TRIUMF

Two-body currents and weak decays in light nuclei

Exploring the role of electro-weak currents in Atomic Nuclei

ECT* Trento, April 23-27, 2018

Petr Navratil

TRIUMF

Collaborators:
P. Gysbers (UBC/TRIUMF), S. Quaglioni, K. Wendt (LLNL)

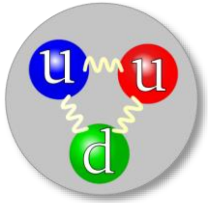
11/05/2018

Discovery, accelerated

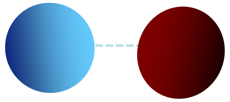
Outline

- Chiral forces and currents
- SRG evolution of forces and transition operators
- Calculations with the new N^4LO NN by Entem, Machleidt and Nosyk
  - Beta decays of light nuclei in NCSM
- Modification of the c_D in the N^3LO NN + 3N
  - Impact on medium mass nuclei
  - Beta decays of light nuclei
- Beta decay results for light nuclei with the N^2LO_{sat}, Hebeler's EM 1.8/2.0, and an inconsistent N^4LO NN + 3N

From QCD to nuclei

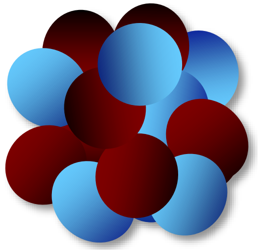


Low-energy QCD



NN+3N interactions from chiral EFT

…or accurate meson-exchange potentials

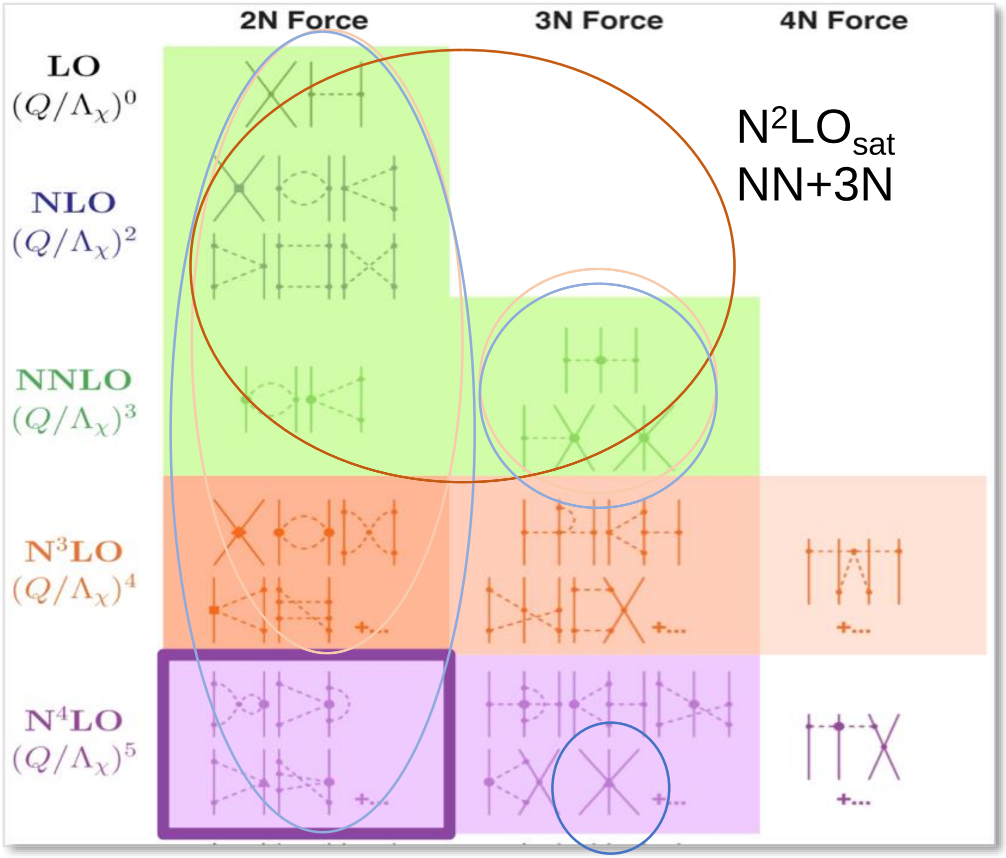


Nuclear structure and reactions

Chiral Effective Field Theory

- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Chiral symmetry of QCD ($m_u \approx m_d \approx 0$), spontaneously broken with pion as the Goldstone boson
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order (Q/Λ_χ)
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD

Λ_χ~1 GeV :
Chiral symmetry breaking scale



N^4LO500 NN
+ N^2LO 3N

N^3LO NN+N^2LO 3N
(NN+3N400, NN+3N500)

Currents in chiral EFT

- Meson-exchange current

PHYSICAL REVIEW C **67**, 055206 (2003)

Parameter-free effective field theory calculation for the solar proton-fusion and hep processes

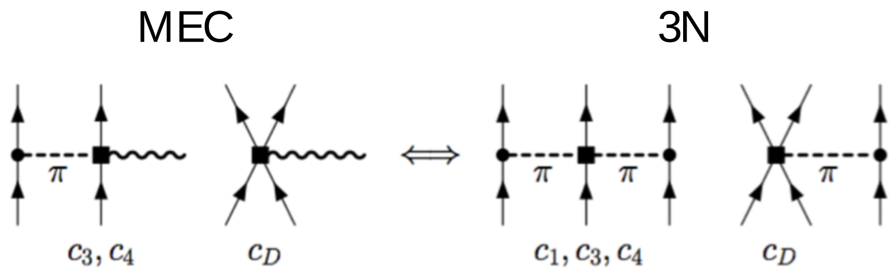
T.-S. Park,[1,2,3] L. E. Marcucci,[4,5] R. Schiavilla,[6,7] M. Viviani,[5,4] A. Kievsky,[5,4] S. Rosati,[5,4] K. Kubodera,[1,2]
D.-P. Min,[8] and M. Rho[1,9]

  - weak axial current
    - one-body: LO - Gamow-Teller

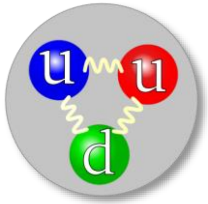
$$\boldsymbol{A}_l = -g_A \tau_l^- e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_l}\left[\boldsymbol{\sigma}_l + \frac{2(\bar{\boldsymbol{p}}_l \boldsymbol{\sigma}_l \cdot \bar{\boldsymbol{p}}_l - \boldsymbol{\sigma}_l \bar{\boldsymbol{p}}_l^2) + i\boldsymbol{q}\times\bar{\boldsymbol{p}}_l}{4m_N^2}\right]$$

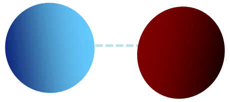
    - two-body: MEC

$$\boldsymbol{A}_{12} = \frac{g_A}{2m_N f_\pi^2}\frac{1}{m_\pi^2+\boldsymbol{k}^2}\left[-\frac{i}{2}\tau_\times^- \boldsymbol{p}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{k} + 4\hat{c}_3 \boldsymbol{k}\boldsymbol{k}\cdot(\tau_1^- \boldsymbol{\sigma}_1 + \tau_2^- \boldsymbol{\sigma}_2) + \left(\hat{c}_4 + \frac{1}{4}\right)\tau_\times^- \boldsymbol{k}\times[\boldsymbol{\sigma}_\times \times \boldsymbol{k}]\right] + \frac{g_A}{m_N f_\pi^2}[2\hat{d}_1(\tau_1^- \boldsymbol{\sigma}_1 + \tau_2^- \boldsymbol{\sigma}_2) + \hat{d}_2 \tau_\times^a \boldsymbol{\sigma}_\times],$$



From QCD to nuclei





Low-energy QCD

↓

NN+3N interactions from chiral EFT

…or accurate meson-exchange potentials

↓

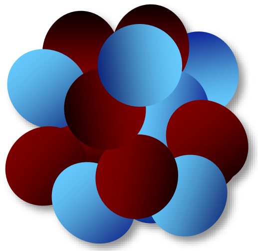
$$H|\Psi\rangle = E|\Psi\rangle$$

Many-Body methods

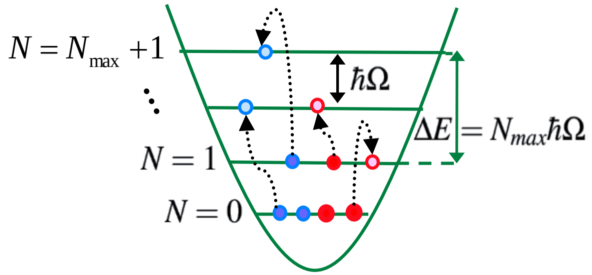
NCSM, NCSM/RGM, NCSMC, CCM, IMSRG, SCGF, GFMC, HH, Nuclear Lattice EFT…

↓

Nuclear structure and reactions



No-core shell model



- No-core shell model (NCSM)
  - *A*-nucleon wave function expansion in the harmonic-oscillator (HO) basis
  - Short- and medium range correlations
  - Bound-states, narrow resonances
  - Equivalent description in relative-coordinate and Slater determinant basis

(A) 

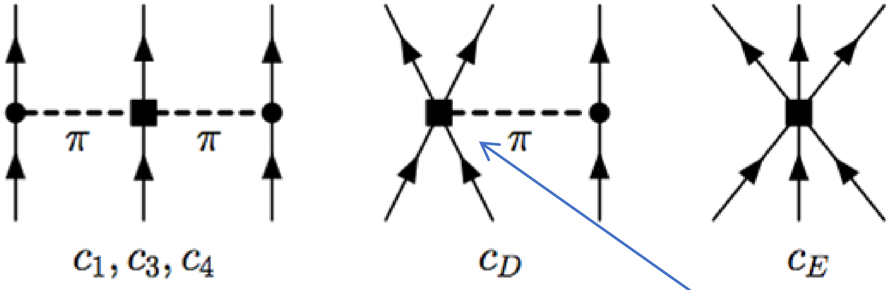
$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

(A) 

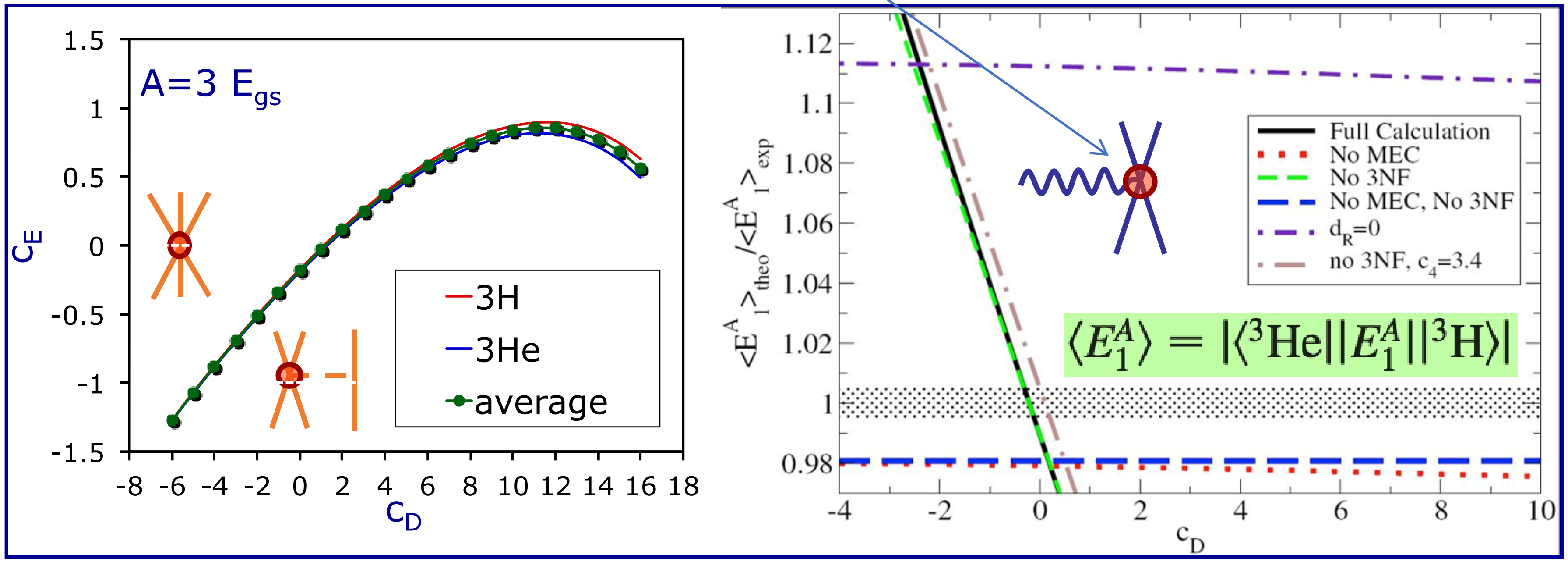
$$\Psi_{\mathrm{SD}}^A = \sum_{N=0}^{N_{\max}} \sum_j c_{Nj}^{\mathrm{SD}} \Phi_{\mathrm{SD}\,Nj}^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A \varphi_{000}(\vec{R}_{CM})$$

