EMMI Rapid Reaction Task Force

The systematic treatment of the Coulomb interaction in few-body systems,

***Second meeting*.**

May 31-June 3, 2016

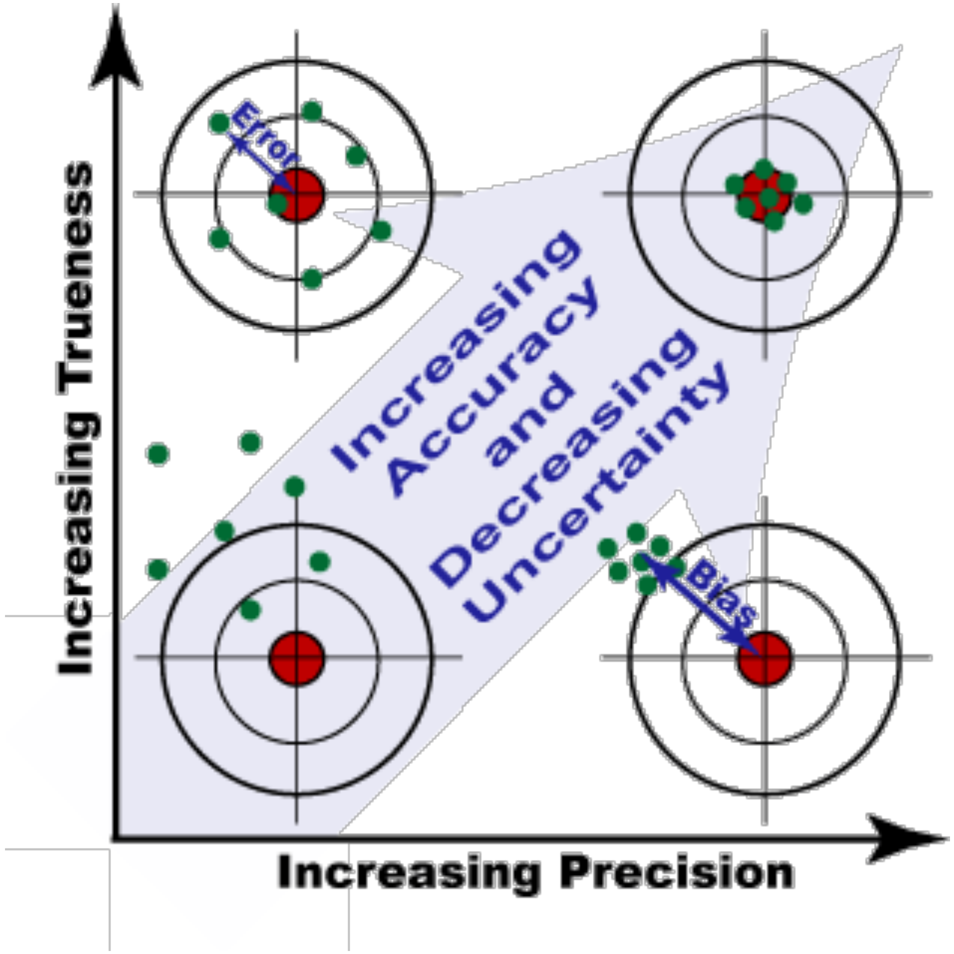
Updates on solar proton-proton fusion from $\not\pi$EFT

Doron Gazit, *Hilla De-Leon*

Racah Institute of Physics

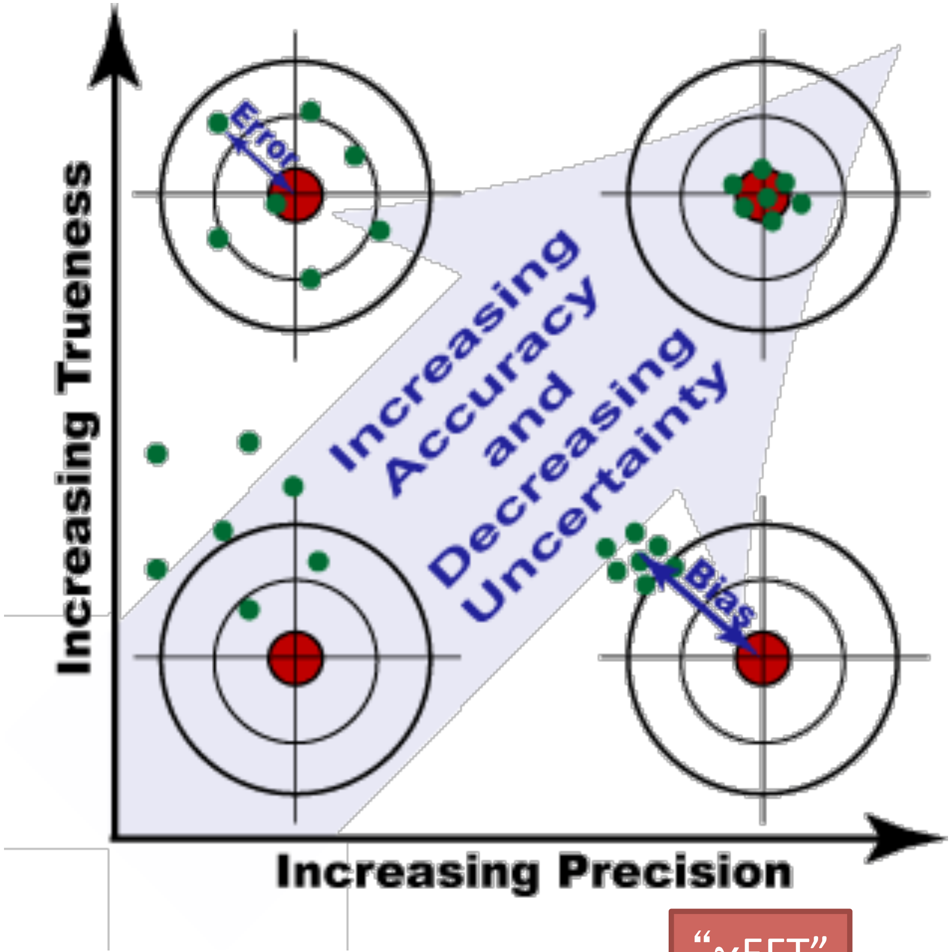
Hebrew University of Jerusalem

Precision, Uncertainty, and predictions



Precision, Uncertainty, and predictions

Widely believed:



“χEFT”

Weak proton-proton fusion in the Sun – theory standards

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

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

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

"χEFT" calculation by Marcucci et al., Phys. Rev. Lett. (2013):
Use consistent ^{3}H decay-rate to constrain consistently axial MEC (DG, Quaglioni, Navratil, PRL 2009), and predict pp-fusion rate.

$$S(0) = (4.030 \pm 0.006) \times 10^{-23}\ \mathrm{MeV\ fm}^2$$

Including: p-wave contribution (+0.005%), full EM (-0.0025-(-0.0075)%), difference between 500 and 600 MeV cutoff and potential models.

