Electroweak properties of Weakly-Bound Light Nuclei

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האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Weakly-Bound Systems in Atomic and Nuclear Physics – March 2010

INSTITUTE FOR NUCLEAR THEORY

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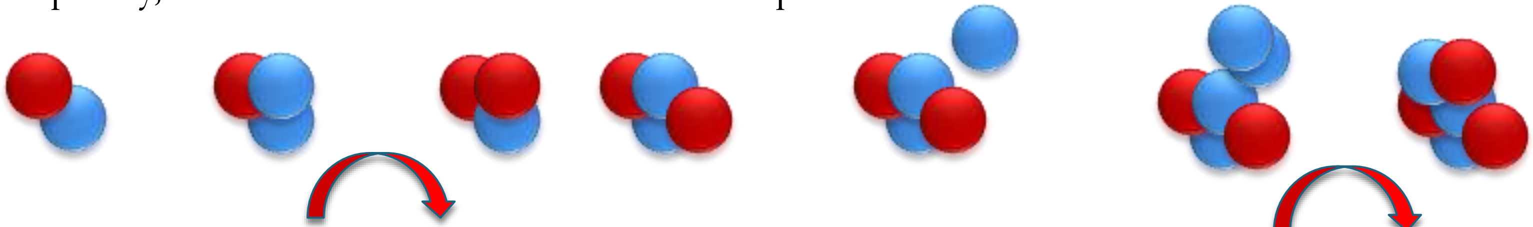
Introduction

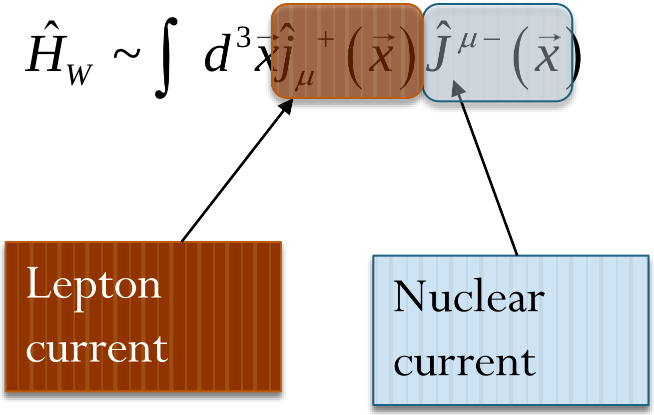
- ***Light nuclei are special:***
  - Weakly-bound:
    - Usually include few (if any) bound excited states.
    - Consequently, inelastic reaction often leads to break-up of the nucleus.



	^{2}H	^{3}H	^{3}He	^{4}He	^{5}He	^{6}He	^{6}Li	…
B.E [MeV]	-2.22	-8.48	-7.72	-28.3	unbound	-29.3	-32.0	
B.E/mass	$1\cdot10^{-3}$	$3\cdot10^{-3}$	$3\cdot10^{-3}$	$7\cdot10^{-3}$	unbound	$5\cdot10^{-3}$	$5\cdot10^{-3}$	

Introduction

- ***Why looking at electro-weak properties?***
  - One can immediately relate ***electro-weak reaction*** of a probe with nucleus to currents inside the nucleus.



$$\hat{H}_W \sim \int d^3\vec{x}\, \hat{j}_\mu^{\,+}(\vec{x})\, \hat{J}^{\mu-}(\vec{x})$$

Lepton current

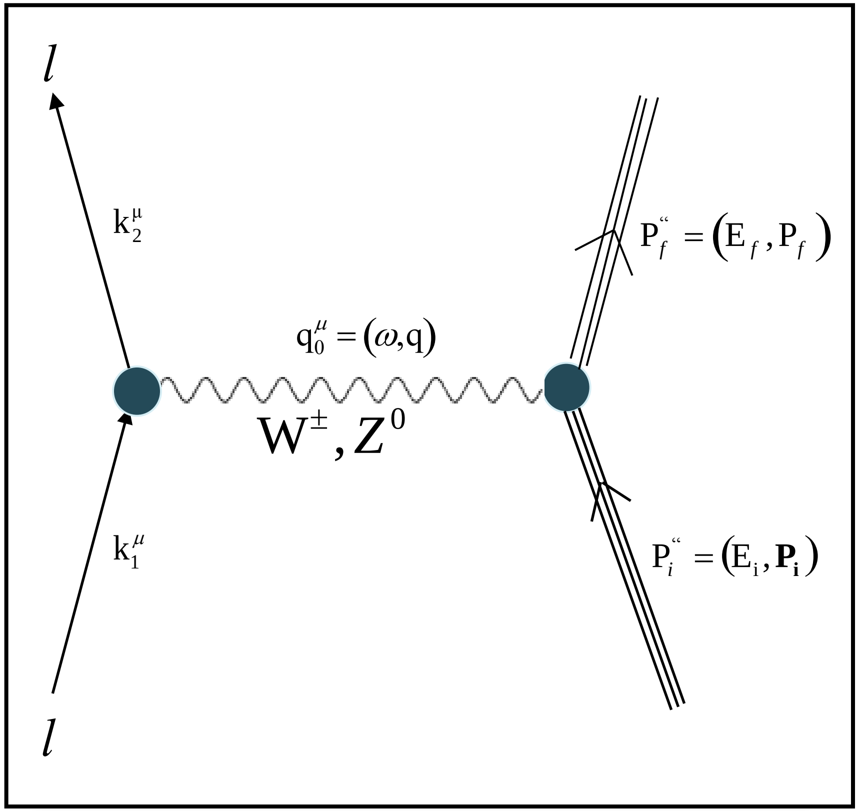
Nuclear current

$$\mathcal{O} \sim \left\langle \psi_i \middle| \hat{J}^\mu \middle| \psi_f \right\rangle$$

Scattering operator

⇕

Currents in the nucleus



$$W,Z\ propagator = \frac{g_{\mu\nu} + \dfrac{q_\mu q_\nu}{M_W^2}}{q^2 + M_W^2} \xrightarrow[q<<M_W]{} \frac{g_{\mu\nu}}{M_W^2}$$

Introduction

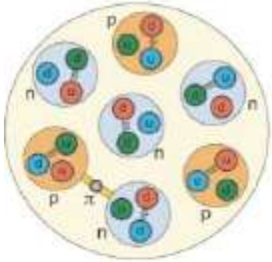
- ***Why looking at electro-weak properties?***
  - One can immediately relate ***electro-weak reaction*** of a probe with nucleus to currents inside the nucleus.
  - The currents are ***reflections*** of the ***symmetries*** of the nuclear interaction.
  - Thus, one can ***relate electro-weak properties and reaction rates*** with non-trivial properties not only of the ***target***, but also of the ***fundamental theory*** leading to its structure!
- In addition, electro-weak properties are important as a microscopic input for simulations of astrophysical phenomena.
  - Solar fusion.
  - Supernovae.
- These are often very challenging, or even impossible to measure, thus need accurate, parameter free predictions.

Introduction

- ***Why looking at electro-weak properties?***
- ***Why light Nuclei***?
  - Available methods for ***solving exactly the Schrödinger equation for few body systems***, from nucleonic dof: no core shell model, expansions in Hyperspherical Harmonics, Green's function Monte Carlo, ….
  - ***Chiral effective field theory (χPT)***, enables a connection between the fundamental theory of QCD and the nuclear interaction.
- ***Allow accurate, parameter free calculations, of weakly bound systems, and their properties***, from their nucleonic dof.

