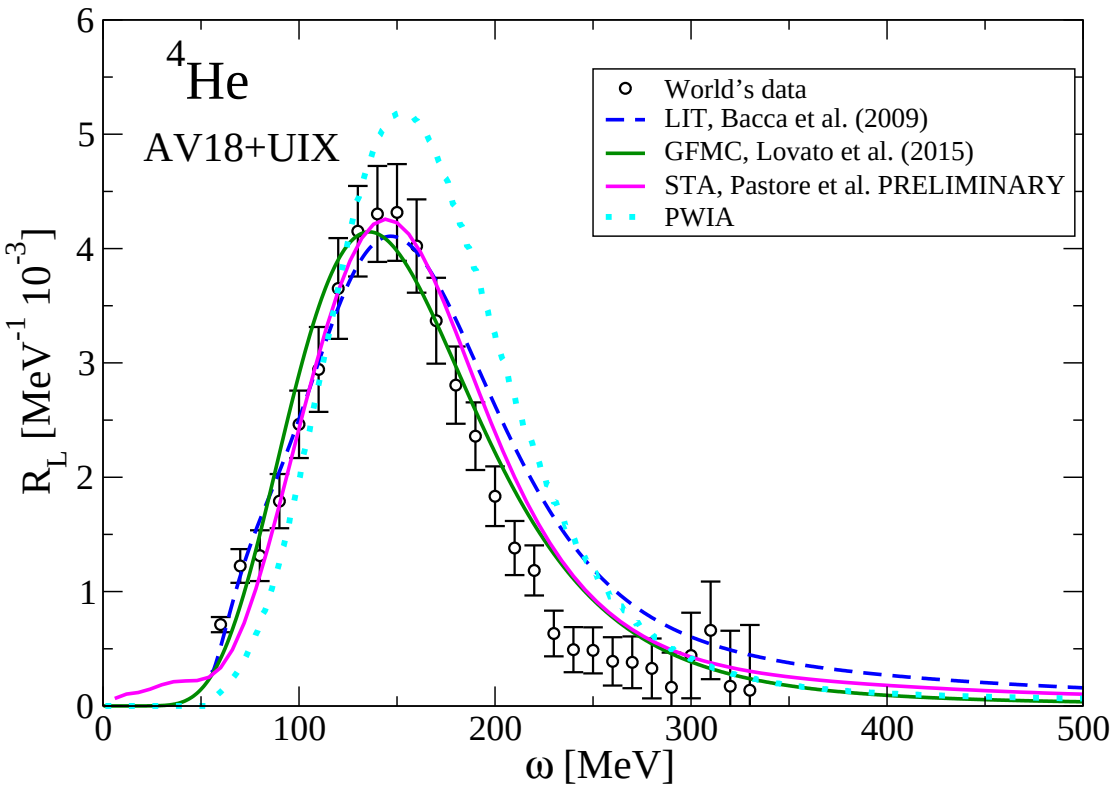
Preliminary results

1b vs 1b+2b


Longitudinal @ q=500 MeV - 1b vs 1b+2b
gfmc-Lovato 1b+2b
STA 1b
STA 1b+2b
R 1/MeV
omega MeV
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
100
200
300
400
500
600

