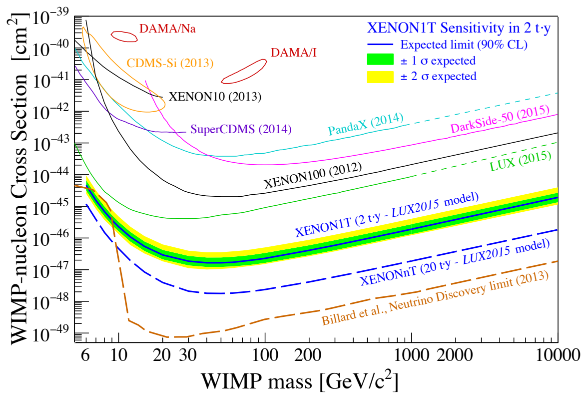
DORON GAZIT
RACAH INSTITUTE OF PHYSICS
HEBREW UNIVERSITY OF JERUSALEM

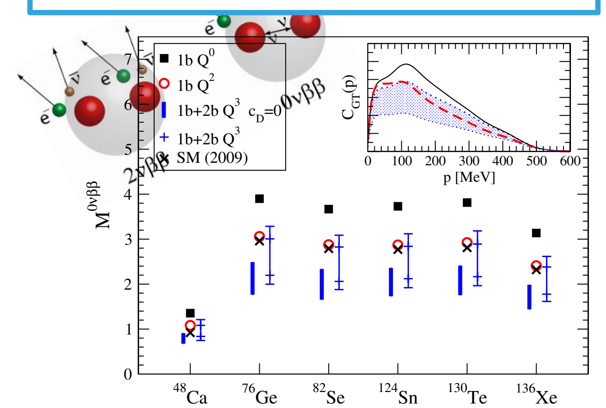
LOW-ENERGY ELECTROWEAK REACTIONS IN NUCLEI

ROLE OF NUCLEAR CURRENTS IN ATOMIC NUCLEI

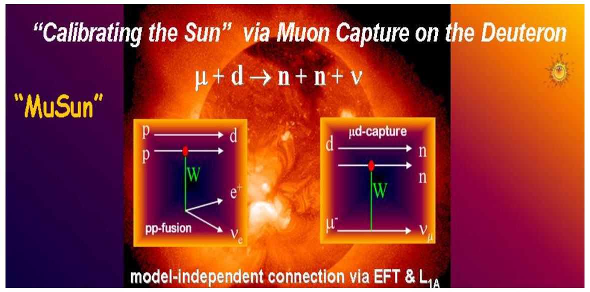
Dark Matter Direct Detection



Double beta decays

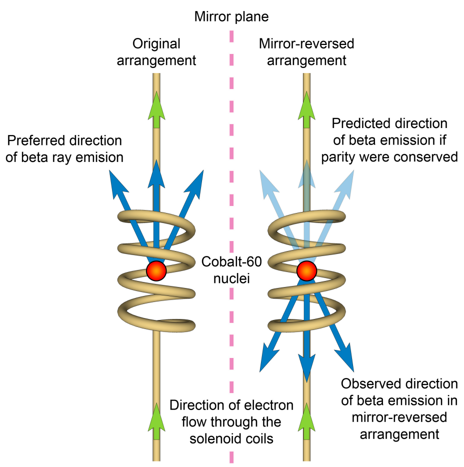


Solar fusion and Astrophysics

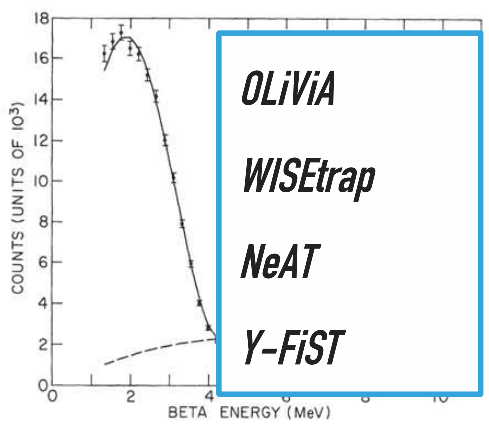


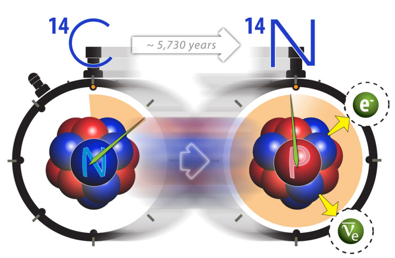
Beta decay studies for BSM studies

Precision Correlation Studies



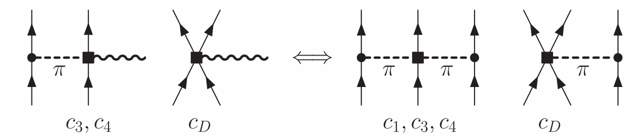
Precision spectrum/correlation studies



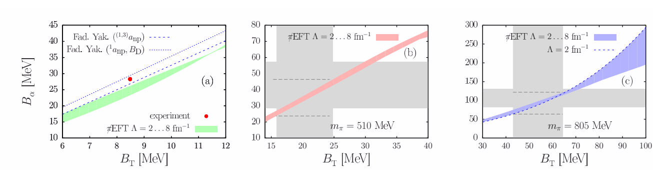


Nuclear structure

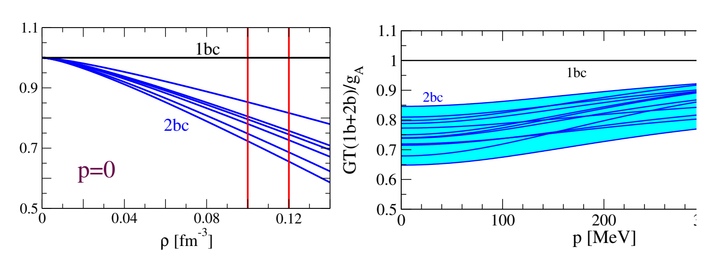
Strong from weak:



EFT for lattice nuclei



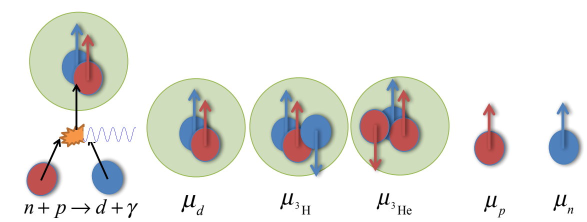
quenching



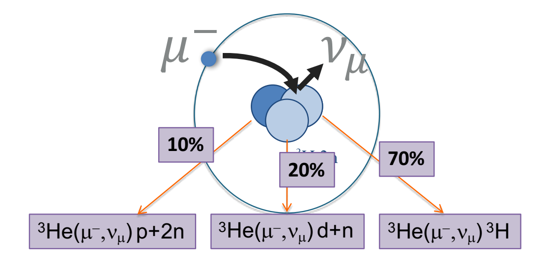
2b currents predict g_A quenching $q = 0.85 \ldots 0.66$

Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Magnetic moments and BBN



Muon capture



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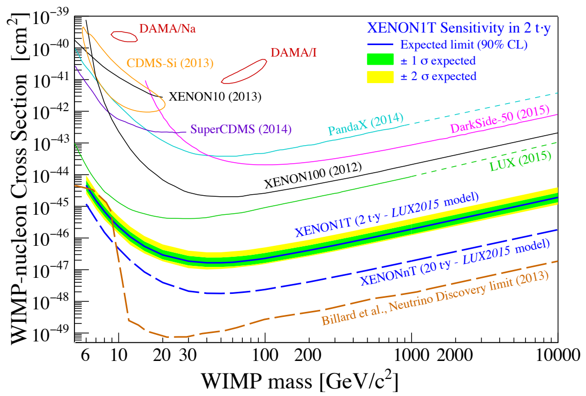

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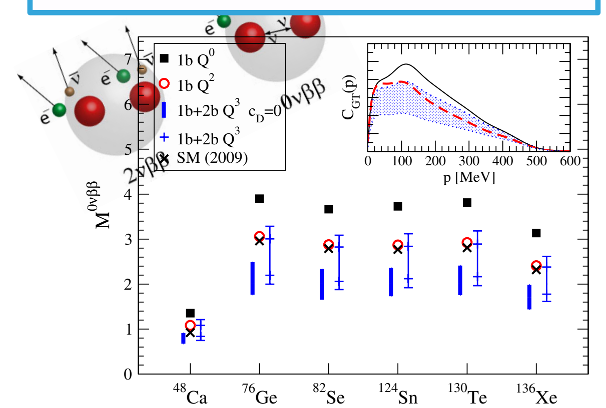

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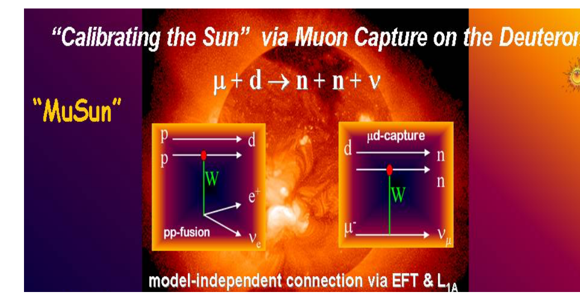
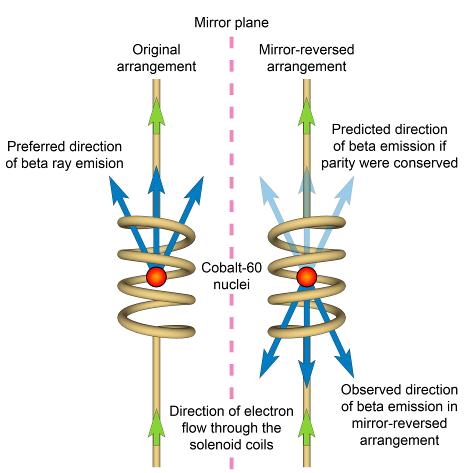


Beta decay studies for BSM studies

Precision Correlation Studies



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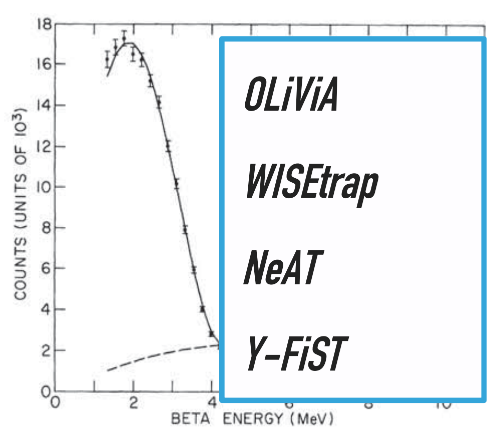

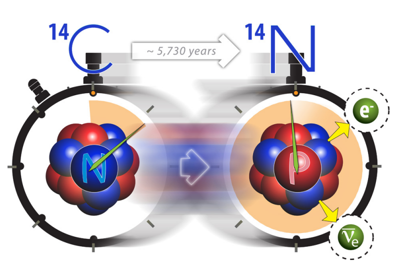

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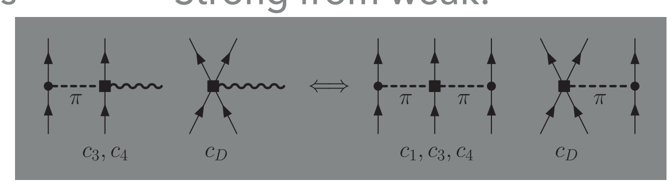

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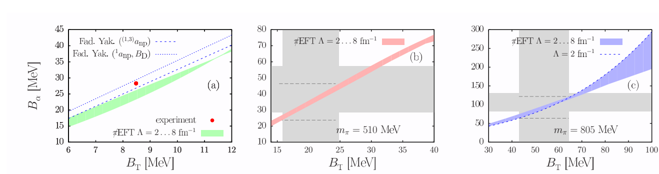
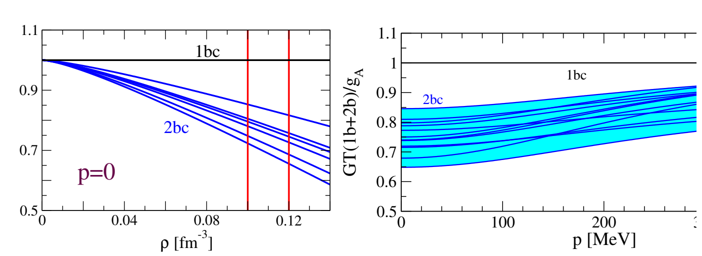


quenching



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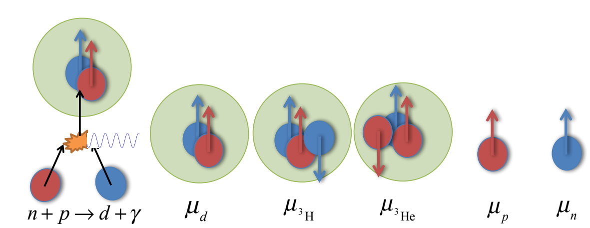

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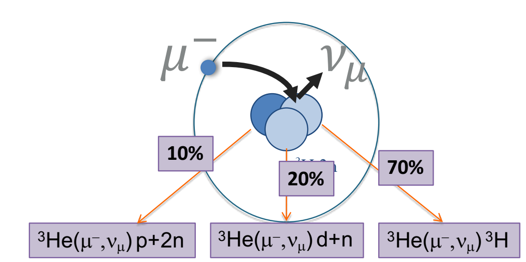

Ninio, DG (2018).

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LOW-ENERGY ELECTROWEAK REACTIONS IN NUCLEI:

CALCULATION OF MATRIX ELEMENTS IN PIONLESS EFT @ NLO
ELECTROWEAK REACTIONS OF A=2, 3 NUCLEAR SYSTEMS: M1, 3H BETA DECAY AND PP FUSION
PRECISION BETA DECAYS STUDIES FOR BSM SEARCHES

COLLABORATORS IN THIS WORK

Hilla De-Leon, Ayala Glick Magid, Gadi Ninio

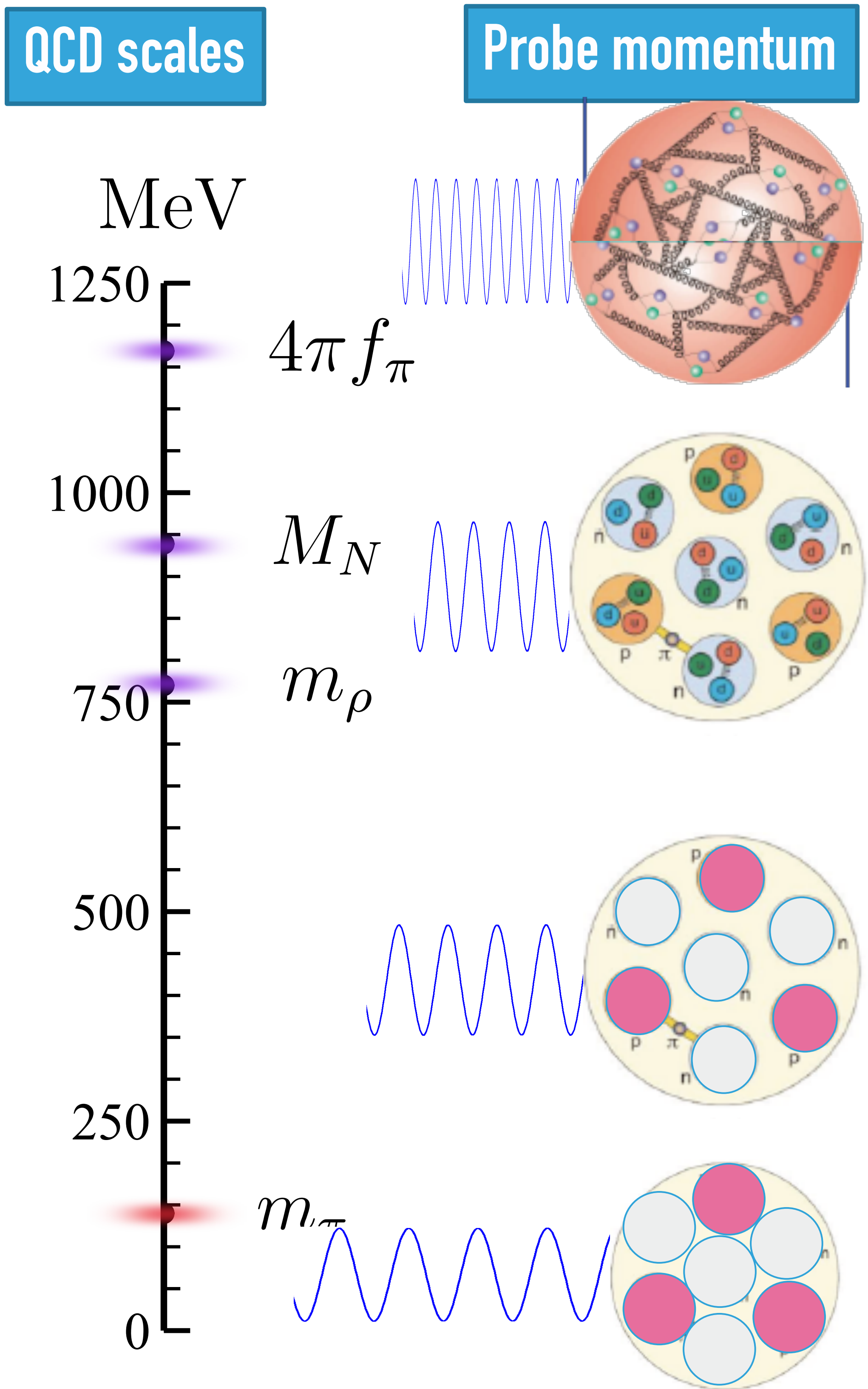
Guy Ron, Yonatan Mishnayot, Ben Ohayon

Michael Hass, Sergey Vaintraub, Ish Mukul

Lucas Platter

PIONLESS EFT AT NLO: CALCULATING MATRIX ELEMENTS OF A=2, 3 TRANSITIONS

De-Leon, Platter, DG (2018), in prep.



