האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Triton β–decay up to NLO in pionless EFT

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Precise β-decay calculations for searches for new physics
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Motivation

- Weak decays of nuclei are used to study the limits of the Standard Model.

- Triton β-decay is the lightest nuclear β $-$decay. It is simpler for calculations, and has very low endpoint (19 KeV) which is applicable for pionless EFT calculations.

- The triton β-decay, as the only $A = 3$ β-decay, can probe unique properties of the nuclear force for both ^3H and ^3He.

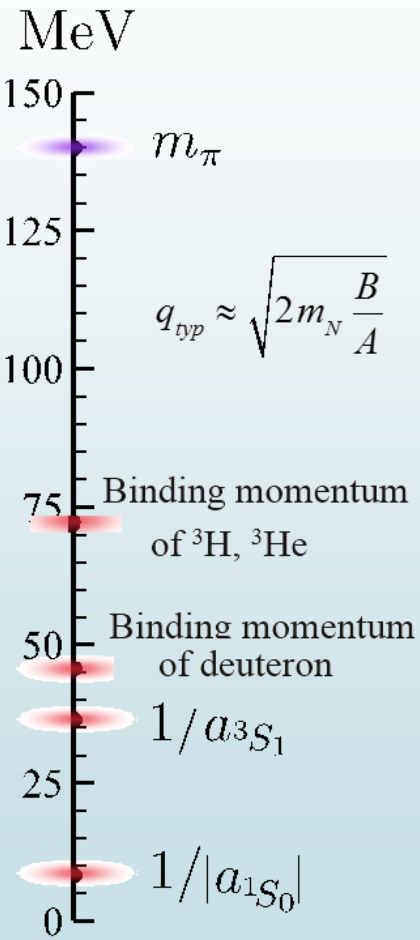
- These calculations can serve as a benchmark for χEFT which will be used in heavier nuclei.

Effective Field Theory

- The fundamental theory is QCD, which is non-perturbative in the low-energy regime.
- If the momentum scale, q, is small compared to the physical cutoff, Λ_{cut}, a physical process can be described using Effective Field Theory.
- For low energies ($q < \Lambda_{cut} = m_\pi$), pion can be integrated out and only nucleons are left as effective degrees of freedom.

$$\text{QCD} \rightarrow \not{\pi}\text{EFT}$$

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



Kaplan, Savage ,Wise, (1998-1999), Bedaque, Hammer, van Kolck (1999)

Building $\not\pi$EFT Lagrangian

Scale separation:

$$a \sim \frac{1}{q} \qquad \rho \sim \frac{1}{\Lambda_{\text{cut}}}$$

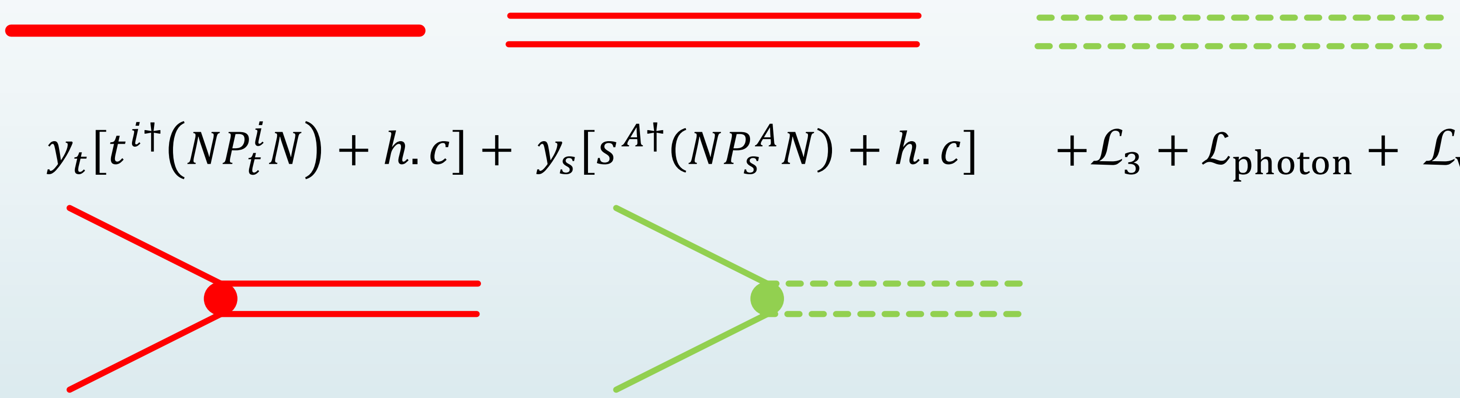
Parameter	Value		Parameter	Value
γ_t	45.701 MeV		ρ_t	1.765 fm
a_s	-23.714 fm		ρ_s	2.73 fm
a_p	-7.8063 fm		ρ_p	2.794 fm

$\underbrace{\qquad\qquad}_{\textbf{LO}}$ $\qquad\qquad$ $\underbrace{\qquad\qquad}_{\textbf{NLO}}$

Building $\not{\pi}$EFT Lagrangian

$$\mathcal{L} = N^T\left(iD_0 + \frac{D^2}{2M_N}\right)N \; - t^{i\dagger}\left(\sigma_t + iD_0 + \frac{D^2}{4M_N}\right)t^i - s^{A\dagger}\left(\sigma_s + iD_0 + \frac{D^2}{4M_N}\right)s^A$$

$$y_t[t^{i\dagger}(NP_t^iN) + h.c] + \; y_s[s^{A\dagger}(NP_s^AN) + h.c] \quad + \mathcal{L}_3 + \mathcal{L}_{\text{photon}} + \; \mathcal{L}_{\text{weak}} + \mathcal{L}_{\text{magnetic}}$$



Where:

$$t^i(^3\mathrm{S}_1, \mathrm{I} = 0), \qquad s^A(^1\mathrm{S}_0, \mathrm{I} = 1)$$

$$P_t^i = \frac{1}{\sqrt{8}}\sigma^2\sigma^i\tau^2 \;, P_s^A = \frac{1}{\sqrt{8}}\sigma^2\tau^2\tau^A$$

$$D_\mu = \partial_\mu + iA_\mu\hat{Q}$$

$$y_{t,s}^2 = \frac{8\pi}{M_N^2\rho_{t,s}}$$

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

Beane and Savage, (2001), Bedaque et al. (1999)

Weak interaction in $\not{\pi}$EFT, $q \rightarrow 0$

- The Lagrangian of the weak interaction for low energies ($E \ll W, Z$) is given by:

$$\mathcal{L}_{weak} = -\frac{G_F}{\sqrt{2}} l_+^{\mu} J_{\mu}^- + h.c$$

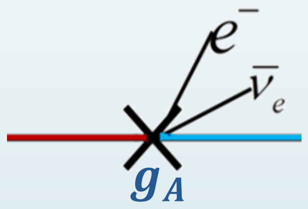
- l_+^{μ} is the leptonic current and j_{μ}^- is the hadronic current.