Recently Archaya et al (1603.01593) *χEFT:* $S(0) = (4.081^{+0.024}_{-0.032}) \times 10^{-23}\ \mathrm{MeV\ fm}^2$

Precision, Uncertainty, and predictions

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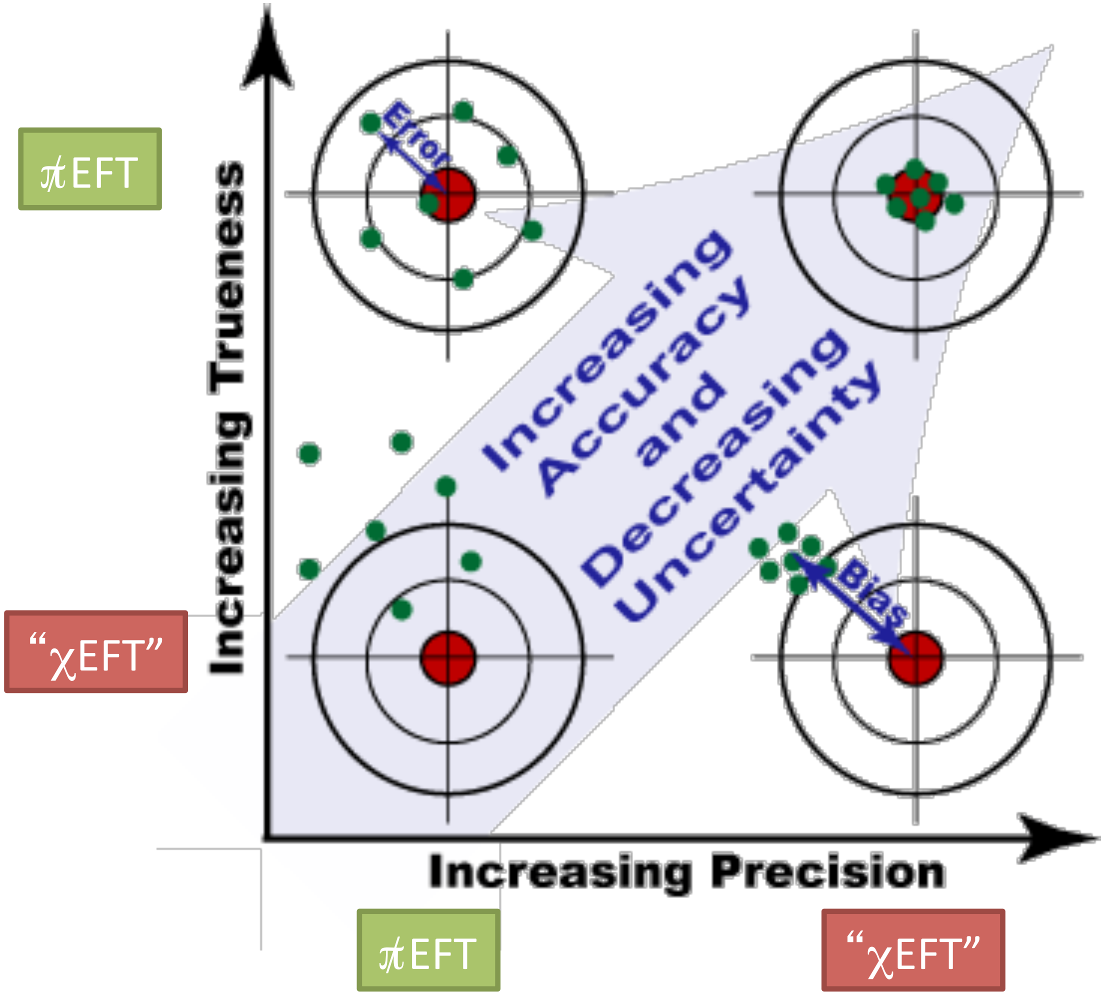
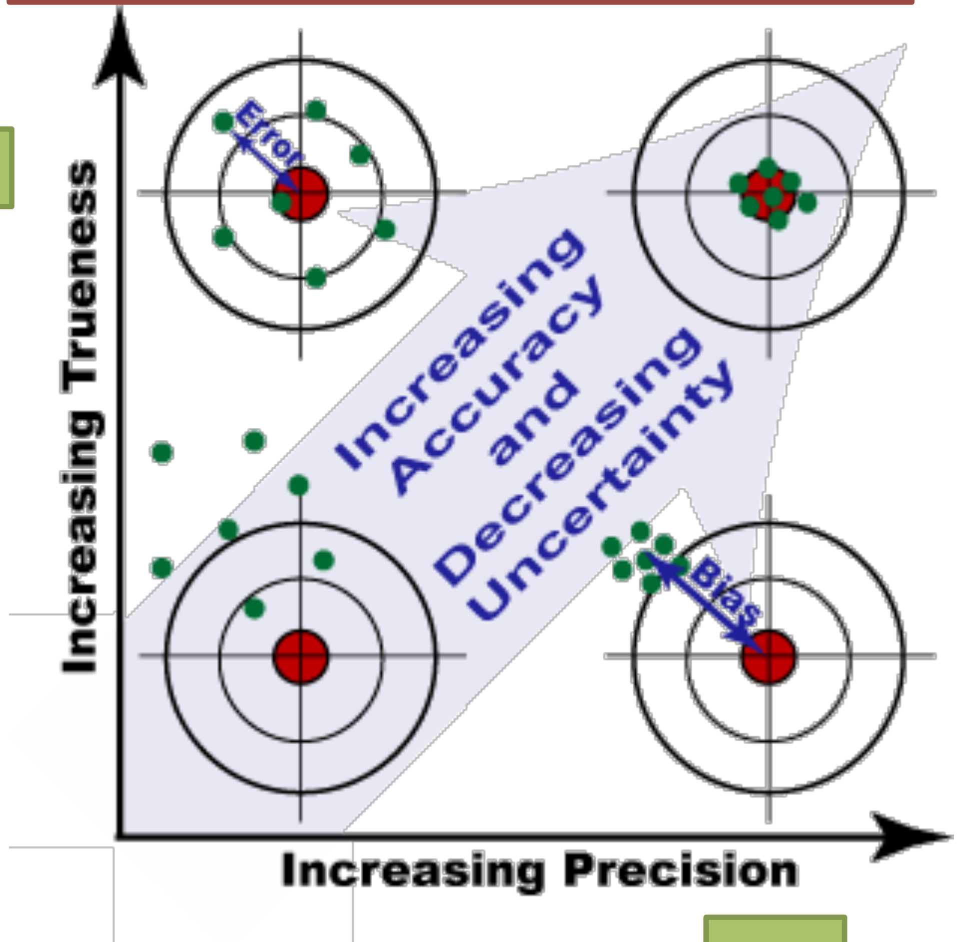


Precision, Uncertainty, and predictions

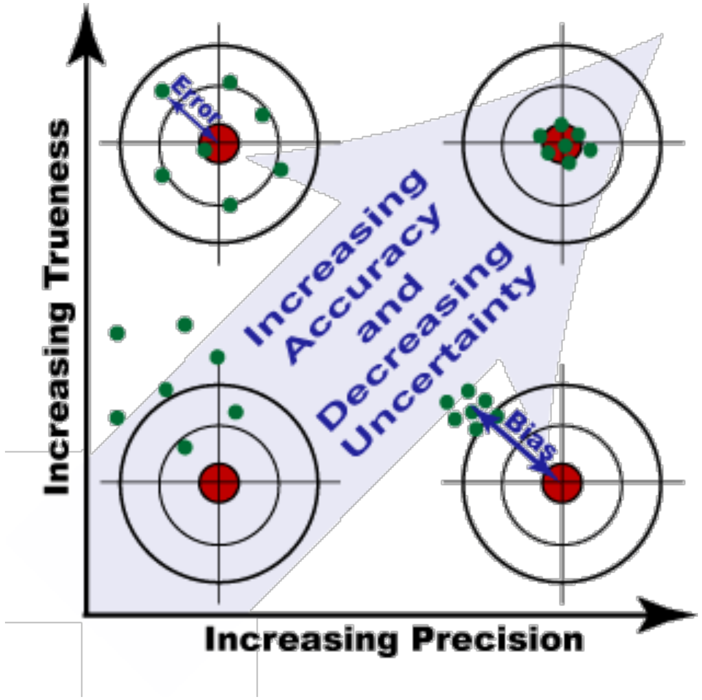
Can we reach precision physics with $\pi\!\!\!/$EFT?