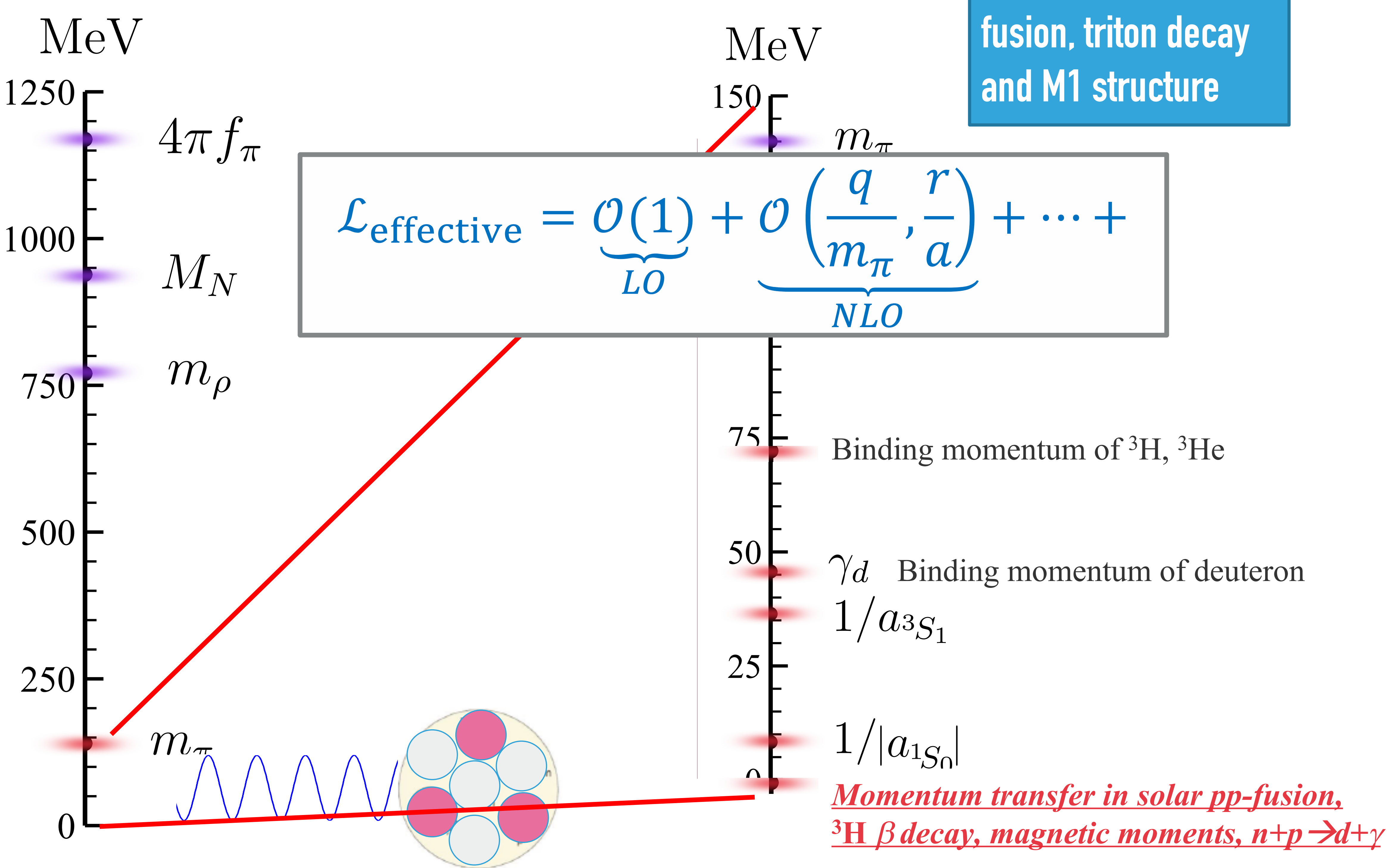
Weinberg (1991), van-Kolck (1992), Kaplan (1996)...

QCD scales

Probe momentum

Pionless EFT scales

Pionless EFT is the natural EFT for solar fusion, triton decay and M1 structure



$$\mathcal{L}_{\text{effective}} = \underbrace{\mathcal{O}(1)}_{LO} + \underbrace{\mathcal{O}\left(\frac{q}{m_\pi}, \frac{r}{a}\right)}_{NLO} + \cdots +$$

- $a_{^3S_1} \approx 5.4$ fm, $a_{^1S_0} \approx -23.7$ fm $\gg 1/m_\pi \approx 1.4$ fm
- effective ranges (1.8 fm, 2.7 fm) are natural

DIBARYON REPRESENTATION

$$\mathcal{L} = N^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2M}\right) N - t^{i\dagger}\left[\left(iD_0 + \frac{\mathbf{D}^2}{4M}\right) - \sigma_t\right] t^i$$
$$- s^{A\dagger}\left[\left(iD_0 + \frac{\mathbf{D}^2}{4M}\right) - \sigma_s\right] s^A$$
$$- y_t\left[t^{i\dagger}\left(N^T P_t^i N\right) + h.c\right]$$
$$- y_s\left[s^{A\dagger}\left(N^T P_s^A N\right) + h.c\right] + \ldots, \quad (1)$$

$$y_{t,s} = \frac{\sqrt{8\pi}}{M\sqrt{\rho_{t,s}}},$$

$$\sigma_{t,s} = \frac{2}{M\rho_{t,s}}\left(\frac{1}{a_{t,s}} - \mu\right),$$

Kaplan, Savage, van Kolck, Rupak, Chen…

DIBARYON REPRESENTATION

$$\mathcal{L} = N^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2M} \right) N - t^{i\dagger} \left[\left(iD_0 + \frac{\mathbf{D}^2}{4M} \right) - \sigma_t \right] t^i$$
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Parameter	Value	Parameter	Value
γ_t	45.701 MeV [18]	ρ_t	1.765 fm [19]
a_s	-23.714 fm [20]	ρ_s	2.73 fm [20]
a_p	-7.8063 fm [21]	ρ_C	2.794 fm [21]
LO		NLO	

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The bound deuteron creates redundancy: between ρ_t and the normalization: $Z_d = \frac{1}{1-\gamma_t\rho_t}$

➔ 2 NLO rearrangements:

$$Z_d^{LO} = 1 \qquad \rho_t^{LO} = 0$$
$$Z_d^{NLO} = 1 + \gamma_t\rho_t \approx 1.408 \qquad \rho_t^{NLO} = \rho_t^{exp}$$

EFFECTIVE RANGE PARAMETERIZATION

$$Z_d^{LO} = 1 \qquad \rho_t^{LO} = 0$$
$$Z_d^{NLO} = 1 + \left(Z_d^{full} - 1\right) = Z_d^{full} \qquad \rho_t^{NLO} = \frac{Z_d - 1}{\gamma_t} \approx \frac{0.690}{\gamma_t}$$

Z-PARAMETERIZATION

Phillips, Rupak, Savage (2000), Griesshammer (2004)

PHOTON ABIDES – STATIC PHOTONS

- Since the typical momentum is $Q \geq \sqrt{M_N E^B_{^3\mathrm{He}}} \simeq 85\mathrm{MeV}$, then the Coulomb interaction is perturbative:

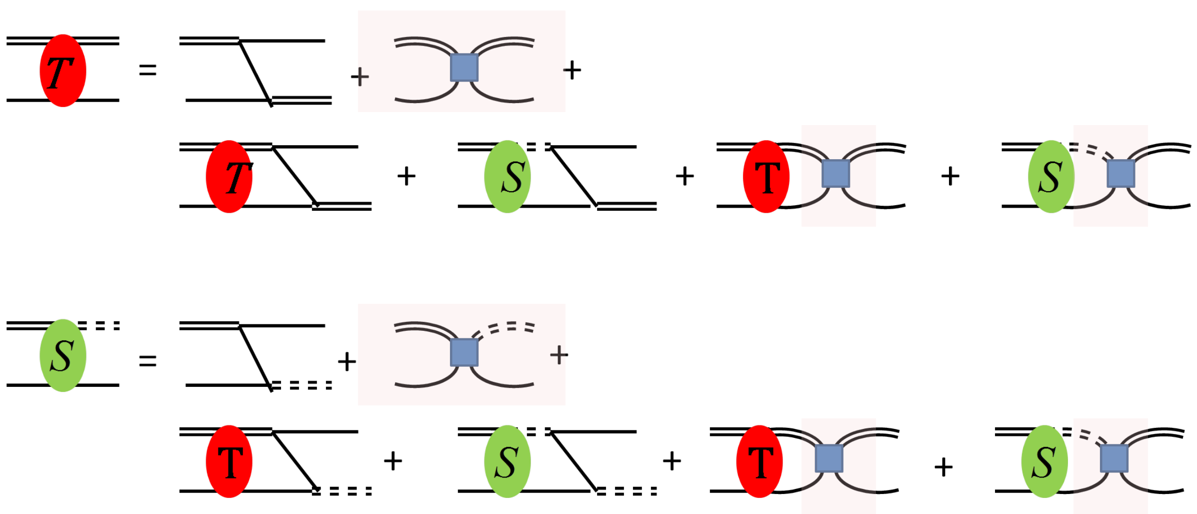
$$\eta(Q) = \frac{\alpha M_N}{2Q} << 1$$

- However, the pp propogator always has to be renormalized (as Q can be low).
- Photons are added already at LO.

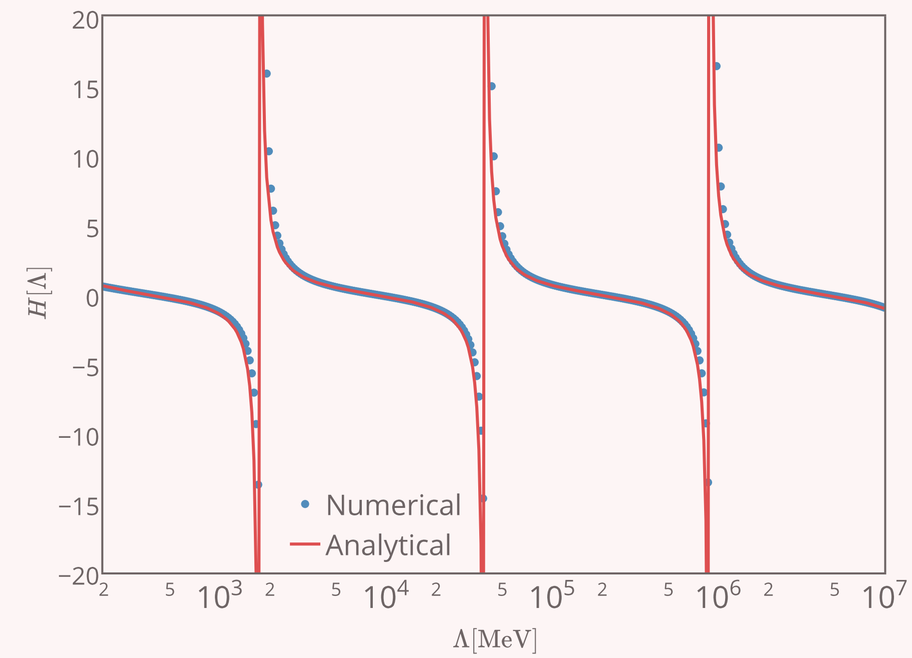
Kong and Ravndal (1999), Ruoak (2000), König, et al.(2014), Kirscher, DG (2015)

DIBARYON REPRESENTATION OF THREE BODY SCATTERING

Neutron-dibaryon scattering:



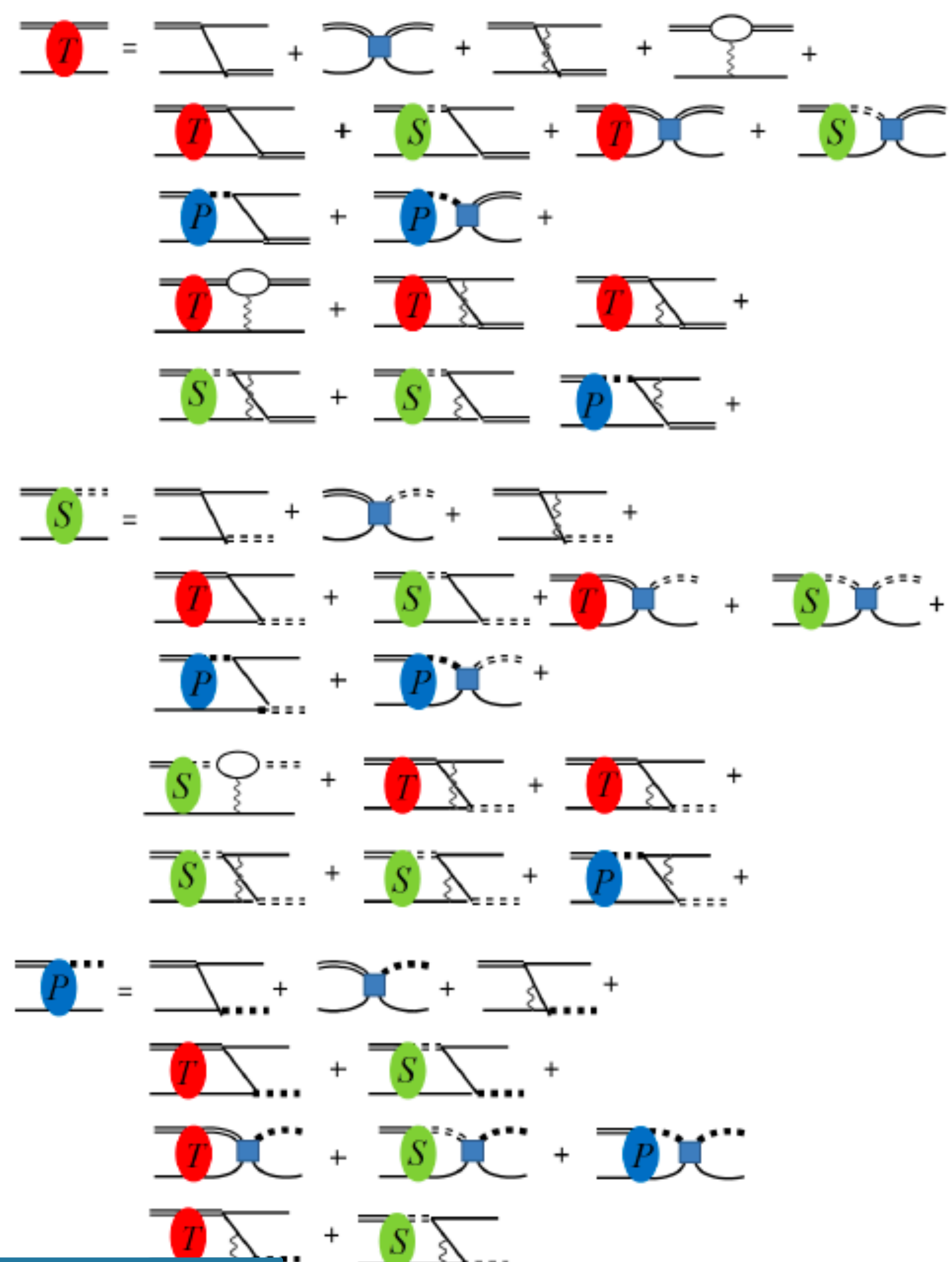
LO ISOSPIN IND. 3-BODY FORCE



Bedaque, Hammer, van Kolck (1999)

DIBARYON REPRESENTATION OF THREE BODY SCATTERING WITH COULOMB

Proton-deuteron scattering:



König, et al. (2012, 14, 15), Vanasse et al. (2015)

FROM SCATTERING TO BOUND STATE

For a bound state:

AMPUTATED WAVE FUNCTION

$$t(E,k,p) = \frac{\mathcal{B}^\dagger(E,k)\mathcal{B}(E,p)}{E-E_B} + \mathcal{R}(E,k,q)$$

REGULAR FOR E→E_B
NEGLIGIBLE AT POLE

A non-relativistic Bethe-Salpeter equation:

$$\mathcal{B}(E,p) = \mathcal{B}(E,q) \otimes K_0^S(q,p,E)$$

e.g., for ^{3}H:

$$\begin{pmatrix} \Gamma_T(E,p) \\ \Gamma_S(E,p) \end{pmatrix} = \left[K_0(q,p,E) \begin{pmatrix} My_t^2 D_t(E,q) & -3My_t y_s D_s(E,q) \\ -3My_t y_s D_t(E,q) & My_s^2 D_s(E,q) \end{pmatrix} + \frac{H(\Lambda)}{\Lambda^2} \begin{pmatrix} My_t^2 D_t(E,q) & -My_t y_s D_s(E,q) \\ -My_t y_s D_t(E,q) & My_s^2 D_s(E,q) \end{pmatrix} \right] \otimes \begin{pmatrix} \Gamma_T(E,q) \\ \Gamma_S(E,q) \end{pmatrix}. \quad (33)$$

FROM SCATTERING TO BOUND STATE

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$$\mathcal{B}(E,p) = \mathcal{B}(E,q) \otimes K_0^S(q,p,E)$$

$$\langle \boldsymbol{E}, \boldsymbol{p} | \boldsymbol{\Gamma} \rangle$$

AMPUTATED WAVE FUNCTION DEFINED UP TO A CONSTANT.
BETHE-SALPETER NORMALIZATION CONDITION:

$$1 = \langle \Gamma | \mathcal{D} \frac{\partial}{\partial_E} \left(D^{-1} - \mathcal{K} \right) \mathcal{D} | \Gamma \rangle |_{E=E_B}$$

HOWEVER, LOSES DIAGRAMMATIC REPRESANTATION

König, Vanasse et al. (2012, 14, 15)

BOUND STATE NORMALIZATION – DIAGRAMMATIC REPRESENTATION

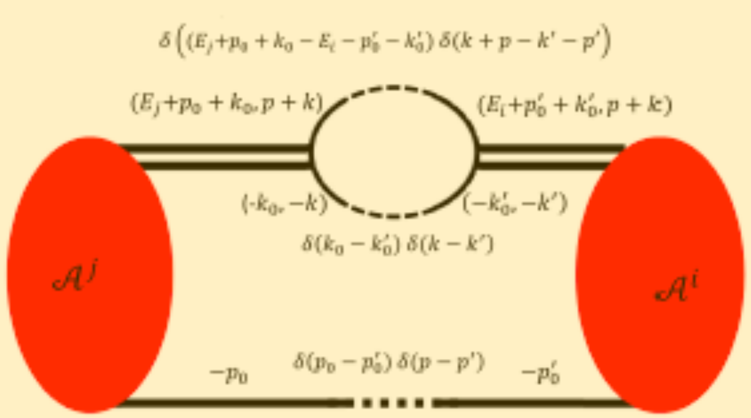
$$\langle E, p|\,\psi\rangle = \int dp_0 \mathcal{B}(p_0, p) S(p_0, \mathbf{p}) \mathcal{D}(p_0, \mathbf{p})$$

$$1 = \int dq_0 \int \frac{d^3q}{(2\pi^3)} \int dq_0' \int \frac{d^3q'}{(2\pi^3)} \mathcal{B}(q_0, q) S(q_0, \mathbf{q}) \times$$
$$\left\{ \mathcal{D}(q_0, \mathbf{q}) \left[\frac{d}{dE} \left(\hat{I} - \mathcal{K} \right)_{E=E_B} \right] \mathcal{D}(q_0', \mathbf{q}') \right\} \times S(q_0', \mathbf{q}') \mathcal{B}(q_0', q') =$$
$$\int \frac{d^3q}{(2\pi^3)} \int \frac{d^3q'}{(2\pi^3)} \psi(E, q) \left[\frac{d}{dE} \left(\hat{I} - \mathcal{K} \right)_{E=E_B} \right] \psi(E, q').$$

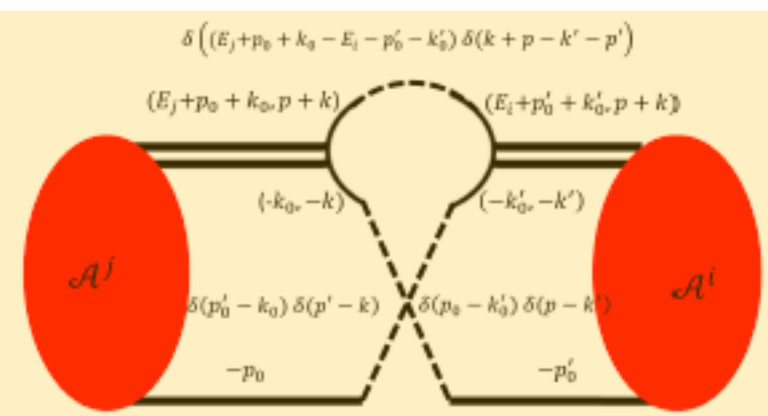
However: $\frac{\partial}{\partial_E} S(E, \mathbf{q}) = S(E, \mathbf{q}) \times S(E, \mathbf{q}') \delta(\mathbf{q} - \mathbf{q}')$