Leading terms of the chiral NNN force and axial currents

From NN & pion-nucleon scattering



Chiral EFT provides a link between the medium-range (c_D term) NNN force and the meson-exchange current appearing in nuclear beta decay



NNN parameters determined from the ^{3}H binding energy and half life


PRL 103, 102502 (2009) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2009

Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory

Doron Gazit

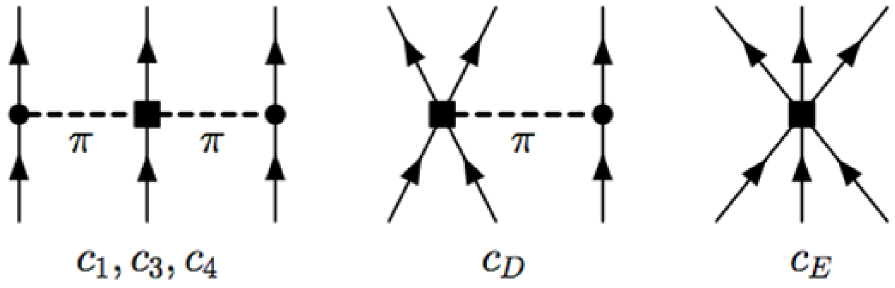
Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195, USA

Sofia Quaglioni and Petr Navrátil

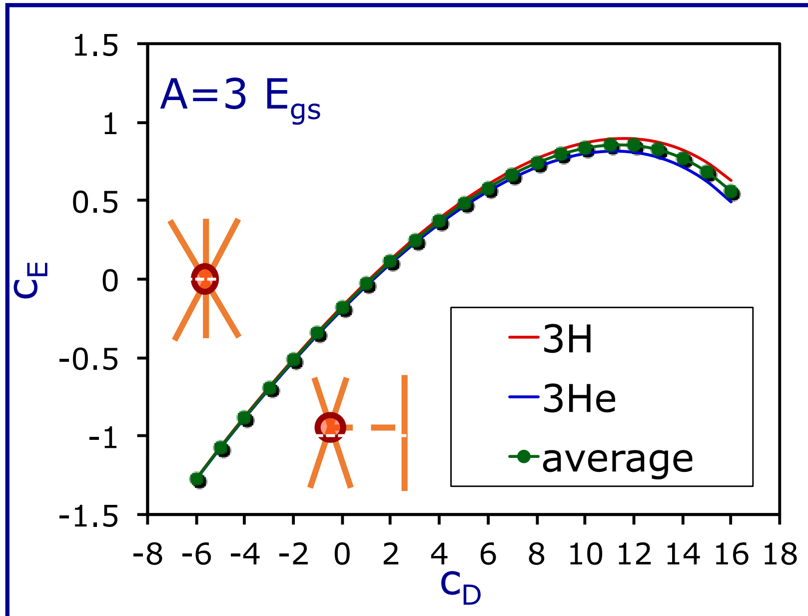
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

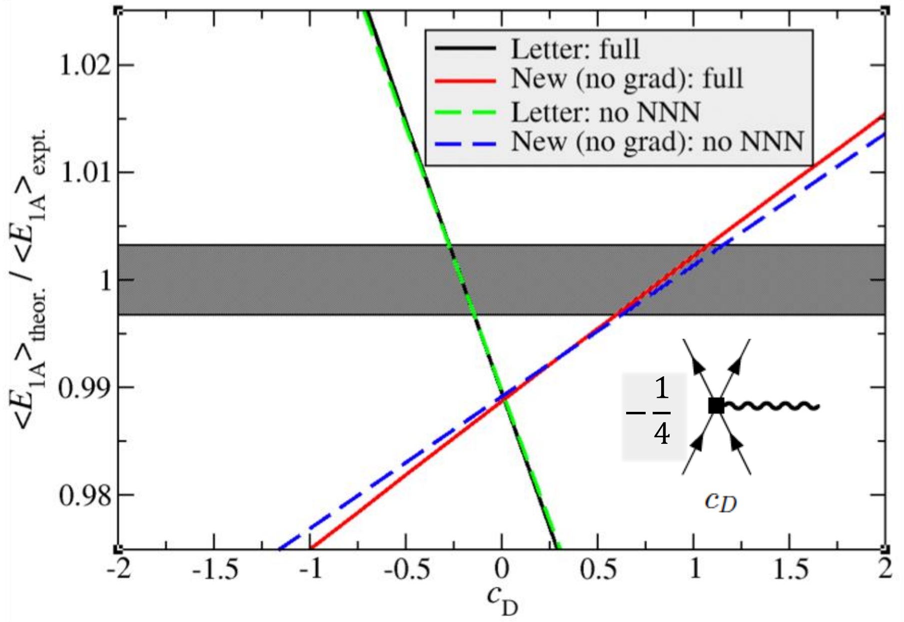
Leading terms of the chiral NNN force and axial currents

From NN & pion-nucleon scattering



Chiral EFT provides a link between the medium-range (c_D term) NNN force and the meson-exchange current appearing in nuclear beta decay





After 10 years… corrected multiplicative factor
Dozens of papers affected

NNN parameters determined from the ^{3}H binding energy and half life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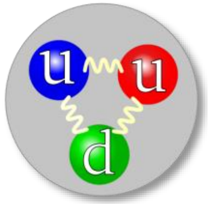
From QCD to nuclei



Low-energy QCD

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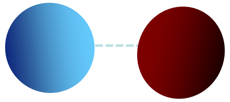
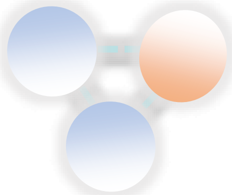


NN+3N interactions from chiral EFT — …or accurate meson-exchange potentials

↓



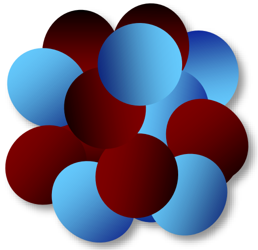
Unitary/similarity transformations — Identity or SRG or OLS or UCOM … Softens NN, induces 3N

↓

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

Many-Body methods — NCSM, NCSM/RGM, NCSMC, CCM, IMSRG, SCGF, GFMC, HH, Nuclear Lattice EFT…

↓



Nuclear structure and reactions

Similarity Renormalization Group (SRG) evolution

- Continuous transformation driving Hamiltonian to band-diagonal form with respect to a chosen basis
- Unitary transformation $H_\alpha = U_\alpha H U_\alpha^\dagger \qquad U_\alpha U_\alpha^\dagger = U_\alpha^\dagger U_\alpha = 1$

$$\frac{dH_\alpha}{d\alpha} = \frac{dU_\alpha}{d\alpha} H U_\alpha^\dagger + U_\alpha H \frac{dU_\alpha^\dagger}{d\alpha} = \frac{dU_\alpha}{d\alpha} U_\alpha^\dagger U_\alpha H U_\alpha^\dagger + U_\alpha H U_\alpha^\dagger U_\alpha \frac{dU_\alpha^\dagger}{d\alpha}$$

$$= \frac{dU_\alpha}{d\alpha} U_\alpha^\dagger H_\alpha + H_\alpha U_\alpha \frac{dU_\alpha^\dagger}{d\alpha} = [\eta_\alpha, H_\alpha]$$

$$\eta_\alpha \equiv \frac{dU_\alpha}{d\alpha} U_\alpha^\dagger = -\eta_\alpha^\dagger$$

anti-Hermitian generator

- Setting $\eta_\alpha = [G_\alpha, H_\alpha]$ with Hermitian G_α

$$\frac{dH_\alpha}{d\alpha} = \left[[G_\alpha, H_\alpha], H_\alpha\right]$$

- Customary choice in nuclear physics $G_\alpha = T$ …kinetic energy operator
  - band-diagonal in momentum space plane-wave basis
- Initial condition $H_{\alpha=0} = H_{\lambda=\infty} = H \qquad \lambda^2 = 1/\sqrt{\alpha}$
- **Induces many-body forces**
  - **In applications to chiral interactions three-body induced terms large, four-body small**

SRG evolution for *A*-nucleon system

- Evolution induces many-nucleon terms (up to *A*)

$$\tilde{H}_\alpha = \tilde{H}_\alpha^{[1]} + \tilde{H}_\alpha^{[2]} + \tilde{H}_\alpha^{[3]} + \tilde{H}_\alpha^{[4]} + \ldots + \tilde{H}_\alpha^{[A]}$$

- SRG "magic" – $\tilde{H}_\alpha^{[2]}$ determined completely in A=2 system, $\tilde{H}_\alpha^{[3]}$ determined in A=3 system, etc.

- In actual calculations so far only terms up to $\tilde{H}_\alpha^{[3]}$ kept

- Three types of SRG-evolved Hamiltonians used
  - **NN only**: Start with initial T+V_{NN} and keep $\tilde{H}_\alpha^{[1]} + \tilde{H}_\alpha^{[2]}$
  - **NN+3N-induced**: Start with initial T+V_{NN} and keep $\tilde{H}_\alpha^{[1]} + \tilde{H}_\alpha^{[2]} + \tilde{H}_\alpha^{[3]}$
  - **NN+3N-full**: Start with initial T+V_{NN}+V_{NNN} and keep $\tilde{H}_\alpha^{[1]} + \tilde{H}_\alpha^{[2]} + \tilde{H}_\alpha^{[3]}$

α variation (Λ variation) provides a diagnostic tool to asses the contribution of omitted many-body terms, tests the unitarity of the SRG transformation

SRG evolution of general operators

The SRG transformation maintains the same eigenvalues for the Hamiltonian

$$\hat{H}\left|\psi_k\right\rangle = E_k\left|\psi_k\right\rangle \rightarrow \hat{H}_\alpha\left|\psi_{k,\alpha}\right\rangle = E_k\left|\psi_{k,\alpha}\right\rangle$$

But to extract additional observables from the wavefunction while taking advantage of the SRG tranformation, the corresponding operators must be transformed

$$\left\langle\psi_i\right|\hat{O}\left|\psi_f\right\rangle = \left\langle\psi_{i,\alpha}\right|\hat{O}_\alpha\left|\psi_{f,\alpha}\right\rangle \text{ where } \hat{O}_\alpha = U_\alpha\hat{O}U_\alpha^\dagger$$

The transformation matrix can be extracted from the eigenfunctions of the Hamiltonian

$$U_\alpha = \sum_k \left|\psi_{k,\alpha}\right\rangle\left\langle\psi_k\right|$$

H_α, O_α:
2-body part determined in A=2 system,
3-body part determined in A=3 system,
…

SRG evolution of general operators

Peter Gysbers (UBC/TRIUMF)

Implementation up to two-body terms:

The matrix U is calculated blockwise, for relative coordinate two-nucleon eigenstates:

$$|(A=2)kJ^{\pi}TT_z\rangle = \sum_{n,\ell} c^{k}_{n\ell s} \, |n\ell s J^{\pi}TT_z\rangle$$

The corresponding submatrix of $\hat{H}$ is evolved then diagonalized to produce a matrix $U_{\alpha}^{J^{\pi}TT_z}$

Compute the matrix elements of the bare operator: $\langle k' J'^{\pi'} T' T'_z || \, \hat{O}^{(K)} \, || k J^{\pi} T T_z \rangle$

Matrix elements of the evolved operator are:

$$\langle k' J'^{\pi'} T' T'_z, \alpha || \, U_{\alpha}^{J'^{\pi'} T' T'_z} \hat{O}^{(K)} U_{\alpha}^{\dagger J^{\pi} TT_z} \, || k J^{\pi} T T_z, \alpha \rangle$$

SRG evolution of general operators

Peter Gysbers (UBC/TRIUMF)

Implementation up to two-body terms:

The matrix U is calculated blockwise, for relative coordinate two-nucleon eigenstates:

$$|(A=2)kJ^\pi TT_z\rangle = \sum_{n,\ell} c^k_{n\ell s}\, |n\ell s J^\pi TT_z\rangle$$