$\pi\!\!\!/$EFT



$\pi\!\!\!/$EFT

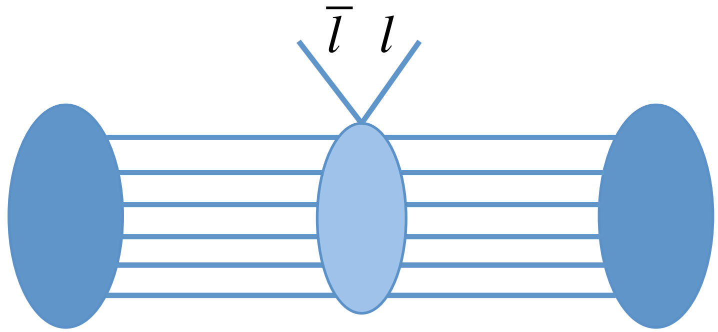
Precision, Uncertainty, and predictions



Role of $\not\pi$EFT:
Coherent and sysytematic (theoretical) uncertainty quantification.
Big question: is precision physics a possible frontier of $\not\pi$EFT?

We revisit the pp-fusion problem within pionless EFT, fixing the unknown LEC using triton decay.

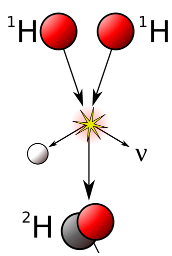
Weak decays:



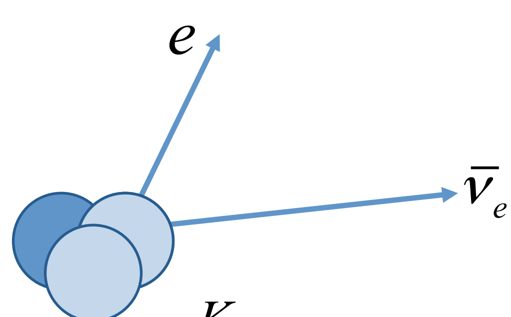
Initial amplitude — Weak Interaction — Final amplitude

$$\left\langle \psi_i \middle| \mathcal{J}_\mu \middle| \psi_f \right\rangle$$

$$\mathcal{J}_\mu^\pm = \frac{\tau_\pm}{2}\left(\mathcal{V}_\mu^\pm - \mathcal{A}_\mu^\pm\right)$$



$$\left\langle pp \middle| \mathcal{A}_\mu^- \middle| {}^2\mathrm{H} \right\rangle$$



$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \middle\| \mathcal{V}_\mu^+ \middle\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \middle\| \mathcal{A}_\mu^+ \middle\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$

Advantages of $\pi\!\!\!/$EFT for proton-proton fusion:

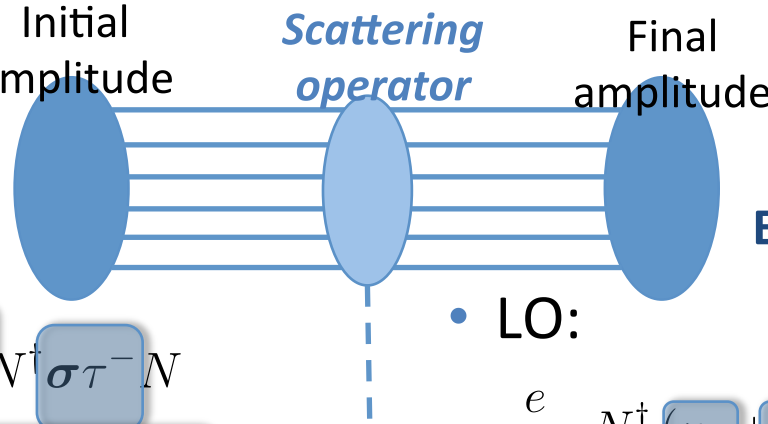
1. Small number of parameters.
2. Two NLO $\pi\!\!\!/$ EFT arrangements.
3. A "cheat-sheet" in the electromagnetic sector.
4. Cutoff independence up to infinity.

A fully perturbative pionless EFT A=2, 3 calculation @NLO

- LO Parameters:
  - nn and 2-np Scattering lengths: $^3S_1$, $^1S_0$.
  - pp scattering length.
  - Fine structure constant.
  - Three body force strength to prevent Thomas collapse.

- NLO parameters:
  - 2 effective ranges.
  - Renormalizations of pp and 3NF.
  - (isospin dependent 3NF to prevent logarithmic divergence in the binding energy of ^{3}He).

- ***Weak Interaction: LO (g_A – 1 body), NLO (L_{1A} – 2 body)***
- ***EM Interaction: LO (κ_S , κ_V) – 1 body), NLO (L_1 , L_2– 2 body)***



Weak

EM

- LO:

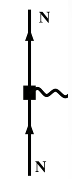
$$N^\dagger \frac{\tau^-}{2} N + \frac{g_A}{2} N^\dagger \boldsymbol{\sigma}\tau^- N$$

Fermi

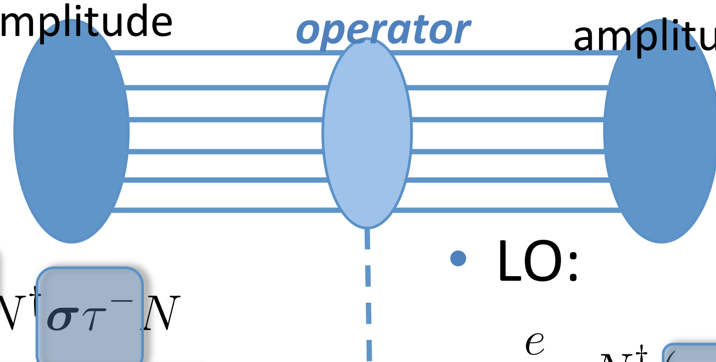
Gamow-Teller

- LO:

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



Single nucleon interaction



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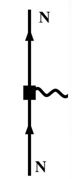


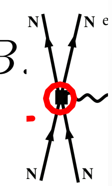
Single nucleon interaction

- NLO (correction to GT):

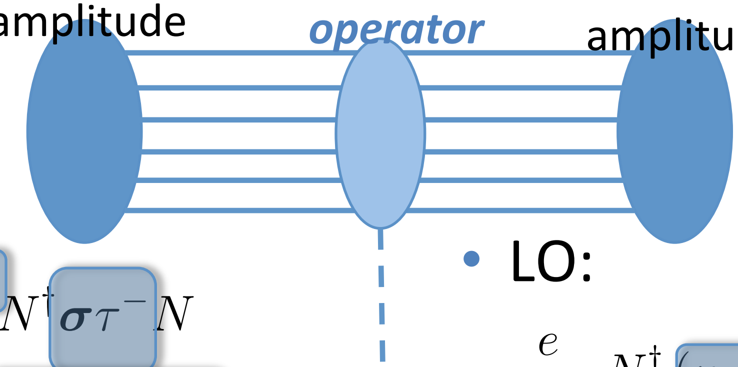
$$-L'_{1A}(t^\dagger s + s^\dagger t)$$

- NLO:

$$-L'_1(t^\dagger s + s^\dagger t) \cdot B + L'_2(t^\dagger t) \cdot B.$$



Simultaneous interaction with two nucleons coupled to singlet (s) / triplet (t)