Chiral Effective Field Theory

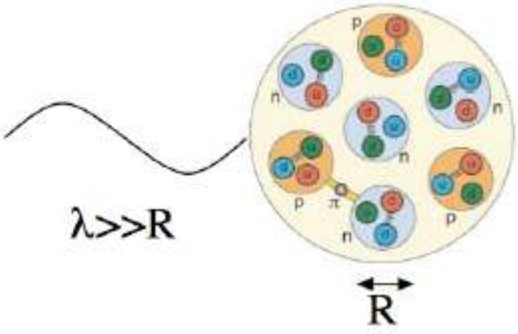
- Symmetries are important *NOT* degrees of freedom.
- In QCD – an approximate chiral symmetry:
  - The *u* and *d* are (almost) massless.



$$SU(2)_L \times SU(2)_R \cong SU(2)_V \times SU(2)_A \rightarrow SU(2)_V$$

  - The $SU(2)_V$ symmetry is the isospin symmetry.
  - However, no degenerate parity doublets are found in the spectrum.
  - The axial symmetry is spontaneously broken.
- Chiral EFT is based on this observation.
  - Identify Q – the momentum scale of the process.
  - Choose Λ – the theory cutoff.
  - In view of these-identify the effective degrees of freedom.

$$\lambda \sim \frac{1}{Q} \gg \frac{1}{\Lambda} \sim R$$



Chiral Effective Field Theory

- The pions are interpreted as the Goldstone bosons of the spontaneously broken $SU(2)_A$ symmetry.
- Their mass is a result of the explicit symmetry breaking due to the finite ***u*** and ***d*** masses. This introduces an additional scale.
  - If $Q \ll \Lambda \ll m_\pi$ then the effective theory is of point particles (pionless χPT).
  - If $Q \sim m_\pi \ll \Lambda$ then the effective theory should consist of both pions and nucleons (pionfull χPT), and even higher dof: Delta resonance, etc.
- Write a Lagrangian composed of ALL possible operators invariant under symmetries of the underlying theory.
- Find a ***systematic*** way to organize diagrams according to their contribution to the observable.

Weinberg’s Power Counting Scheme

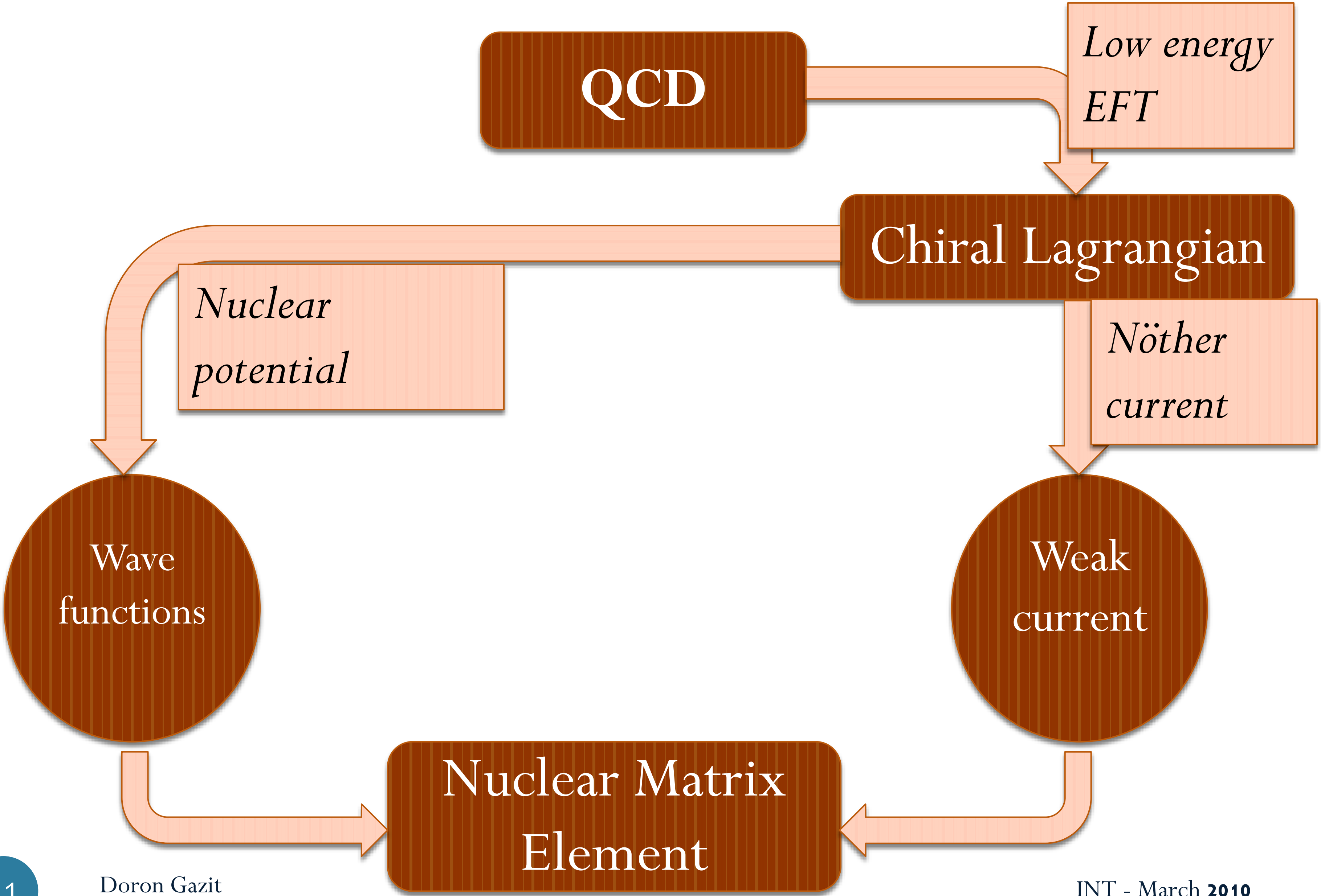
- Each Feynman diagram can be characterized by: $\left(\frac{Q}{\Lambda}\right)^{\nu}$
- Weinberg showed that ν is bound from below.
- In addition, expand in the inverse of the nucleon’s mass (take $\Lambda \sim M_N$) ➔ ***Heavy Baryon χPT***.
- This power counting is based on an expansion around the RG fixed point Q=0.
- There are indications that this is correct only for a limited range of Λ, due to the existence of a non-trivial, unitary, fixed point.
- This is also evident in the abnormal size of the NN interaction induced by a pion exchanege (however, expansions based on the latter seem to have convergence problems (KSW)).

20 years of debate led by: Weinberg, Kaplan, Savage, Wise, van-Kolck, Nogga, Timmermans, Birse, Meissner, Epelbaum…

The big deal in χPT

- A perturbation theory/expansion in small parameter of the observable, gives control over the accuracy of the calculation.
- Varying the cutoff gives estimate of the theoretical error-bar.
- Allows connection between *a-priori* unrelated operators:
  - In particular the nuclear force and the electro-weak currents in the nucleus (that the Su(2)xSu(2) structure is a gauging of).
- When the low-energy constants are known: the calculations are predictions of QCD.