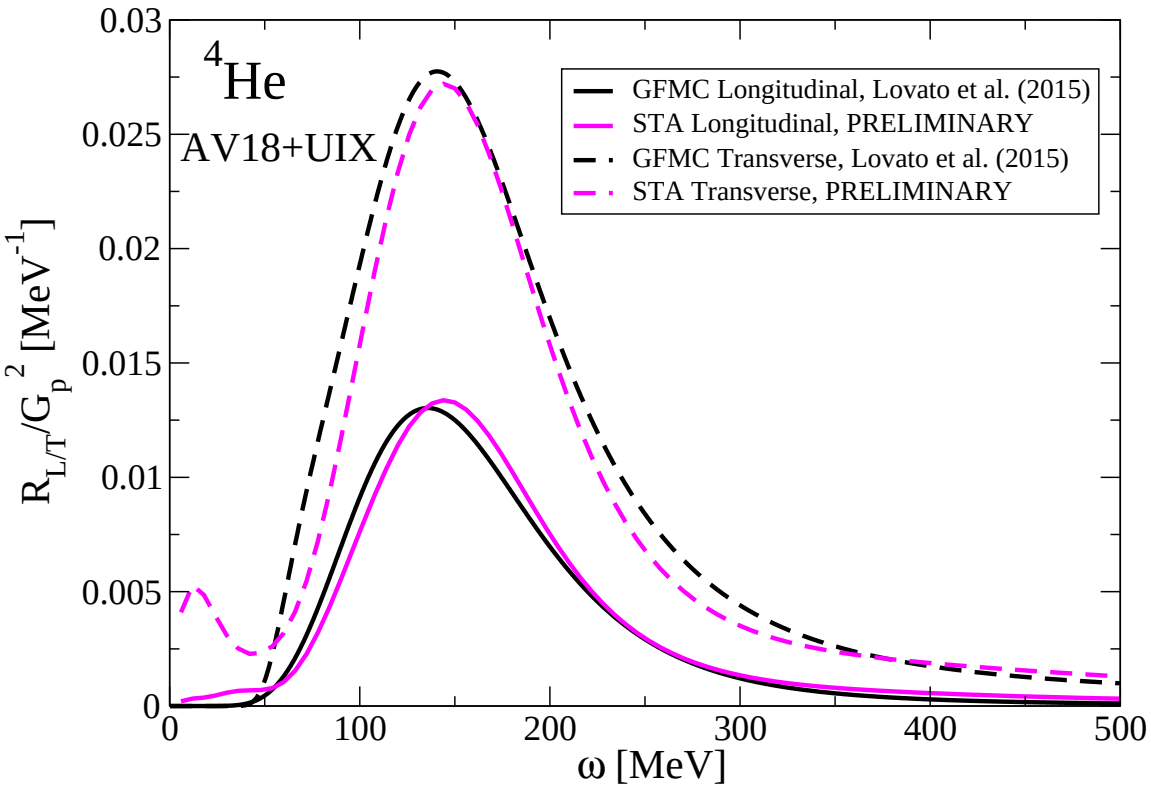

Transverse @ q=500 MeV - 1b vs 1b+2b
gfmc-Lovato 1b+2b
STA 1b
STA 1b+2b
R 1/MeV
omega MeV
0.03
0.025
0.02
0.015
0.01
0.005
0
0
100
200
300
400
500
600

The Short-Time Approximation



Longitudinal Response function at $q = 500$ MeV

The Short-Time Approximation

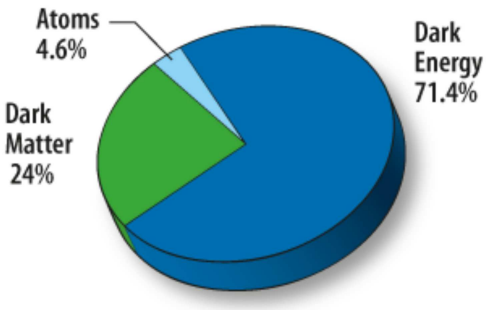


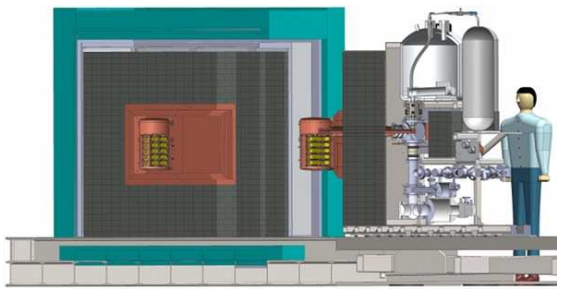
Longitudinal vs Transverse Response Function at $q = 500$ MeV