Thus the normalization is equivalent to:

$$\frac{\partial}{\partial_E} \hat{I}$$



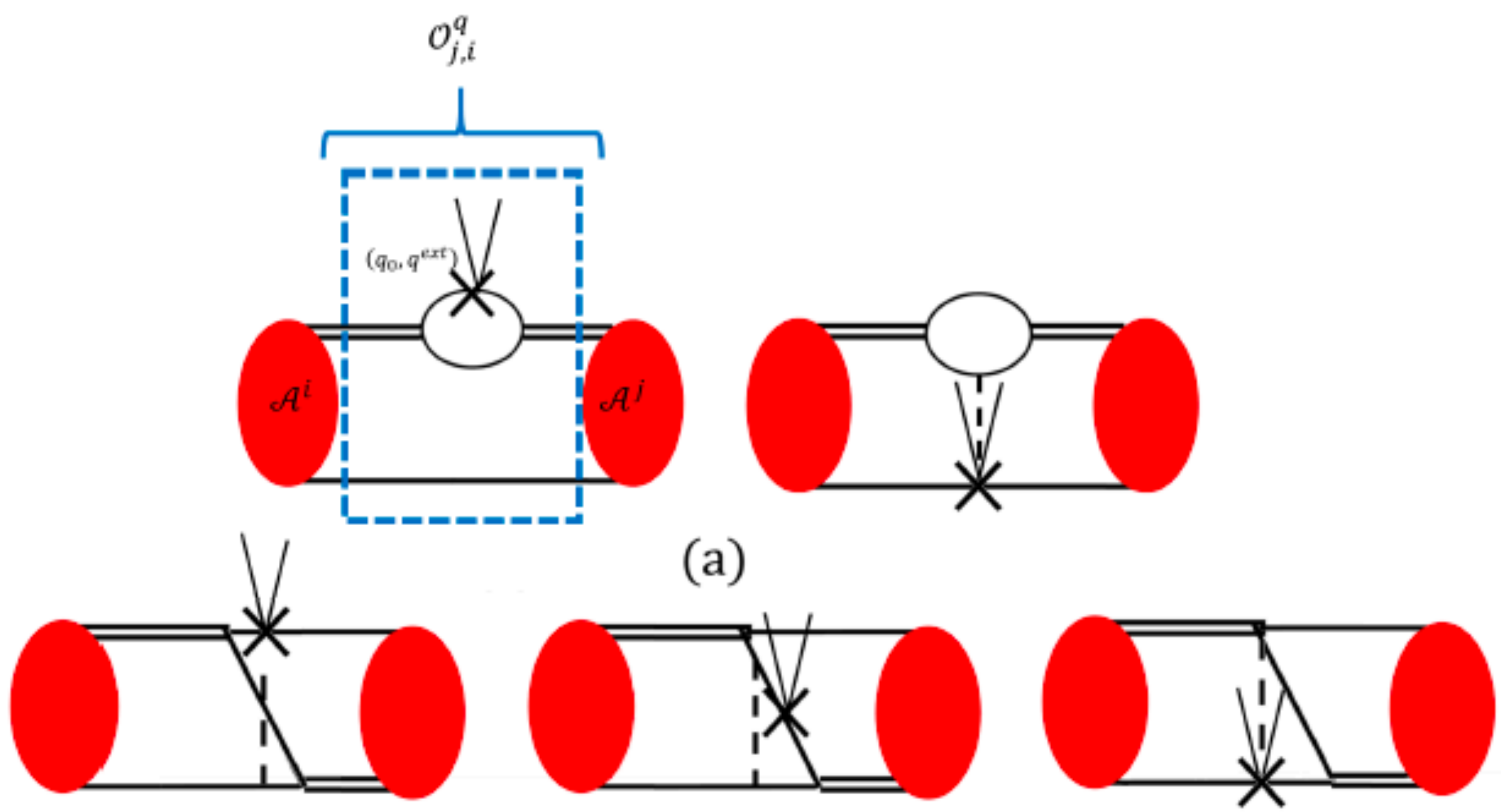
$$\frac{\partial}{\partial_E} \mathcal{K}$$



EASY GENERALIZATION: MATRIX ELEMENT OF A 1-BODY OPERATOR

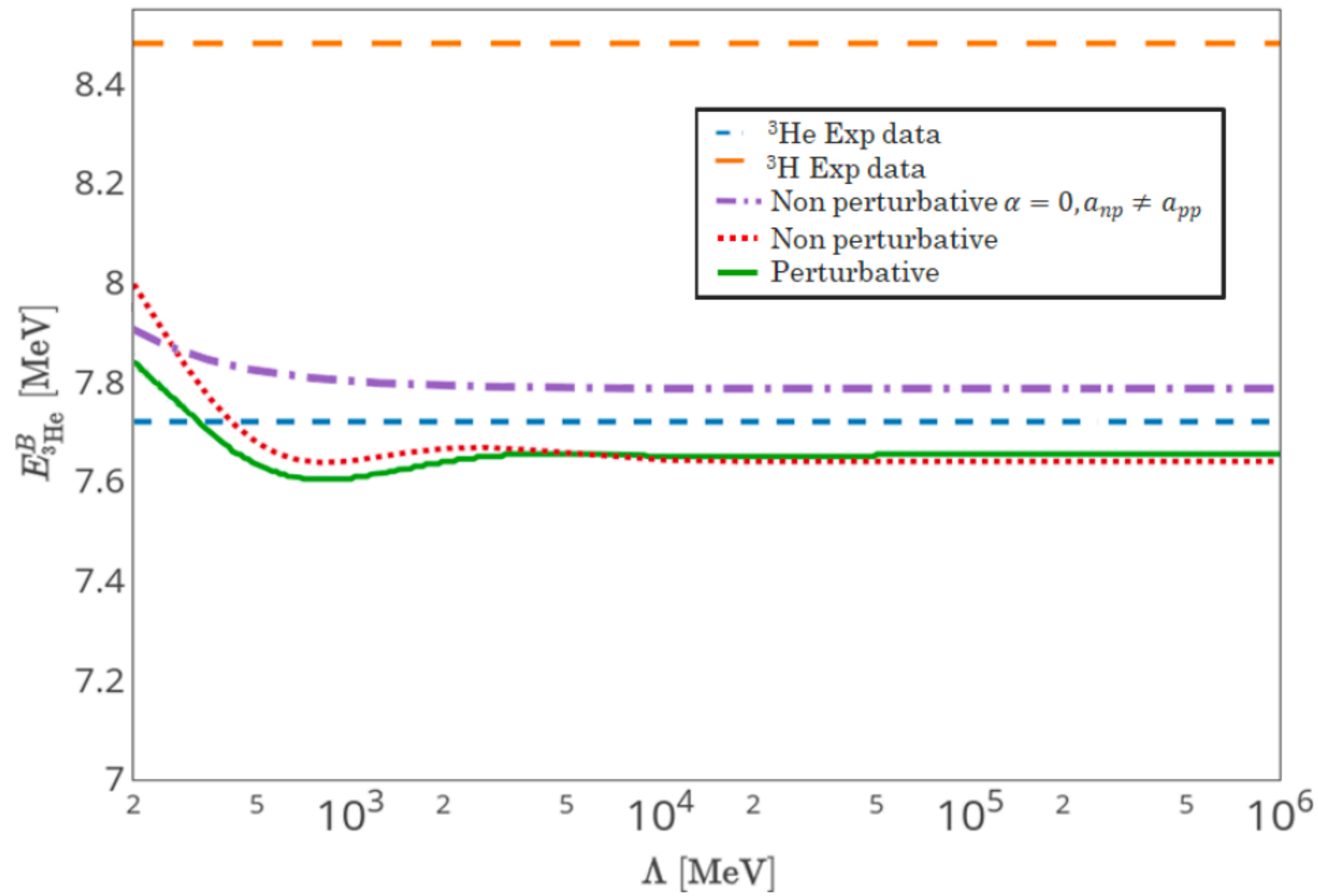
- 1-body common operators, e.g., electroweak, create transitions inside isospin-spin multiplet. $\mathcal{O}_{j,i} = \mathcal{O}^J \mathcal{O}^I \mathcal{O}^q_{j,i}$
- It is easy to generalize this:

$$\mathcal{O}^q_{j,i}(q_0, p_i, p_j) = \sum P_A y_A P_B y_B \left(I^q - \mathcal{K}^q\right)\big|_{E=E_i} \times \delta\left(q - (p_i - p_j)\right)\delta\left(q_0 - (E_i - E_j)\right),$$



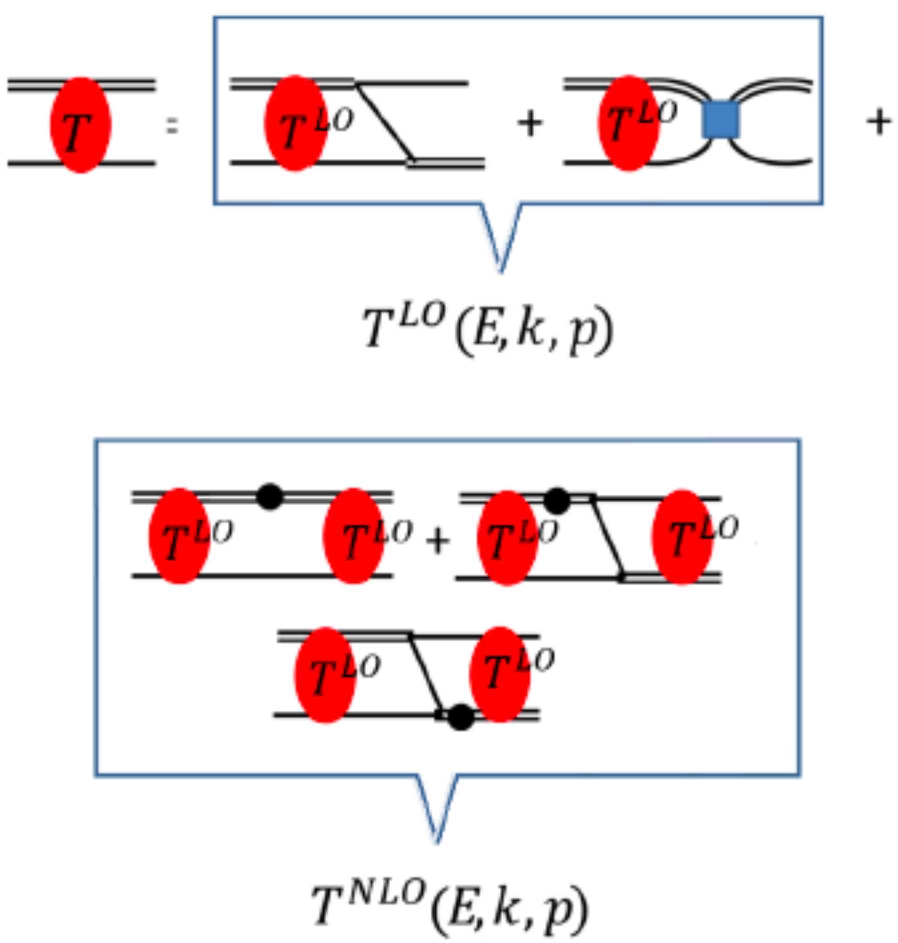
APPLICATION: ^3H–^3HE B.E. DIFFERENCE AT LO

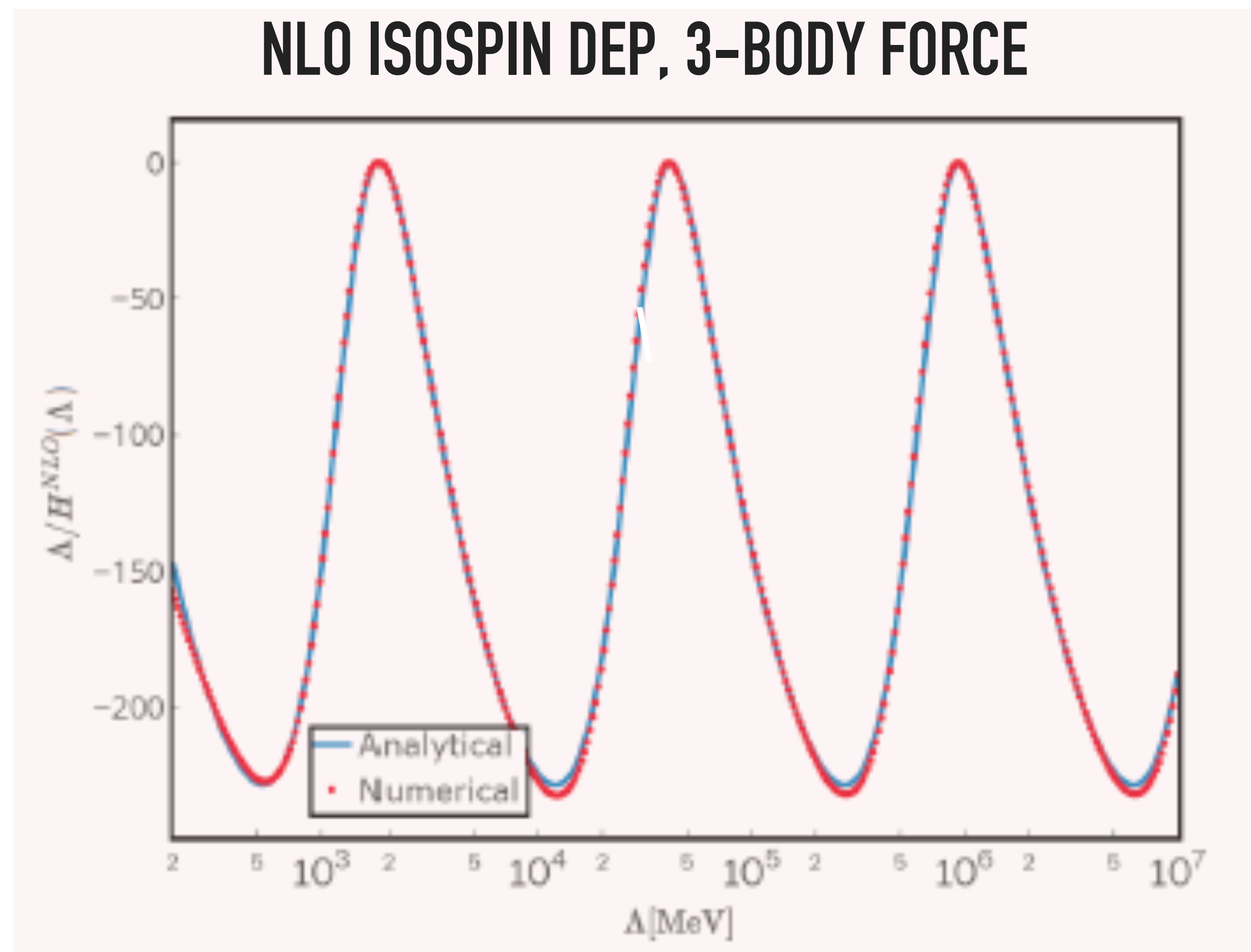
- two ways to find the A=3 b.e. difference:
  - Find the pole of a non-perturbative solution of the homogenous Fadeev equations with Coulomb (i.e., 3He w.f.).
  - Since Coulomb is perturbative in ^{3}He, one can calculate the energy shift in the one photon approximation, as a matrix element.



APPLICATION: PIONLESS EFT AT NLO FOR BOUND STATE W.F'S

- A fully perturbative calculation at NLO means that the all NLO insertions are perturbative, i.e., no more than one NLO insertion per diagram.
- This means that they can be stated as matrix elements.





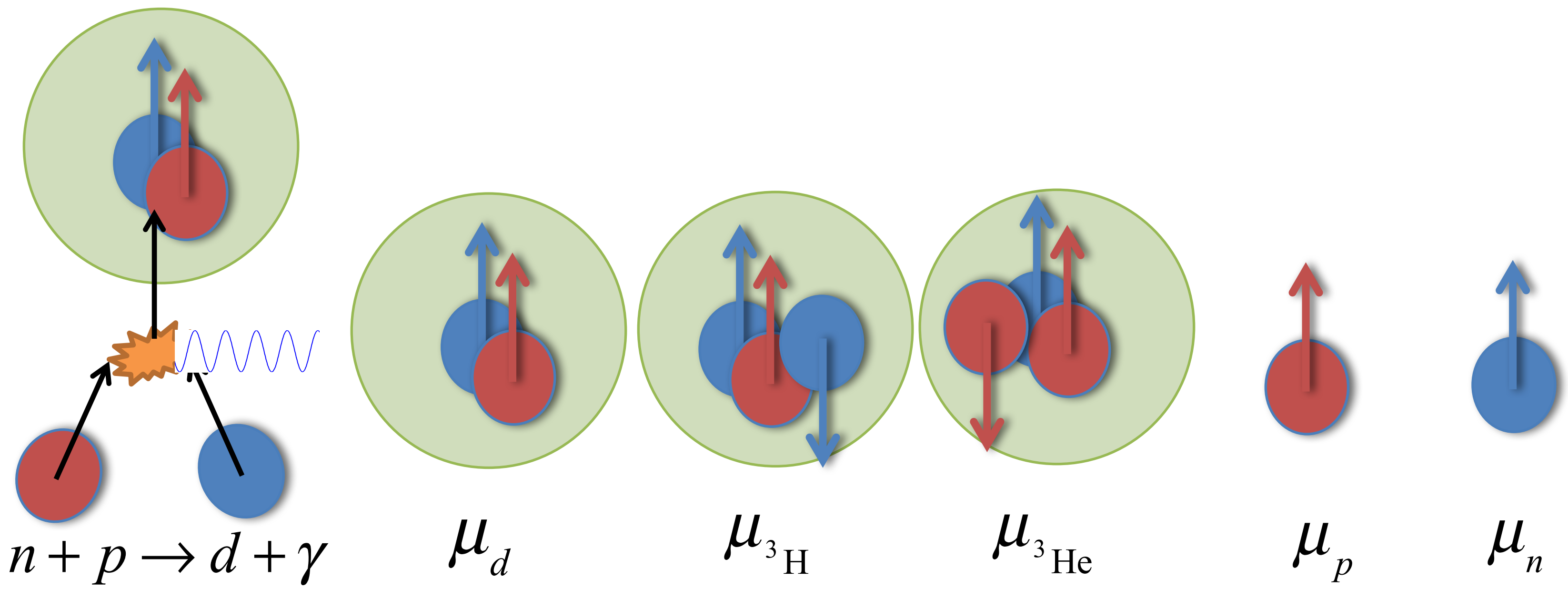
Vanasse et al. (2015)

A FULLY PERTURBATIVE PIONLESS EFT A=2, 3 CALCULATION @NLO

- **4** Leading Order Parameters
  - nn and np Scattering lengths: $^3S_1$, $^1S_0$.
  - pp scattering length.
  - Three body force strength to prevent Thomas collapse.
- **5** Next-to Leading Order parameters:
  - 2 effective ranges.
  - Renormalizations of pp and 3NF.
  - isospin dependent 3NF to prevent logarithmic divergence in the binding energy of ^{3}He.
- Only ^{3}H and ^{3}He binding energies are "many-body" parameters. All the rest- very well known scattering parameters.

MAGNETIC “M1” A=2, 3 OBSERVABLES IN PIONLESS EFT

De-Leon, DG (2018) in prep.