χPT approach for low-energy EW nuclear reactions:



QCD

Low energy EFT

Chiral Lagrangian

Nuclear potential

Nöther current

Wave functions

Weak current

Nuclear Matrix Element

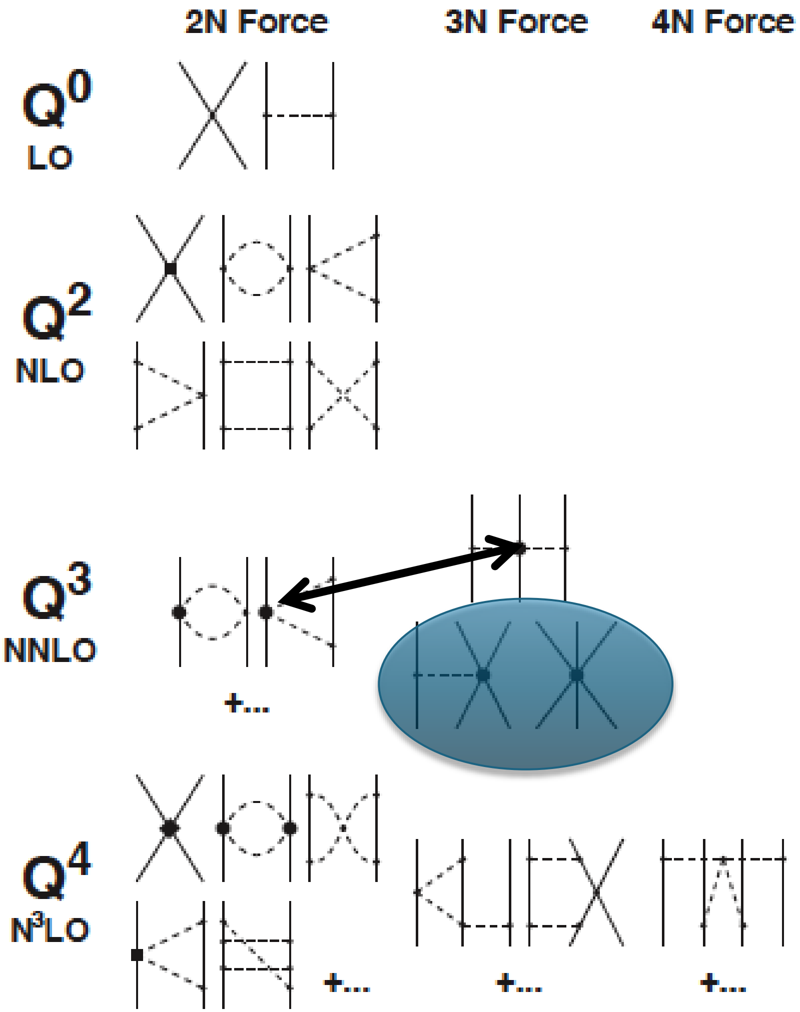
Forces in χPT

- The leading order NNN forces are at N^{2}LO.
- They include 2 new contact parameters.
- No new parameters at N^{3}LO.

χ^2/datum for the reproduction of the

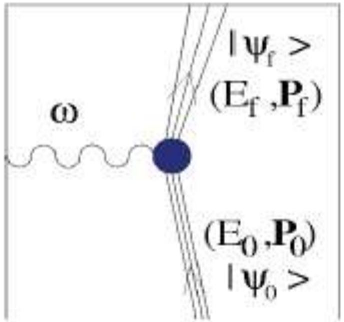
1999 *np* database

Bin (MeV)	# of data	N^{3}LO	NNLO	NLO	AV18
0–100	1058	1.06	1.71	5.20	0.95
100–190	501	1.08	12.9	49.3	1.10
190–290	843	1.15	19.2	68.3	1.11
0–290	2402	1.10	10.1	36.2	1.04



Weinberg, van Kolck, Ordonez, Meissner, Epelbaum, Nogga, Bernard, Kaiser, Krebs, Machleidt, Entem…

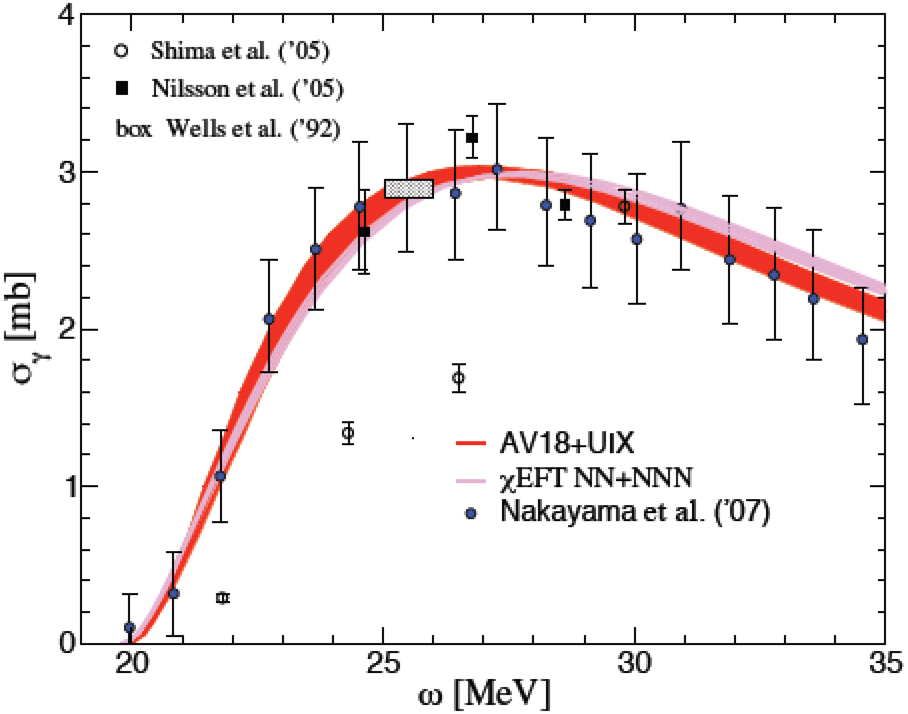
Photo-dissociation



- Current conservation leads to a connection between the spatial current and charge density.
- At low energy transfer the scattering operator is simply the dipole operator (Siegert theorem).
- This approximation is accurate to about 10% at 100 MeV.

Photo-dissociation of ^{4}He

- Sensitivity to NN force model.
- Sensitivity vanishes when adding the 3NF.
- The theoretical prediction is much more accurate than the experimental measurement, and actually "chooses" the "correct" measurement.



AV18, UIX D.Gazit, S.B. et al. PRL **96** 112301 (2006)

Chiral EFT S.Quaglioni and P.Navratil PLB **652** (2007)

The structure of ^{4}He

- ^{4}He is a spherical nucleus (J=0), but what is its symmetry in the body frame?
- The unretarted dipole approximation to the photodissociation cross-section can be related to the mean inter-nucleon distances:

$$\begin{aligned}
\Sigma_{BSR} &= \int_{\omega_{th}}^{\infty} \omega^{-1} \sigma_{\gamma}^{E1UR} d\omega = \frac{3}{4\pi^2\alpha} \left\langle 0 \,|\, \hat{D} \cdot \hat{D} \,|\, 0 \right\rangle \\
&= \frac{3}{4\pi^2\alpha} \left(Z^2 \left\langle r_p^2 \right\rangle - \frac{Z(Z-1)}{2} \left\langle r_{pp}^2 \right\rangle \right) = \\
&= \frac{3}{4\pi^2\alpha} \left(N^2 \left\langle r_n^2 \right\rangle - \frac{N(N-1)}{2} \left\langle r_{nn}^2 \right\rangle \right) = \\
&= \frac{3}{4\pi^2\alpha} \frac{NZ}{2} \left(\left\langle r_{np}^2 \right\rangle - \left\langle r_n^2 \right\rangle - \left\langle r_p^2 \right\rangle \right) =
\end{aligned}$$