The corresponding submatrix of $\hat{H}$ is evolved then diagonalized to produce a matrix $U_\alpha^{J^\pi TT_z}$

Compute the matrix elements of the bare operator: $\langle k' J'^{\pi'} T' T'_z || \hat{O}^{(K)} || k J^\pi TT_z\rangle$

Matrix elements of the evolved operator are:

$$\langle k' J'^{\pi'} T' T'_z, \alpha || U_\alpha^{J'^{\pi'} T' T'_z} \hat{O}^{(K)} U_\alpha^{\dagger J^\pi TT_z} || k J^\pi TT_z, \alpha\rangle$$

Converting from the two-nucleon Jacobi basis to the single particle basis:

$$\langle a'b' J'^{\pi'} T' T'_z || \hat{O}^{(K)}_\alpha || ab J^\pi TT_z\rangle \qquad a \equiv \{n_a, \ell_a, j_a\}$$

$$= \sum C^{*a'b'}_{n'\ell's'} C^{ab}_{n\ell s} \langle n'\ell's' J'^{\pi'} T' T'_z || \hat{O}^{(K)}_\alpha || n\ell s J^\pi TT_z\rangle$$

Code NCSMV2B

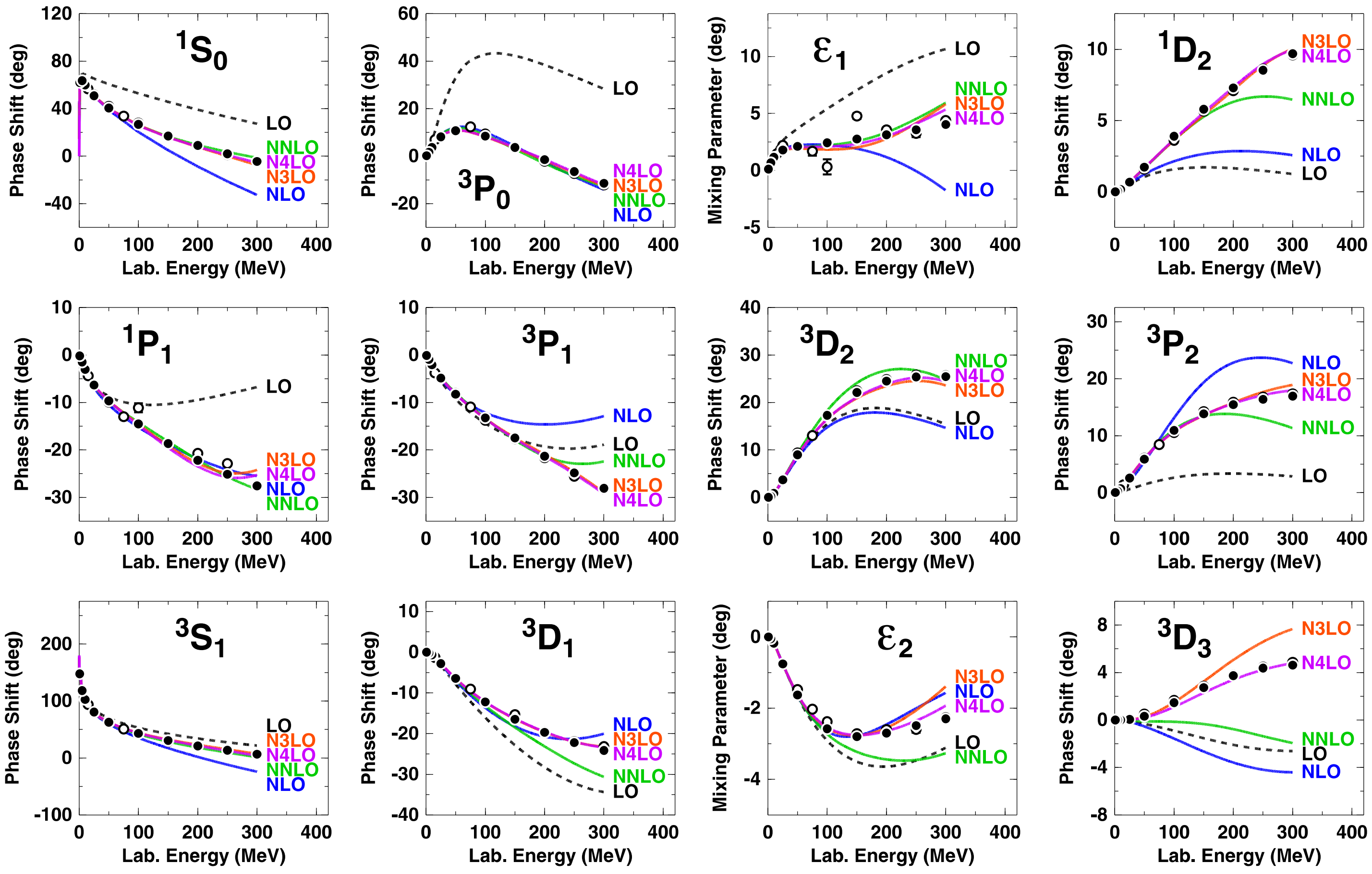
The NN interaction from chiral EFT

PHYSICAL REVIEW C **96**, 024004 (2017)

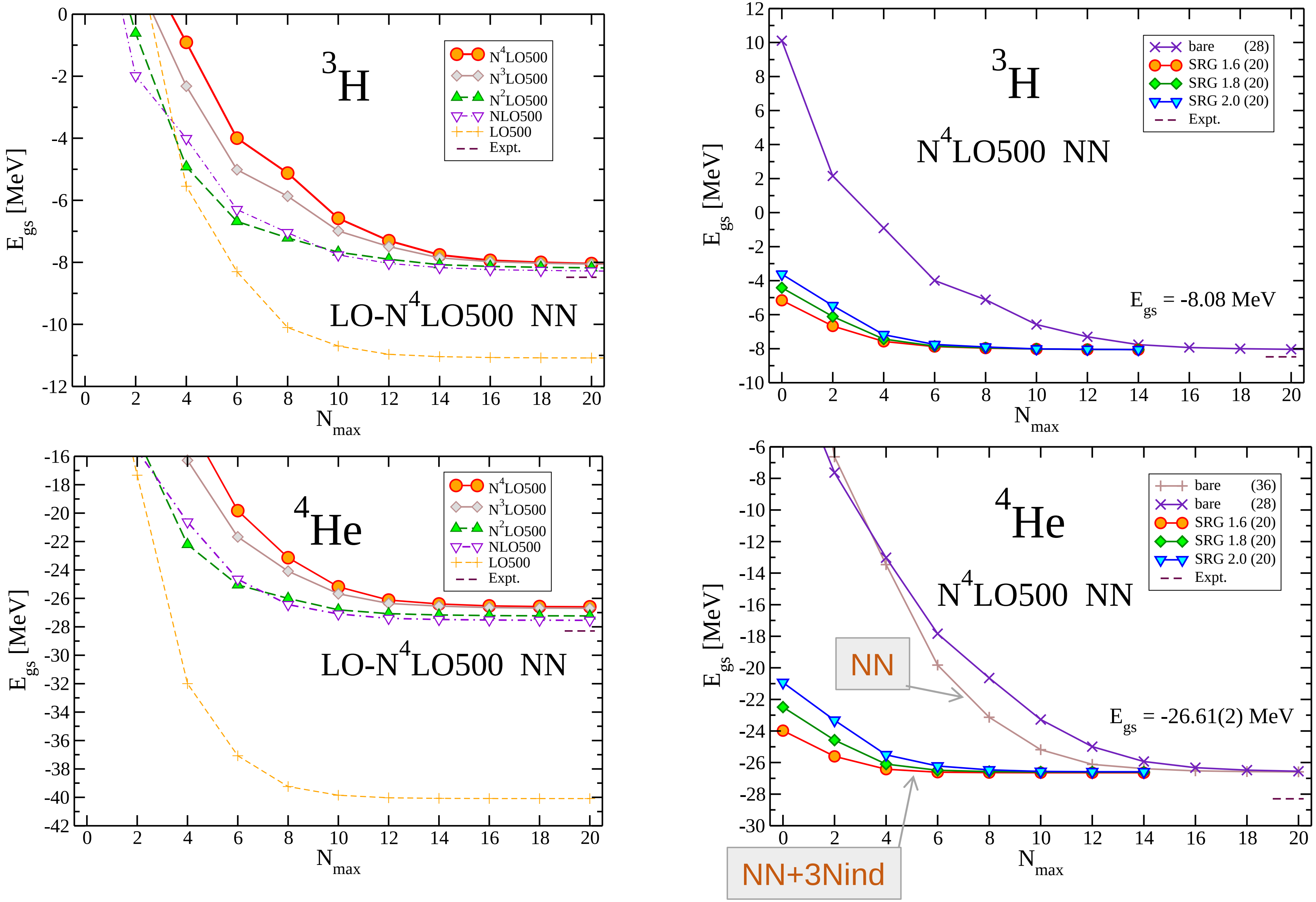
High-quality two-nucleon potentials up to fifth order of the chiral expansion

D. R. Entem,[1,*] R. Machleidt,[2,†] and Y. Nosyk[2]

- Chiral NN potential up to N^{4}LO
- Set of five potentials constructed
  - Sequence of LO, NLO,…,N^{4}LO
  - Uncertainty quantification
- At N^{3}LO and N^{4}LO:
  - 24 LECs fitted to the *np* scattering data and the deuteron properties
    - Including c_i LECs (i=1-4) from pion-nucleon scattering
- N^{4}LO NN fitted to data up to pion production threshold with χ^2/datum~1.15



^{3}H and ^{4}He with chiral EFT interactions up to N^{4}LO



Properties of ^{3}H, ^{3}He and ^{4}He with the new N^{4}LO NN

- N^{4}LO500 NN
  - ^{3}H

    E = -8.08 MeV

    point-proton radius = 1.62 fm
  - ^{3}He

    E = -7.33 MeV

    point-proton radius = 1.82 fm
  - ^{4}He

    E= -26.61(2) MeV

    point-proton radius = 1.475(5) fm

$^3H \rightarrow {}^3He$ β decay

Peter Gysbers (UBC/TRIUMF)

$$\hat{O} = GT^{(1)} \rightarrow \hat{O}_\lambda = GT^{(1)} + GT^{(2)}_\lambda + \dots$$

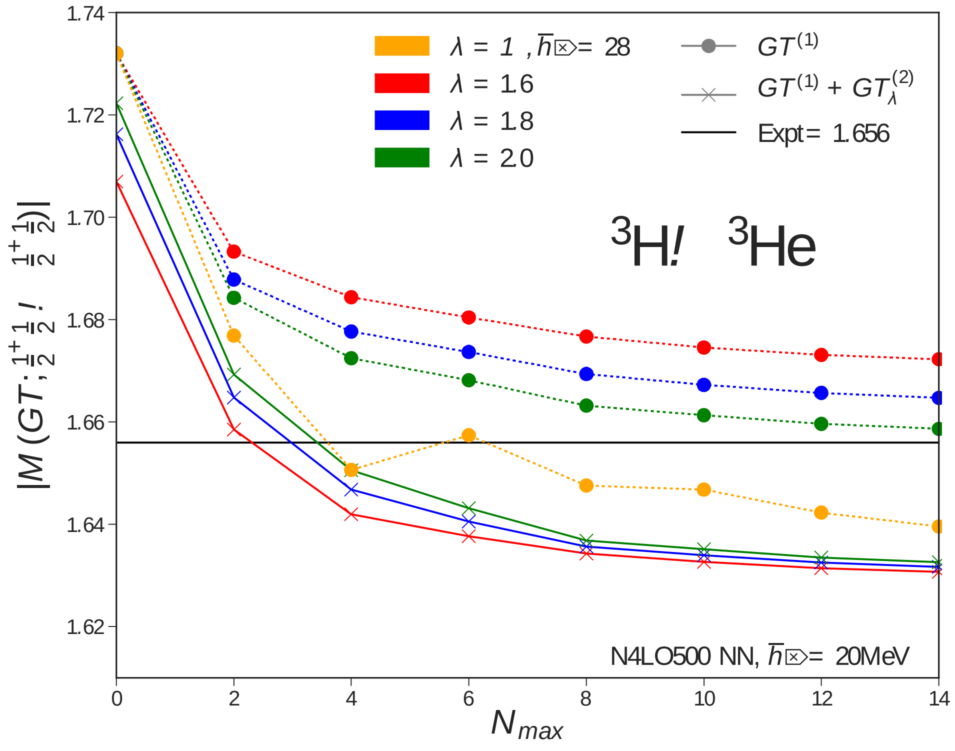
Operator:

Gamow-Teller (1-body)

$$\langle GT^{(2)}_\lambda \rangle_{A=2} = \langle (GT^{(1)})_\lambda \rangle_{A=2} - \langle GT^{(1)} \rangle_{A=2}$$

Potential: "N^4LO NN"

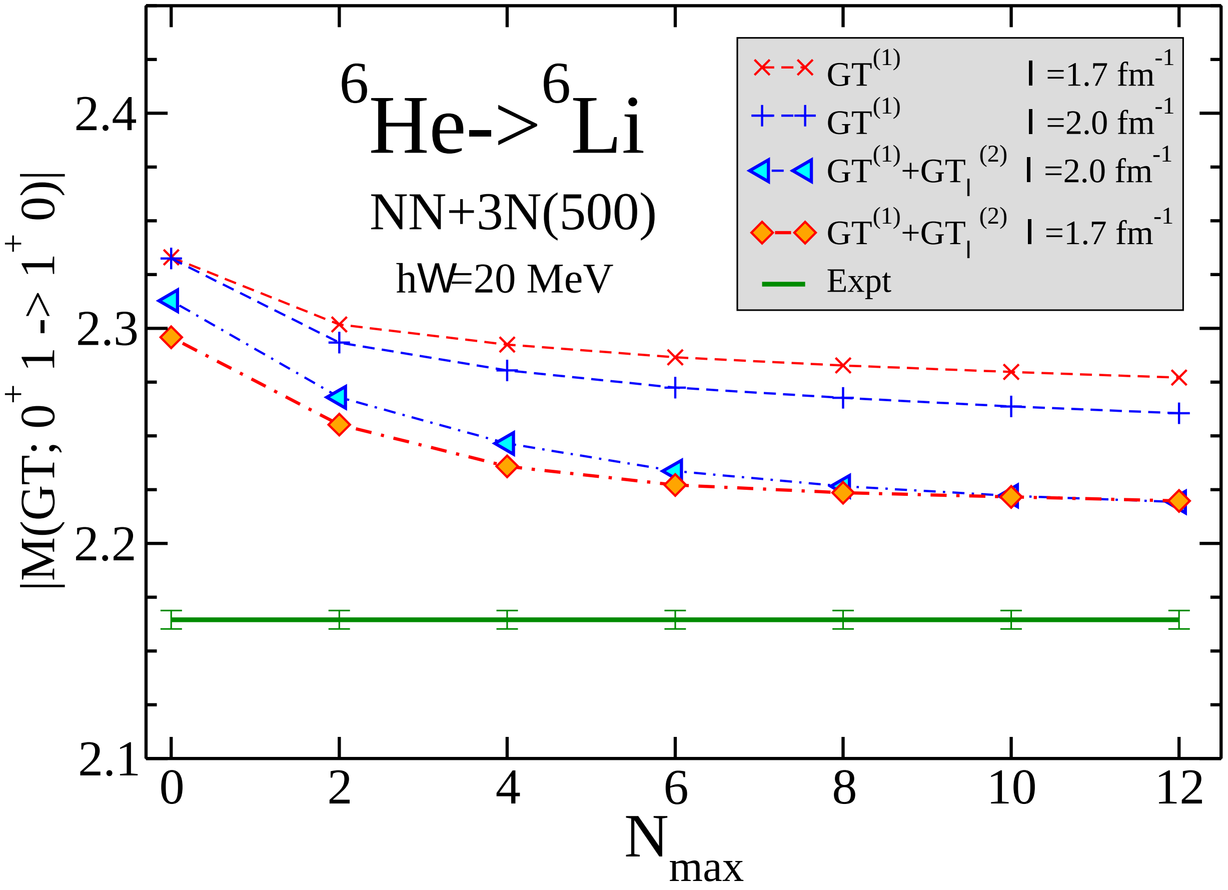
- chiral NN @N^4LO, Machleidt PRC96 (2017), 500MeV cutoff



Hamiltonian:
chiral NN with SRG 2- and 3-body induced
(except orange line: bare chiral NN)

$^{6}He \rightarrow {}^{6}Li$ β decay

Peter Gysbers (UBC/TRIUMF)



Hamiltonian:
chiral NN with SRG 2- and 3-body induced

$^3H \rightarrow {}^3He$ β decay

Peter Gysbers (UBC/TRIUMF)

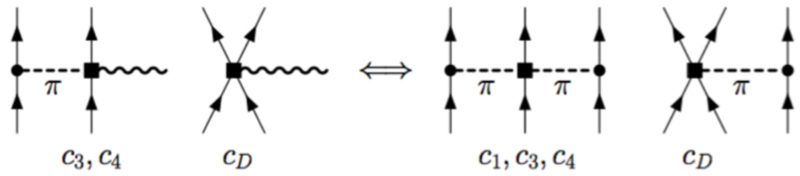
$$\hat{O} = GT^{(1)} + MEC^{(2)} \rightarrow \hat{O}_{\lambda} = GT^{(1)} + GT_{\lambda}^{(2)} + MEC_{\lambda}^{(2)} + \ldots$$

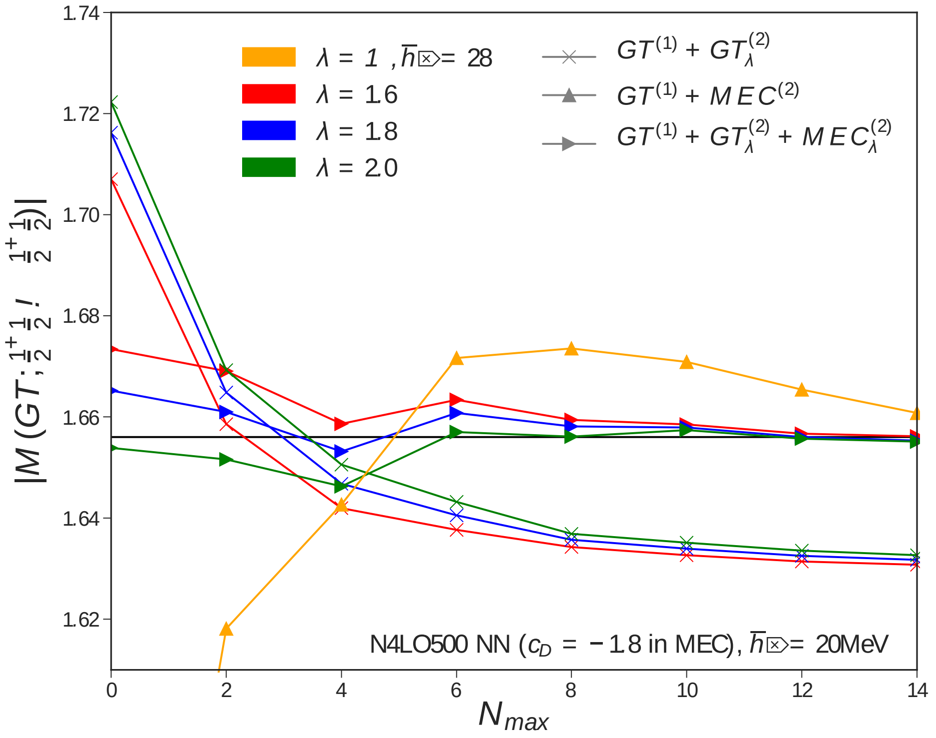
Operator:

Gamow-Teller (1-body) + chiral meson exchange current (2-body) Park (2003)

Potential: "N^4LO NN"

- chiral NN @N^4LO, Machleidt PRC96 (2017), 500MeV cutoff
- LEC $c_D = -1.8$ determined





Original EM 2003 N^3LO NN c_D=+0.8 (3N repulsive)

Determination of the c_D parameter relevant to chiral 3N force c_D=-1.8 (3N attractive)

Properties of ^{3}H, ^{3}He and ^{4}He with the new $N^{4}LO$ NN + $N^{2}LO$ $3N_{lnl}$

- $N^{4}LO500$ NN
  - ^{3}H
    - E = -8.08 MeV
    - point-proton radius = 1.62 fm
  - ^{3}He
    - E = -7.33 MeV
    - point-proton radius = 1.82 fm
  - ^{4}He
    - E= -26.60(1) MeV
    - point-proton radius = 1.475(5) fm

- $N^{4}LO500$ NN + $N^{2}LO$ $3N_{lnl}$

  3N fitted to ^{3}H β decay and binding energy

  c_1= -0.73, c_3= -3.38, c_4= 1.69, Λ_{loc}= 650 MeV, Λ_{nonloc}= 500 MeV, c_D= -1.8, c_E= -0.31
  - ^{3}H
    - E = -8.48 MeV $\langle V_{3N2\pi} \rangle$= -0.54 MeV $\langle V_{3ND} \rangle$= -0.32 MeV $\langle V_{3NE} \rangle$= 0.40 MeV
    - point-proton radius = 1.60 fm
  - ^{3}He
    - E = -7.73 MeV
    - point-proton radius = 1.78 fm
  - ^{4}He
    - E = -28.25(2) MeV $\langle V_{3N2pi} \rangle$= -2.16(5) MeV $\langle V_{3ND} \rangle$= -2.22(5) MeV $\langle V_{3NE} \rangle$= 2.41(5) MeV
    - point-proton radius = 1.46(1) fm

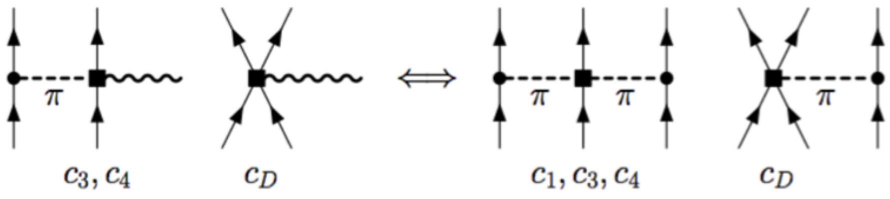
Preliminary

Applications to β decays in p-shell nuclei and beyond

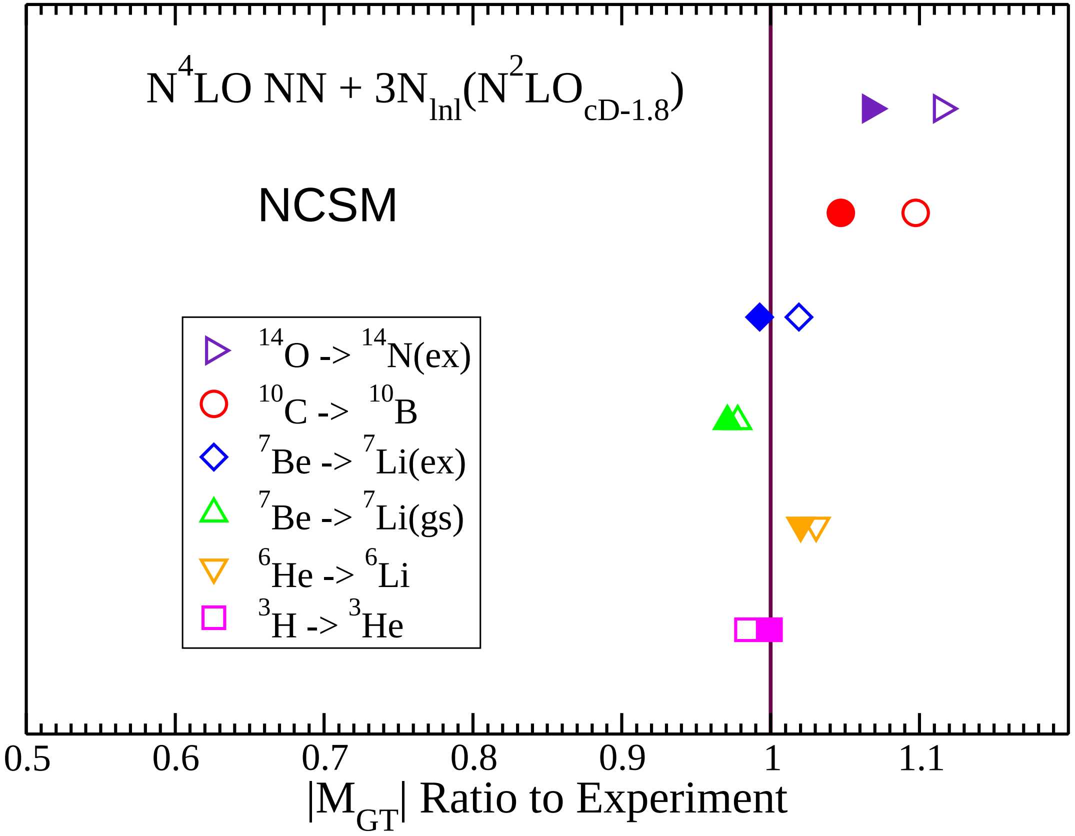
- Does inclusion of the MEC explain g_A quenching?
- In light nuclei correlations present in *ab initio* (NCSM) wave functions explain almost all of the quenching compared to the standard shell model
  - MEC inclusion overall improves agreement with experiment
- The effect of the MEC inclusion is greater in heavier nuclei
- SRG evolved matrix elements used in coupled-cluster and IM-SRG calculations (up to ^{100}Sn)