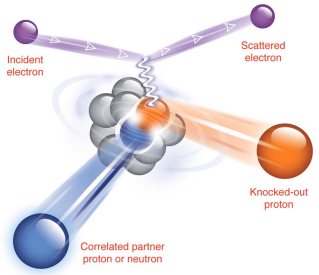
Conclusion and Outlook III

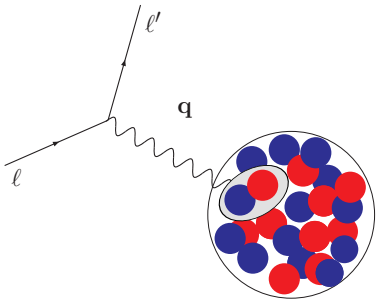
* We are constructing a coherent picture of neutrino-nucleus interactions spanning wide rage of energy and momenta
* Many-body correlations contribute to explain the "g_A-problem"
* Studies on neutrinoless double beta decay indicate a less severe "g_A-problem" at moderate values of momentum transfer
* Two-body physics, correlations and two-body currents, play a crucial role in the explanation of electromagnetic responses of nuclei
* Microscopic Calculations of weak response indicate that two-body physics important in electroweak responses More by Alessandro Lovato on THUR @ 2:00 pm
* We are addressing how to retain two-body physics in approximated Microscopic calculations of responses in $A > 12$ nuclei with the Short Time Approximation
* Benchmark with existing exact calculations by Lovato *et al.* is excellent
* All this work impacts on Fundamental Physics Quests! *

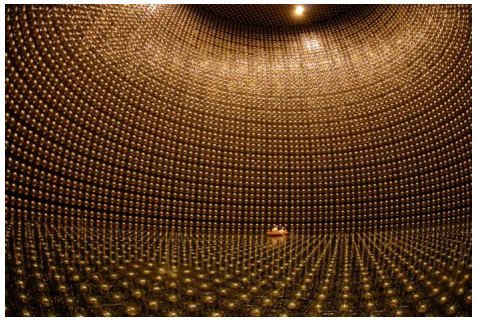
Outlook

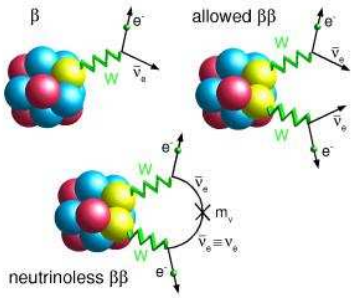


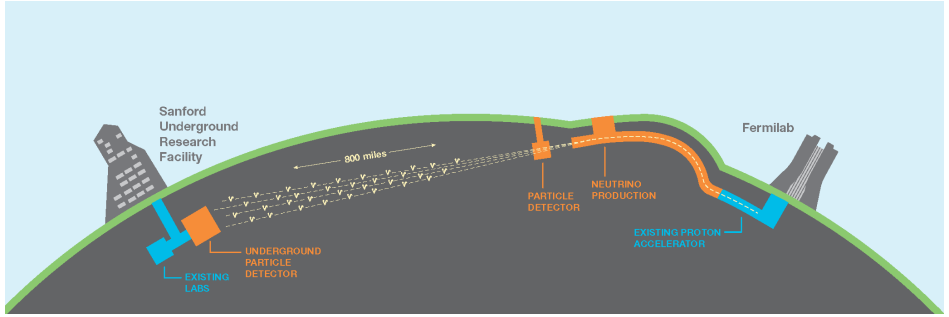


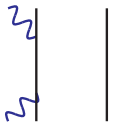




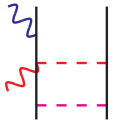








$$\langle \mathbf{j}_{1b}^{\dagger} \ \mathbf{j}_{1b} \rangle \ > 0$$



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

Fundamental Physics with Electroweak Probes of Light Nuclei

June 12 - July 13, 2018

S. Bacca, R. J. Hill, S. Pastore, D. Phillips

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