$$J_{\mu}^{\pm} = V_{\mu}^{\pm} - A_{\mu}^{\pm} = \frac{N^{\dagger}\tau^{\pm}N}{2} - \left[\frac{g_A}{2} N^{\dagger}\tau^{\pm}N + L'_{1,A}\left(\mathrm{t}^{\dagger}\mathrm{s} + \mathrm{h.c}\right)\right]$$

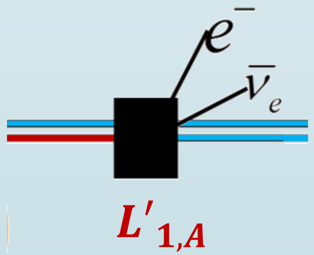
- g_A: axial coupling constant, known from neutron β-decay.
- $L'_{1,A} = -\frac{\rho_t + \rho_s}{\sqrt{\rho_t \rho_s}} + l_{1,A}(\mu)$
- $l_{1,A}(\mu)$ is an RG invariant combination of the unknown two-body $L_{1,A}$.

$l_{1,A}(\mu)$ can be calibrated from: ${}^3\mathrm{H} \rightarrow \bar{\nu}_e + e^- + {}^3\mathrm{He}$

One body



Two body



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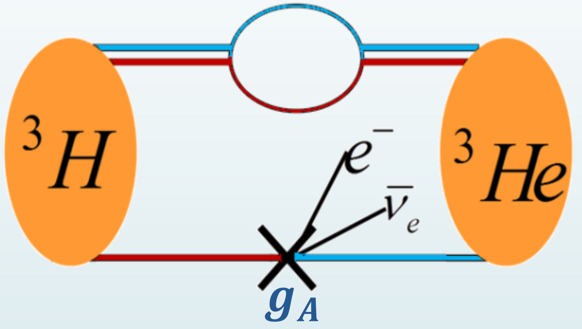
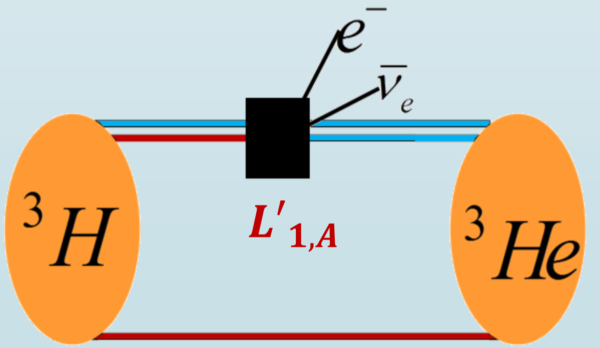
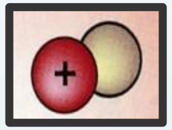
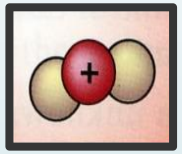


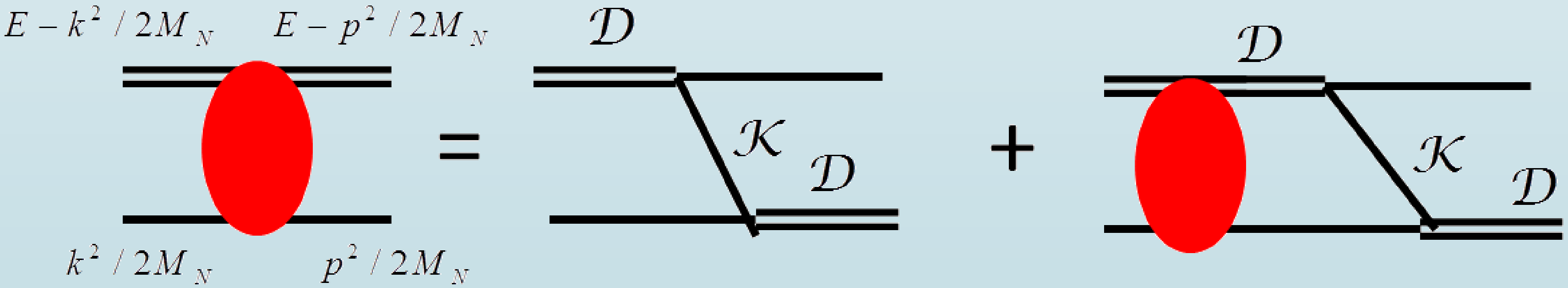
Two body



$\not{\pi}$EFT: $1 + 2 \neq 3$

- For $\not{\pi}$EFT there is a **big difference** between nuclear systems with **2 particles and 3 particles**
- Deuteron: $\psi_d(k) = \frac{\sqrt{8\pi\gamma_t}}{k^2+\gamma_t^2}$ 
- Triton: $T(E,k,p) = \int_0^\Lambda \frac{d^3p\prime}{(2\pi)^3} T(E,k,p')\mathcal{D}(E,p')\mathcal{K}(E,p',p)$ 

Summing over all possible amplitudes (Faddeev equation)



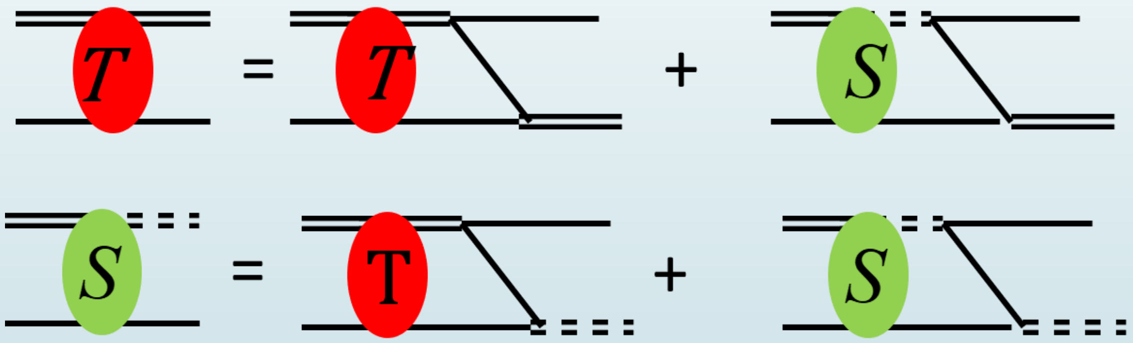
Bedaque, Hammer, van Kolck (1999), König and Hammer (2011), König et al (2014)

$\not{\pi}$EFT: $A = 3$ scattering amplitude

- For bound state: $T(E_B, k, p) = \frac{\mathcal{B}(k)^\dagger \mathcal{B}(p)}{E - E_B} + \mathcal{R}$

$$\mathcal{B}(p) = \int_0^\Lambda \frac{d^3p'}{(2\pi)^3} \mathcal{B}(p')\mathcal{D}(E_B, p')\mathcal{K}(E_B, p', p)$$

- Triton, $J = \frac{1}{2}$, coupled channels Faddeev equation:



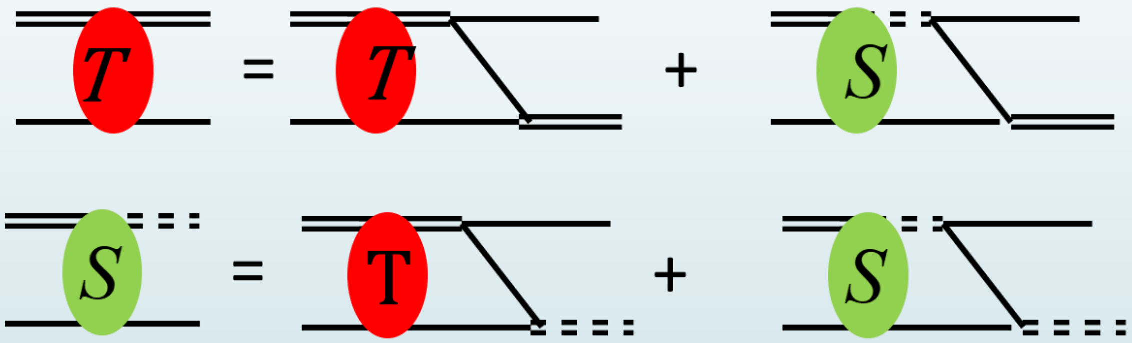
$$\mathcal{B}(p) = \begin{pmatrix} \Gamma_t(p) \\ \Gamma_s(p) \end{pmatrix}, \qquad \Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu a_{\mu\nu} K_0(E, p, p')\, D_\nu(E, p')\Gamma_\nu(p')$$

$$a_{tt} = \frac{4}{3}\left[(\sigma^i)^\alpha_\beta (P_t^i)^\dagger_{\gamma\delta} \left(P_t^j\right)^{\delta\beta} (\sigma^i)^\chi_\gamma\right] = -1$$

Bedaque, Hammer, van Kolck (1999), König and Hammer (2011), König et al (2014)

$\not{\pi}$EFT: $A = 3$ scattering amplitude

- Triton, $J = \frac{1}{2}$, coupled channels Faddeev equation:



$$\vec{\mathcal{B}} = \overleftrightarrow{\boldsymbol{M}} \times \vec{\mathcal{B}}$$

Eigenvalue problem

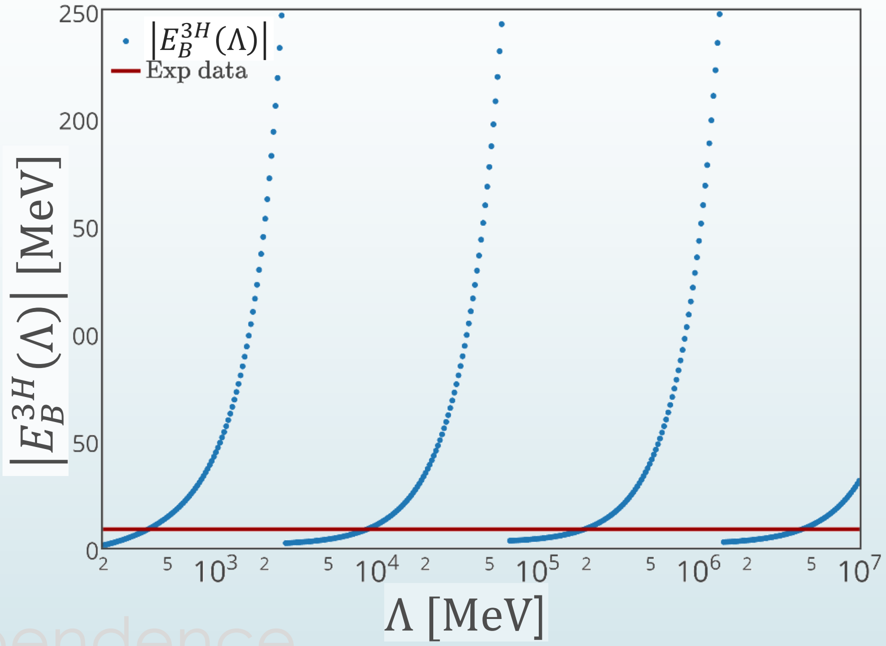
$$\vec{\mathcal{B}} = \begin{pmatrix} \Gamma_t \\ \Gamma_s \end{pmatrix}, \ \boldsymbol{M}_{\mu,\nu} = M_N y_\mu y_\nu a_{\mu\nu} K_0(E,p,p') D_\nu(E,p')$$

Bedaque, Hammer, van Kolck (1999), König and Hammer (2011), König et al (2014)

Binding energy:

- Deuteron: $E_B = -\frac{\gamma_t^2}{M_N}$
- Triton:

$$\Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int_0^\Lambda \frac{d^3p}{(2\pi)^3} y_\mu y_\nu a_{\mu\nu} D_\nu(E,p') K_0(E,p,p') \Gamma_\nu(p')$$



- $E_B = E_B(\Lambda)$, Efimov effect
- 3-body system has strong cutoff dependence

→add 3-body force at LO.

$$\Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu a_{\mu\nu} \left[K_0(E,p,p') + \frac{2H(\Lambda)}{\Lambda^2} \right] D_\nu(E,p') \Gamma_\nu(p')$$

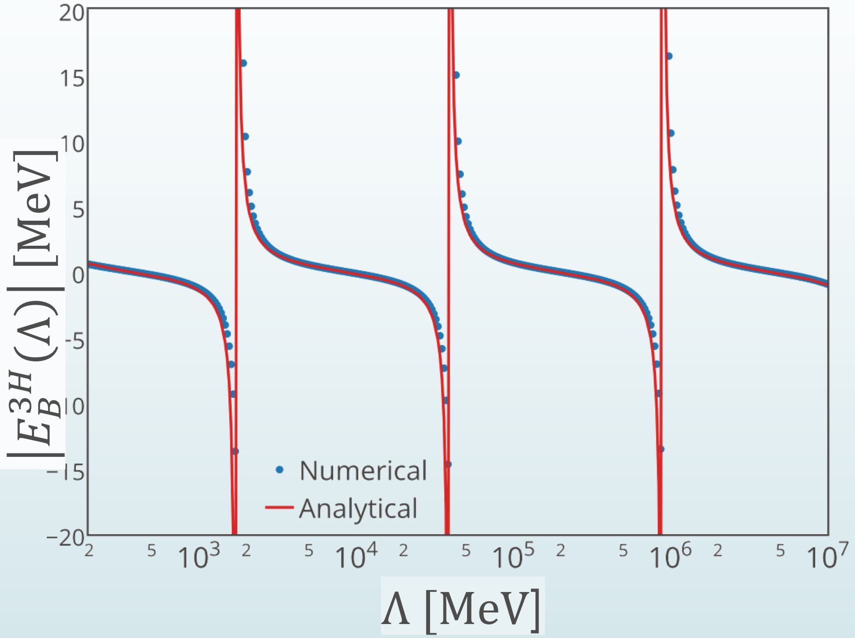
Bedaque, Hammer, van Kolck (1999)