MEC

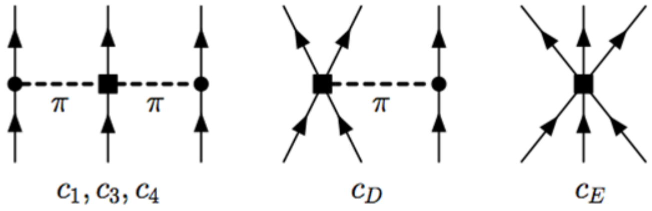
3N



Hollow symbols – GT
Filled symbols – GT+MEC
Both Hamiltonian and operators SRG evolved



Original N^3LO NN + 3N(400,500) vs. N^2LO_{sat} vs. new N^3LO NN + $3N_{lnl}$



- Local: chiral N^3LO NN + N^2LO 3N(500)
  - c_D=-0.2 c_E=-0.205 (^3H E_{gs}=-8.48 MeV)
  - ^4He

<H>=-28.4939   <V3b_2pi>= -5.8819   <V3b_D>= -0.2206   <V3b_E>= 1.2665

- Local: chiral N^3LO NN + N^2LO 3N(400)
  - c_D=-0.2 c_E=+0.098 (^3H E_{gs}=-8.32 MeV)
  - ^4He

<H>=-28.2839   <V3b_2pi>= -2.7173   <V3b_D>= -0.2801   <V3b_E>= -0.6630

- Non-local: chiral N^2LO_{sat} NN + 3N
  - c_D=+0.8168 c_E=-0.0396 (^3H E_{gs}=-8.53 MeV)
  - ^4He

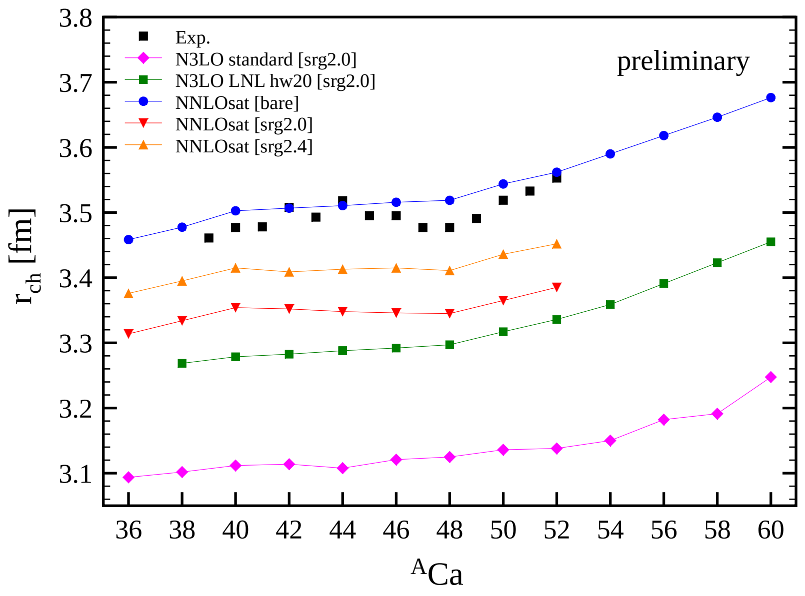
<H>=-28.4596   <V3b_2pi>= -4.7260   <V3b_D>= 1.3897   <V3b_E>= 0.4174

- Local/Non-local: chiral N^3LO NN + N^2LO $3N_{lnl}$
  - c_D=+0.7 c_E=-0.06 (^3H E_{gs}=-8.44 MeV)
  - ^4He

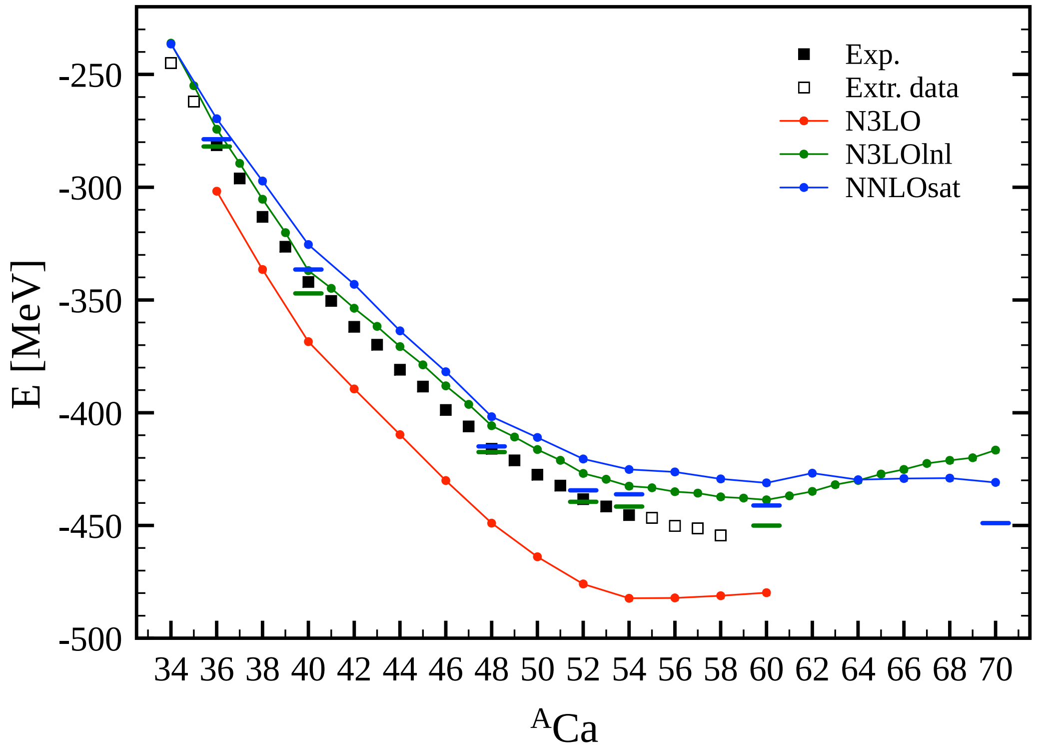
<H>=-28.2530   <V3b_2pi>= -4.8124   <V3b_D>= 0.7414   <V3b_E>= 0.4255

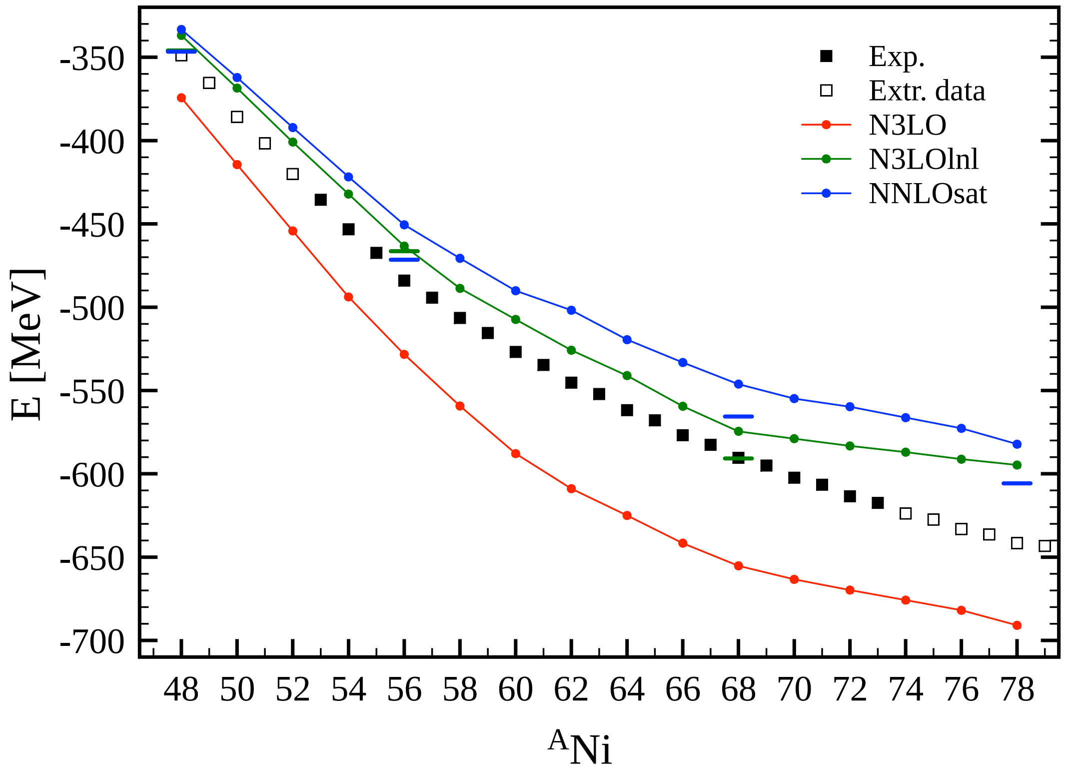
Original N^3LO NN + 3N(400,500) vs. N^2LO_{sat} vs. new N^3LO NN + $3N_{lnl}$

- SCGF, GGF
  - Carlo Barbieri, Vittorio Soma, Thomas Duguet, Francesco Raimondi



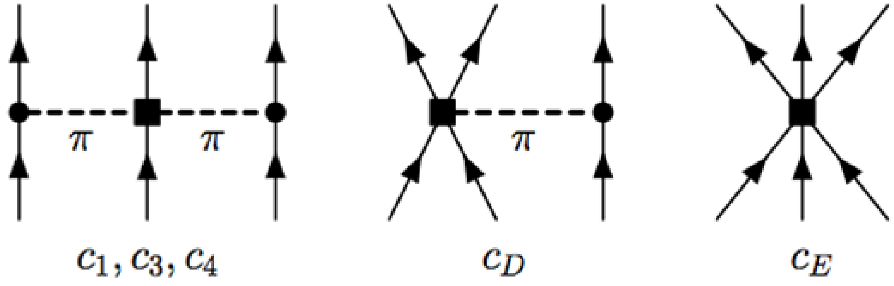
Preliminary



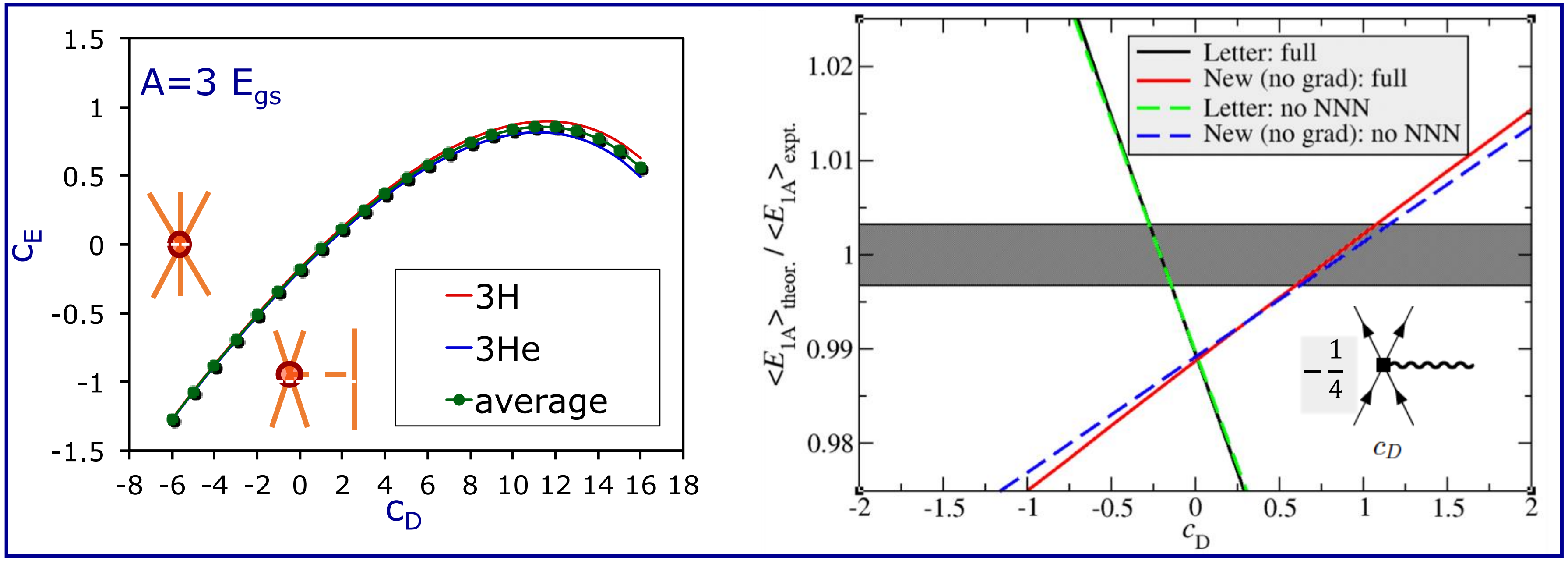


Leading terms of the chiral NNN force and axial currents

From NN & pion-nucleon scattering



Chiral EFT provides a link between the medium-range (c_D term) NNN force and the meson-exchange current appearing in nuclear beta decay