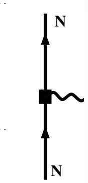
- LO:

$$N^\dagger \frac{\tau^-}{2} N + \frac{g_A}{2} N^\dagger \boldsymbol{\sigma}\tau^- N$$

Fermi — Gamow-Teller

- LO:

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



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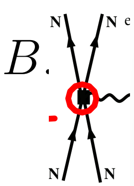

Simultaneous interaction with two nucleons coupled to singlet (s) / triplet (t)

$$L'_{1A} = g_A \left[\frac{1}{2}\frac{\rho_t + \rho_s}{\sqrt{\rho_t \rho_s}} - L_{1A}\frac{1}{2\pi\sqrt{\rho_t\rho_s}g_A}\left(\mu - \frac{1}{a_t}\right)\left(\mu - \frac{1}{a_s}\right)\right]$$

$$L_1' = \frac{e}{2M_N}\left[-\frac{1}{2}\frac{\rho_t + \rho_s}{\sqrt{\rho_t\rho_s}}(\kappa_p - \kappa_n) + L_1\frac{M_N}{\pi\sqrt{\rho_t\rho_s}}\left(\mu - \frac{1}{a_t}\right)\left(\mu - \frac{1}{a_s}\right)\right]$$

$$L_2' = \frac{e}{2M_N}\left[L_2\frac{2M_N}{\pi\rho_t}\left(\mu - \frac{1}{a_t}\right)^2 - (\kappa_p + \kappa_n)\right]$$

Should be cutoff invariant, nu +photon bremsstralung

Advantages of $\not\pi$EFT for proton-proton fusion:

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4. Cutoff independence up to infinity.

The role of the deuteron tail

- Many low energy reactions depend on deuteron normalization.

$$Z_d^{-1} = i \frac{\partial}{\partial_{p_0}} \frac{1}{i\mathcal{D}_t(p_0, p)} \Big|_{p_0 = \frac{\gamma_t^2}{M_N}, p=0}$$

- One has a choice of rearranging the expansion:
  - rho-parameterization: $Z_d = \frac{1}{1-\gamma\rho} \approx 1 + \gamma\rho + (\gamma\rho)^2 + \ldots$
  - Z(ed)-parameterization: $Z_d = \frac{1}{1-\gamma\rho} \approx 1 + (Z_d - 1) + 0 + \ldots$

LO NLO $N^2LO+\ldots$

Both are valid rearrangements!
Z-parameterization has quicker convergence, especially for observables sensitive to the deuteron tail.

Phillips, Rupak, Savage, Phys. Lett. **B473**, 209 (2000)
Grießhammer, Nucl. Phys. **A744**, 192 (2004)

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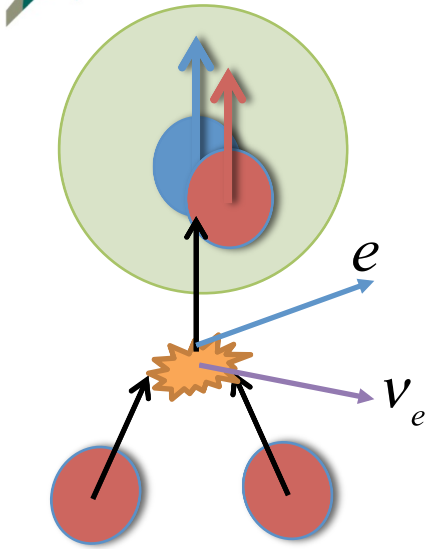
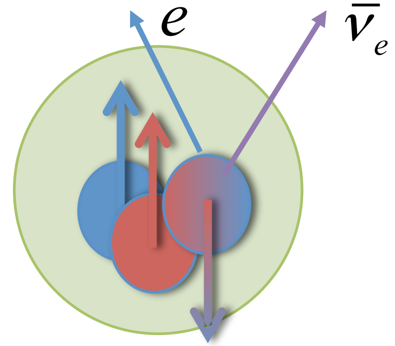
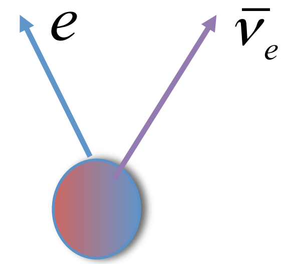
Analogy between weak and EM:



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



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

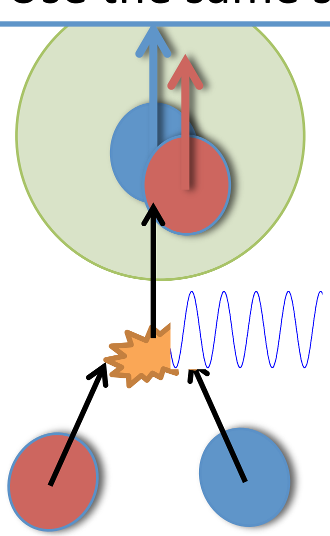


$n\rightarrow p+e^-+\bar{\nu}_e$

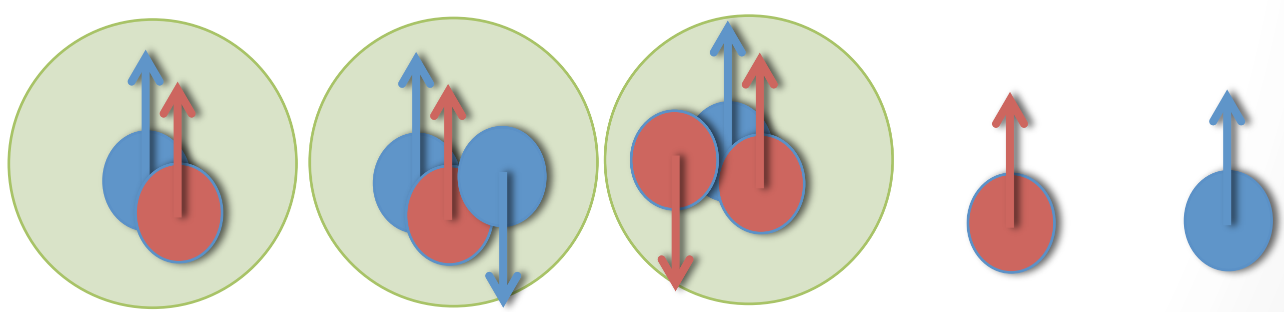
Weak observables

Use the same strategy in both cases: fix probe LECs at A=3 and predict A=2.