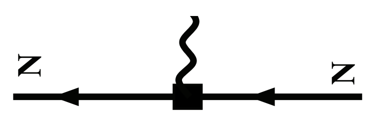


Pionless: Kirscher, et al. (2017), Vanasse (2017)
chiral: Pastore et al (2013), Bacca and Pastore (2014)

ADDING THE MAGNETIC PHOTON

- **4+2** LO Parameters

One body

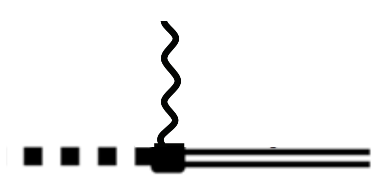


$$\frac{e}{2M_N} N^\dagger \left(\kappa_0 + \kappa_1 \tau_3\right) \sigma \cdot B N$$

Nucleon magnetic moments –well known experimentally

- **5+2** NLO parameters:

Two body



$$- L_1' (t^\dagger s + s^\dagger t) \cdot B + L_2' (t^\dagger t) \cdot B.$$

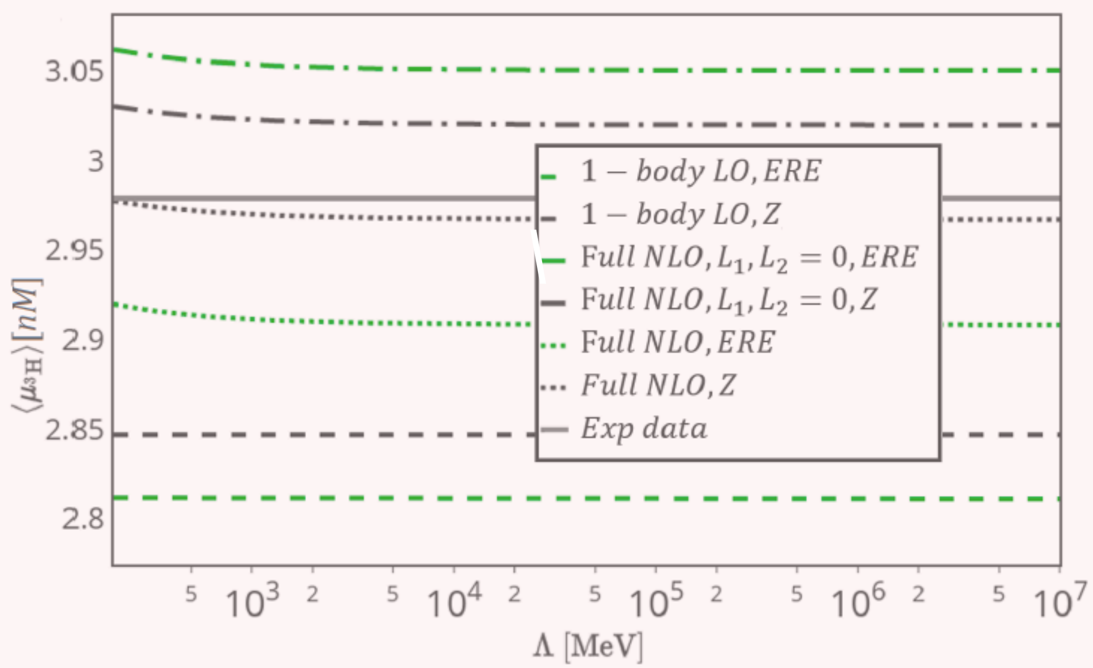
$$l_1(\mu) = \frac{M}{\pi\sqrt{\rho_t \rho_s}} \frac{L_1}{\kappa_1} \left(\mu - \frac{1}{a_t}\right)\left(\mu - \frac{1}{a_s}\right)$$

$$l_2(\mu) = \frac{2M}{\pi \rho_t} \frac{L_2}{\kappa_0} \left(\mu - \frac{1}{a_t}\right)^2.$$

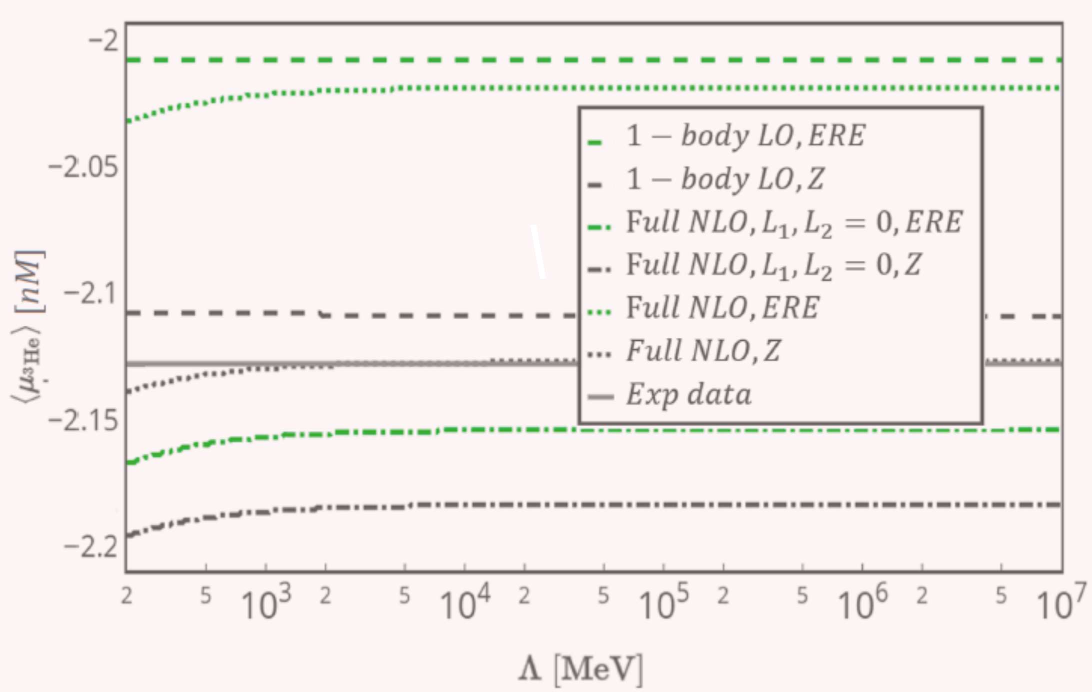
LECs can be calibrated by any 2 of the experimentally known A=2, 3 observables, and then to be used to post-dict the other 2 observables.

A FULLY PERTURBATIVE PIONLESS EFT CALCULATION OF A=3 M.M @NLO

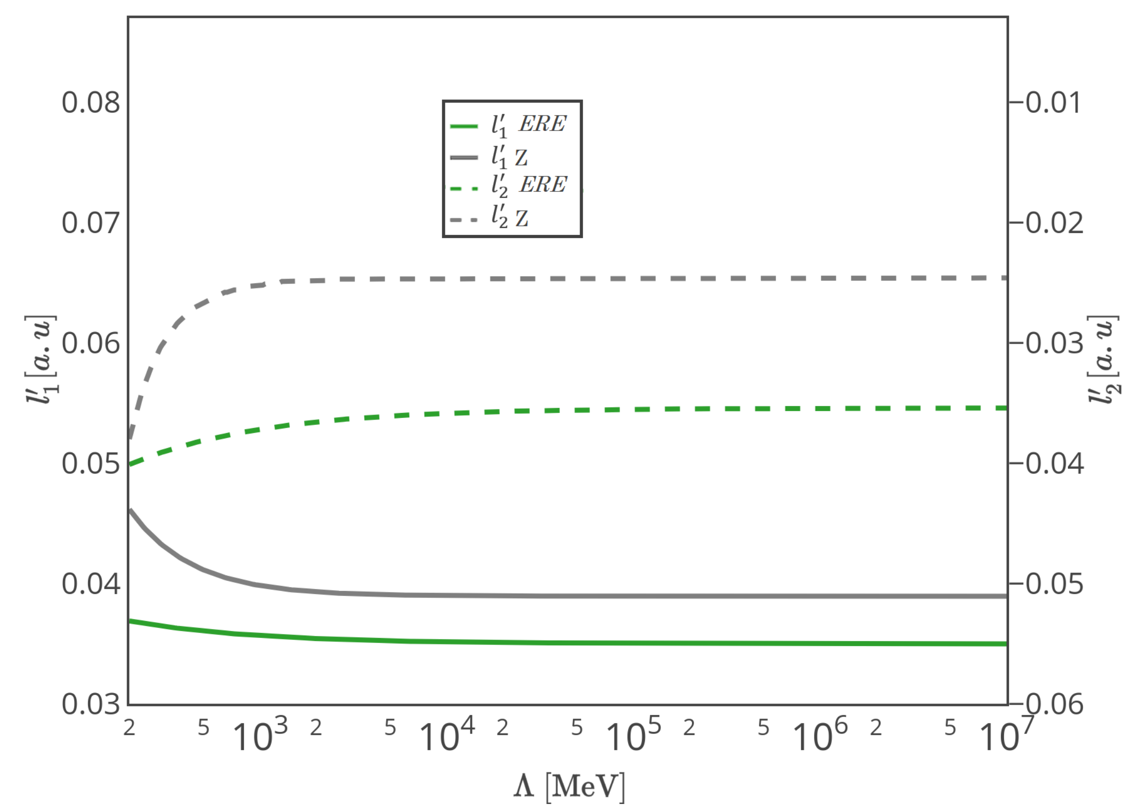
TRITON MAGNETIC MOMENT



³HE MAGNETIC MOMENT

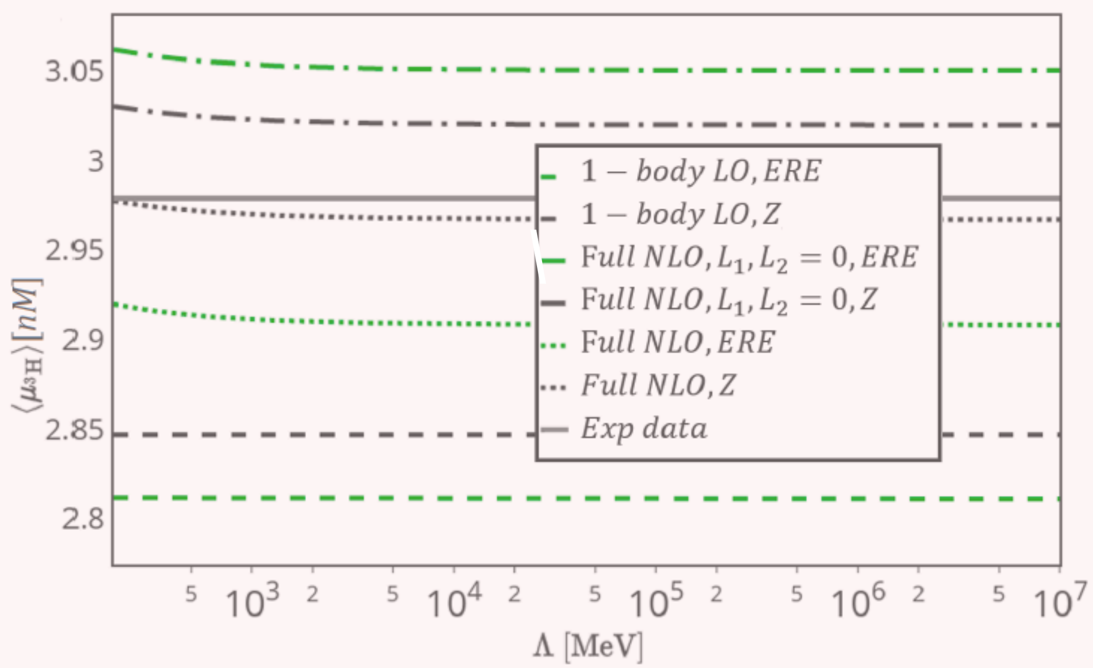


Using A=3 experimental magnetic moments to calibrate LECs
-RG invariance!

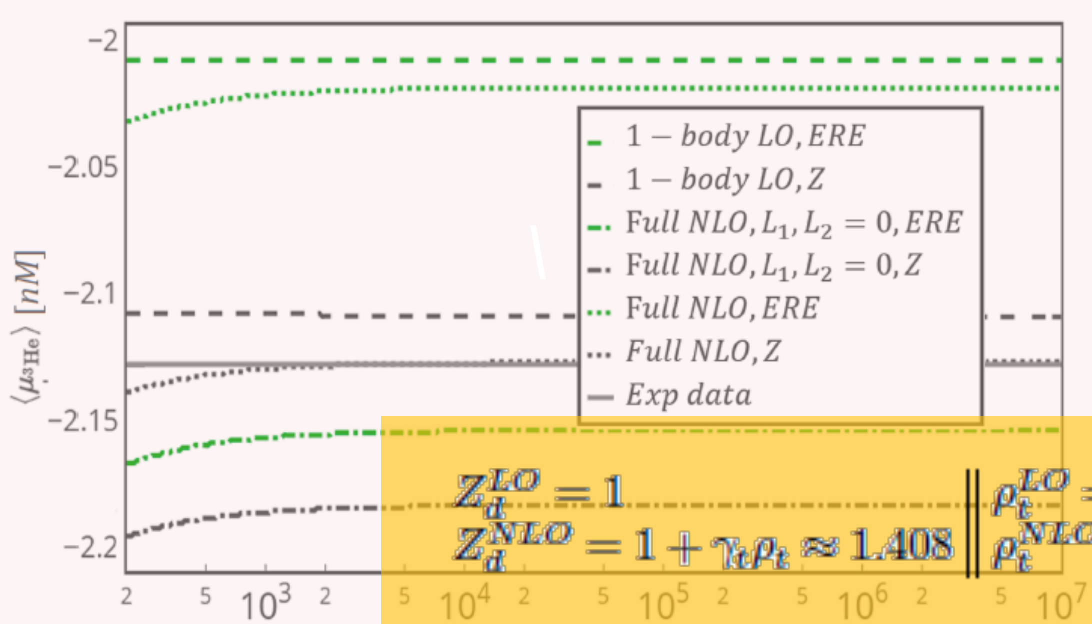


A FULLY PERTURBATIVE PIONLESS EFT CALCULATION OF A=3 M.M @NLO

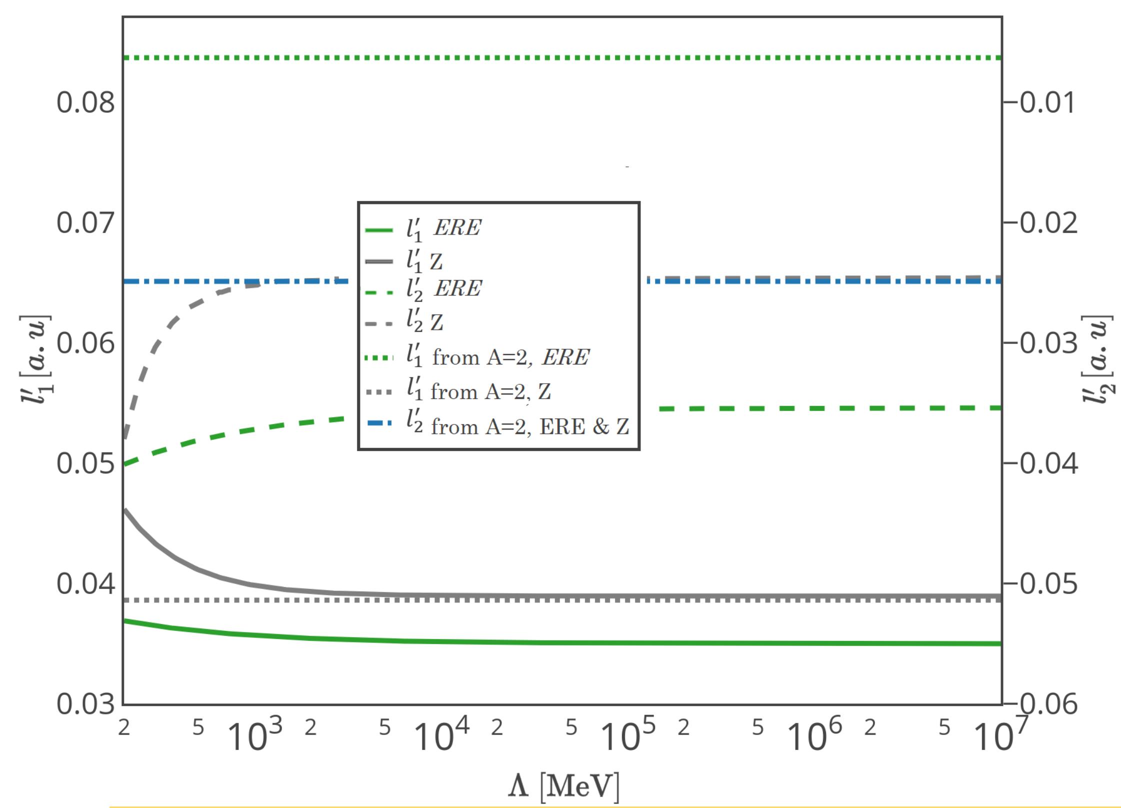
TRITON MAGNETIC MOMENT



^{3}HE MAGNETIC MOMENT



Using experimental A=2 or A=3 data to calibrate LECs



$$Z_d^{LO}=1 \qquad \rho_t^{LO}=0$$
$$Z_d^{NLO}=1+\gamma_t\rho_t\approx 1.408 \qquad \rho_t^{NLO}=\rho_t^{exp}$$

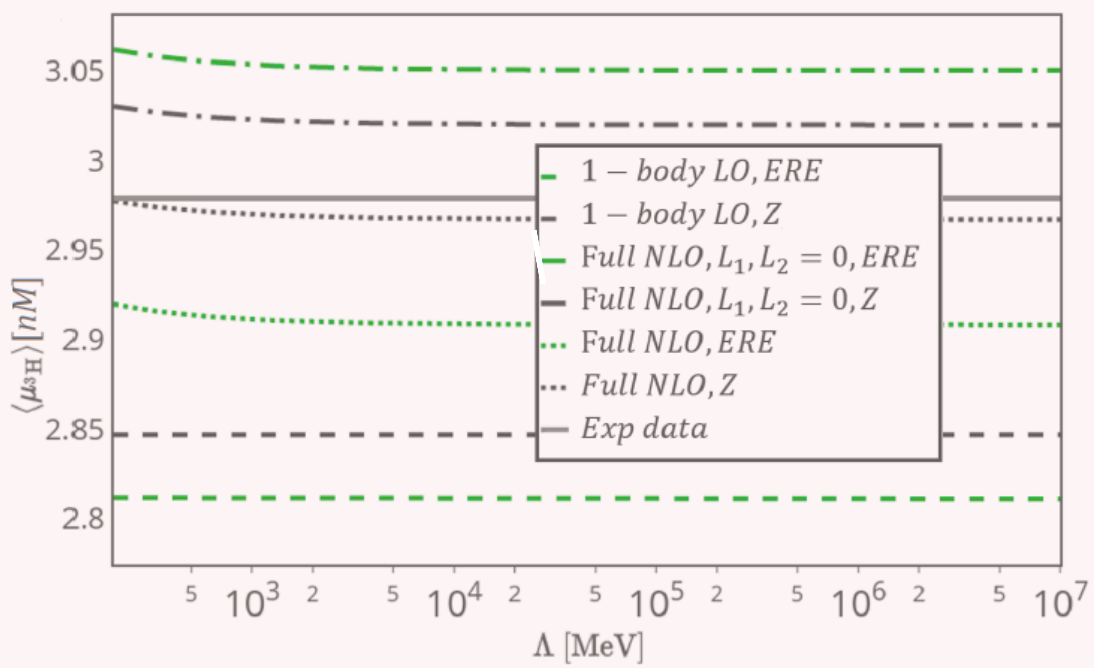
EFFECTIVE RANGE PARAMETERIZATION

$$Z_d^{LO}=1 \qquad \rho_t^{LO}=0$$
$$Z_d^{NLO}=1+\left(Z_d^{full}-1\right)=Z_d^{full} \qquad \rho_t^{NLO}=\frac{Z_d-1}{\gamma_t}\approx\frac{0.690}{\gamma_t}$$