After 10 years… corrected multiplicative factor
Dozens of papers affected

NNN parameters determined from the ^{3}H binding energy and half life


PRL 103, 102502 (2009) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2009

Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory

Doron Gazit

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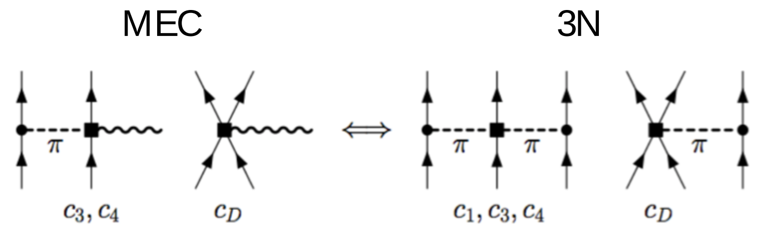
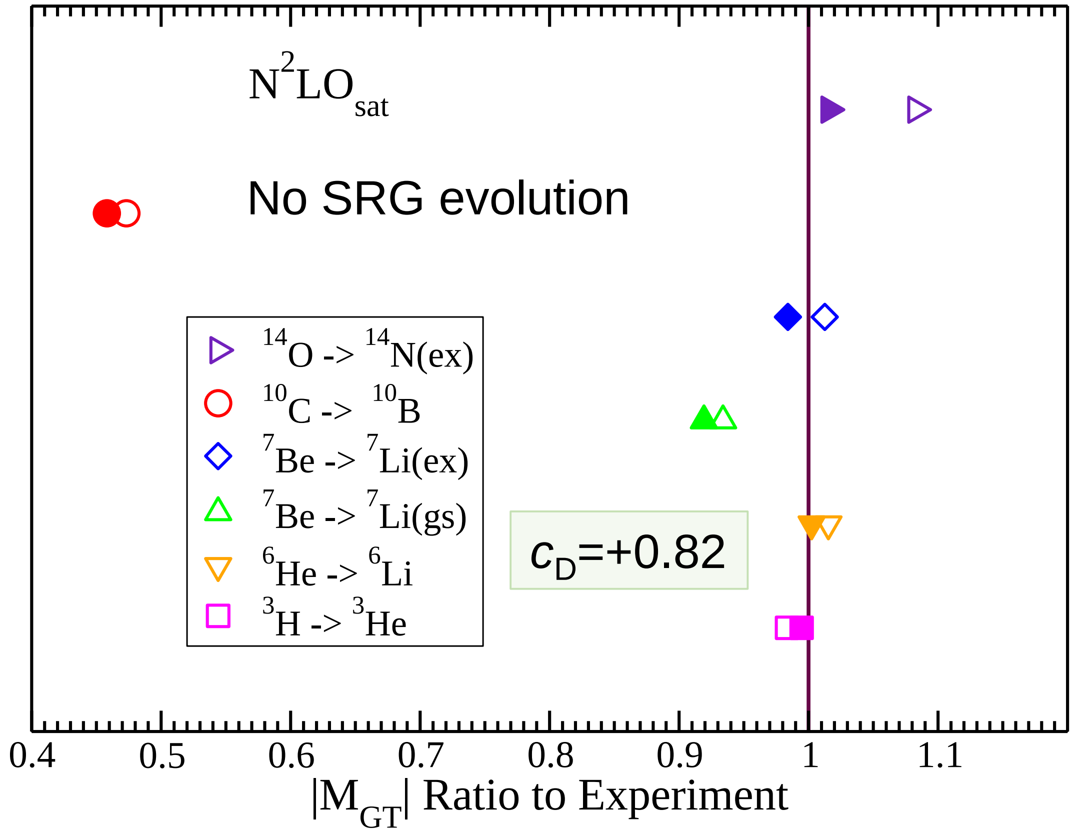
Sofia Quaglioni and Petr Navrátil

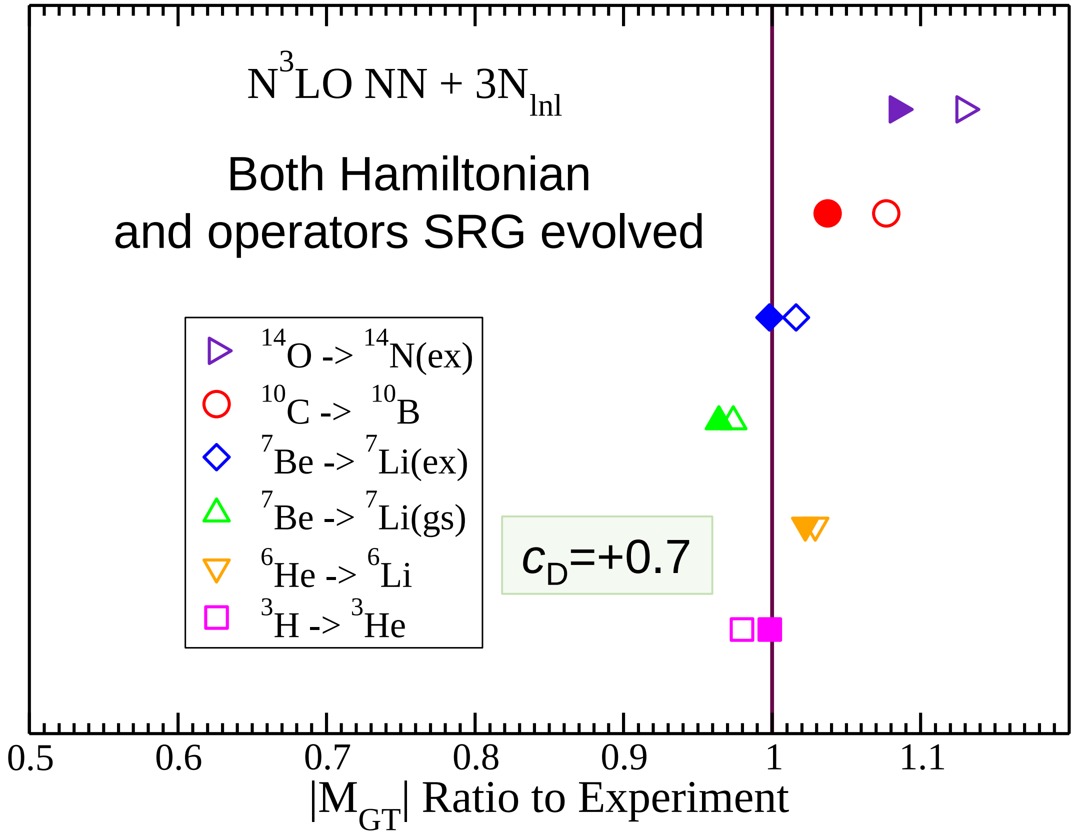
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

Applications to β decays in p-shell nuclei



Hollow symbols – GT
Filled symbols – GT+MEC





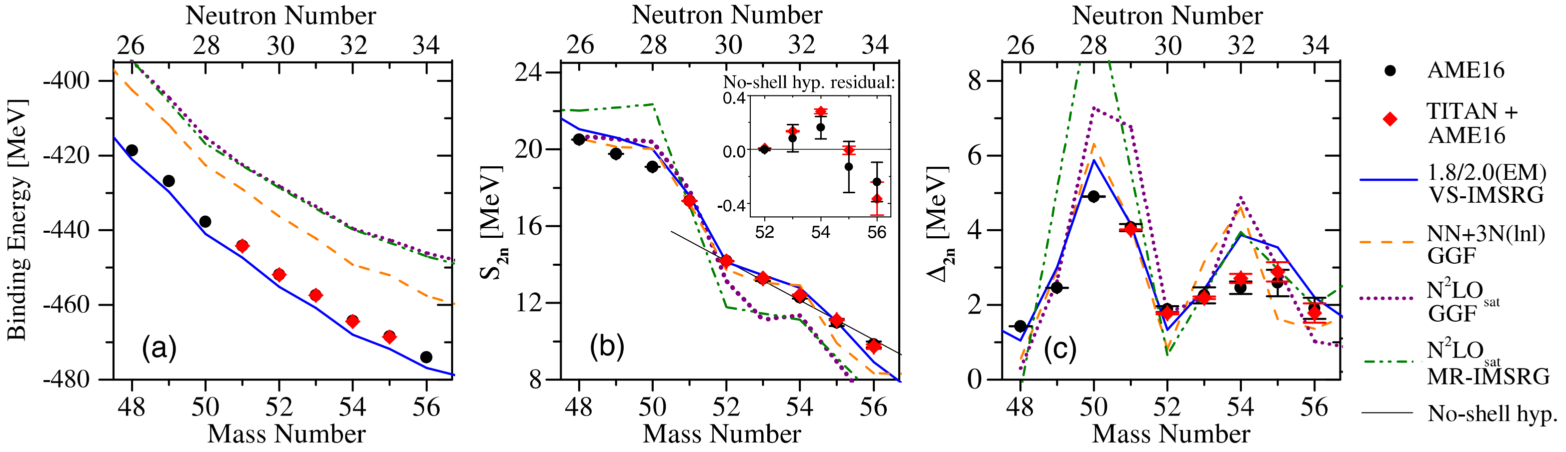
New N^3LO NN + $3N_{lnl}$ applied to Ti isotopes

PHYSICAL REVIEW LETTERS **120,** 062503 (2018)

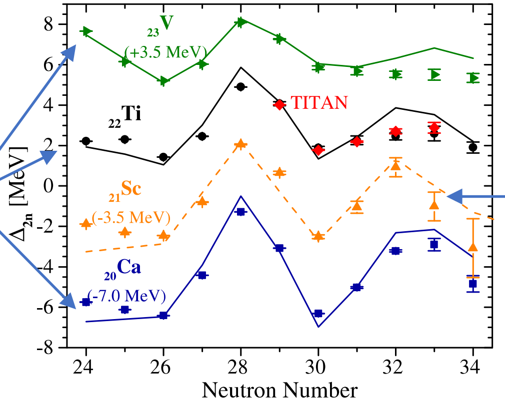
Dawning of the $N = 32$ Shell Closure Seen through Precision Mass Measurements of Neutron-Rich Titanium Isotopes

E. Leistenschneider,[1,2,*] M. P. Reiter,[1,3] S. Ayet San Andrés,[3,4] B. Kootte,[1,5] J. D. Holt,[1] P. Navrátil,[1] C. Babcock,[1] C. Barbieri,[6] B. R. Barquest,[1] J. Bergmann,[3] J. Bollig,[1,7] T. Brunner,[1,8] E. Dunling,[1,9] A. Finlay,[1,2] H. Geissel,[3,4] L. Graham,[1] F. Greiner,[3] H. Hergert,[10] C. Hornung,[3] C. Jesch,[3] R. Klawitter,[1,11] Y. Lan,[1,2] D. Lascar,[1,†] K. G. Leach,[12] W. Lippert,[3] J. E. McKay,[1,13] S. F. Paul,[1,7] A. Schwenk,[11,14,15] D. Short,[1,16] J. Simonis,[17] V. Somà,[18] R. Steinbrügge,[1] S. R. Stroberg,[1,19] R. Thompson,[20] M. E. Wieser,[20] C. Will,[3] M. Yavor,[21] C. Andreoiu,[16] T. Dickel,[3,4] I. Dillmann,[1,13] G. Gwinner,[5] W. R. Plaß,[3,4] C. Scheidenberger,[3,4] A. A. Kwiatkowski,[1,13] and J. Dilling[1,2]