EM observables



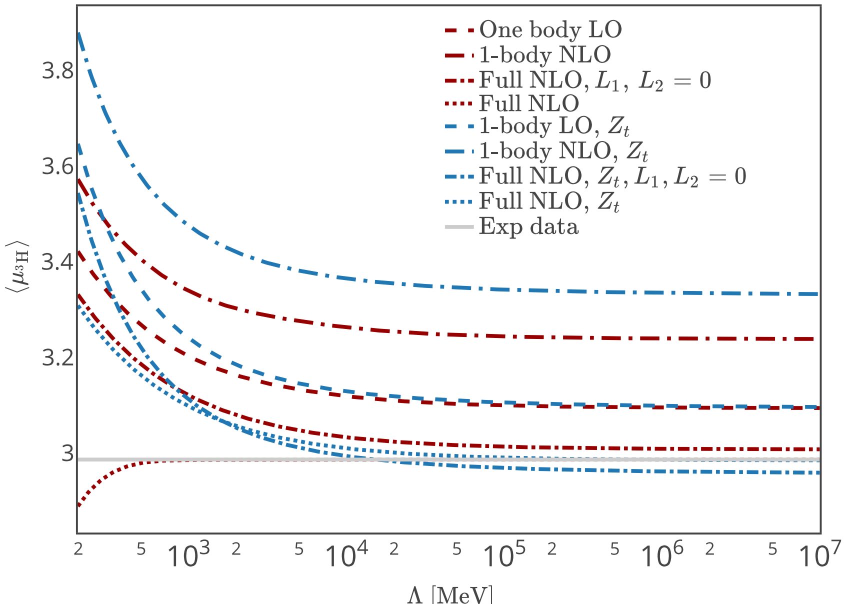
$n+p\rightarrow d+\gamma$



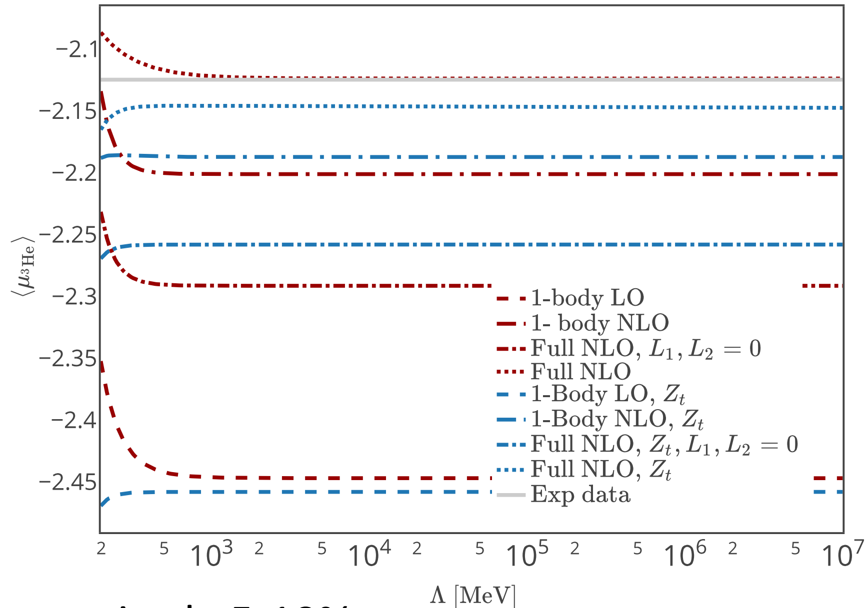
μ_d $\mu_{^3\mathrm{H}}$ $\mu_{^3\mathrm{He}}$ μ_p μ_n

A=3 magnetic moments calculations:

^{3}H



^{3}He



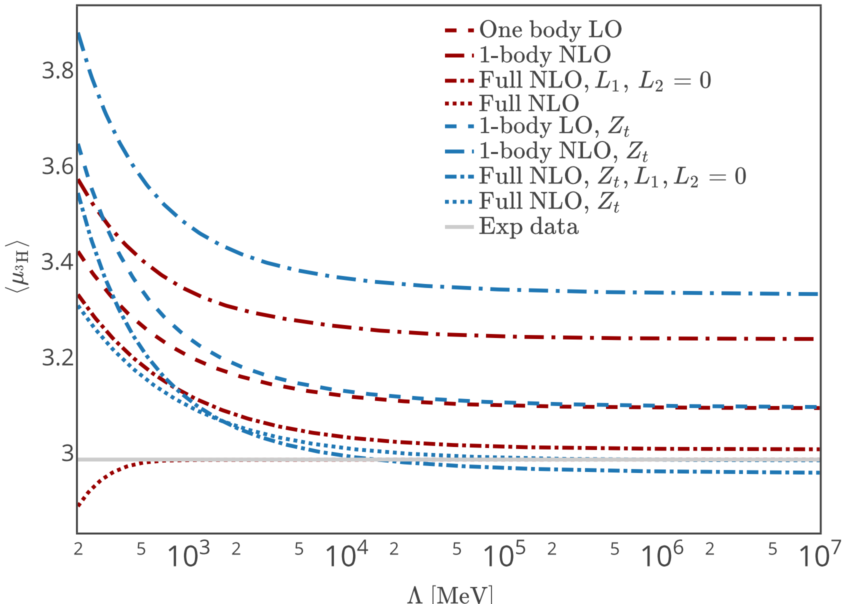
- All NLO contributions of the same order of magnitude 5-10% – Natural NLO contributions – useful for theoretical error estimates!
- No effect due to Zed-Rho parameterizations.
- Cutoff independence.
- When L_1 and L_2 are fixed **from A=2 observables**:

LO:	$\mu^{LO}_{^3\mathrm{H}} = 3.09 \pm_{Z_d} 0.01$	$\mu^{LO}_{^3\mathrm{He}} = -2.455 \pm_{Z_d} 0.005$
NLO:	$\mu^{NLO}_{^3\mathrm{H}} = 3.005 \pm_{Z_d} 0.01$	$\mu^{NLO}_{^3\mathrm{He}} = -2.13 \pm_{Z_d} 0.01$
exp:	$\mu^{\exp}_{^3\mathrm{H}} = 2.9789\ldots$	$\mu^{\exp}_{^3\mathrm{He}} = -2.1276\ldots$

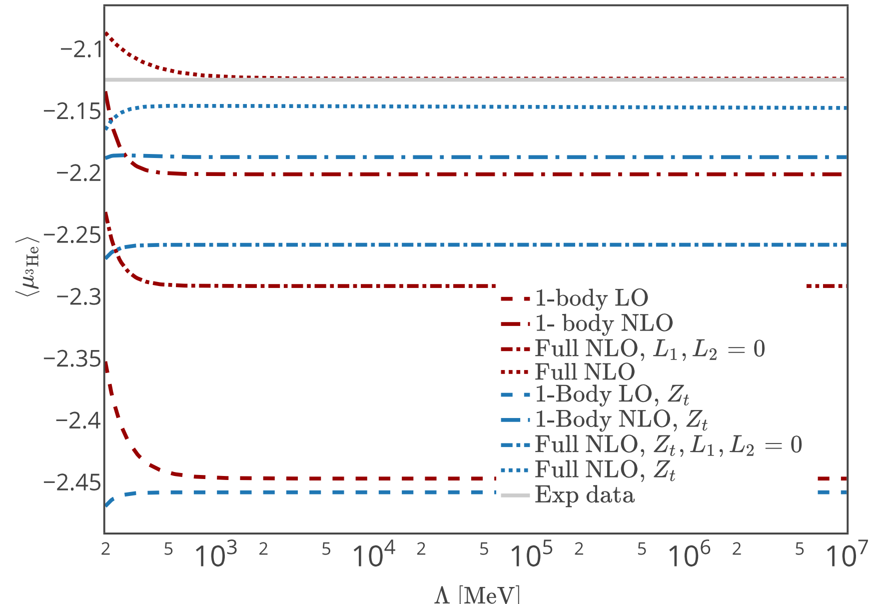
, 2016

A=3 magnetic moments calculations:

^{3}H



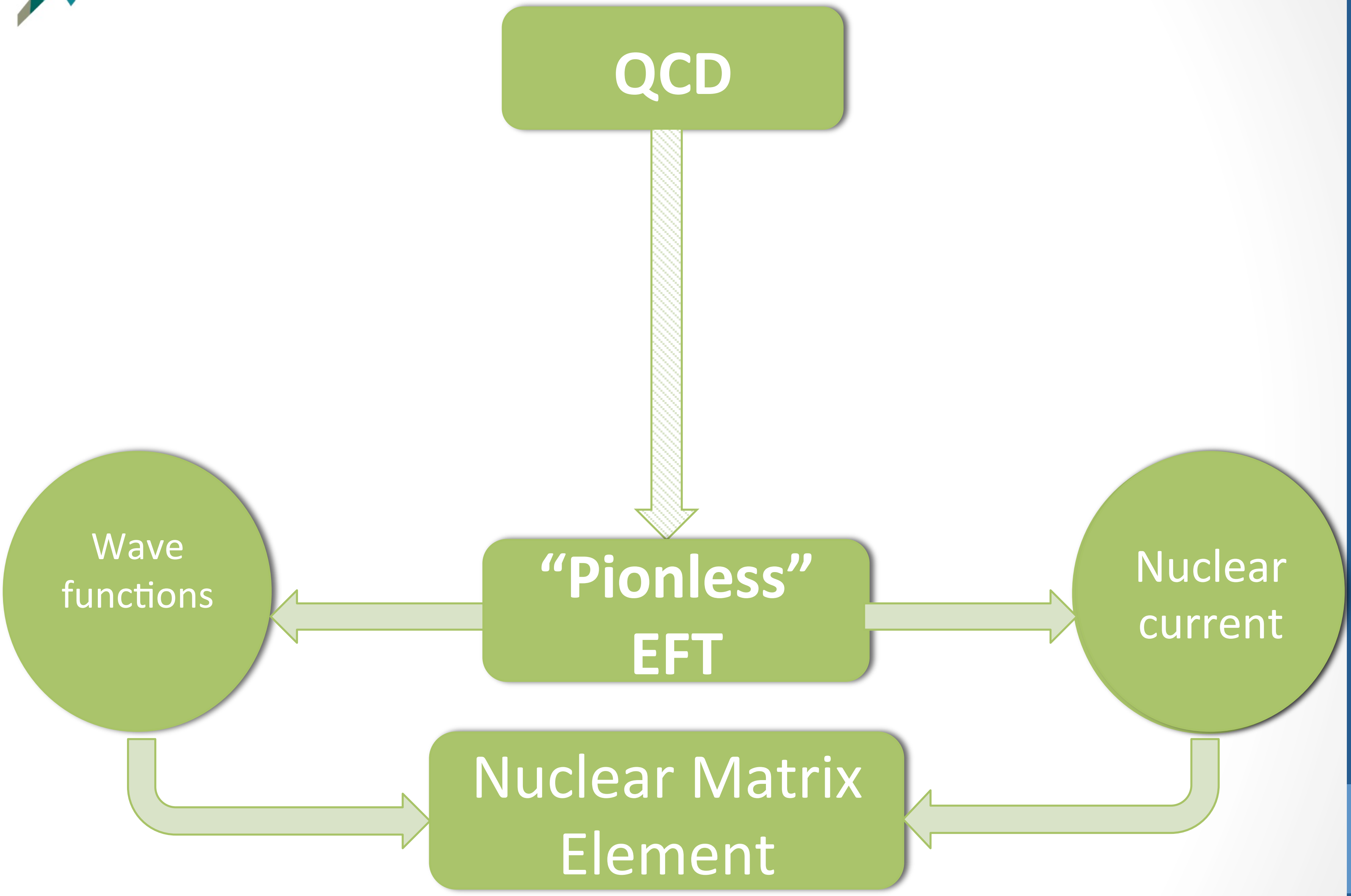
^{3}He



- All NLO contributions of the same order of magnitude 5-10% – Natural NLO contributions – useful for theoretical error estimates!
- No effect due to Zed-Rho parameterizations.
- Cutoff independence.
- When L_1 and L_2 are fixed **from A=3 magnetic moments**:

LO:	$\mu_d^{LO} = 0.8798$	$\sigma_{np}^{LO} = 298.2\,\mathrm{mb}$
NLO:	$\mu_d^{NLO} = 0.8617 \pm_{Z_d} 0.0002$	$\sigma_{np}^{NLO} = 335(Z_d) - 320(\rho)$
exp:	$\mu_d^{\exp} = 0.8574\ldots$	$\sigma_{np}^{\exp} = 334.2 \pm 0.5\mathrm{mb}\ldots$

The interaction of a nucleus with an external (weak) probe



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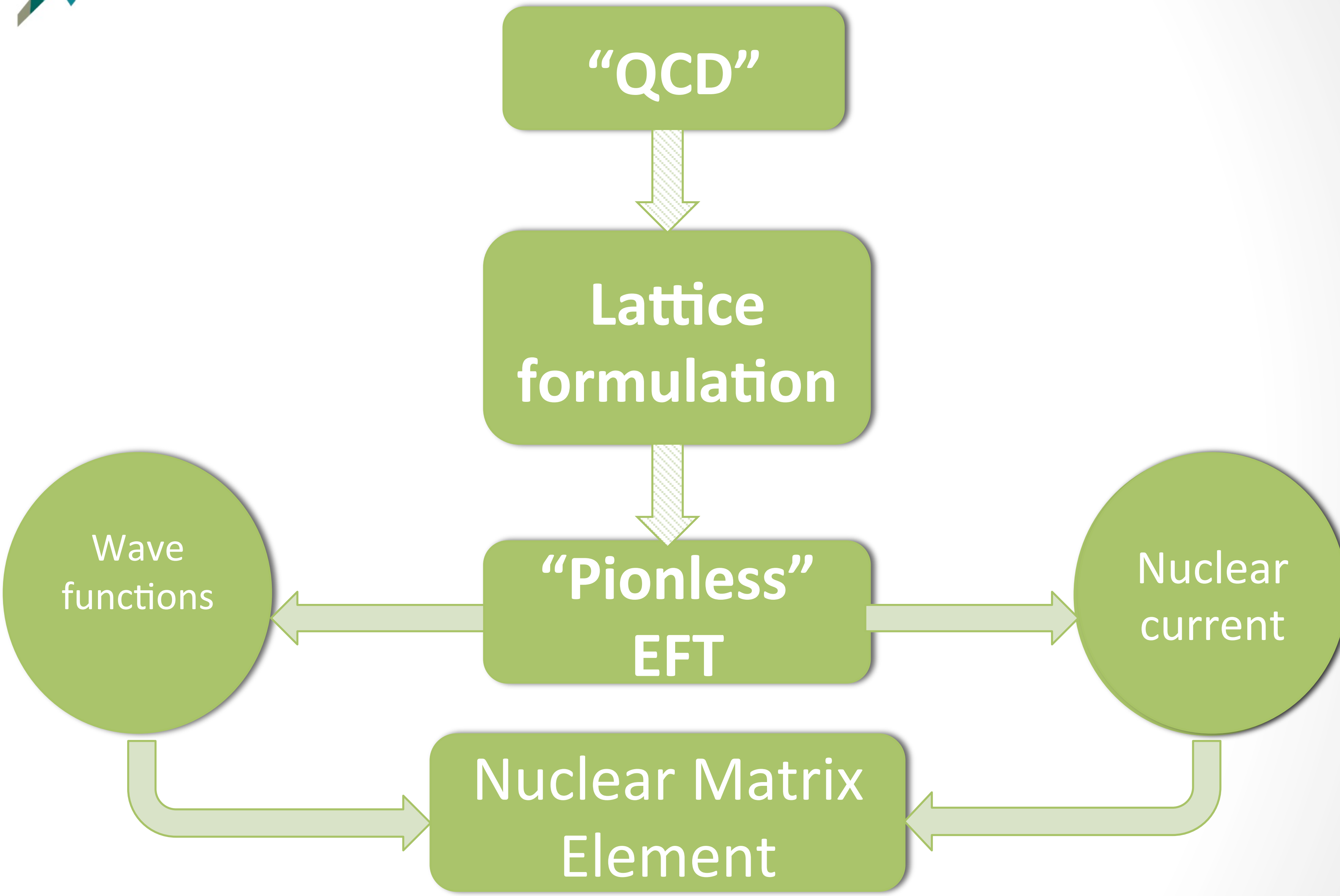