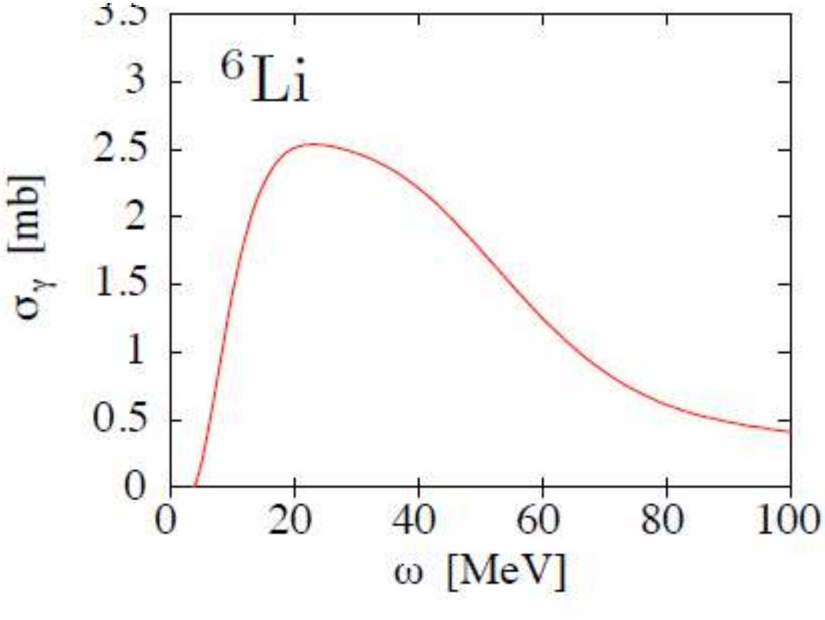
- In ^{4}He this is enough to reconstruct the structure:
- Thus, ^{4}He has a slightly deformed internal tetrahedral symmetry…

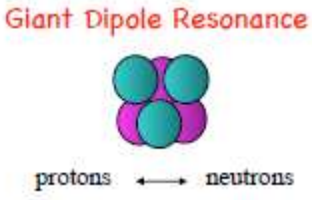
$$\frac{\left\langle r_{pp}^2 \right\rangle}{\left\langle r_p^2 \right\rangle} = \frac{\left\langle r_{nn}^2 \right\rangle}{\left\langle r_n^2 \right\rangle} = 2.78\,\mathrm{fm}^2 \quad \frac{\left\langle r_{np}^2 \right\rangle}{\left\langle r_n^2 \right\rangle} = 2.62\,\mathrm{fm}^2$$

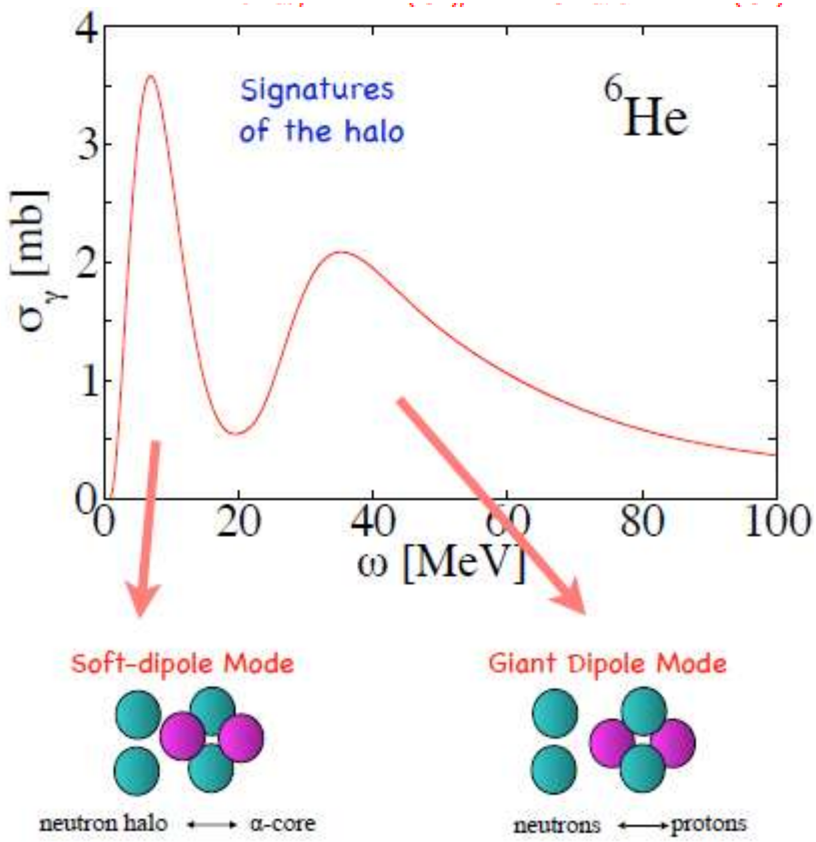
DG et al., Phys. Rev. C, **74** 061001(R) (2006)

Photodissociation of 6 body nuclei

From S. Bacca





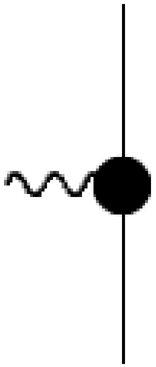


Sonia Bacca *et al*, **Phys. Rev. Lett. 89**, 052502 (2002); **Phys. Lett. B603,** 159 (2004); **Phys. Rev. C 69,** 057001 (2004).

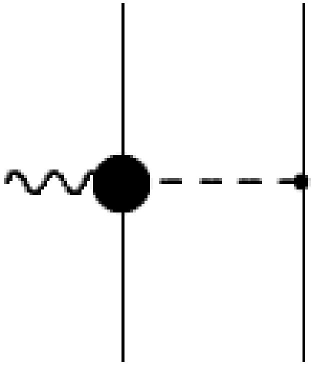
χPT axial weak currents to fourth order

$$\hat{d}_R \equiv \frac{M_N}{\Lambda_\chi g_A} c_D + \frac{1}{3} M_N (c_3 + 2c_4) + \frac{1}{6}$$

Single nucleon current

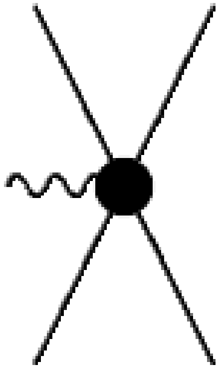


1 pion exchange

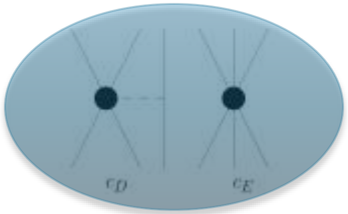


Nucleon-pion interaction,
NO new parameters

Contact term



Contact term

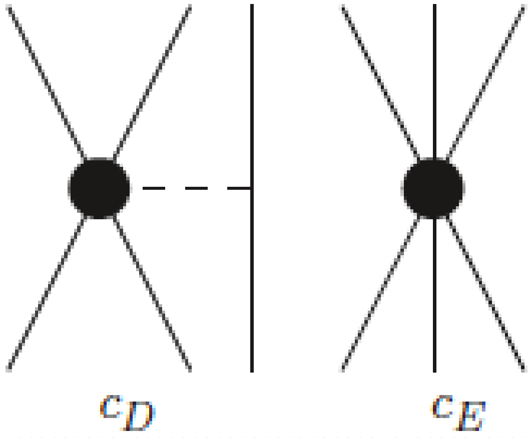


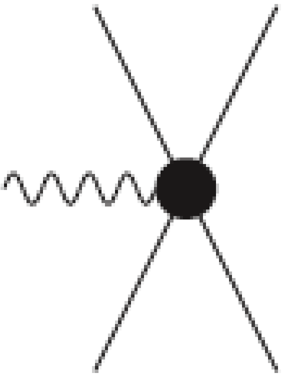
Gårdestig, Phillips, **Phys. Rev. Lett. 98**, 232301 (2006); **DG**, Quaglioni, Navratil, **Phys. Rev. Lett. 103,** 102502 (2009).