- TRIUMF TITAN Penning trap mass measurements & several *ab initio* calculations

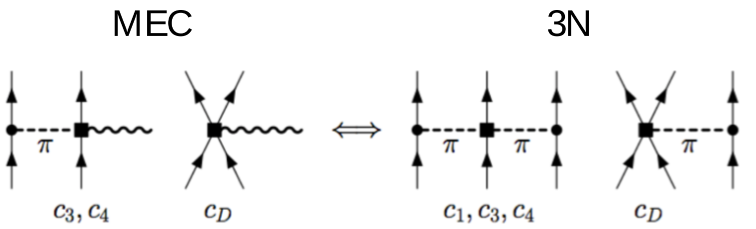


Hebeler's magic interaction

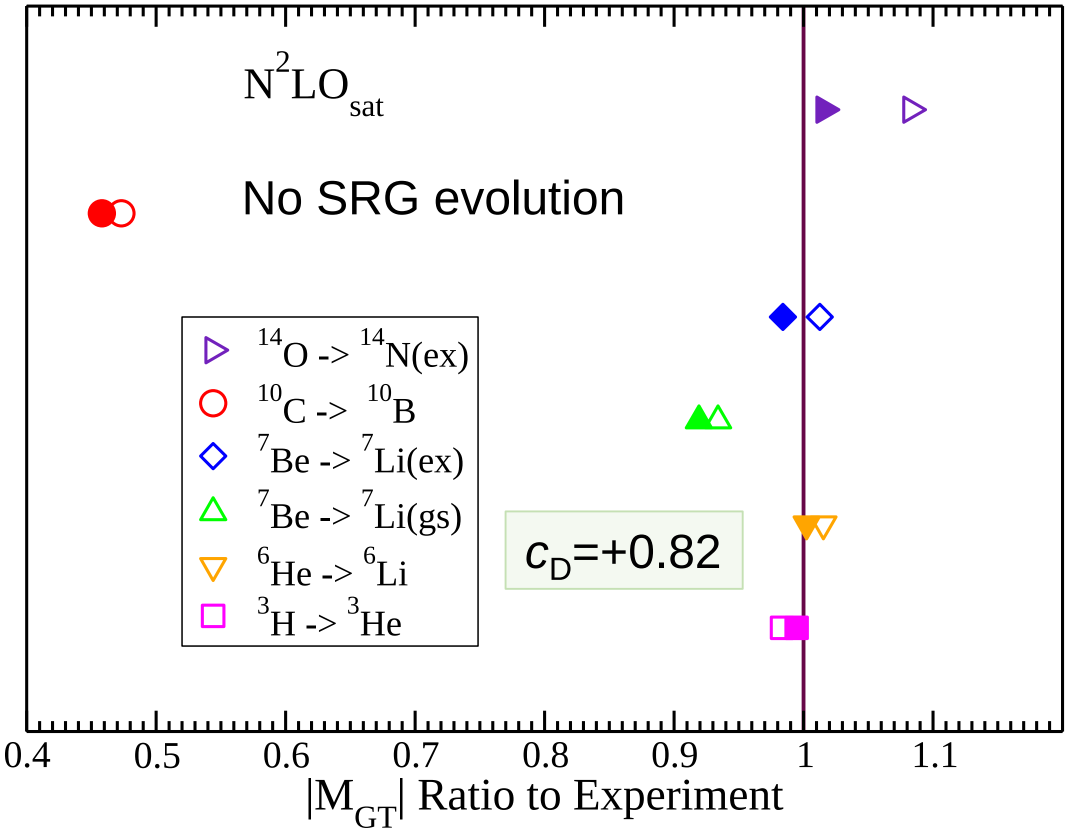


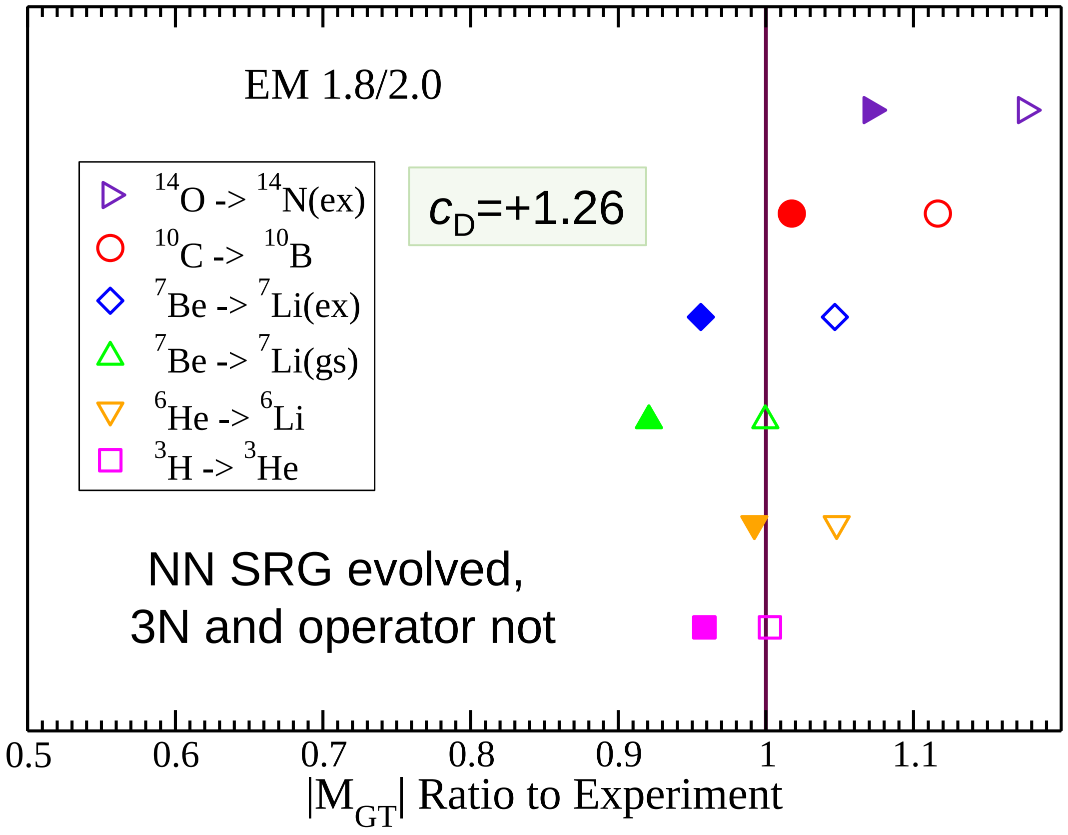
Accidentally magic interaction

Applications to β decays in p-shell nuclei



Hollow symbols – GT
Filled symbols – GT+MEC





Chiral NNN interaction with N^4LO contacts

- Ten contact terms
- Include spin-orbit contribution that helps to fix the famous A_y puzzle in p-d scattering

$$V^{(2)} = \sum_{i\neq j\neq k} (E_1 + E_2 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j + E_3 \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j + E_4 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\left[Z_0''(r_{ij}) + 2\frac{Z_0'(r_{ij})}{r_{ij}}\right] Z_0(r_{ik})$$

$$+(E_5 + E_6 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j) S_{ij}\left[Z_0''(r_{ij}) - \frac{Z_0'(r_{ij})}{r_{ij}}\right] Z_0(r_{ik})$$

$$+(E_7 + E_8 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_k)(\mathbf{L}\cdot\boldsymbol{S})_{ij}\frac{Z_0'(r_{ij})}{r_{ij}} Z_0(r_{ik})$$

$$+(E_9 + E_{10} \boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k)\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij}\boldsymbol{\sigma}_k\cdot\hat{\mathbf{r}}_{ik} Z_0'(r_{ij}) Z_0'(r_{ik})$$

- I used the E_7 (and E_8) terms

PHYSICAL REVIEW C **84**, 014001 (2011)

Subleading contributions to the three-nucleon contact interaction

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PROCEEDINGS OF SCIENCE

Progress in the quest for a realistic three-nucleon force

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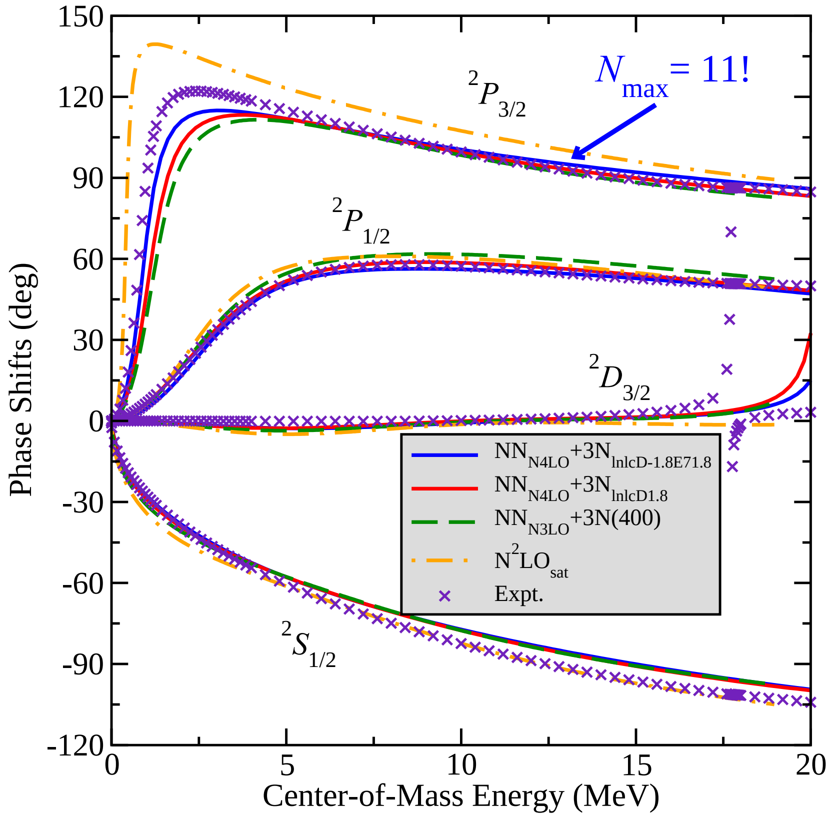
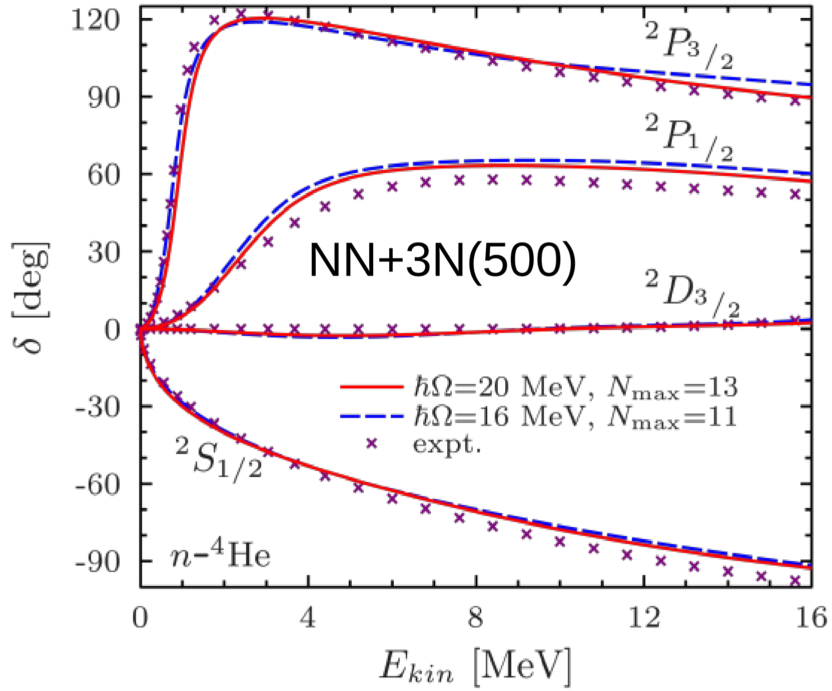
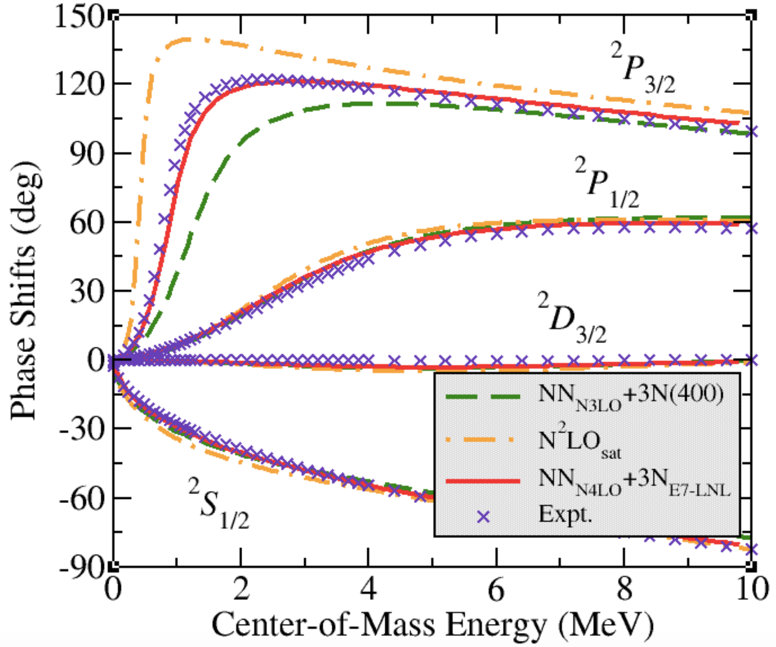
Chiral NNN interaction with N^4LO contacts