Lattice QCD calculation of l_1

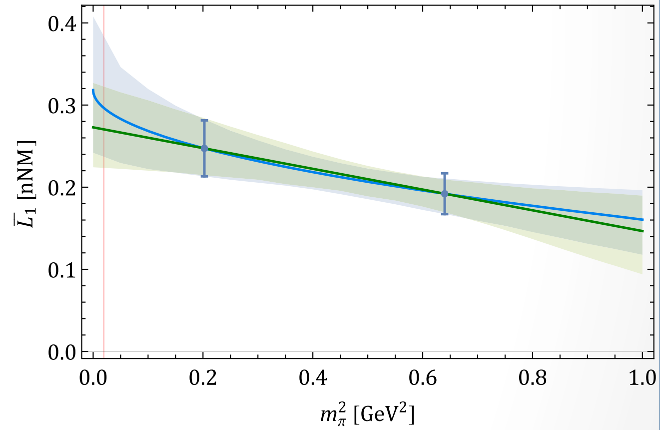
PRL **115,** 132001 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

Ab initio Calculation of the $np \to d\gamma$ Radiative Capture Process

Silas R. Beane,[1] Emmanuel Chang,[2] William Detmold,[3] Kostas Orginos,[4,5] Assumpta Parreño,[6]
Martin J. Savage,[2] and Brian C. Tiburzi[7,8,9]

(NPLQCD Collaboration)

$$\Delta E_{^3S_1,^1S_0}(\mathbf{B}) = 2(\kappa_1 + \gamma_0 Z_d^2 \tilde{l}_1)\frac{e}{M}|\mathbf{B}| + \mathcal{O}(|\mathbf{B}|^2),$$



$$\tilde{X}_{M1} = \frac{Z_d}{-\frac{1}{a_1} + \frac{1}{2}r_1|\mathbf{p}|^2 - i|\mathbf{p}|} \times \left[\frac{\kappa_1\gamma_0^2}{\gamma_0^2 + |\mathbf{p}|^2}\left(\gamma_0 - \frac{1}{a_1} + \frac{1}{2}r_1|\mathbf{p}|^2\right) + \frac{\gamma_0^2}{2} l_1\right]$$

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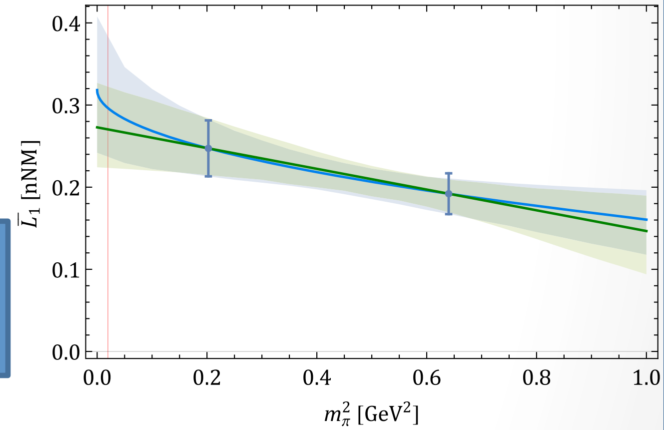
$$l_1^{\rm lqcd} = -4.41\left(\begin{smallmatrix}+15\\-16\end{smallmatrix}\right)\ \text{fm}.$$

$$\sigma^{\rm lqcd} = 332.4\left(\begin{smallmatrix}+5.4\\-4.7\end{smallmatrix}\right)\ \text{mb}$$



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Lattice QCD calculation of l_1

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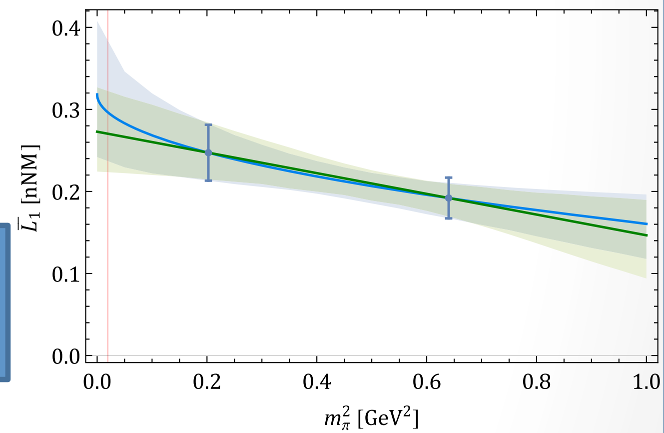

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Lattice QCD calculation of l_1

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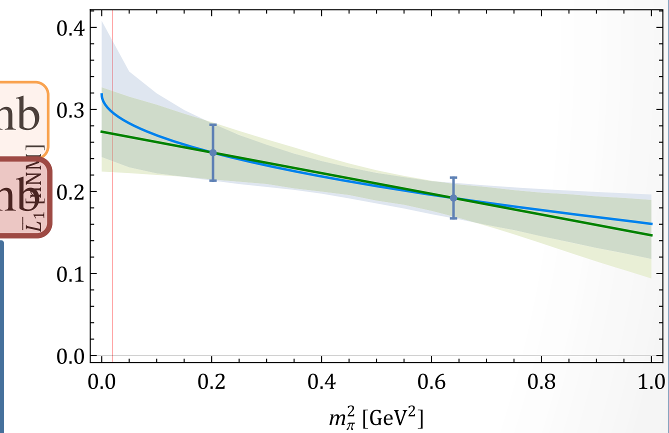
Rho paramet.	$l_1 = -3.934\,fm \;\; --> \;\; \sigma_{np} = 322.9\,\mathrm{mb}$	
Z-paramet.	$l_1 = -5.48\,fm \;\; --> \;\; \sigma_{np} = 342.6\,\mathrm{mb}$	



This could be regarded as a measure of the NPLQCD uncertainty in predicting n+p fusion, due to the EFT Expansion.

$$\tilde{X}_{M1} = \frac{Z_d}{-\frac{1}{a_1} + \frac{1}{2}r_1|\mathbf{p}|^2 - i|\mathbf{p}|} \times \left[\frac{\kappa_1\gamma_0^2}{\gamma_0^2 + |\mathbf{p}|^2}\left(\gamma_0 - \frac{1}{a_1} + \frac{1}{2}r_1|\mathbf{p}|^2\right) + \frac{\gamma_0^2}{2} l_1\right]$$