Axial MEC – remarks

- The MEC include "OπEC" and contact topologies.
- MEC involve only TWO nucleons.
- Thus, in principle c_D can be calibrated using two-body weak processes.
- So – *three nucleon force constrained at the two nucleon level*!
- The most attractive process –
  - Muon capture on deuteron – known only at the 5% level. An experiment at PSI "MuD (MuSun)" aims to measure this process to 1%.
- However, many 3 nucleon processes are measured very well.

A calculation of ^{3}H β decay using consistent χPT interaction and currents

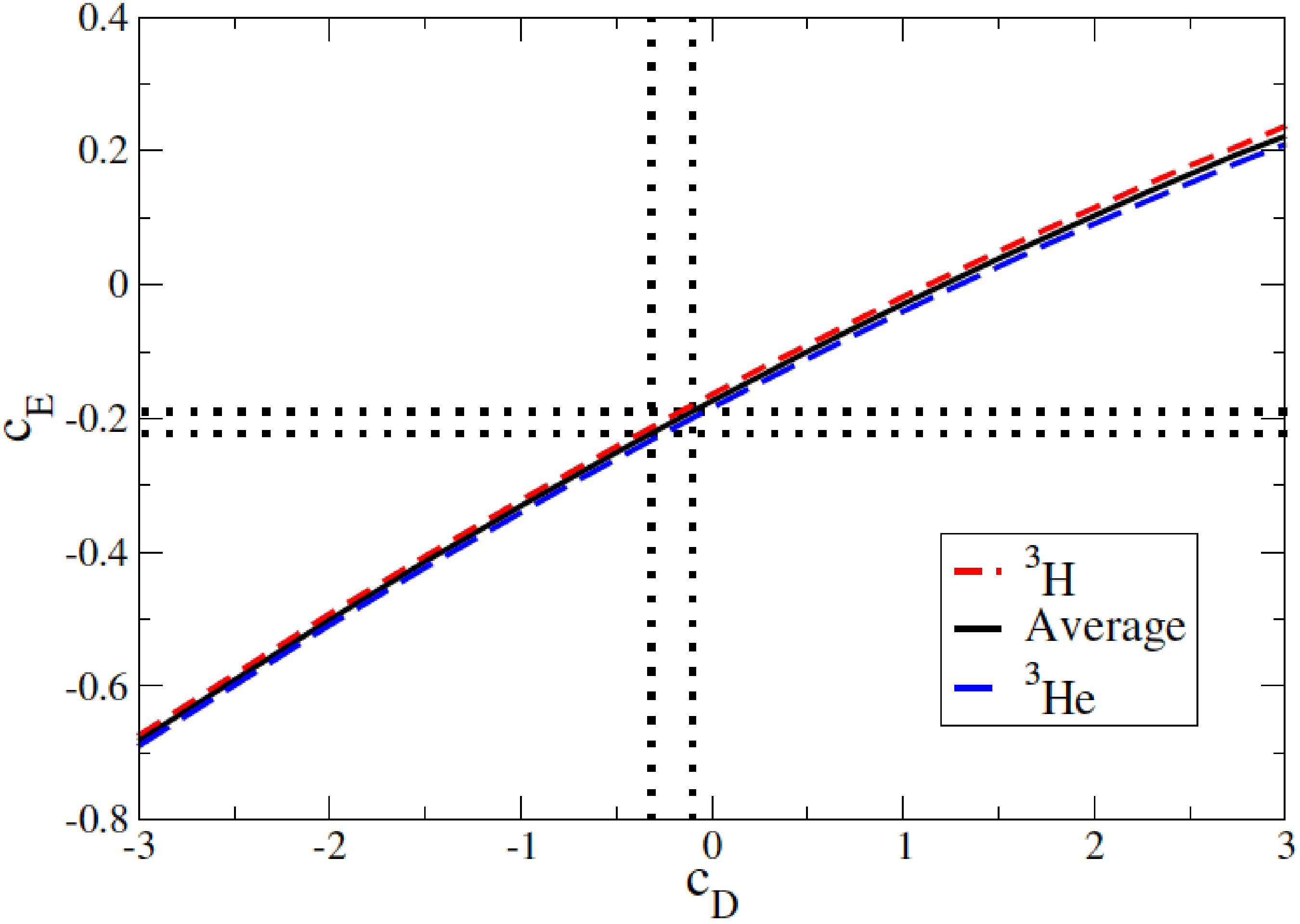




$$\hat{d}_R \equiv \frac{M_N}{\Lambda_\chi g_A} c_D + \frac{1}{3} M_N (c_3 + 2c_4) + \frac{1}{6}$$

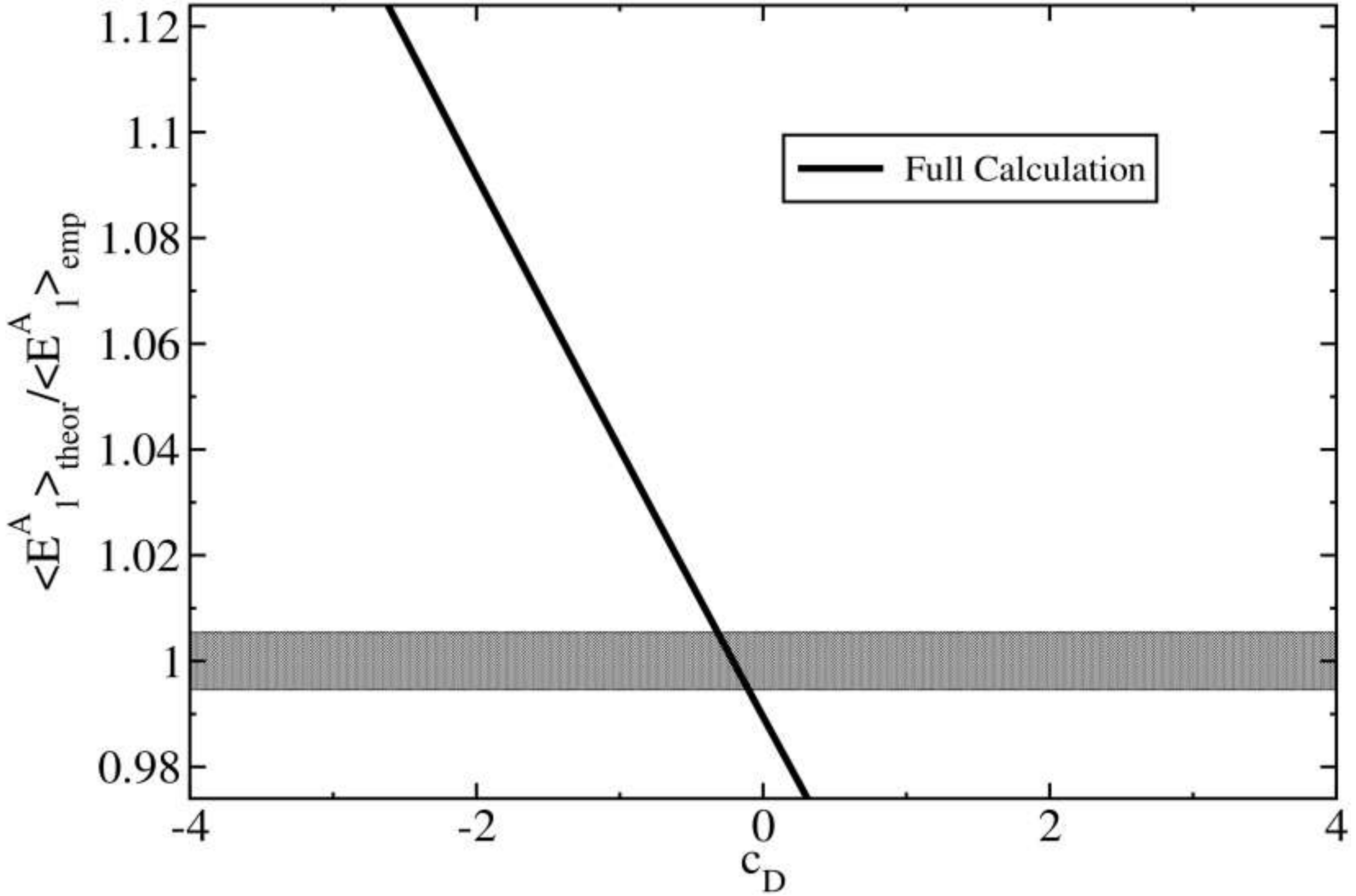
DG, Quaglioni, Navratil, Phys. Rev. Lett. **103,** 102502 (2009).