Binding energy:

- Deuteron: $E_B = -\frac{\gamma_t^2}{M_N}$
- Triton:

$\Gamma_\mu(p) =$

$$M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu a_{\mu\nu} D_\nu(E,p')K_0(E,p,p')\Gamma_\nu(p')$$



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$$\Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu \left[a_{\mu\nu} K_0(E,p,p') + b_{\mu\nu}\frac{H(\Lambda)}{\Lambda^2}\right] D_\nu(E,p')\Gamma_\nu(p')$$

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Normalization of the A=3 wave-function

- Non relativistic Bethe-Salpeter equation (for a bound state):

$$|\Gamma\rangle = -V G_{BS} |\Gamma\rangle$$

- Bethe-Salpeter (B.S.) normalization condition:

$$\mathbf{1} = \langle \Gamma | G_{BS} \frac{\partial}{\partial E} \left(-G_{BS}^{-1} - V \right) G_{BS} | \Gamma \rangle$$

Triton scattering amplitude: $|\mathcal{B}\rangle = \hat{D}\hat{K}|\mathcal{B}\rangle$

$$\Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu \left[a_{\mu\nu} K_0(E,p,p') + b_{\mu\nu} \frac{H(\Lambda)}{\Lambda^2} \right] D_\nu(E,p') \Gamma_\nu(p')$$

$$\langle \hat{1} \rangle = \sum_{\mu,\nu=t,s} \left\langle \Gamma_\mu \middle| D_\mu \left\{ \frac{\partial}{\partial E} \left[D_\mu^{-1}(E) \delta_{\mu\nu} - a_{\mu\nu} K_0(E) \right] \Big|_{E=E_B} \right\} D_\nu \middle| \Gamma_\nu \right\rangle$$

König and Hammer (2011), De-Leon, Platter and Gazit (2019)

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König and Hammer (2011), De-Leon, Platter and Gazit (2019)

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Triton scattering amplitude:

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König and Hammer (2011), De-Leon, Platter and Gazit (2019)

Normalization of the A=3 wave-function

Triton scattering amplitude:

$$\Gamma_\mu(p) = M_N \sum_{\nu=t,s} \int \frac{d^3p}{(2\pi)^3} y_\mu y_\nu \left[a_{\mu\nu} K_0(E,p,p') + b_{\mu\nu} \frac{H(\Lambda)}{\Lambda^2} \right] D_\nu(E,p')\Gamma_\nu(p')$$

$$\langle \hat{1} \rangle = \sum_{\mu,\nu=t,s} \left\langle \Gamma_\mu D_\mu \left| \left\{ \frac{\partial}{\partial E} \left[D_\mu^{-1}(E)\delta_{\mu,\nu} - a_{\mu\nu} K_0(E) \right] \right|_{E=E_B} \right\} \right| D_\nu \Gamma_\nu \right\rangle$$

$$\langle \hat{1} \rangle = \sum_{\mu,\nu=t,s} \langle \psi_\mu | \hat{O}_{\mu\nu}^{norm} | \psi_\nu \rangle$$

Matrix element!

König and Hammer (2011), De-Leon, Platter and Gazit (2019)

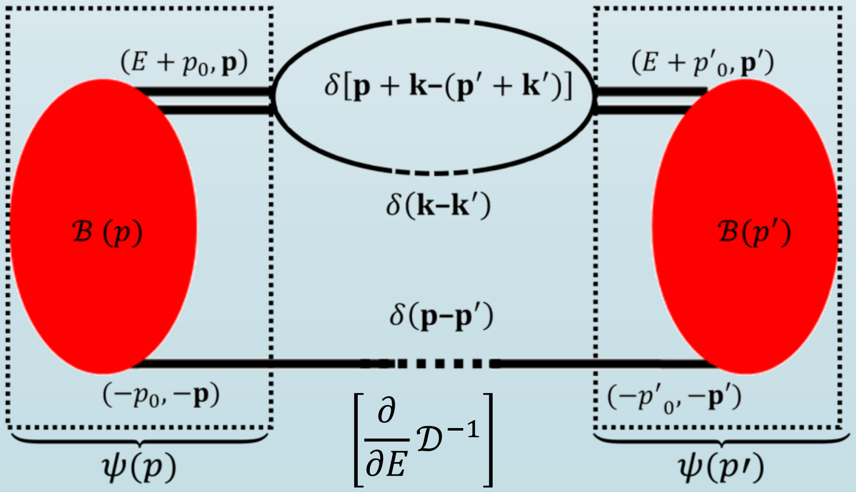
Normalization of the A=3 wave-function:

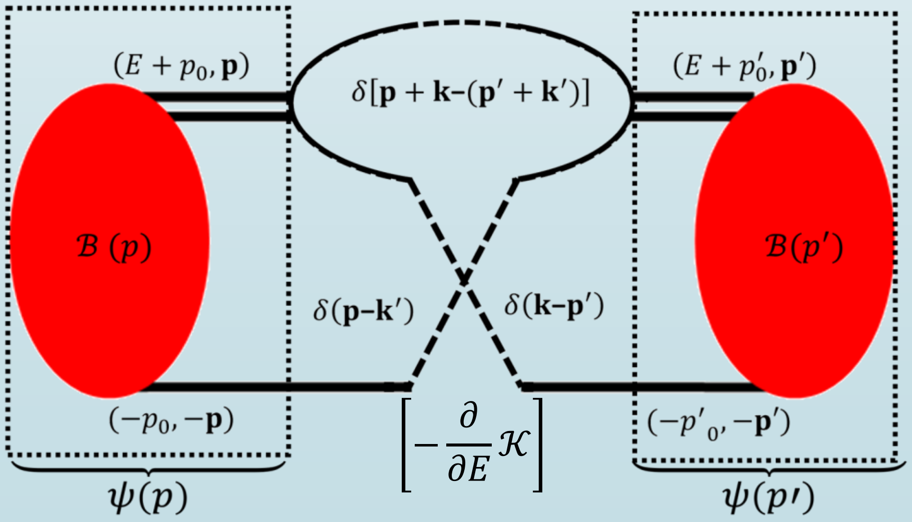
$$1 = \sum_{\mu,\nu} \left\langle \psi_\mu \left| \frac{\partial}{\partial E} \left[D_\mu^{-1}(E)\delta_{\mu,\nu} - a_{\mu\nu} K_0(E\ ) \right] \right|_{E=E_B} \left| \psi_\nu \right\rangle$$

$$\frac{\partial S(E,p)}{\partial E} = \int \frac{d^3p\prime}{(2\pi)^3} S(E,p) S(E,p') \frac{2\pi^2}{p'^2} \delta(p-p')$$

The normalization is equivalent to

all possible connections between two identical bubbles:

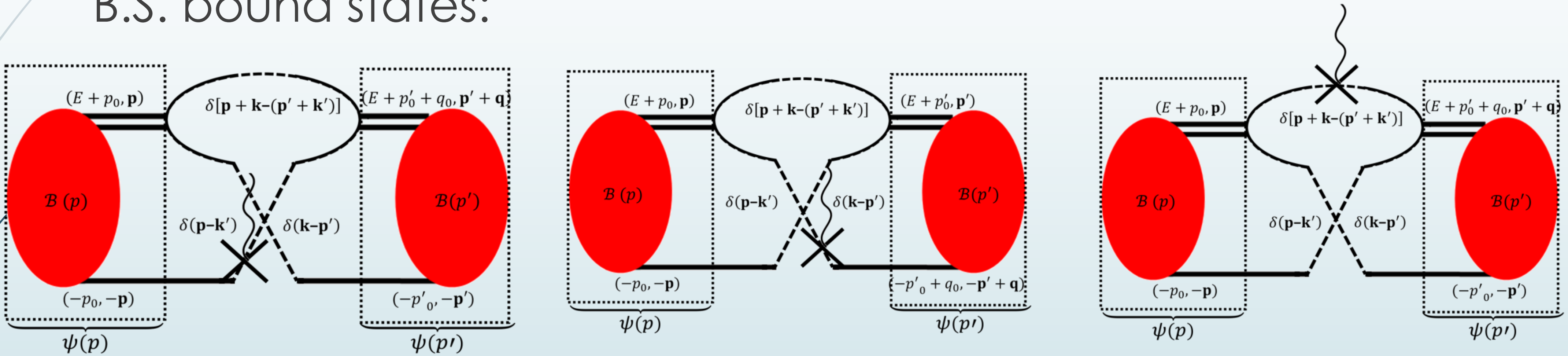




De-Leon, Platter and Gazit (2019)

Reduced matrix element

- A matrix element is equivalent to all possible connections, with B.S. bound states:



- Reduced matrix element:

$$\langle\mathcal{O}\rangle = a^J \left\langle \frac{1}{2}\middle\|\mathcal{O}^J\middle\|\frac{1}{2}\right\rangle \left\langle \frac{1}{2}\middle|\mathcal{O}^I\middle|\frac{1}{2}\right\rangle \sum_{\mu,\nu} \left\langle \psi_\nu^j \middle| a_{\mu\nu}^{i,j}\hat{\mathcal{K}}(q_0,q) + d_{\mu\nu}^{i,j}\hat{\mathcal{I}}\,(q_0,q) \middle| \psi_\mu^i \right\rangle$$

- For the case where $i=j$: $a_{\mu\nu}^{i,j}{=}a_{\mu\nu}$, $\quad d_{\mu\nu}^{i,j}{=}\delta_{\mu,\nu}$

De-Leon, Platter and Gazit (2019)

NLO A=3, general EW matrix element

$$\langle \mathcal{O}_{\mathrm{EW}} \rangle_{\mathrm{LO}} + \langle \mathcal{O}_{\mathrm{EW}} \rangle_{\mathrm{NLO}} =$$

$$\langle \psi^{\mathrm{LO}} | \mathcal{O}^{\mathrm{LO}}_{\mathrm{EW}} | \psi^{\mathrm{LO}} \rangle + \langle \psi^{\mathrm{NLO}} | \mathcal{O}^{\mathrm{LO}}_{\mathrm{EW}} | \psi^{\mathrm{LO}} \rangle + \langle \psi^{\mathrm{LO}} | \mathcal{O}^{\mathrm{NLO}}_{\mathrm{EW}} | \psi^{\mathrm{LO}} \rangle + \langle \psi^{\mathrm{LO}} | \mathcal{O}^{\mathrm{LO}}_{\mathrm{EW}} | \psi^{\mathrm{NLO}} \rangle$$

- One-body NLO corrections:

$$\psi^{\mathrm{NLO}}_{\mu}(E,p) = Z^{\mathrm{NLO}}\left[D^{\mathrm{NLO}}_{\mu}(E,p)\Gamma^{\mathrm{LO}}_{\mu}(E,p) + D^{\mathrm{LO}}_{\mu}(E,p)\Gamma^{\mathrm{NLO}}_{\mu}(E,p)\right]$$

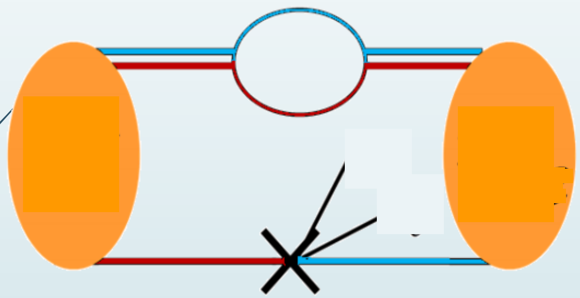
- NLO operator (two-body): $\mathrm{t}^{\dagger}t, s^{\dagger}s, (\mathrm{t}^{\dagger}s + h.c)$
- $\psi^{\mathrm{NLO}}_{\mu}$ is determined by the $A = 3$ charge radius:

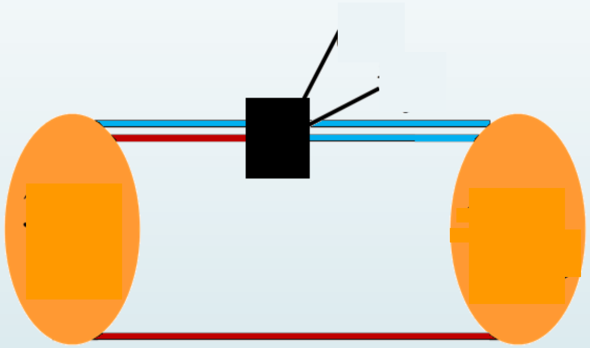
$$F^{\mathrm{LO}}_{C}(0) + F^{\mathrm{NLO}}_{C}(0) = F^{\mathrm{LO}}_{C}(0) = 1$$

$$\sum_{\mu,\nu=t,s} \langle \psi^{\mathrm{NLO}}_{\mu} | \hat{\mathcal{O}}^{\mathrm{norm}}_{\mu\nu} | \psi^{\mathrm{LO}}_{\nu} \rangle + \langle \psi^{\mathrm{LO}}_{\mu} | \hat{\mathcal{O}}^{\mathrm{norm}}_{\mu\nu} | \psi^{\mathrm{NLO}}_{\nu} \rangle - \frac{2}{3} \langle \psi^{\mathrm{LO}}_{t} | \psi^{\mathrm{LO}}_{t} \rangle = 0$$

Vanasse et al (2014-2018) , De-Leon, Platter and Gazit (2019)

EW matrix element, Power counting





$$\left\langle \left|\left|\mathcal{O}^{1\mathrm{B}}\right|\right| \right\rangle = \psi^2 \mathcal{O}[y^2 S^3(q_0, q) d^3 q dq_0]$$