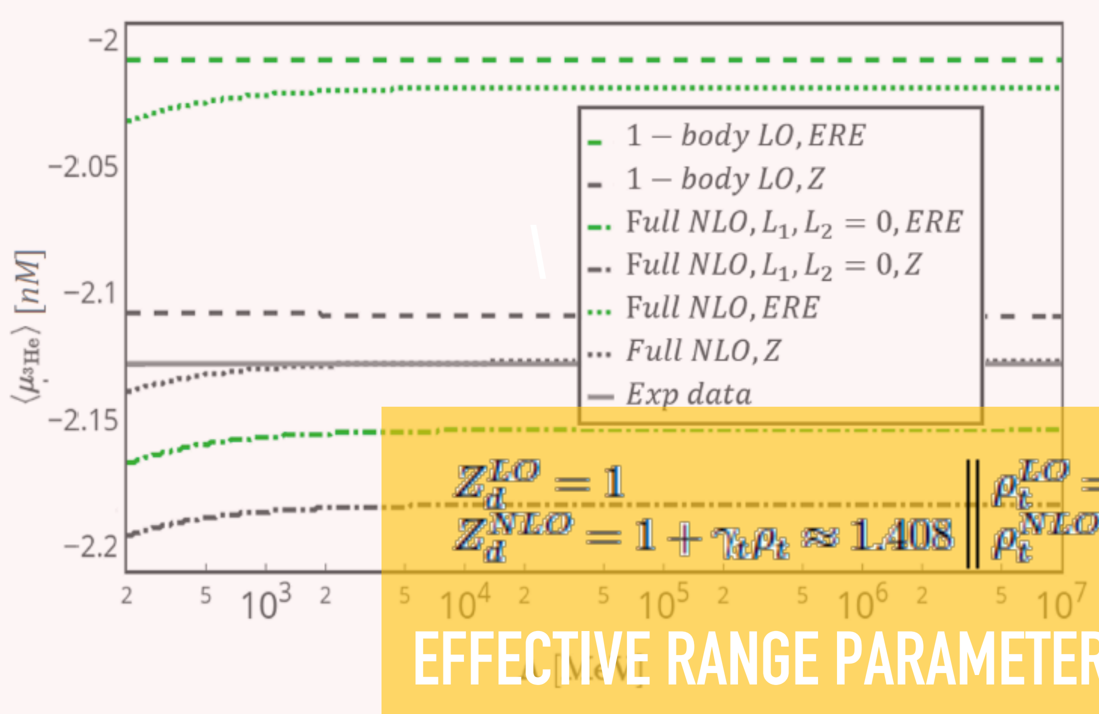
Z-PARAMETERIZATION

A FULLY PERTURBATIVE PIONLESS EFT CALCULATION OF A=3 M.M @NLO

TRITON MAGNETIC MOMENT



^{3}HE MAGNETIC MOMENT



Using experimental A=2 or A=3 data to calibrate LECs

From A=3

$$l_1'^{\infty} = 3.83_{Z_d}(3.49_{\mathrm{ERE}}) \cdot 10^{-2}$$
$$l_2'^{\infty} = -2.46_{Z_d}(-3.53_{\mathrm{ERE}}) \cdot 10^{-2}.$$

From A=2

$$l_1'^{\infty} = 3.86_{Z_d}(8.37_{\mathrm{ERE}}) \cdot 10^{-2}$$
$$l_2'^{\infty} = -2.49_{Z_d}(-2.49_{\mathrm{ERE}}) \cdot 10^{-2}.$$

$$Z_d^{LO}=1 \quad \Big\| \quad \rho_t^{LO}=0$$
$$Z_d^{NLO}=1+\gamma_t\rho_t \approx 1.408 \quad \Big\| \quad \rho_t^{NLO}=\rho_t^{exp}$$

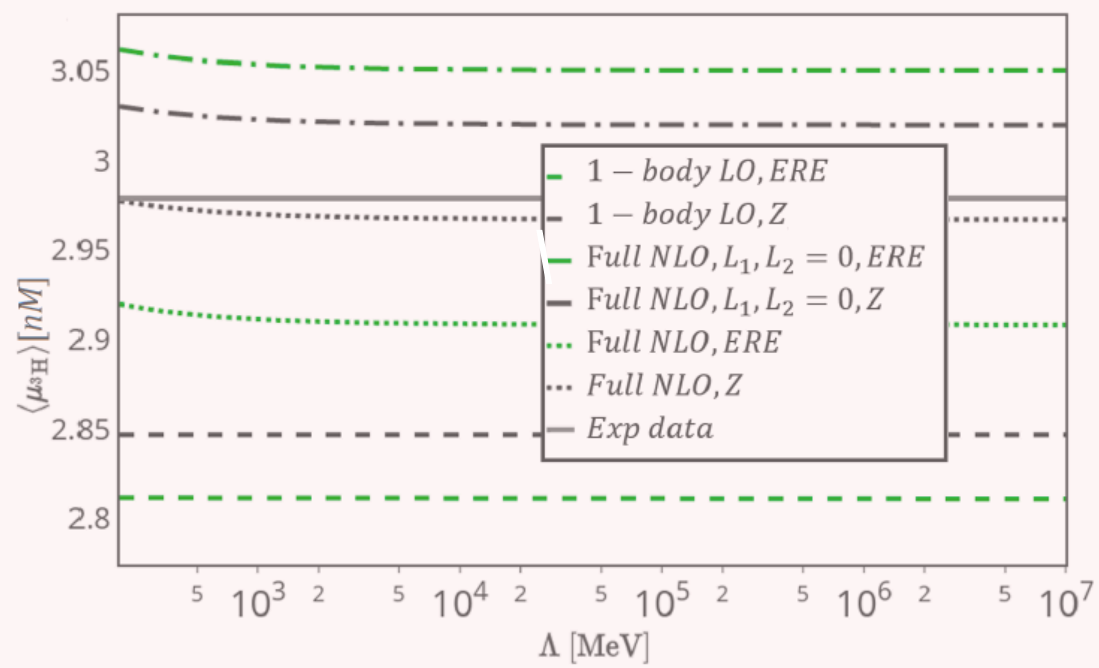
EFFECTIVE RANGE PARAMETERIZATION

$$Z_d^{LO}=1 \quad \Big\| \quad \rho_t^{LO}=0$$
$$Z_d^{NLO}=1+\left(Z_d^{full}-1\right)=Z_d^{full} \quad \Big\| \quad \rho_t^{NLO}=\frac{Z_d-1}{\gamma_t}\approx\frac{0.690}{\gamma_t}$$

Z-PARAMETERIZATION

A FULLY PERTURBATIVE PIONLESS EFT CALCULATION OF A=3 M.M @NLO

TRITON MAGNETIC MOMENT



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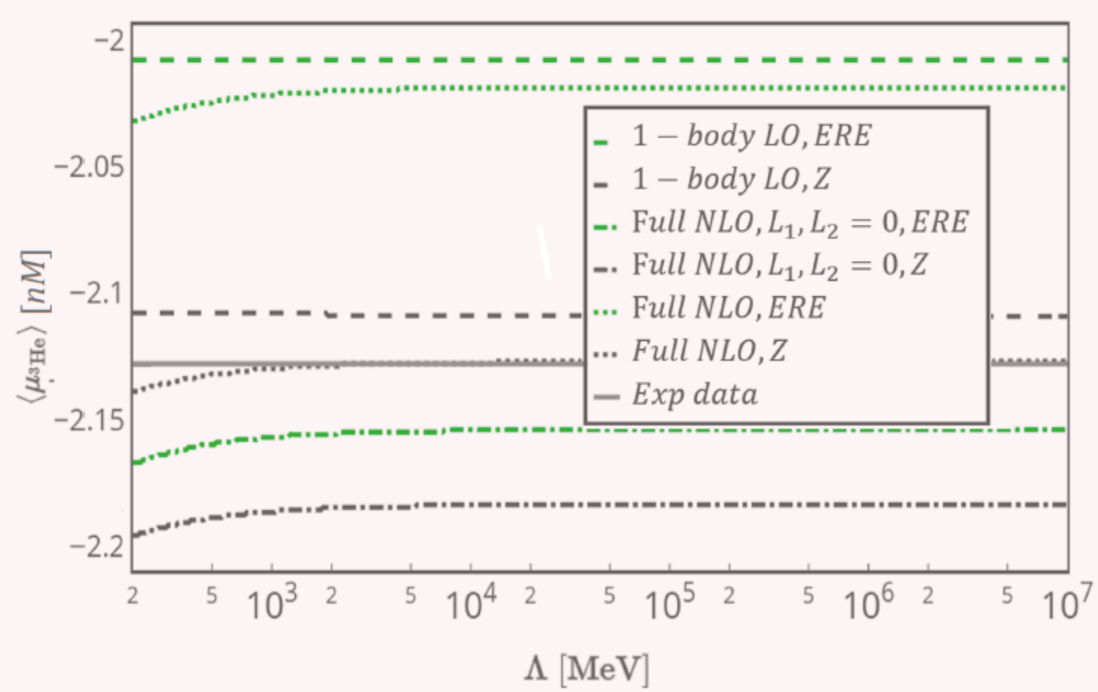


$$l_1'^{\infty} = 3.83_{Z_d}(3.49_{\mathrm{ERE}}) \cdot 10^{-2}$$
$$l_2'^{\infty} = -2.46_{Z_d}(-3.53_{\mathrm{ERE}}) \cdot 10^{-2}.$$

Unnaturally small LECs:

$$l_1(\mu) = \frac{M}{\pi\sqrt{\rho_t\rho_s}}\frac{L_1}{\kappa_1}\left(\mu - \frac{1}{a_t}\right)\left(\mu - \frac{1}{a_s}\right) \qquad l_1'(\mu) \equiv \gamma_t\sqrt{\rho_t\rho_s}\frac{l_1(\mu)}{4}$$

$$l_2(\mu) = \frac{2M}{\pi\rho_t}\frac{L_2}{\kappa_0}\left(\mu - \frac{1}{a_t}\right)^2. \qquad l_2'(\mu) \equiv \gamma_t\rho_t\frac{l_2(\mu)}{2}$$

$$\frac{l_1'}{l_2'} \approx \frac{L_1}{L_2}\cdot\frac{\kappa_0}{4\kappa_1} \approx \frac{L_1}{20L_2}$$

-- small L_2 might originate in χEFT, where NLO current is pure isovector?

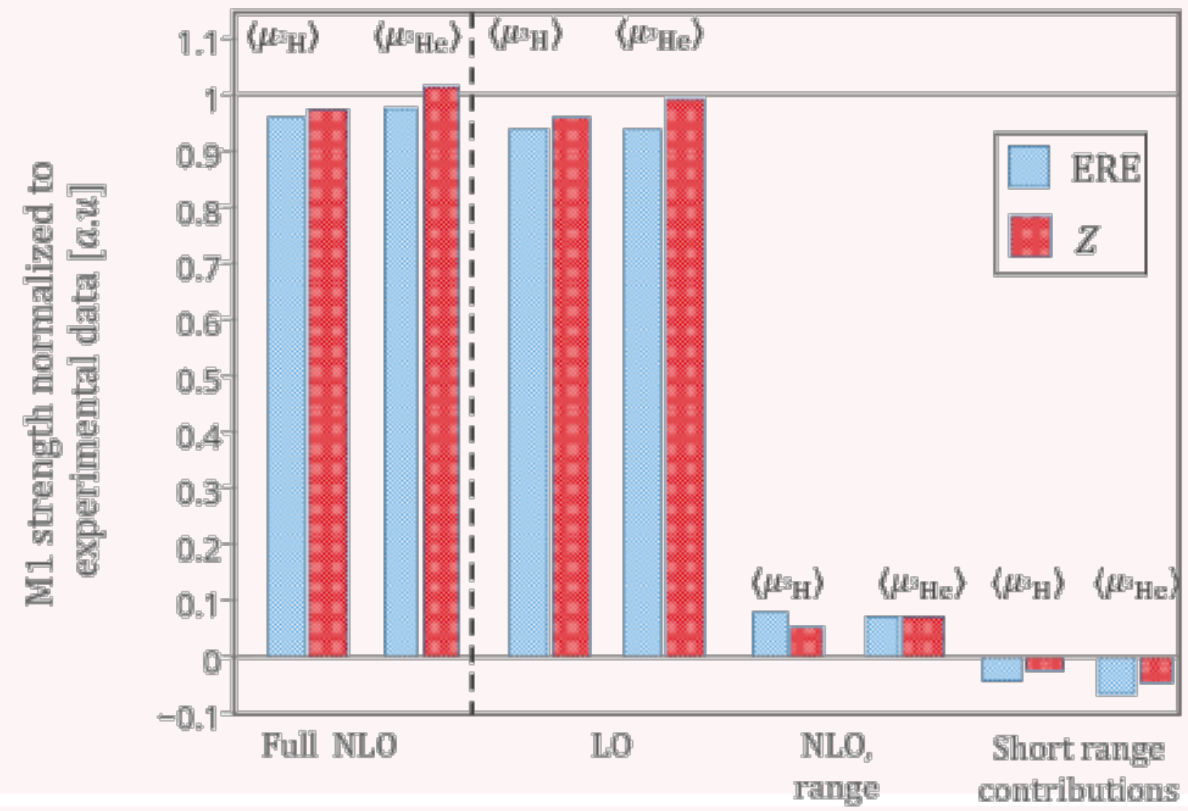
$$\vec{\mathcal{V}}_{1\pi} = i\left(\vec{\tau}_1\times\vec{\tau}_2\right)^3\frac{g_A^2}{4f_\pi^2}\left[\vec{\sigma}_2\frac{\vec{\sigma}_1\cdot\vec{q}_1}{m_\pi^2+q_1^2} + \vec{q}_1\frac{\vec{\sigma}_1\cdot\vec{q}_1}{m_\pi^2+q_1^2}\frac{\vec{\sigma}_2\cdot\vec{q}_2}{m_\pi^2+q_2^2}\right] + (1\leftrightarrow 2)$$

-- small l_1 numerical coincidence?
Both l_1 and l_2 are essential at NLO.

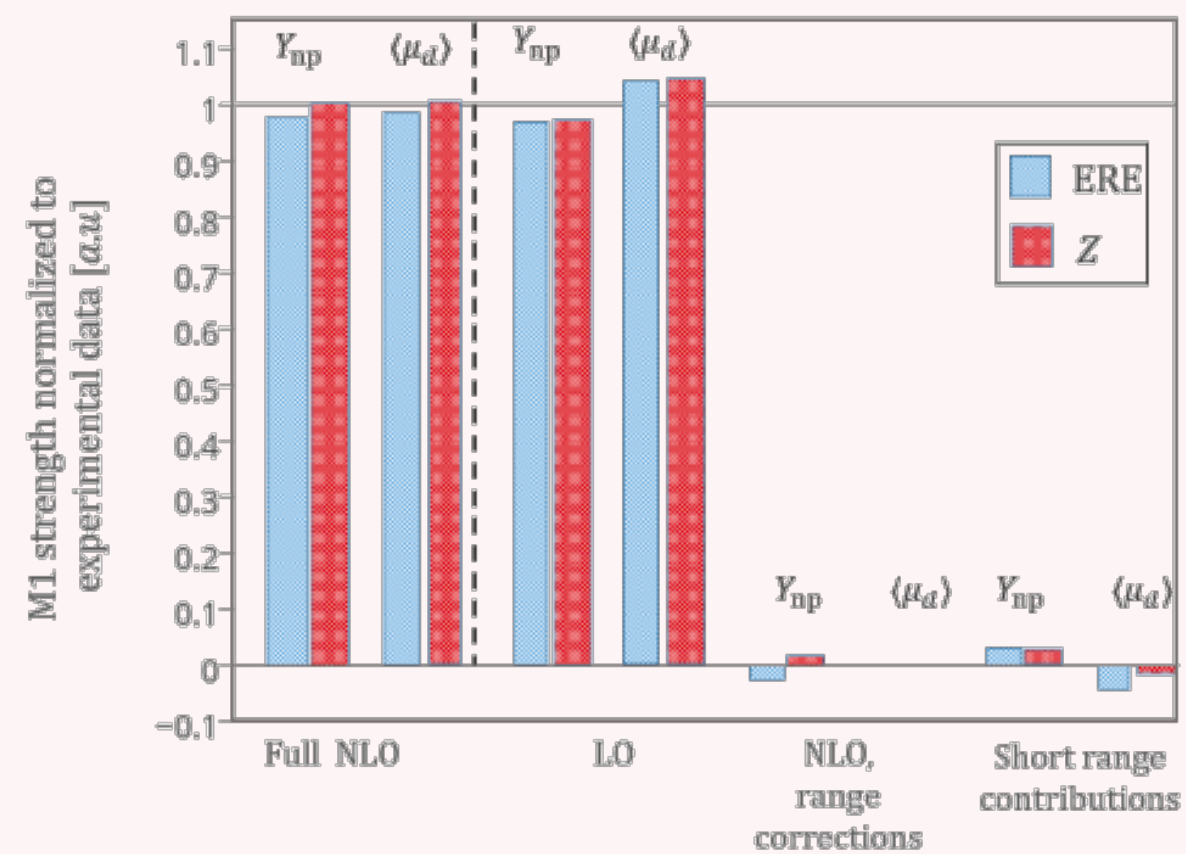
VS. EXP. DATA:

- NLO contributions small –
  - might originate in SU(4) symmetry dominance?
- Post-dictions accurate to <1% (5%) for Z (ERE) parameterizations.
- All observables are consistent with each other in the Z-parameterization.
- ERE parameterization postdictions of A=2 and A=3 inconsistent @ NLO.
- *Theoretical systematic uncertainty?*

3-BODY OBSERVABLES FROM A=2 LECS



2-BODY OBSERVABLES FROM A=3 LECS



VS. EXP. DATA:

- NLO contributions small –
  - might originate in SU(4) symmetry dominance?
- Post-dictions accurate to <1% (5%) for Z (ERE) parameterizations.
- All observables are consistent with each other in the Z-parameterization.
- ERE parameterization postdictions of A=2 and A=3 inconsistent @ NLO.
- *Theoretical systematic uncertainty?*

3-BODY OBSERVABLES FROM A=2 LECS

	$\langle \hat{\mu}_{^3\mathrm{H}} \rangle$[nM]	$\langle \hat{\mu}_{^3\mathrm{He}} \rangle$[nM]
One-body, LO	2.847 (2.811)	-2.11 (-2.007)
NLO range corrections	3.020 (3.050)	-2.185 (-2.156)
Full NLO	2.967 (2.910)	-2.1267 (-2.0202)
Experimental data [9]	2.9789	-2.12762

2-BODY OBSERVABLES FROM A=3 LECS

	Y'_{np}[nM]	$\langle \hat{\mu}_d \rangle$ [nM]
One-body, LO	1.180 (1.180)	0.8798 (0.8798)
Full NLO, L_1, L_2=0	1.206 (1.163)	0.8798 (0.8798)
Full NLO	1.245 (1.198)	0.858 (0.8487)
Experimental data	1.2450±0.0019 [11]	0.8574 [10]

BAYESIAN UNCERTAINTY ESTIMATE

- An EFT expansion of an M1 observable

$$\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + a_{M_1}^{\mathrm{N}LO} + \mathcal{O}(\delta^2)\right)$$

- EFT suggests that $c_{M_1}^{\mathrm{N}LO} = a_{M_1}^{\mathrm{N}LO}/\delta$ are natural.
- δ is the expansion parameter.
- If δ is known, then a Bayesian approach was developed by considering possible values of the next order.