Step 1: use the trinuclei binding energies to find a c_D-c_E relation



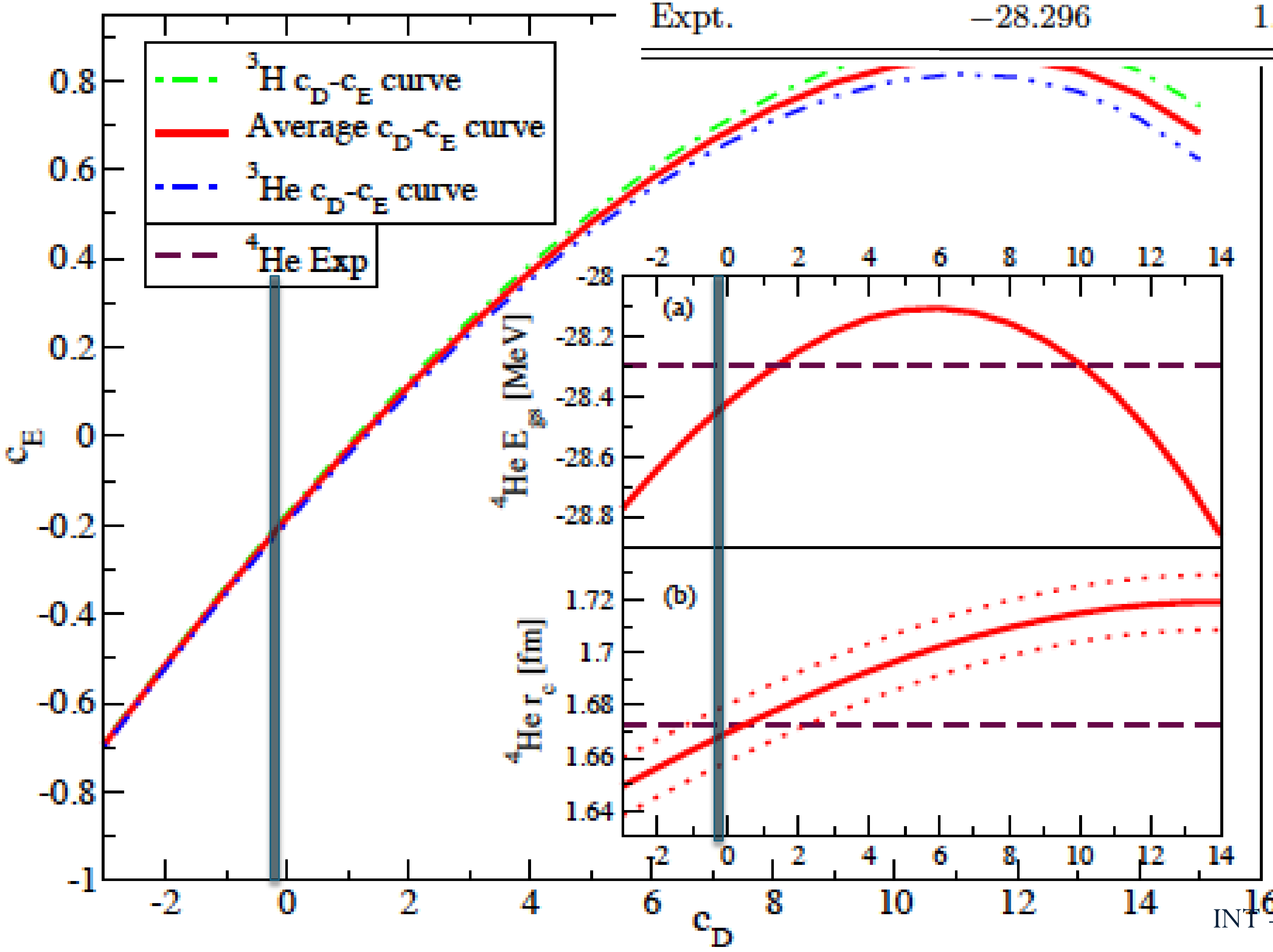
Navratil *et al.*, Phys. Rev. Lett. **99**, 042501 (2007).

Step 2: calibrate c_D according to the triton half life.

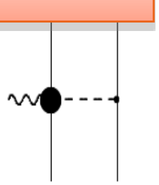


A prediction of ^{4}He

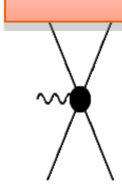
	^{4}He	
	$E_{\mathrm{g.s.}}$	$\langle r_p^2 \rangle^{1/2}$
NN	−25.39(1)	1.515(2)
$NN+NNN$	−28.50(2)	1.461(2)
Expt.	−28.296	1.467(13) [24]