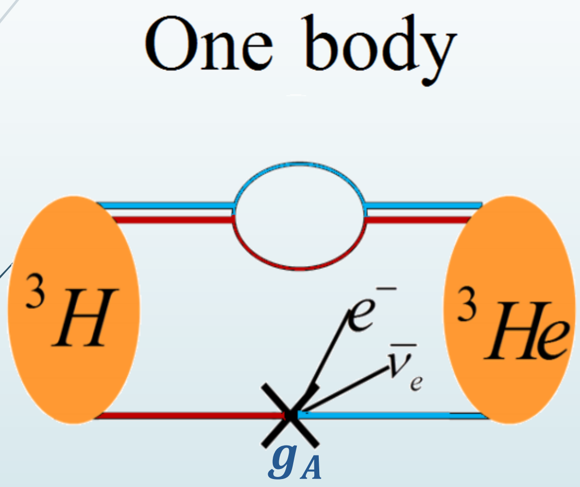
$$= \psi^2 \mathcal{O}\left(\frac{8\pi\Lambda}{M_N^2} \frac{1}{\frac{q^6}{M_N^3}} \frac{q^5}{4\pi M_N} \right) = \psi^2 \mathcal{O}\left(\frac{\Lambda}{q}\right)$$

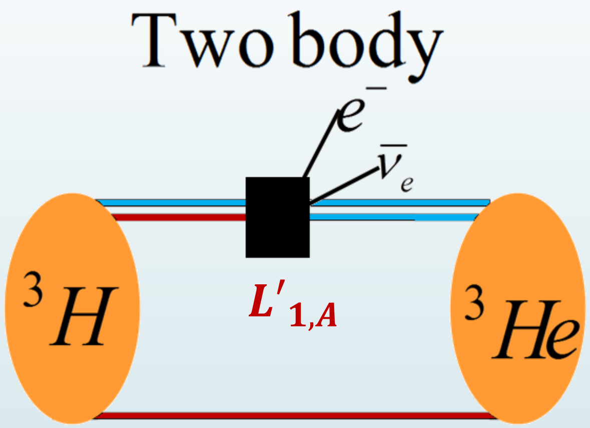
$$= \mathcal{O}(1)$$

$$\left\langle \left|\left|\mathcal{O}^{2\mathrm{B}}\right|\right| \right\rangle = \psi^2 \mathcal{O}(1) = \mathcal{O}\left(\frac{q}{\Lambda}\right)$$

De-Leon, Platter and Gazit (2019)

Weak matrix element, Power counting





$\langle \| \mathcal{O}^{1\mathrm{B}} \| \rangle = \mathcal{O}(1)$

$\langle \| \mathcal{O}^{2\mathrm{B}} \| \rangle = \mathcal{O}\left(\frac{q}{\Lambda}\right)$

- $L'_{1,A} = -\frac{\rho_t+\rho_s}{\sqrt{\rho_t\rho_s}} + l_{1,A}(\mu) \rightarrow \mathcal{O}(L'_{1,A}) = \mathcal{O}(1)$
- Up to NLO, the one-body diagrams must have one NLO insertion

De-Leon, Platter and Gazit (2019)

Triton β-decay matrix elements

The triton comparative half-life:

$$fT_{1/2} = \frac{K/G_V}{\langle||\mathrm{F}||\rangle^2 + \frac{f_A}{f_V}\langle||\mathrm{GT}||\rangle^2}$$

$$\langle||\mathrm{GT}(\Lambda)||\rangle = \langle\psi^{^3\mathrm{He}}||\boldsymbol{A}^+||\psi^{^3\mathrm{H}}\rangle$$

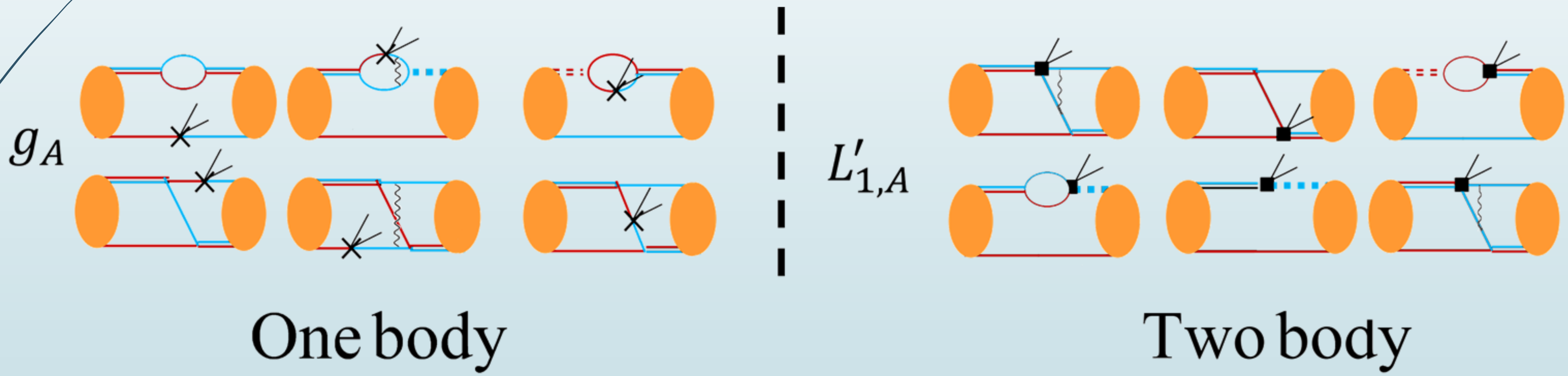
$$= g_A \left\langle\frac{1}{2}||\boldsymbol{\sigma}||\frac{1}{2}\right\rangle \times \left\langle\frac{1}{2}|\tau|\frac{1}{2}\right\rangle \times \int_0^\Lambda \frac{d^3p}{(2\pi)^3}\int_0^\Lambda \frac{d^3p'}{(2\pi)^3}\psi^{^3\mathrm{H}}(p)\mathcal{O}^{\mathrm{GT}}(p,p',q,q_0)\,\psi^{^3\mathrm{He}}(p')$$

$$\langle||\mathrm{F}||\rangle = \langle\psi^{3\mathrm{He}}||V^+||\psi^{3\mathrm{H}}\rangle = \left\langle\frac{1}{2}|\tau|\frac{1}{2}\right\rangle \times \int_0^\Lambda \frac{d^3p}{(2\pi)^3}\int_0^\Lambda \frac{d^3p'}{(2\pi)^3}\psi^{^3\mathrm{H}}(p)\mathcal{O}^{\mathrm{F}}(p,p',q,q_0)\,\psi^{^3\mathrm{He}}(p')$$

$$\langle||\mathrm{F}||\rangle = 1-\epsilon,\quad \langle||\mathrm{GT}||\rangle^{\mathrm{exp}} = \sqrt{3}\times(0.953 \pm 0.002 \pm 0.02)\ ,\langle||\mathrm{GT}||\rangle_{\alpha=0} = \sqrt{3}$$