Cacciari and Houdeau (2011), Furnstahl, Klco, Phillips, Wesolowski (2015), Grießhammer, McGovern, Phillips (2016)

- However, the results show that $\delta \approx 0.05$ – far less than the naïve expansion parameter $\delta_{naive} \approx \frac{1}{3}$.
- Thus, we need first to assess the expansion parameter.

BAYESIAN UNCERTAINTY ESTIMATE

- An EFT expansion of an M1 observable

$$\langle M_1 \rangle = \langle M_1 \rangle_{\mathrm{LO}} \cdot \left(1 + a_{M_1}^{\mathrm{N}LO} + \mathcal{O}(\delta^2)\right)$$

- EFT suggests that . $c_{M_1}^{\mathrm{N}LO} = a_{M_1}^{\mathrm{N}LO}/\delta$ are natural.

$$\langle \mu_d \rangle \approx \langle \mu_d \rangle_{LO} \cdot (1 + c_{\mu_d}\delta)$$
$$\langle \mu_{3H} \rangle \approx \langle \mu_{3H} \rangle_{LO} \cdot (1 + c_{\mu_{3H}}\delta)$$
$$\langle \mu_{3\mathrm{He}} \rangle \approx \langle \mu_{3\mathrm{He}} \rangle_{LO} \cdot (1 + c_{\mu_{3\mathrm{He}}}\delta)$$
$$\langle Y_{n+p\to d+\gamma} \rangle \approx \langle Y_{n+p\to d+\gamma} \rangle_{LO} \cdot (1 + c_{Y_{n+p\to d+\gamma}}\delta)$$

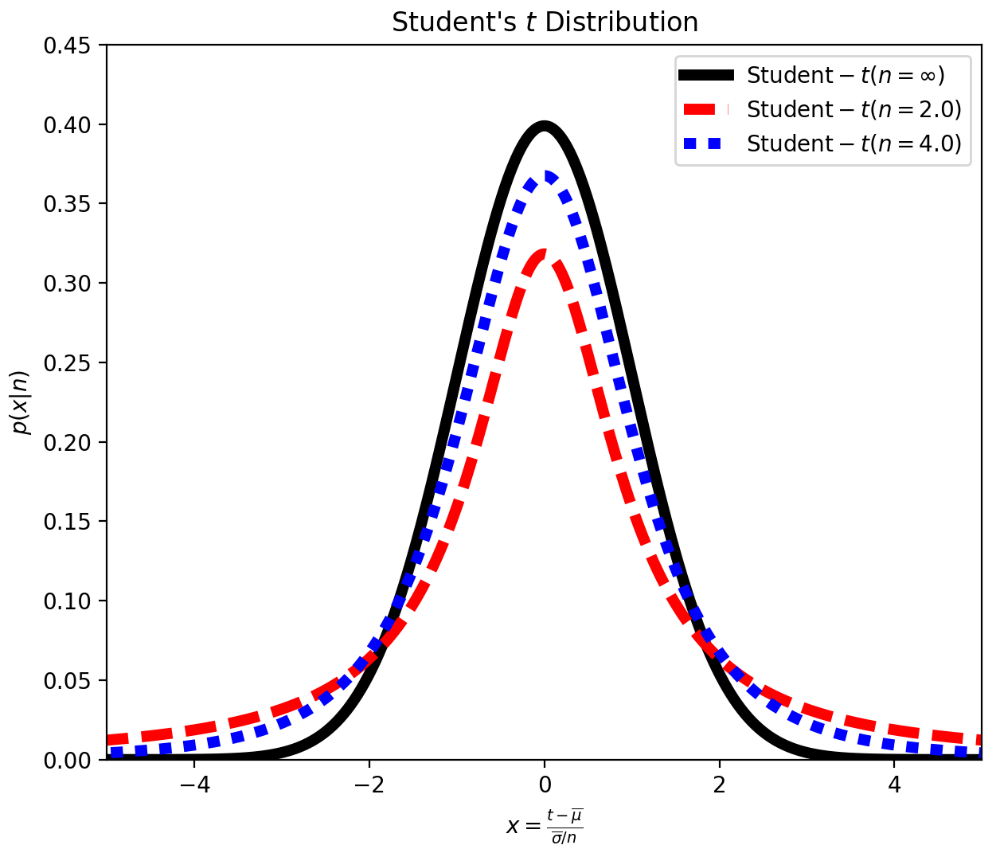
- If $c_{M_1}^{\mathrm{N}LO}$ are natural, and independent, and probe the same physics, then they can be "Bayesian" i.i.d.
- Naturalness means that for many "Bayesian measurements", they would have mean of about 1, and 1-sigma of half an order of magnitude.
- Information theory: $c_{M_1}^{\mathrm{N}LO}$ are log-normal with average 0 and STD of about $\frac{1}{2}\ln 10$.

BAYESIAN UNCERTAINTY ESTIMATE

- How many "measurements" do we have in our study?

$$\langle \mu_d \rangle \approx \langle \mu_d \rangle_{LO} \cdot \left(1 + c_{\mu_d} \delta\right)$$
$$\langle \mu_{3H} \rangle \approx \langle \mu_{3H} \rangle_{LO} \cdot \left(1 + c_{\mu_{3H}} \delta\right)$$
$$\langle \mu_{3\mathrm{He}} \rangle \approx \langle \mu_{3\mathrm{He}} \rangle_{LO} \cdot \left(1 + c_{\mu_{3\mathrm{He}}} \delta\right)$$
$$\langle Y_{n+p \to d+\gamma} \rangle \approx \langle Y_{n+p \to d+\gamma} \rangle_{LO} \cdot \left(1 + c_{Y_{n+p \to d+\gamma}} \delta\right)$$

- For Z-parameterization – n=4 observables probe the same physics – a fact encapsulated in the similar values of LECs.
- For ERE- 2 sets of n=2 observables.
- Thus, on aveeage in both cases, $\delta_Z, \delta_{ERE} \approx 0.03$
- However, a 90% degree of belief:
  - $0.007 < \delta_{ERE} < 0.13$
  - $0.017 < \delta_{ERE} < 0.052$



BAYESIAN UNCERTAINTY ESTIMATE

- The probability that the NLO value will deviate by Δ from the true value of the observable:

$$pr\left(\Delta \middle| \left\{a^{\mathrm{NLO}}_{M_1^k}\right\}_{k=1}^{n}\right) =$$

$$\int d\delta \, pr\left(\Delta \middle| \left\{c^{\mathrm{NLO}}_{M_1^k}\right\}_{k=1}^{n}, \delta\right) \cdot pr\left(\delta \middle| \left\{a^{\mathrm{NLO}}_{M_1^k}\right\}_{k=1}^{n}\right)$$

Grießhammer et al. (2016)

Student's-t with n=4 (n=2) samples for Z (ERE) para.

- Thus, at a 90% degree of belief, the theoretical uncertainty is:
  - 0.5% for Z parameterization
  - 10% for ERE-parameterization

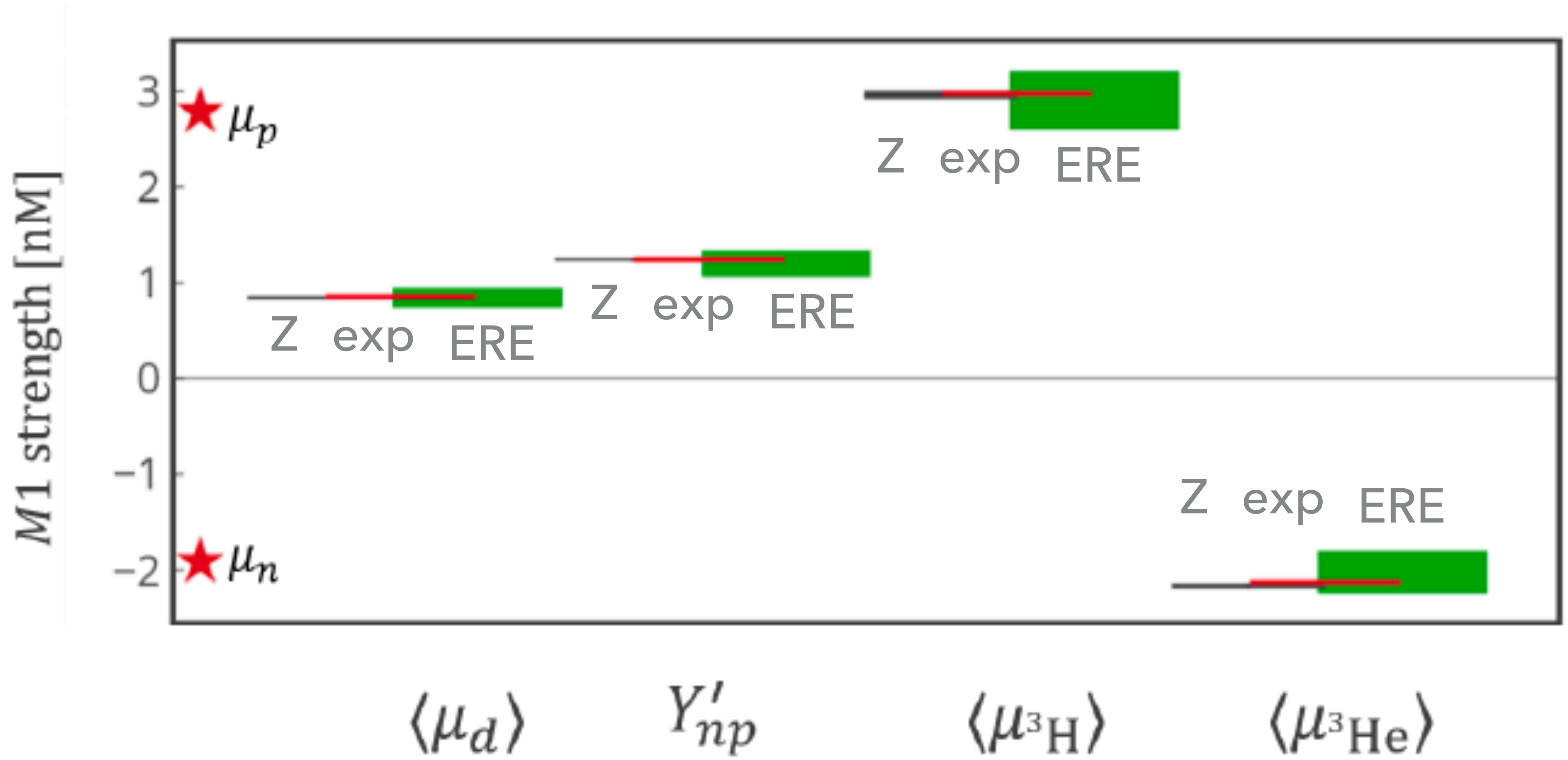
MAIN POINTS – M1 STRUCTURE

- M1 structure of A=2, 3 nuclear systems can be accurately and precisely described with ~ 10 LECs!
- RG invariant, systematic and perturbative EFT (LO and NLO)
- Bayesian theoretical uncertainty assessment, based on naturalness of EFT expansion.
- Precision stems from small NLO contribution.
  - Origin of small size of LECs is unclear: coincidence, SU(4) symmetry, chiral EFT, something else?

M1 STRUCTURE OF A=2, 3 NUCLEAR SYSTEMS ACCURACY AND PRECISION WITH ~ 10 LECS!

- The Z parameterization is superior at this order!
  - Enables consistent A=2 and A=3 description!

	This work [nM]	Experiment [nM]
Y'_{np} =	1.245 ± 0.006	1.2450 ± 0.0019
$\langle \hat{\mu}_d \rangle$ =	0.858 ± 0.004	0.85744...
$\langle \hat{\mu}_{^3\mathrm{H}} \rangle$ =	2.967 ± 0.015	2.97896...
$\langle \hat{\mu}_{^3\mathrm{He}} \rangle$ =	-2.1267 ± 0.011	−2.12750...



PROTON-PROTON FUSION IN THE SUN

De-Leon, DG (2018a,b,c) in prep.

De-Leon, Platter, DG, arxiv (2016).


New Scientist
WEEKLY October 21 - 27, 2017
SPECIAL REPORT
GRAVITATIONAL WAVES
All the fallout from the neutron star smash-up
SWIPE LEFT! How online dating is making society more liberal
SOMETHING STRANGE IS GOING ON INSIDE THE SUN
Science and technology news
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THE NEW PROBLEM WITH THE SUN

- Standard Solar Model (SSM) is a simplified description of the Sun, as inferred by helioseismology and solar neutrinos.
- A former great success of SSM is the acceptance that ***new*** physics was the source for the missing neutrinos problem.
- About a decade ago, a new problem arose: *"Solar Composition Problem"*, a downward revision of $\approx 30\%$ in the amount of "metals" in the Sun.
  - creating, e.g., a $\approx 4\sigma$ **deviation** in helio-seismological observables.
  - Note: 4σ **deviation is just 1.5%...**
- ***A precision type of problem demands assessing uncertainties.***

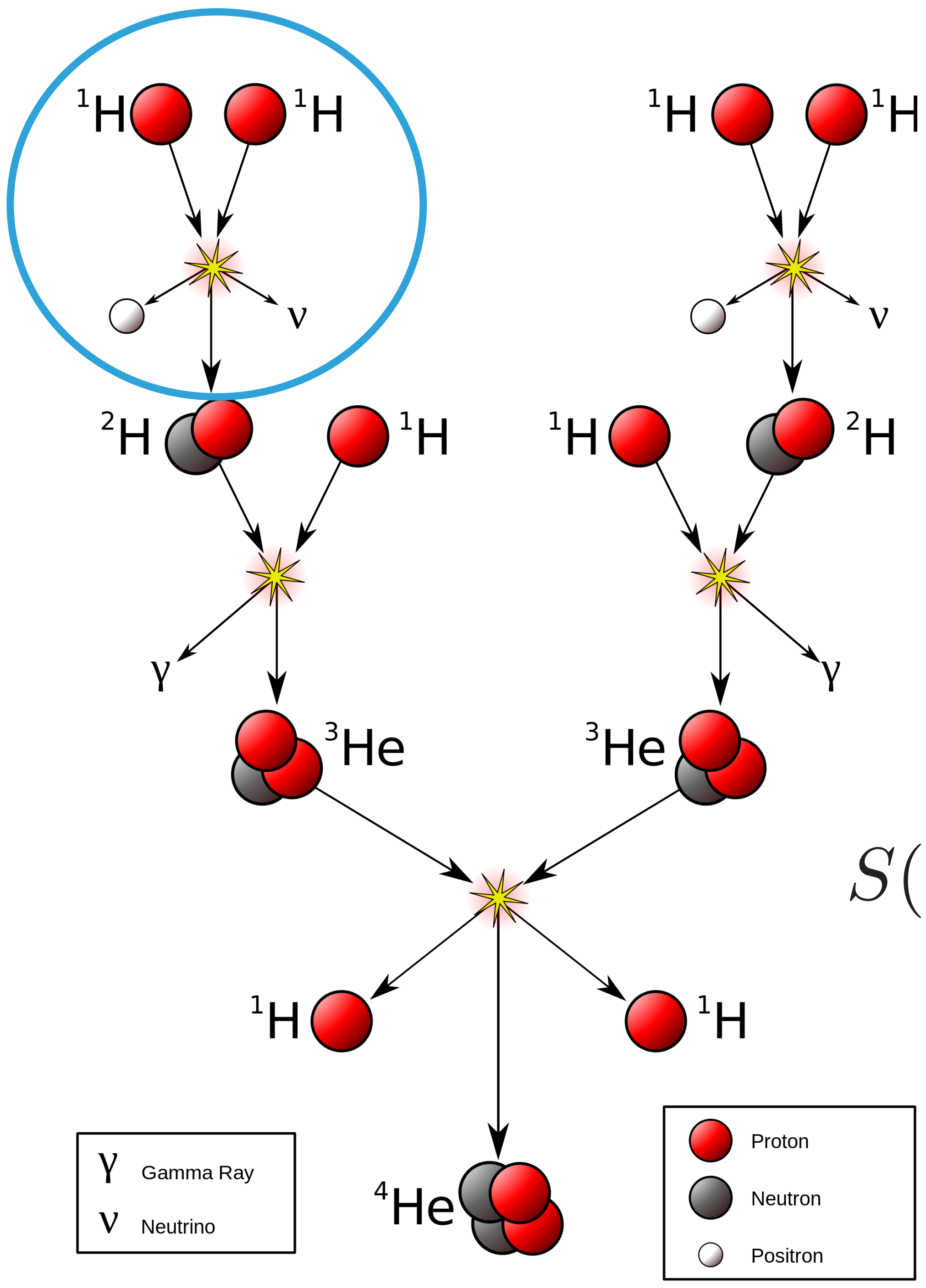
Basu 2009, Villante 2010, Serenelli (2013)

HOW WELL DO WE UNDERSTAND THE MICROSCOPIC PHENOMENA IN THE SUN?

WHAT IS THE ORIGIN OF CURRENT UNCERTAINTY ESTIMATES?

CAN WE IMPROVE THIS KNOWLEDGE?

WEAK PROTON-PROTON FUSION IN THE SUN



Cannot be measured terrestrially – depends on theory

Very low proton-proton relative momentum (*E_{rel}~6 keV*).