Impact of the E_7 term in n-^{4}He scattering



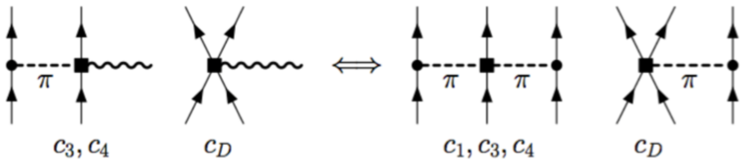


Preliminary
Work in progress…

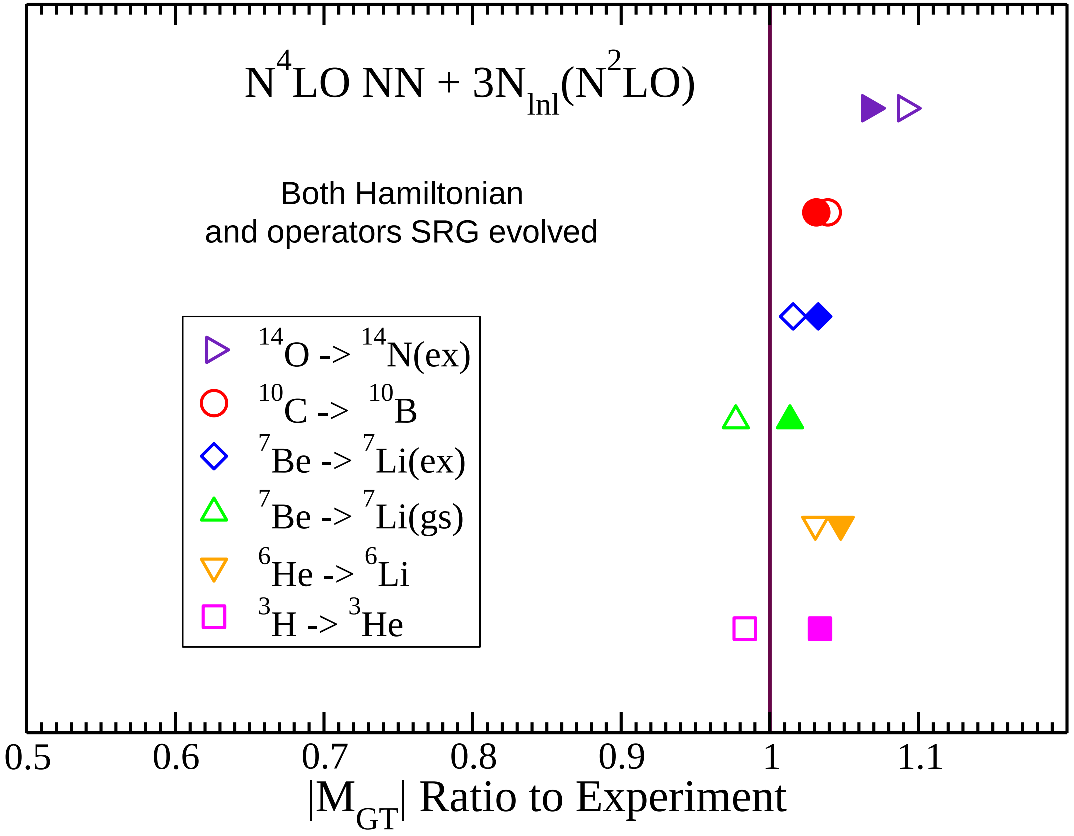


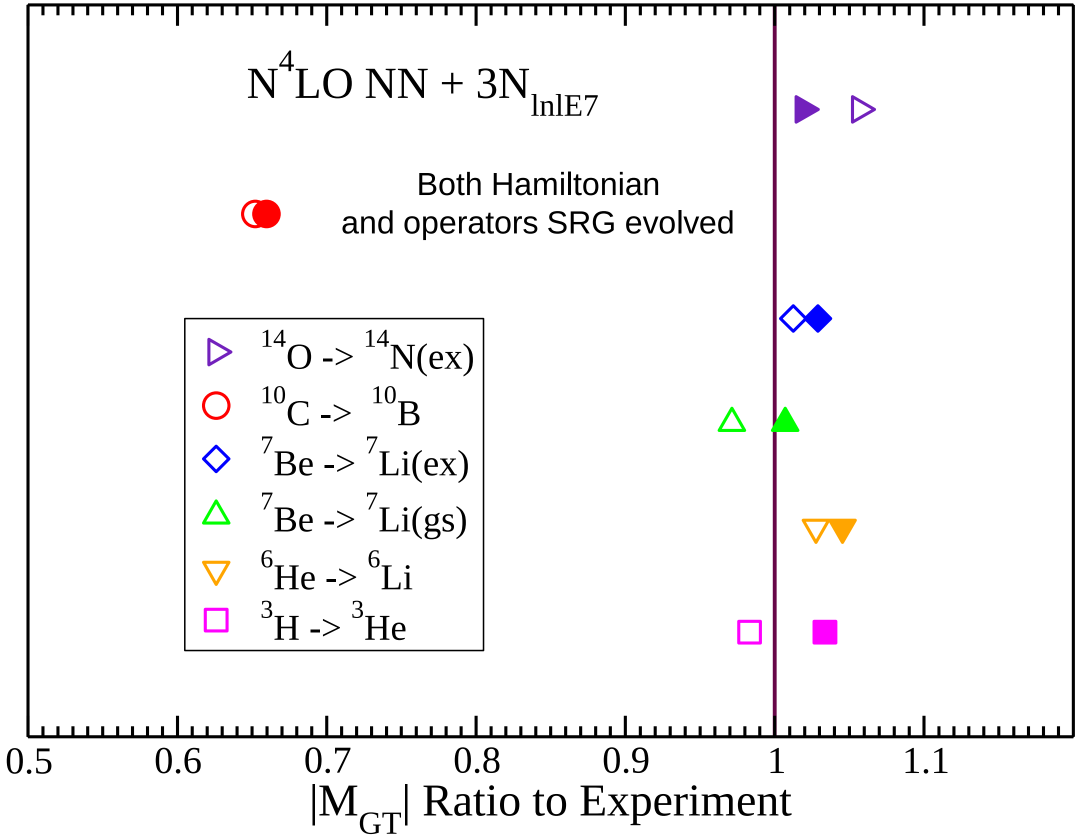
Applications to β decays in p-shell nuclei

MEC 3N



Hollow symbols – GT
Filled symbols – GT+MEC
Inconsistent c_D (+0.45) with ^{3}H beta decay → enhancement of transitions in A=6,7 nuclei, still quenching in A=14



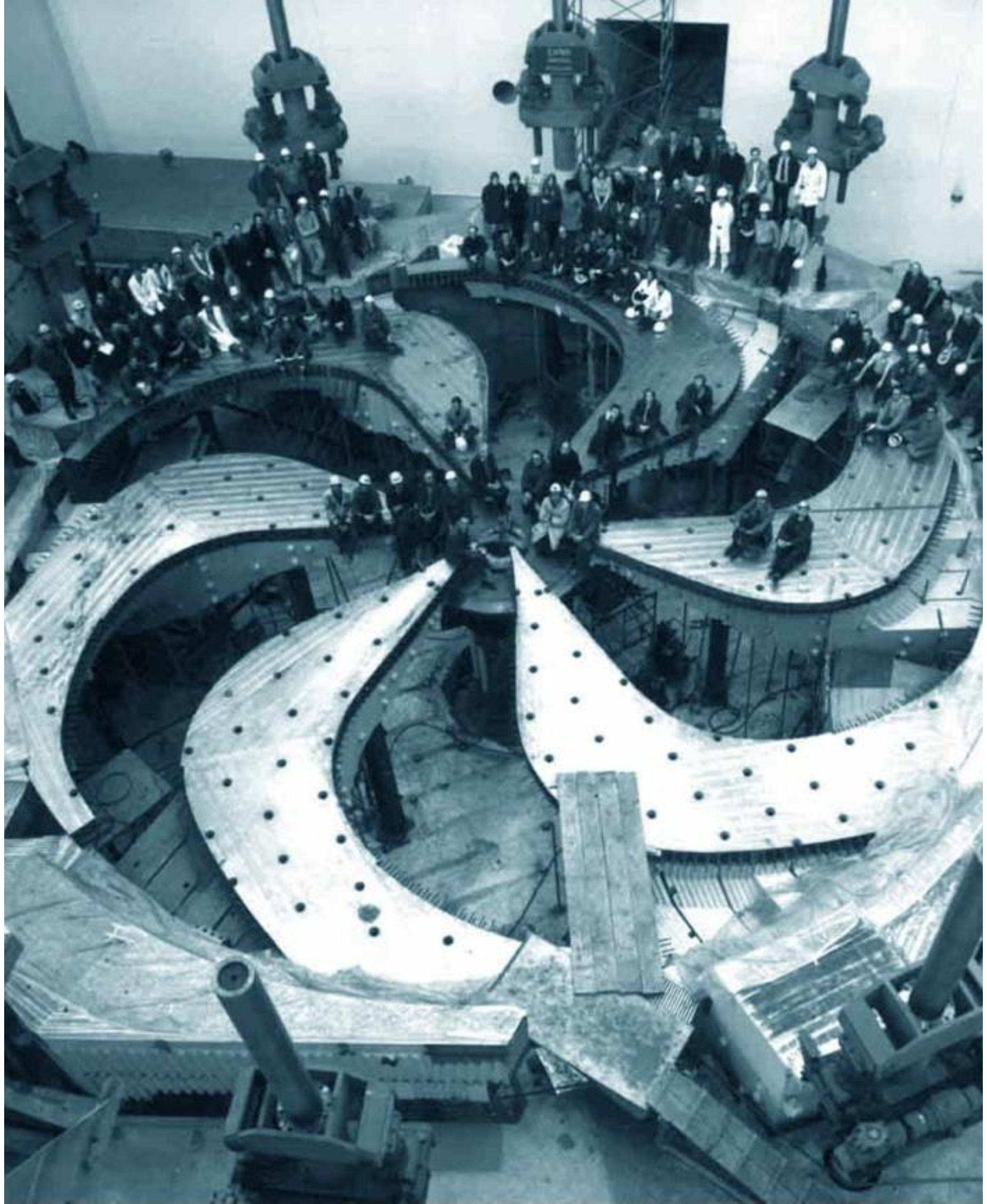


Conclusions and outlook

- *Ab initio* calculations of beta decays with SRG evolved chiral forces: **SRG evolution** of the **transition operators essential**
- Role of 2-body currents small in light nuclei
  - The same seen in the GFMC calculations
- We find a systematic improvement when **consistent** forces and currents are included
- Corrected c_D term in N^3LO NN + 3N leads to a substantially better description of medium mass nuclei
- SRG evolved transition operators provided for VS-IMSRG and CCM medium mass nuclei calculations

TRIUMF

Thank you!
Merci!



Discovery, accelerated