Triton β-decay matrix elements

$$fT_{1/2} = \frac{K/G_V}{\langle||\mathrm{F}||\rangle^2 + \frac{f_A}{f_V}\langle||\mathrm{GT}||\rangle^2}$$



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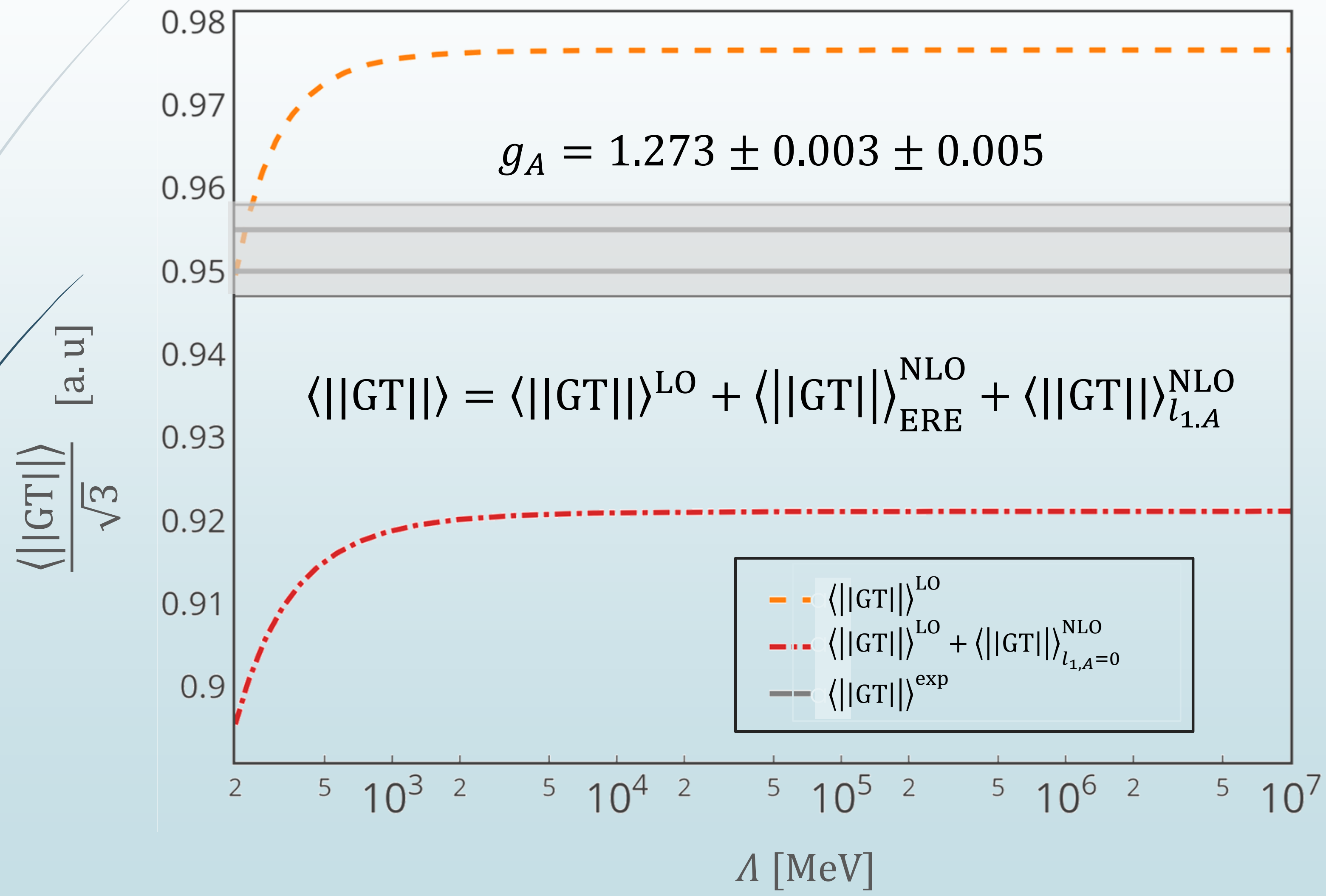
Numerical results $\langle||GT||\rangle$



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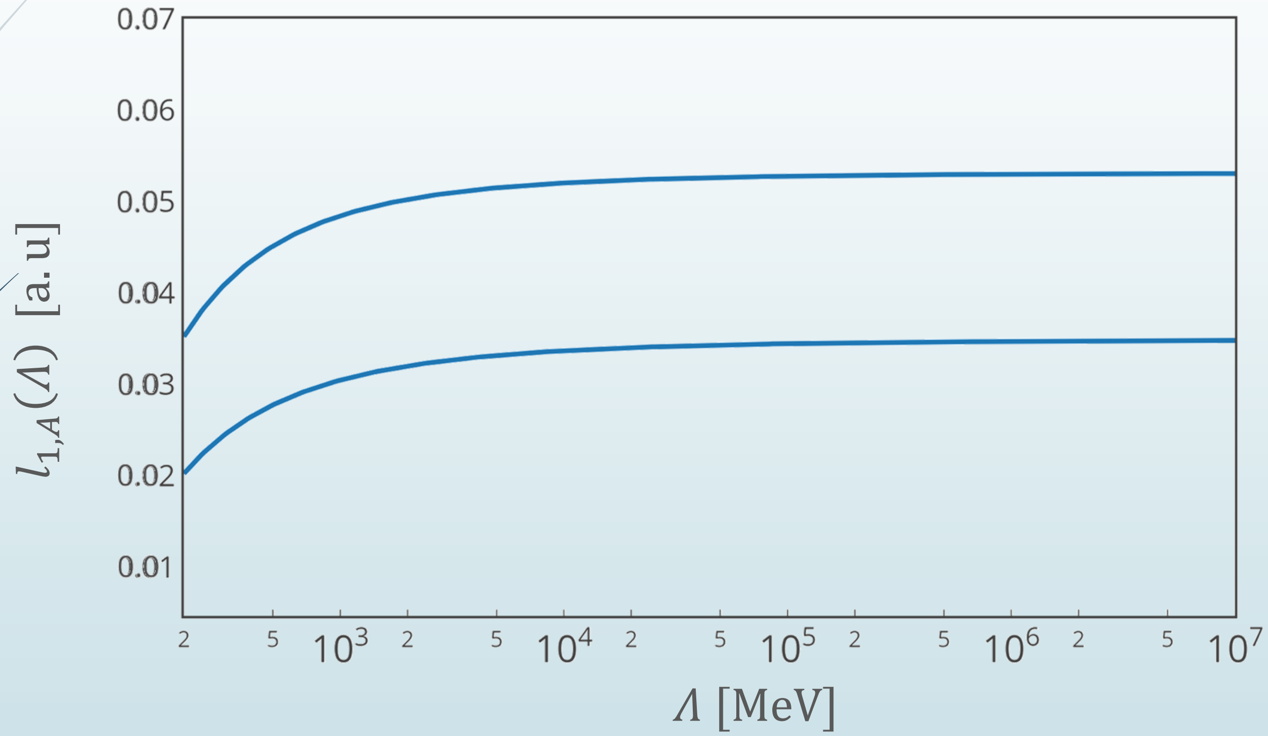
^{3}H β-decay: $L_{1,A}$ calibration



$$l_{1,A}(\Lambda) = L_{1,A}\left(\Lambda - \frac{1}{a_t}\right)\left(\Lambda - \frac{1}{a_s}\right)$$

is RG invariant!!

$$l_{1,A}(\Lambda) = \frac{\langle ||\mathrm{GT}||\rangle^{\exp} - \langle ||\mathrm{GT}||\rangle^{\mathrm{NLO}}_{\mathrm{ERE}}}{\langle ||GT||\rangle^{\mathrm{NLO}}_{l_{1.A}}}$$

De-Leon, Platter and Gazit (2019)

What's next?