Needed accuracy: ~1%.

$$\sigma(E) = \frac{S(E)}{E}\exp[-2\pi\eta(E)]$$

$$S(E) = S(0) + S'(0)E + S''(0)E^2/2 + \cdots$$

Theory challenge: accuracy and precision

WEAK PROTON-PROTON FUSION IN THE SUN – THEORY STANDARDS

SFII – Adelberger et al., Rev. Mod. Phys. 83, 195 (2011)

$$4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b} \quad \text{potential models,}$$
$$4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b} \quad \text{EFT}^*,$$
$$3.99(1 \pm 0.030) \times 10^{-25}\ \text{MeV b} \quad \text{pionless EFT.}$$

2011

SFII recommended value (2011): $S_{11}(0) = 4.01(1 \pm 0.009) \times 10^{-25}\ \text{MeV b}.$

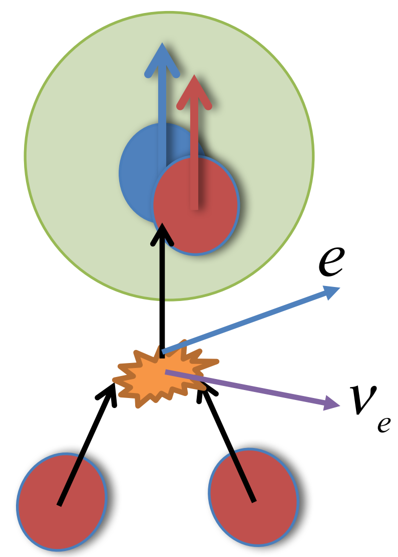
Marcucci et al., PRL (2013), χEFT: $S(0) = (4.030 \pm 0.006) \times 10^{-23}\ \text{MeV fm}^2$ **2013**

Acharya et al, PLB (2017) χEFT: $S(0) = (4.081^{+0.024}_{-0.032}) \times 10^{-23}\ \text{MeV fm}^2$ **2016**

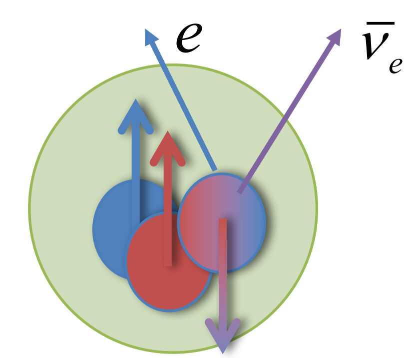
NPLQCD, PRL (2017): $S(0) = 4.029(0.006)(0.03)(0.012)(0.027) \times 10^{-23}\text{MeV fm}^2$ **2017**

A PREDICTIVE AND VERIFIED THEORY, A CHECKLIST:

- ❑ Simplicity
- ❑ Benchmarking vs. past calculations.
- ❑ Reproducing other experimentally measured reactions.
- ❑ Quantitative error assessment.



$$p + p \rightarrow d + \nu_e + e^+$$



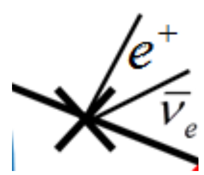
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

ADDING THE WEAK INTERACTION

- **4+1** LO Parameters

One body

$$\mathrm{GT}_n = \langle n \| \mathrm{GT}^{(-)} \| p \rangle = \sqrt{3} \cdot (\tfrac{1}{g_A})$$

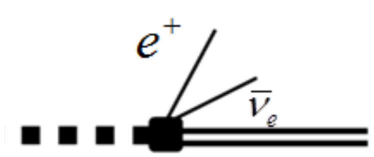


g_A

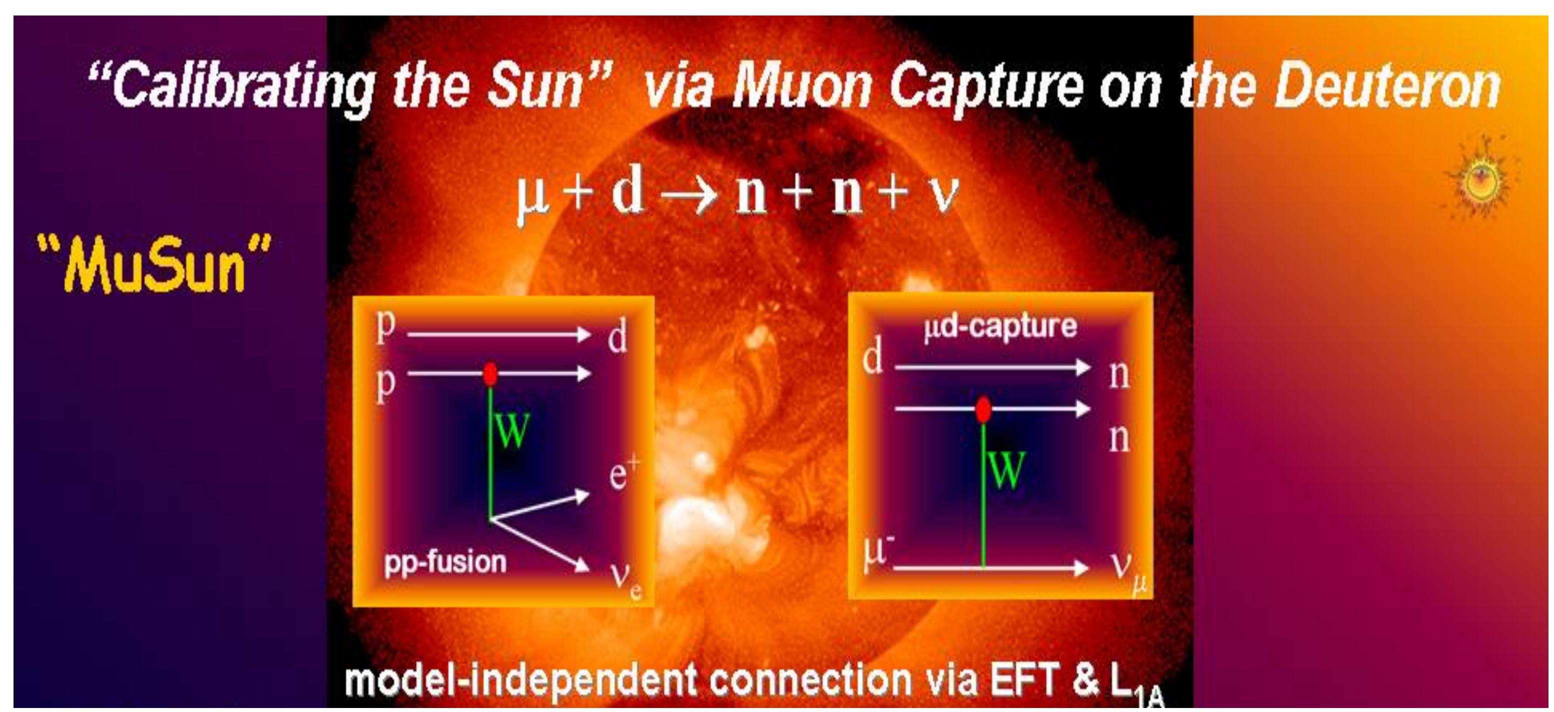
axial coupling constant, "known" from neutron β decay.

- **5+1** NLO parameters:

Two body



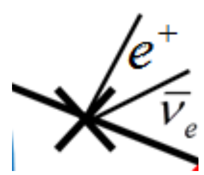
L_{1A}



ADDING THE WEAK INTERACTION

- **4+1** LO Parameters

One body



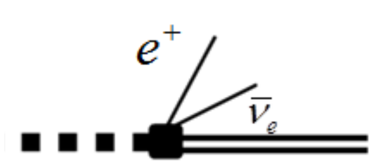
g_A

$$\mathrm{GT}_n = \langle n \| \mathrm{GT}^{(-)} \| p \rangle = \sqrt{3} \cdot \left(\frac{1}{g_A}\right)$$

axial coupling constant, "known" from neutron β decay.

- **5+1** NLO parameters:

Two body



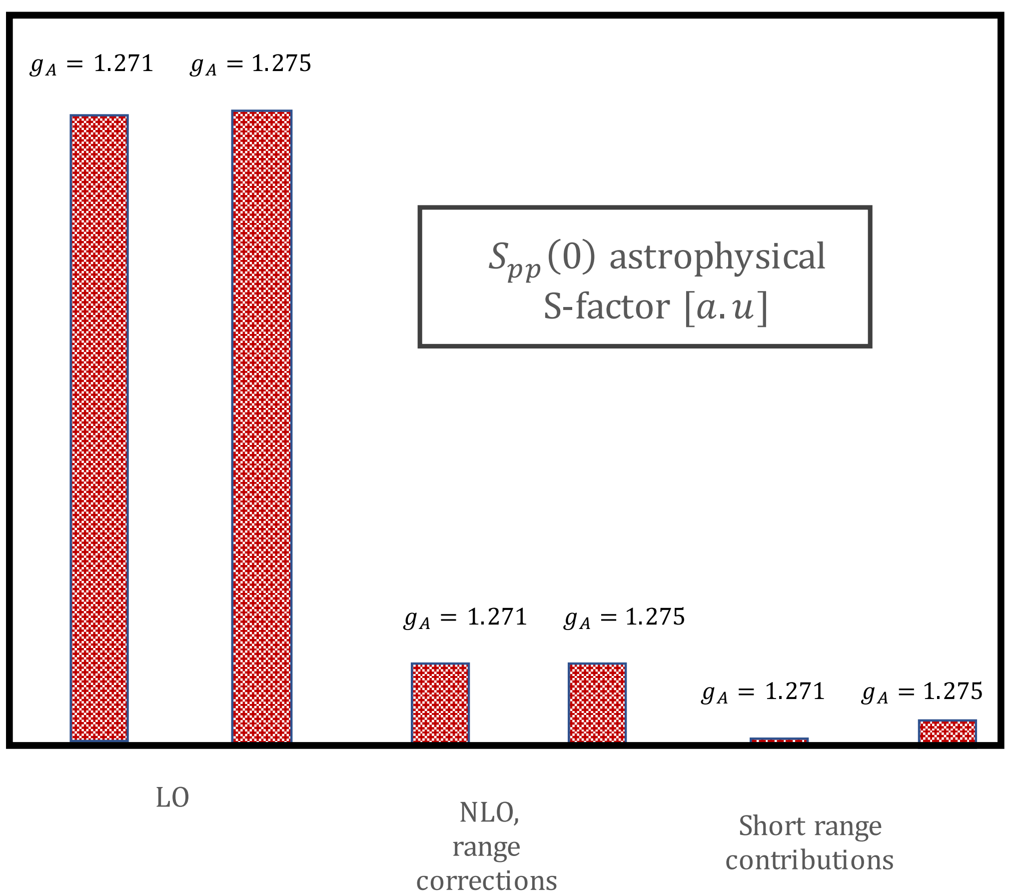
L_{1A}

$$\mathrm{GT}^{emp}_{^3\mathrm{H}} = \langle {}^3\mathrm{H} \| \mathrm{GT}^{(-)} \| {}^3\mathrm{He} \rangle = \sqrt{3} \cdot \left(\frac{1.213 \pm 0.002}{g_A}\right)$$

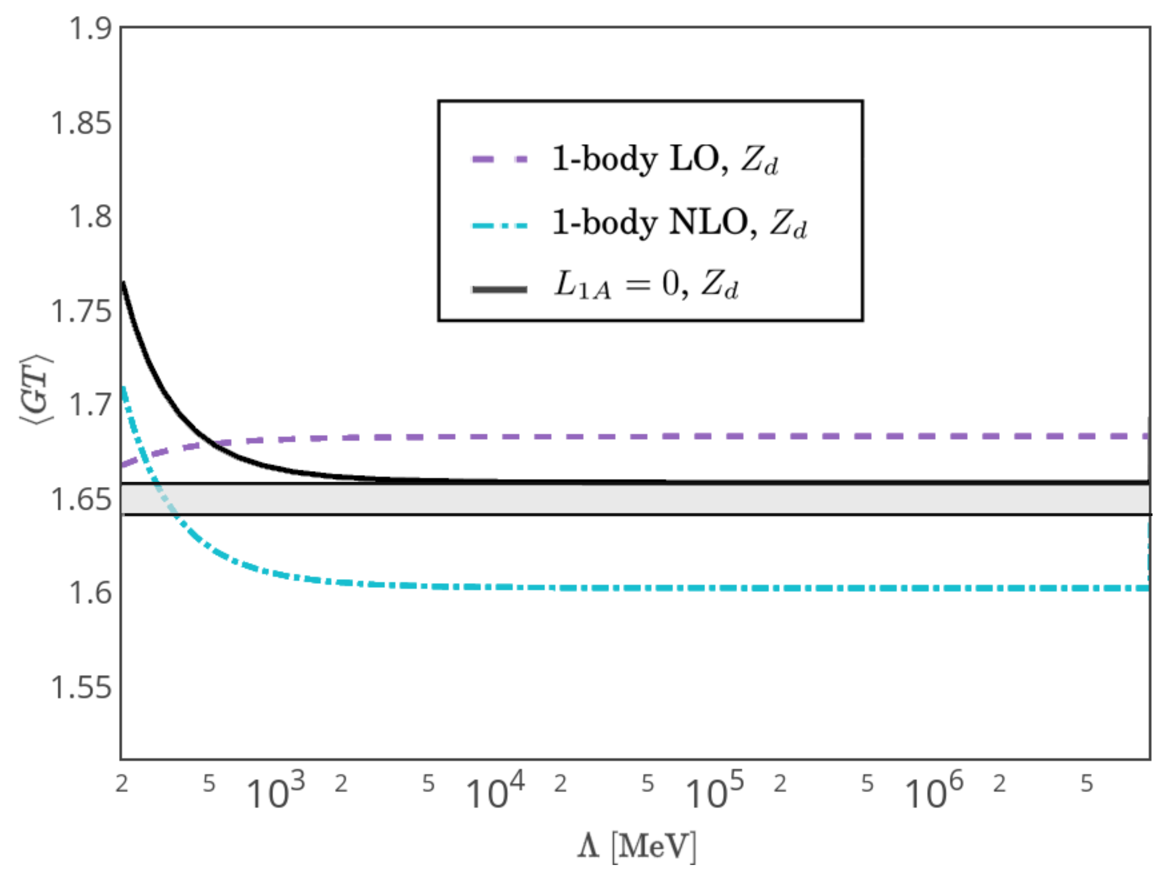
2-body analogue of g_A, we fix it from ^{3}H decay rate,

repeating the procedure taken in χEFT.

RENORMALIZABLE AND NATURAL CONVERGENCE



Astrophysical pp fusion S factor.



^3H decay calculation, fixing L_{1A}

THUS,

- Benchmark: using the same parameters as χEFT calc. (***caveat – pending mistake in c_D***)

$S_{pp}^{\chi EFT}$ (Acharya et al.)	$(4.081^{+0.024}_{-0.032})\times10^{-23}\mathrm{MeV}\cdot\ \mathrm{fm}^2$
S_{pp}	$4.076\times10^{-23}\mathrm{MeV}\cdot\ \mathrm{fm}^2$

- Consistent also with NPLQCD.
- However, recent measurements of the neutron half life indicate that a much higher g_A is favored

$S_{pp}(0, g_A = 1.2701)$	$4.09 \pm_{g_A} 0.06 \pm_{^3\mathrm{H\ half\ life}} 0.02\times10^{-23}\mathrm{MeV}\cdot\ \mathrm{fm}^2$	PDG recom.
$S_{pp}(0, g_A = 1.2766)$	$4.22 \pm_{g_A} 0.06 \pm_{^3\mathrm{H\ half\ life}} 0.02\times10^{-23}\mathrm{MeV}\cdot\ \mathrm{fm}^2$	UCNA

Still missing the theoretical systematic uncertainty…

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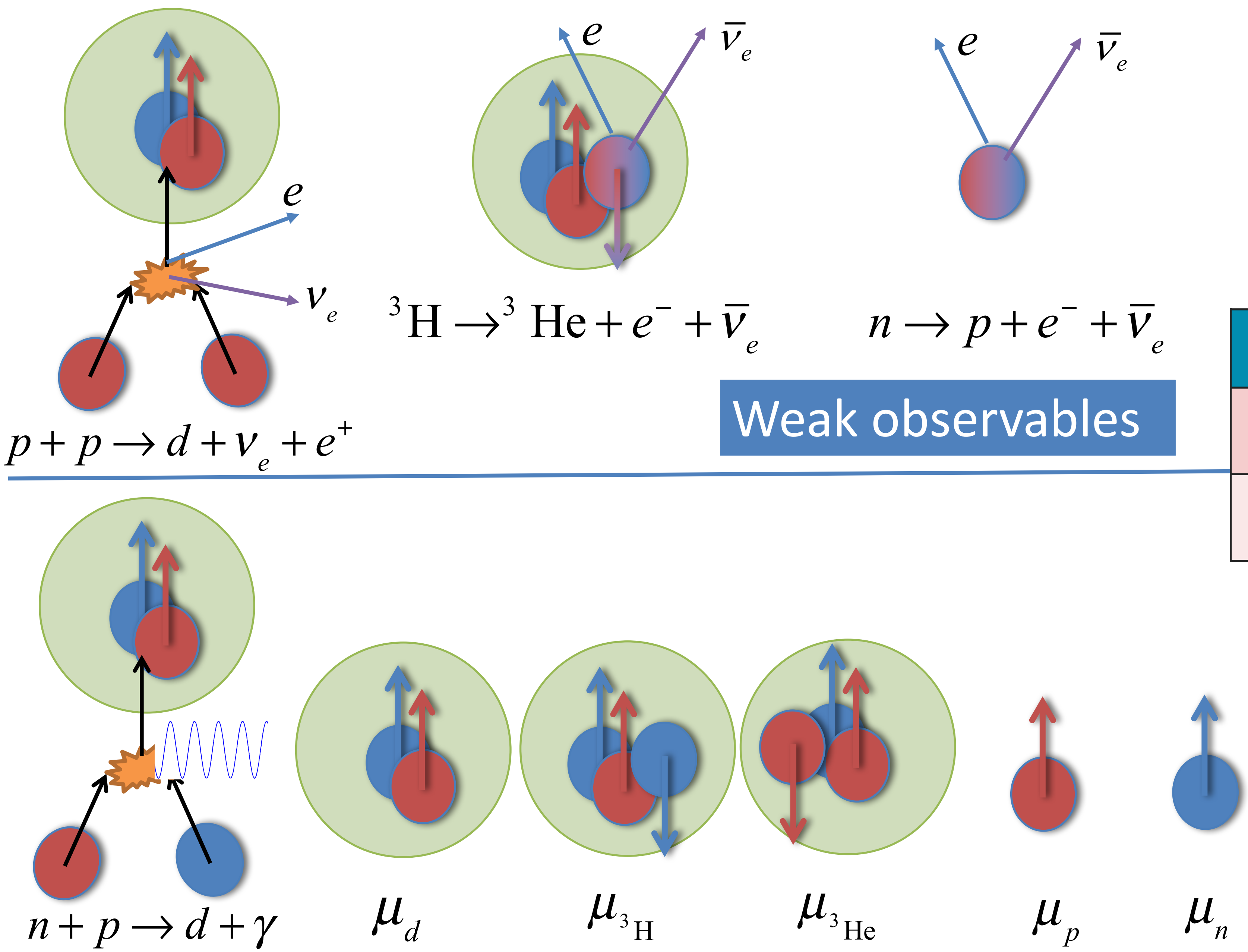
ELECTROMAGNETIC ANALOGUES TO THE WEAK OBSERVABLES



EM observables

Operators:

	EM	Weak
1-b	$(\mu_{n,p})\ \sigma, \sigma\tau^0$	$g_A\ \sigma\tau^{+,-}$
2-b	$L_1 s^\dagger d, L_2 d^\dagger d$	$L_{1A} s^\dagger d$

A PREDICTIVE AND VERIFIED THEORY, A CHECKLIST:

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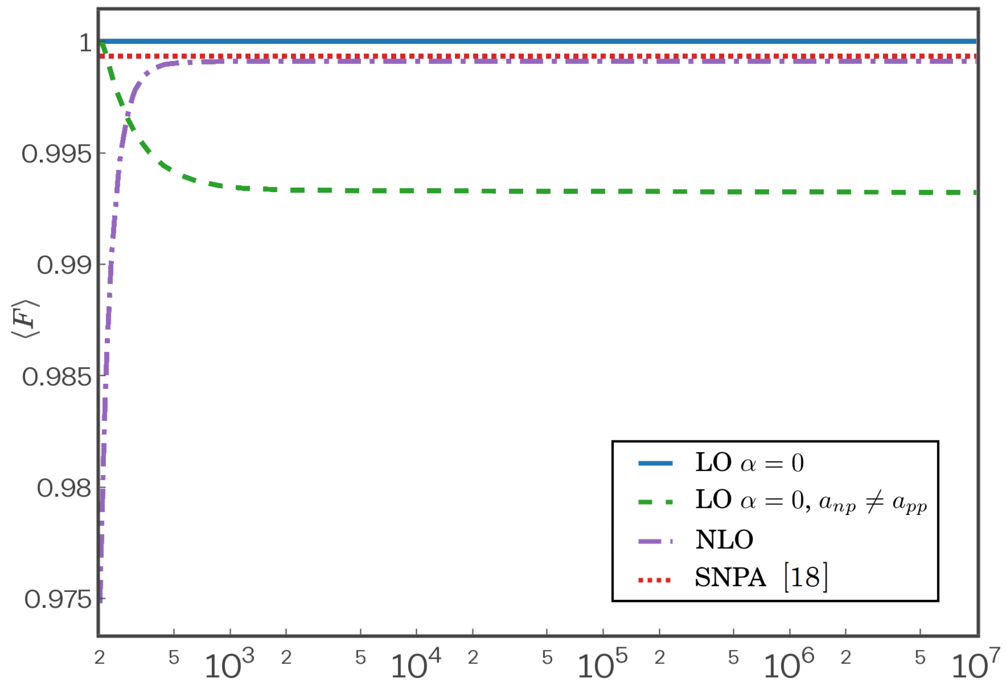
- ✓ Benchmarking vs. past calculations.
- ✓ Reproducing other experimentally measured reactions.
- ❑ Quantitative error assessment.