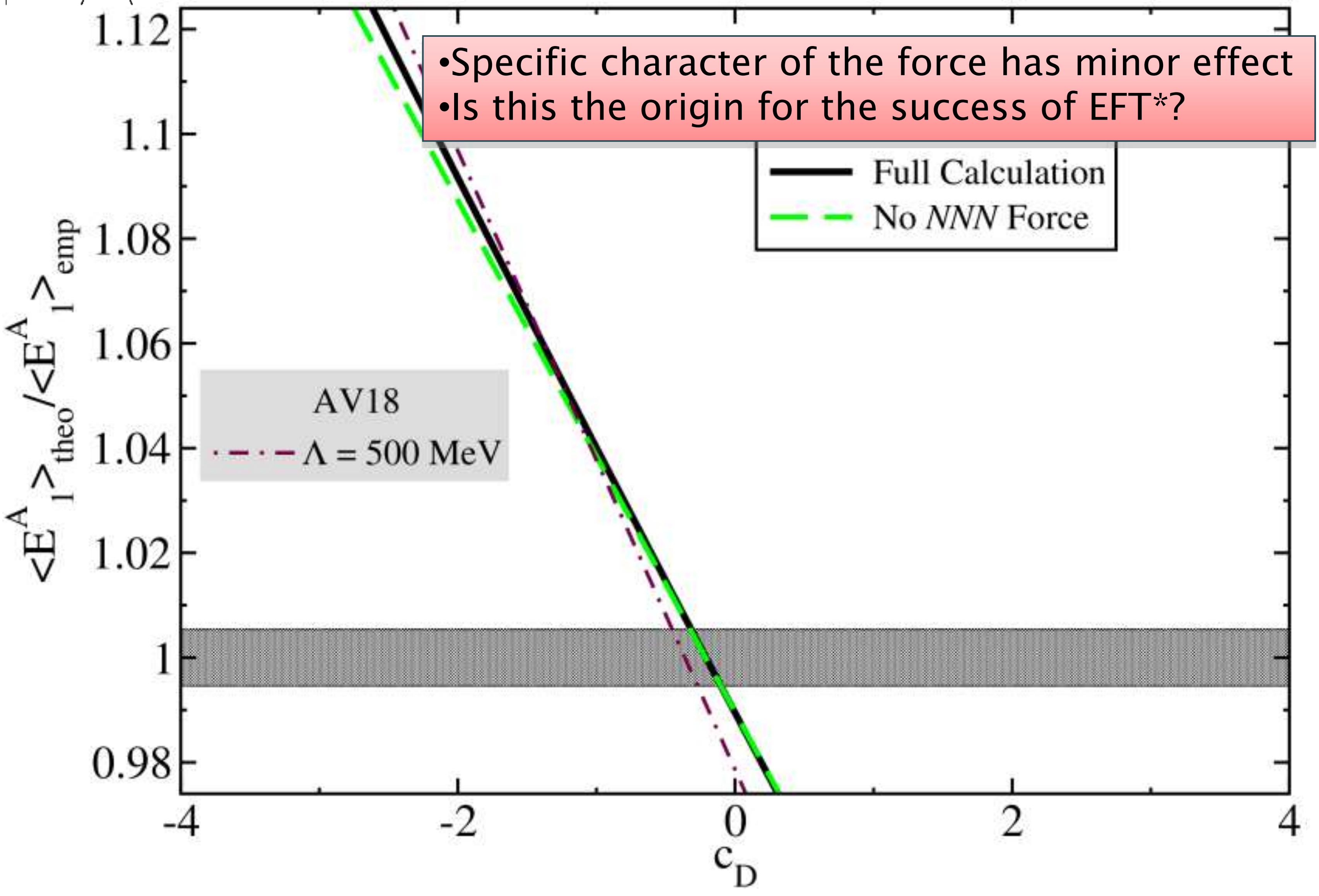
OPEC



Contact

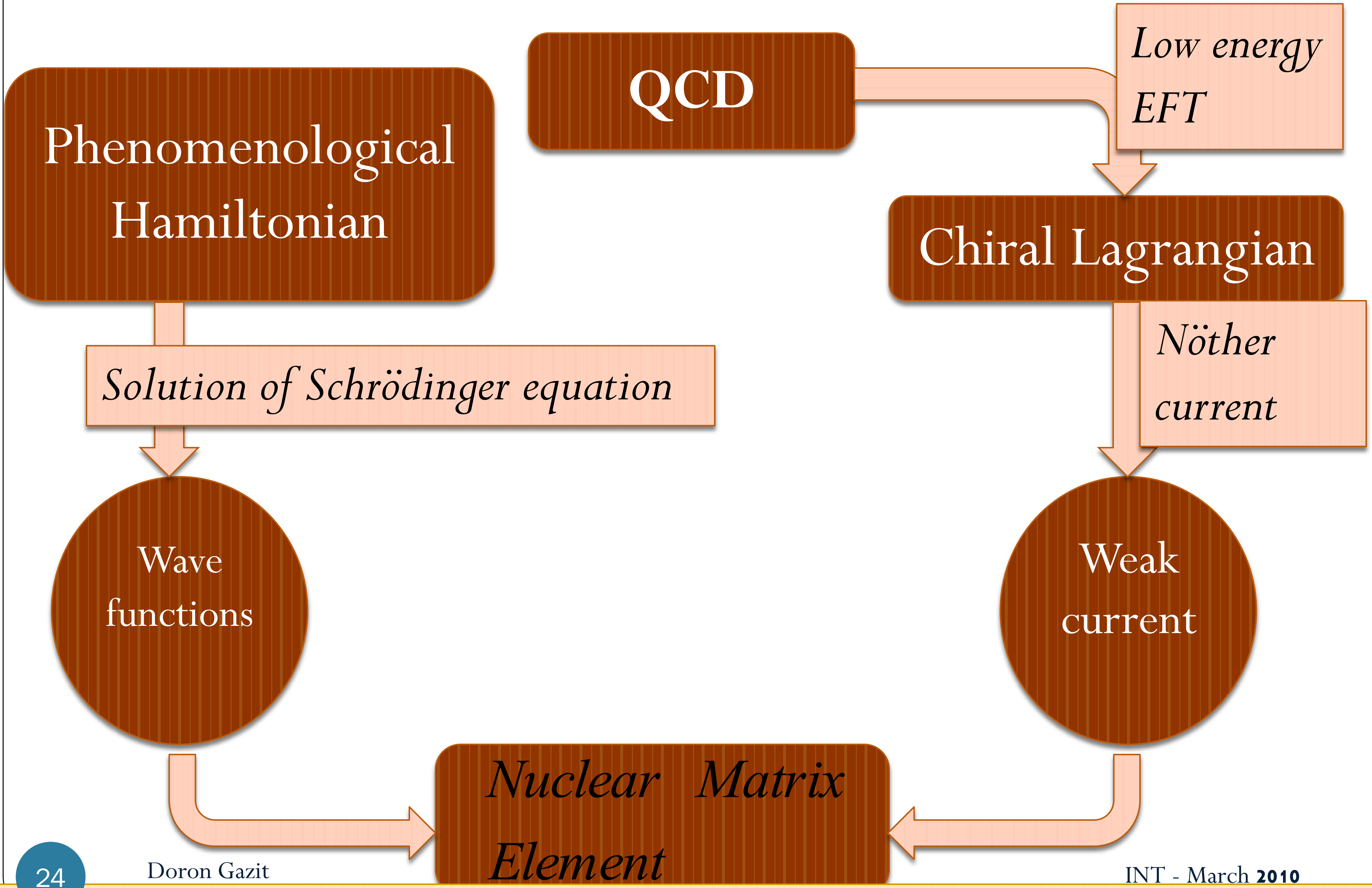


A closer look into the weak axial correlations in ^3H



- Specific character of the force has minor effect
- Is this the origin for the success of EFT*?

EFT approach for low-energy nuclear reactions:*



QCD

Low energy EFT

Chiral Lagrangian

Nöther current

Weak current

Phenomenological Hamiltonian

Solution of Schrödinger equation

Wave functions

Nuclear Matrix Element

T.-S. Park *et al*, **Phys. Rev. C 67**, 055206 (2003), M. Rho **arXiv:** nucl-th/061003.

Applications of the EFT* approach

- p+p fusion in the sun.
- ^{3}He+p fusion in the sun.