- Nuclear structure corrections include, to first order in the momentum transfer, weak magnetism and axial charge ($J = 1$) multipoles.
- We don't have an explicit calculation for the weak transition corrections yet.
- We can use the electromagnetic sector to check the feasibility to use our formalism for the calculation of corrections to the spectrum and other β-decay observables.

Magnetic M_1 observables of A=2, 3 nuclei

- We have applied our formalism to calculate magnetic M_1 observables of A=2,3 systems

	EM
1-body LEC	κ_1, κ_0
1-body operator	$\sigma, \sigma\tau^0$
2-body operator	$l_1(t^\dagger s + \mathrm{h.c})\,, l_2 t^\dagger t$
$A = 2, q \approx 0$ M_1obs.	$\sigma_{np}, \langle\mu_d\rangle$
$A = 3, q \approx 0$ M_1obs.	$\langle\mu_{^3\mathrm{H}}\rangle, \langle\mu_{^3\mathrm{He}}\rangle$

- All $A < 4$ M_1 observables are well measured.
- We used the EM observables to estimate $\not{\pi}\mathrm{EFT}$ theoretical uncertainty and power-counting.

De-Leon and Gazit (2019)

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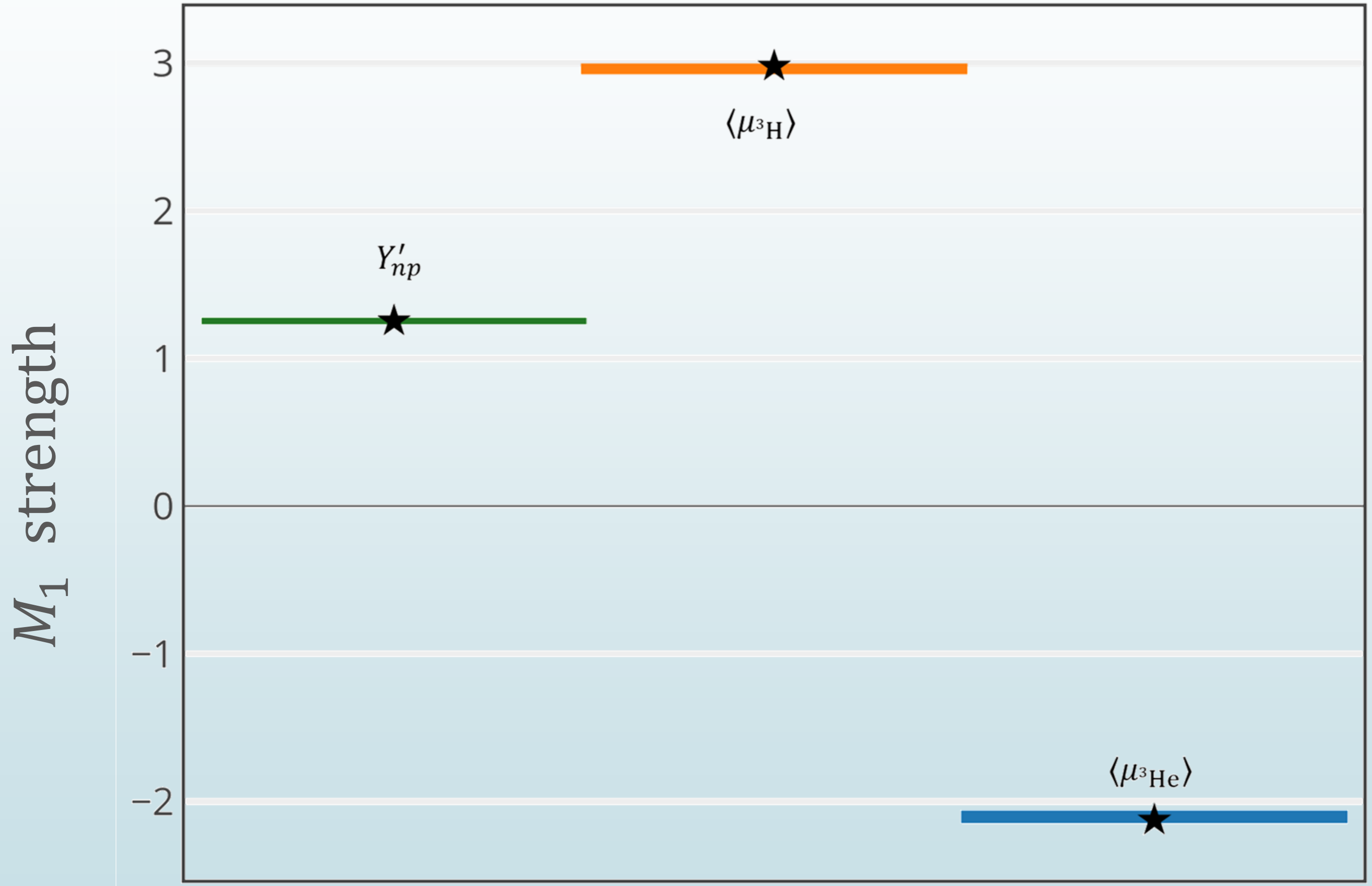
- Naïvely, both l_1, l_2 are of $\mathcal{O}(1)$, *i.e.*, the EM two-body operator is of $\mathcal{O}(q/\Lambda)$.
- We found that up to NLO, l_2 is consistent with 0

De-Leon and Gazit (2019)

EM results, $l_2 = 0$



The theoretical uncertainty for our theory is $\sim 1\%$

De-Leon and Gazit (2019)

Summary and outlook

- Consistent diagrammatic expansion of $\not{\pi}$EFT interactions is the sum of all possible diagrams with a single NLO perturbation insertion.
- We show that the $\not{\pi}$EFT predicts well the A=3 EW observables.
- Triton seems like a very good benchmark between methods, and a candidate nucleus where corrections to β-decay observables can be calculated with high precision and accuracy.

Summary and outlook

- We can extend this method for q>0 weak interactions such as neutrino scattering.
- This method can be also extended for heavier nuclei such as halo nuclei.

Thank you!