E&M AND WEAK: QUANTITATIVE AND QUALITATIVE SIMILARITIES

^{3}H and ^{3}He are very similar!



Operator structure similarity!

		Electromagnetic	weak
LEC	One-body	$\kappa_0,\ \kappa_1$	g_A
	Two-body	L_1, L_2	$L_{1,A}$
oper-ators	One-body	$\sigma,\ \sigma\tau^0$	$\sigma\tau^{+,-},\ \tau^{+,-}$
	Two-body	$L_1 t^\dagger s,\ L_2 t^\dagger t$	$L_{1,A} t^\dagger s$
$Q \approx 0$ observables	$A=2$	Y_{np} d magnetic moment: $\langle\hat{\mu}_d\rangle$	pp fusion: $\Lambda_{pp}(0)$
	$A=3$	^{3}H, ^{3}He magnetic moments: $\langle\hat{\mu}_{^3\mathrm{H}}\rangle,\ \langle\hat{\mu}_{^3\mathrm{He}}\rangle$	^{3}H β-decay: $\langle GT\rangle$,$\langle F\rangle$

Similarity in LEC calibration

$$\frac{\partial}{\partial \ln(g_A)} \ln(l_{1,A}) \approx 51$$

$$\frac{\partial}{\partial \ln(\kappa_1)} \ln(l_1) \approx 50$$

$$-\frac{L_{1,A}}{g_A}\frac{1}{2\pi\sqrt{\rho_t\rho_s}}\left(\mu-\frac{1}{a_t}\right)\left(\mu-\frac{1}{a_s}\right)$$

$$\frac{M}{\pi\sqrt{\rho_t\rho_s}}\frac{L_1}{\kappa_1}\left(\mu-\frac{1}{a_t}\right)\left(\mu-\frac{1}{a_s}\right)$$

The GT operator similarity to the M1V operator suggests that one can *adopt the uncertainty assessment from the E&M sector!*

A PREDICTIVE AND VERIFIED THEORY, A CHECKLIST:

- ✓ Simplicity
- ✓ Benchmarking vs. past calculations.
- ✓ Reproducing other experimentally measured reactions.
- ✓ Quantitative error assessment.

$$S_{11}(g_A = 1.2701) = 4.09 \pm 0.02 \pm_{g_A} 0.06 \pm 0.02 \cdot 10^{-23}\text{MeV} \cdot \text{fm}^2$$
$$S_{11}(g_A = 1.2766) = 4.22 \pm 0.02 \pm_{g_A} 0.06 \pm 0.02 \cdot 10^{-23}\text{MeV} \cdot \text{fm}^2$$

g_A systematic uncertainty

theoretical uncertainty

g_A stat. unc.

^3H halflife syst. unc.

A predicted increase of 2–5% over SFII

PRECISION BETA DECAY STUDIES TO PINPOINT BSM EFFECTS

Glick Magid et al, PLB (2017)

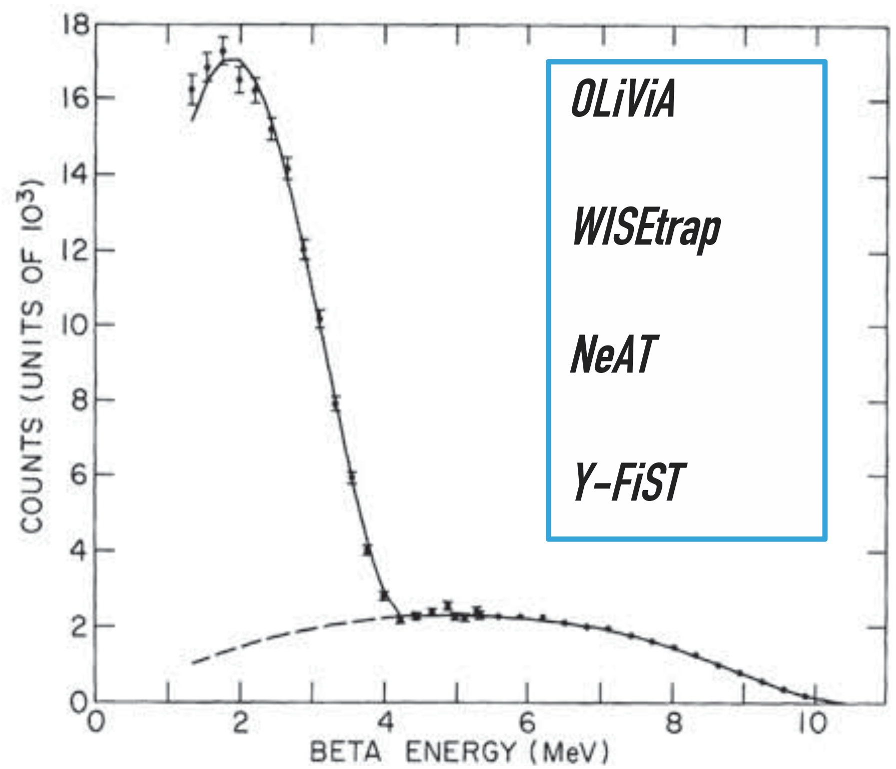
On-going experiments and theory challenges

$^{17-23}$Ne isotopes

^{16}N β decay

^{6}He β decay

^{8}Li β decay



Differential β decay rate

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q, \vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear independent part

$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon),$$

Classification of β decays

$\Delta J^\pi = 0^+$	(Super)allowed - Fermi transition	$\propto q^0$
$\Delta J^\pi = 0,1^+$	Allowed – Fermi/Gamow-Teller	
$\Delta J^\pi = 0,1,2^-$	Unique First forbidden transition	$\propto q^1$

Differential β decay rate

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q,\vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta}=\frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear dependent part

$$\hat{C}_{JM}(q)=\int d\vec{x}\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0(\vec{x}) \quad \propto q^J$$

$$\hat{E}_{JM}(q)=\frac{1}{q}\int d\vec{x}\,\vec{\nabla}\times[j_J(qx)\vec{Y}_{JJM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad \propto q^{J-1}$$

$$\hat{M}_{JM}(q)=\int d\vec{x}\, j_J(qx)\vec{Y}_{JJM}(\hat{x})\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad \propto q^J$$

$$\hat{L}_{JM}(q)=\frac{i}{q}\int d\vec{x}\,\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}), \quad \propto \hat{E}_{JM}$$

$$\begin{aligned}\Theta(q,\vec{\beta}\cdot\hat{\nu}) &= \frac{\Delta J}{2\Delta J+1}\Bigg\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2)\\ &\pm\hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*\\ &+\sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2\\ &+\left(1+\hat{\nu}\cdot\vec{\beta}\right)|\langle\|\hat{C}_J\|\rangle|^2\\ &-2\hat{q}\cdot\left(\hat{\nu}+\vec{\beta}\right)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Big]\Bigg\},\end{aligned} \tag{4}$$

Differential β decay rate

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q,\vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta}=\frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear dependent part

$$\hat{C}_{JM}(q)=\int d\vec{x}\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0(\vec{x}) \quad \propto q^J$$

$$\hat{E}_{JM}(q)=\frac{1}{q}\int d\vec{x}\vec{\nabla}\times[j_J(qx)\vec{Y}_{JJM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad \propto q^{J-1}$$

$$\hat{M}_{JM}(q)=\int d\vec{x}\, j_J(qx)\vec{Y}_{JJM}(\hat{x})\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad \propto q^J$$

$$\hat{L}_{JM}(q)=\frac{i}{q}\int d\vec{x}\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}), \quad \propto \hat{E}_{JM}$$

Nuclear-probe coupling operators

$$\begin{aligned}\Theta(q,\vec{\beta}\cdot\hat{\nu}) &= \frac{\Delta J}{2\Delta J+1}\Bigg\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}\left(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2\right)\\ &\pm \hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*\\ &+\sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2\\ &+\left(1+\hat{\nu}\cdot\vec{\beta}\right)|\langle\|\hat{C}_J\|\rangle|^2\\ &-2\hat{q}\cdot\left(\hat{\nu}+\vec{\beta}\right)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Big]\Bigg\},\end{aligned} \quad (4)$$

e.g., allowed transitions

$$d\omega^{V-A} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot$$

$$\cdot \left\{ \frac{|C_V|^2 + \left|C_V'\right|^2}{2} \left(1 + \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{C}_0^V \right\| J_i \right\rangle\right|^2 \right.$$

$$\left. + \frac{|C_A|^2 + \left|C_A'\right|^2}{2} 3 \left(1 - \frac{1}{3} \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{L}_1^A \right\| J_i \right\rangle\right|^2 \right\} + O(q)$$

Fermi

Gamow-Teller

Correlation coefficient

e.g., allowed transitions

i.e., for general Gamow-Teller transition:

$$\Theta \propto (1 + b\frac{m_e}{\epsilon} + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu})$$

Naïve standard model prediction: $a_{\beta\nu} = -\frac{1}{3}$ and $b = 0$

In the presence of tensor couplings:

$$a_{\beta\nu} \approx -\frac{1}{3}\left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right), \text{ and } b = 2\frac{C_T + C_T'}{C_A}$$

Thus, measurements of correlation coefficients indicative to BSM tensor type of couplings

e.g., allowed transitions

Note (1):

Standard model deviations are nuclear theory challenge:

1) Radiative corrections.
2) Shape corrections

$$\frac{d\omega_{\beta\mp}^{V-A}}{d\epsilon \frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}(Q-\epsilon)^2 k\epsilon F^{\pm}(Z_f,\epsilon)\frac{1}{2J_i+1}\cdot$$
$$\cdot\left\{\frac{|C_V|^2+|C_V'|^2}{2}\left[1+\delta_1^{0^+}+\left(1+\delta_{\beta\nu}^{0^+}\right)\hat{\nu}\cdot\vec{\beta}\right]\left|\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle\right|^2\right.$$
$$\left.+\frac{|C_A|^2+|C_A'|^2}{2}3\left[1+\delta_1^{1^+}-\frac{1}{3}\left(1+\delta_{\beta\nu}^{1^+}\right)\hat{\nu}\cdot\vec{\beta}\right]\left|\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle\right|^2\right\}$$

$$\delta_1^{0^+} = -\frac{\nu+\frac{k^2}{\epsilon}}{q}2\mathfrak{Re}\frac{\left\langle J_f\left\|\hat{L}_0^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle}$$
$$\delta_{\beta\nu}^{0^+} = -\frac{\epsilon+\nu}{q}2\mathfrak{Re}\frac{\left\langle J_f\left\|\hat{L}_0^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle}$$

$$\delta_1^{1^+} = -\frac{2}{3}\left[\frac{\nu+\frac{k^2}{\epsilon}}{q}\mathfrak{Re}\frac{\left\langle J_f\left\|\hat{C}_1^A\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\mp 2\sqrt{2}\frac{\nu-\frac{k^2}{\epsilon}}{q}\mathfrak{Re}\left(\frac{C_V^*C_A+C_V'^*C_A'}{|C_A|^2+|C_A'|^2}\frac{\left\langle J_f\left\|\hat{M}_1^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\right)\right]$$
$$\delta_{\beta\nu}^{1^+} = 2\left[\frac{\epsilon+\nu}{q}\mathfrak{Re}\frac{\left\langle J_f\left\|\hat{C}_1^A\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\mp 2\sqrt{2}\frac{\epsilon-\nu}{q}\mathfrak{Re}\left(\frac{C_V^*C_A+C_V'^*C_A'}{|C_A|^2+|C_A'|^2}\frac{\left\langle J_f\left\|\hat{M}_1^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\right)\right] \quad (39)$$

e.g., allowed transitions

$$\Theta \propto (1 + b\frac{m_e}{\epsilon} + a_{\beta\nu}\vec{\beta} \cdot \hat{\nu})$$

$$a_{\beta\nu} \approx -\frac{1}{3}(1 - \frac{|C_T|^2+|C_T'|^2}{|C_A|^2}), \text{ and } b = 2\frac{C_T+C_T'}{C_A}$$

Note (2):

a) Sensitive to combination of tensor couplings, with spectrum averaging of energy

b) Spectrum, i.e., integration over angle, sensitive only to Fierz term, i.e., insensitive to fully right handed couplings.

M. González-Alonso, O. Naviliat-Cuncic, Kinematic sensitivity to the Fierz term of β-decay differential spectra, Phys. Rev. C 94 (2016) 035503.

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

$$\Theta(q, \vec{\beta} \cdot \hat{\nu}) \propto 1 \pm 2\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon} - \frac{1}{5}\left(2(\hat{\nu} \cdot \vec{\beta}) - (\hat{\nu} \cdot \hat{q})(\vec{\beta} \cdot \hat{q})\right)\left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right).$$

$$\propto \quad 1 - \left(\hat{\beta} \cdot \hat{\nu}\right)^2$$

Spectrum, i.e., integration over angle:

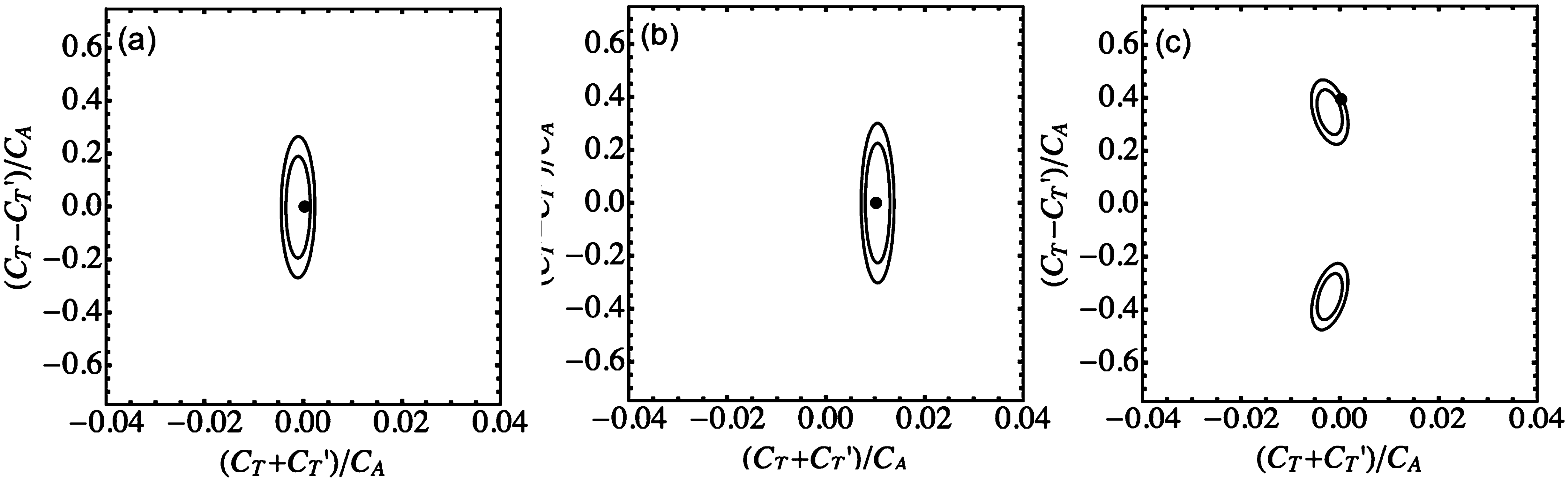
$$\frac{dw_{\beta^{\mp}}}{d\epsilon} \propto \Sigma(\epsilon)\left(2 + 4\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon} + \frac{\beta}{5} \frac{(a^2 - 1)\tanh^{-1}(a) + a}{a^2} \times \left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right)\right),$$

$$a = 2k\nu/(k^2 + \nu^2)$$

Glick-Magid et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

Unique possibility to separate between left and right-handed couplings!



$C_T = C_T' = 0$ $\quad$ $C_T/C_A = C_T'/C_A = 0.005$ $\quad$ $C_T/C_A = -C_T'/C_A = 0.2$

Glick-Magid et al, Beta spectrum of unique first forbidden devays as a

Novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique first forbidden $\Delta J^\pi = 2^-$

Again:

Standard model deviations are nuclear theory challenge:

1) Radiative corrections.
2) Nuclear shape corrections – note the natural $\hbar c q \ll 1$ suppression.

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \frac{2G^2}{\pi^2}\frac{1}{2J_i+1}(\epsilon_0-\epsilon)^2 k\epsilon\, F^\pm(Z_f,\epsilon) \times \left\{\frac{5}{2}\left[1+\delta_1+\frac{2}{5}(1+\delta_{\hat{\nu}\cdot\vec{\beta}})\hat{\nu}\cdot\vec{\beta} + \frac{1}{5}(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right]\langle\|\hat{L}_2^A\|\rangle^2\right\},$$

with

$$\delta_1 = \frac{4}{5}\left\{\pm\sqrt{\frac{3}{2}}\frac{\nu-\frac{k^2}{\epsilon}}{q}\Re\frac{\langle\|\hat{M}_2^V\|\rangle}{\langle\|\hat{L}_2^A\|\rangle} - \frac{\nu+\frac{k^2}{\epsilon}}{q}\Re\frac{\langle\|\hat{C}_2^A\|\rangle}{\langle\|\hat{L}_2^A\|\rangle}\right\},$$

$$\delta_{\hat{\nu}\cdot\vec{\beta}} = 2\left\{\pm\sqrt{\frac{3}{2}}\frac{\epsilon-\nu}{q}\Re\frac{\langle\|\hat{M}_2^V\|\rangle}{\langle\|\hat{L}_2^A\|\rangle} - \frac{\nu+\epsilon}{q}\Re\frac{\langle\|\hat{C}_2^A\|\rangle}{\langle\|\hat{L}_2^A\|\rangle}\right\}$$

SUMMARY

- Solar p-p fusion: a simple, validated, pionless theory with only few parameters predicts the fusion rate with high precision.
  - High experimental uncertainty stemming from g_A
- For electromagnetic regime: accurate and precise theory with unique theoretical uncertainty estimate.
  - Reviving the role of magnetic moments in understanding nuclear structure: flow of EFTs? SU(4) symmetry?
- Some mysteries regarding NPLQCD/pionless EFT works.
- Beta decays are an intersection of new approaches in experiment and theory – to study BSM physics.