T.-S. Park *et al*, **Phys. Rev. C 67**, 055206 (2003).
R. Schiavilla *et al*, **Phys. Rev. C 58**, 1263 (1998).
M. Butler, J.-W. Chen, **Phys. Lett. B 520**, 87 (2001).
L. Marcucci *et al*, **Phys. Rev. C 66**, 054003 (2002)
Solar Fusion II, **Rev. Mod. Phys.** [to be published].

- The weak structure of the nucleon from μ capture on ^{3}He.

DG, **Phys. Lett. B666**, 471 (2008).

- Neutrino scattering on light nuclei in core-collapse supernovae.

DG, Barnea **Phys. Rev. C 70**, 048801 (2004); **Phys. Rev. Lett. 75**, 192501 (2007); **Nucl. Phys. A 790**, 356 (2007); **Few Body Syst.** (2008). DG, PhD. thesis, **arXiv: 0807.0216** (2007).
O'Connor, DG, Horowitz, Schwenk, Barnea, **Phys. Rev. C 75**, 055803 (2007).

- β decay of ^{6}He and the suppression of the axial constant in nuclear matter.

Vaintraub, Barnea, DG, **Phys. Rev. C, 79** 065501 (2009).

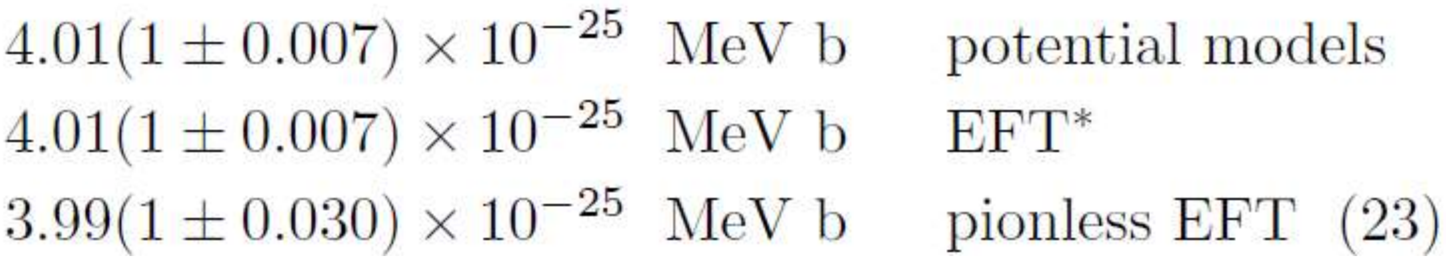
Go to summary

Few Solar Fusion open problems

T.-S. Park *et al*, **Phys. Rev. C 67**, 055206 (2003).
R. Schiavilla *et al,* **Phys. Rev. C 58**, 1263 (1998).
M. Butler, J.-W. Chen, **Phys. Lett. B 520**, 87 (2001).
L. Marcucci *et al,* **Phys. Rev. C 66**, 054003 (2002)
Solar Fusion II, **Rev. Mod. Phys.** [to be published].

pp fusion

- The weak fusion process p+p→d+ν+e^+, is sun's clock – it's the process determining the sun's evolution rate.
- An open field for state of the art/benchmark calculations with immense prospects.

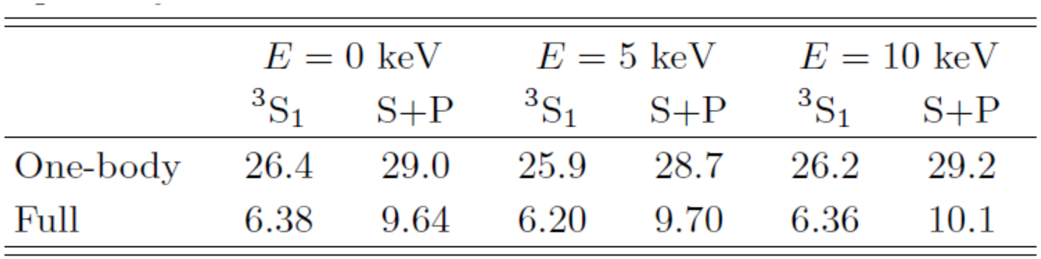


$$\begin{array}{lll}
4.01(1\pm 0.007)\times 10^{-25}\ \mathrm{MeV\ b} & \text{potential models} \\
4.01(1\pm 0.007)\times 10^{-25}\ \mathrm{MeV\ b} & \mathrm{EFT}^{*} \\
3.99(1\pm 0.030)\times 10^{-25}\ \mathrm{MeV\ b} & \text{pionless EFT} \quad (23)
\end{array}$$

- Needed:
  - 3 nucleon currents in pionless EFT.
  - Consistent calculations in pionfull EFT.

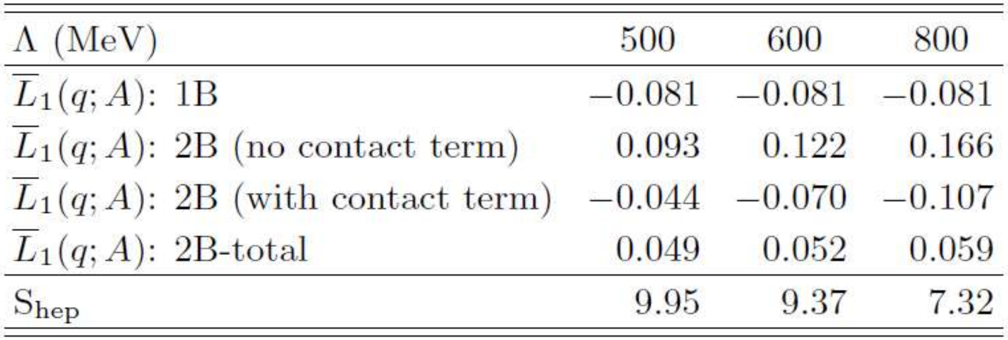
hep process

- The weak fusion p+^{3}He→^{4}He+ν+e$^+$ is the source of the most energetic neutrinos.
- The single nucleon current is highly suppressed.
- The EFT* calculation depends strongly on the EFT cutoff.



	$E = 0$ keV		$E = 5$ keV		$E = 10$ keV	
	$^3S_1$	S+P	$^3S_1$	S+P	$^3S_1$	S+P
One-body	26.4	29.0	25.9	28.7	26.2	29.2
Full	6.38	9.64	6.20	9.70	6.36	10.1

$$S_{hep}(0)=8.3\pm1.3\,\mathrm{keV}\cdot\mathrm{b}$$



Λ (MeV)	500	600	800
$\overline{L}_1(q;A)$: 1B	−0.081	−0.081	−0.081
$\overline{L}_1(q;A)$: 2B (no contact term)	0.093	0.122	0.166
$\overline{L}_1(q;A)$: 2B (with contact term)	−0.044	−0.070	−0.107
$\overline{L}_1(q;A)$: 2B-total	0.049	0.052	0.059
S_{hep}	9.95	9.37	7.32

Summary and outlook

- Electro-weak reactions with light nuclei can be used to:
  - Constrain the Nuclear interaction.
  - Give information regarding the structure of the nucleus.
  - Extract microscopic information about the fundamental theory and its symmetries.
  - Predict, to a percentage level accuracy, reaction rates for astrophysical phenomena.
- Halo helium isotopes (^{6}He and ^{8}He) are a great challenge for ab-initio calculation.
- Many challenges in the astrophysical sector. (pp fusion in a consistent manner as an important benchmark).