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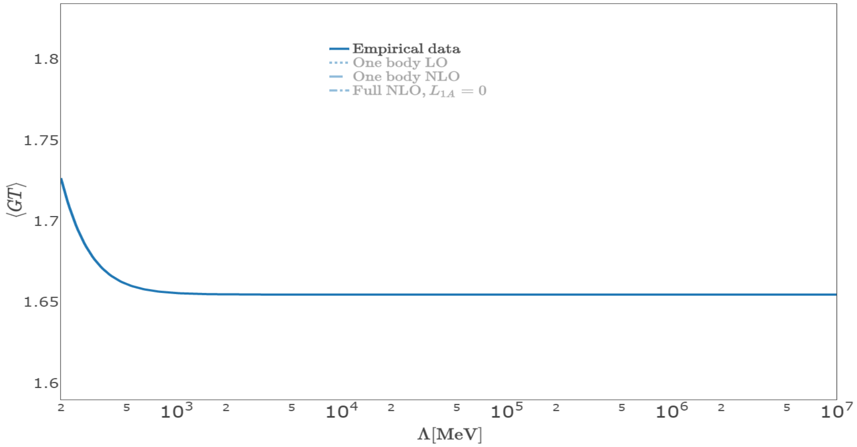
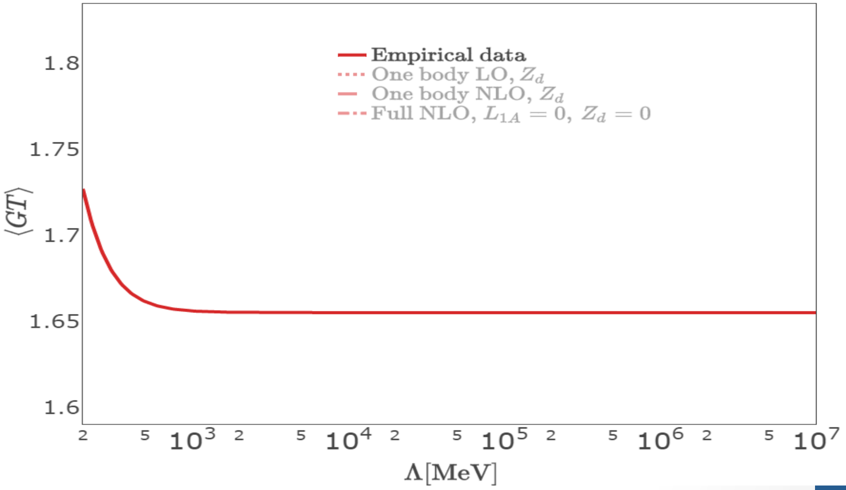
Triton decay – GT cutoff independence

Rho-parameterization | **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \left\| \mathcal{V}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \left\| \mathcal{A}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$



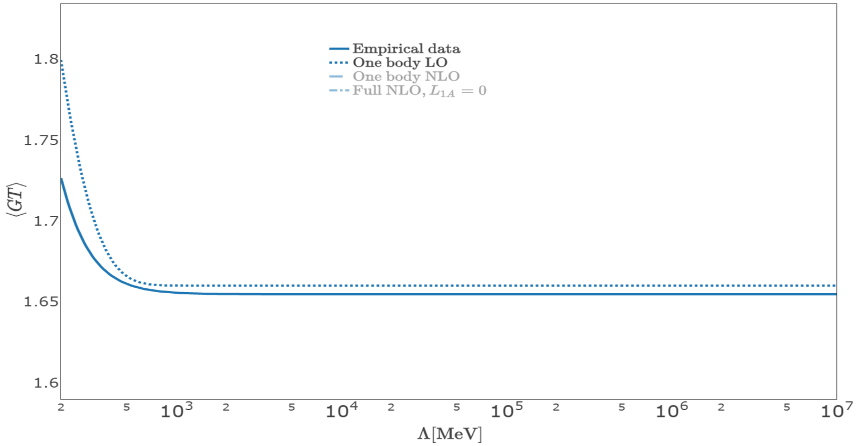


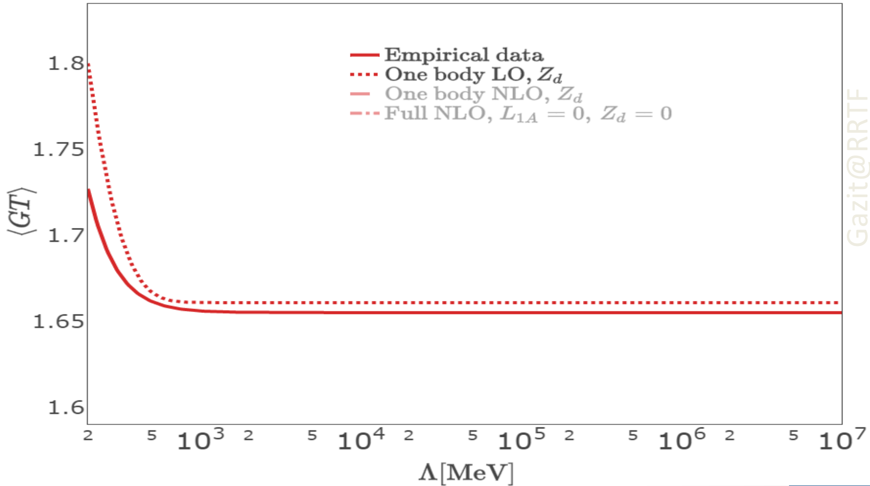
"Empirical" extraction of GT (using calculated F strength)

Triton decay – GT cutoff independence

Rho-parameterization **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \middle\| \mathcal{V}_\mu^+ \middle\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \middle\| \mathcal{A}_\mu^+ \middle\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$



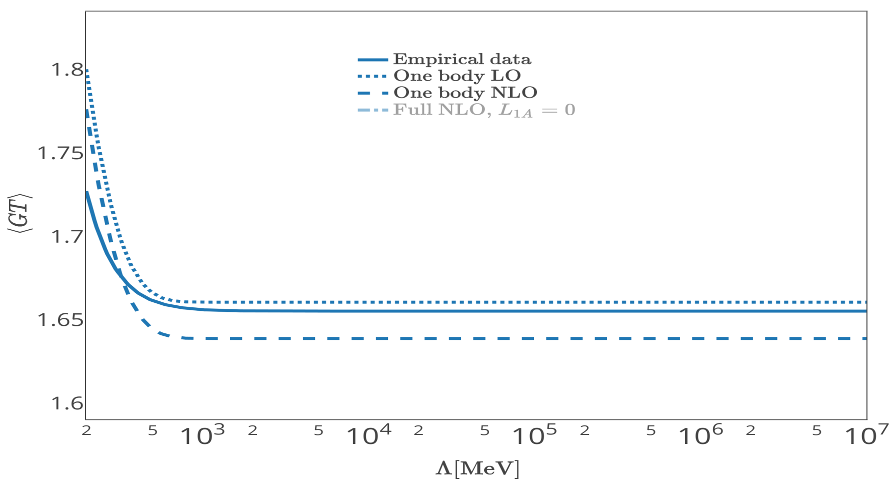


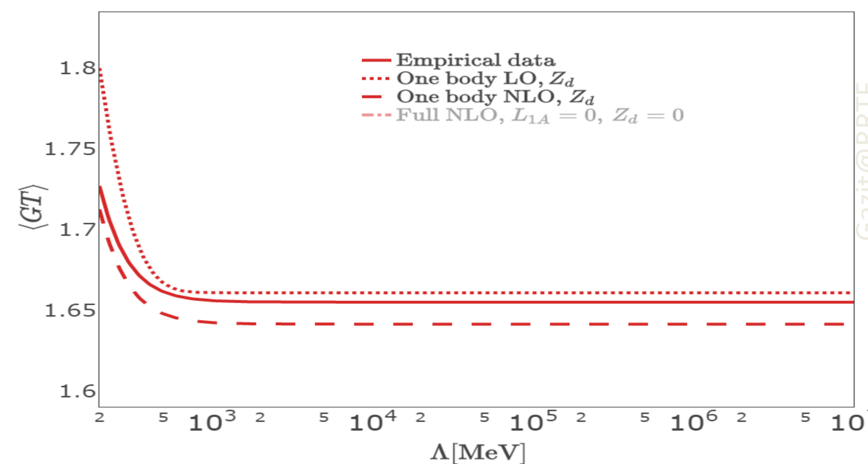
Adding the LO 1-body contribution

Triton decay – GT cutoff independence

Rho-parameterization **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \left\| \mathcal{V}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \left\| \mathcal{A}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$



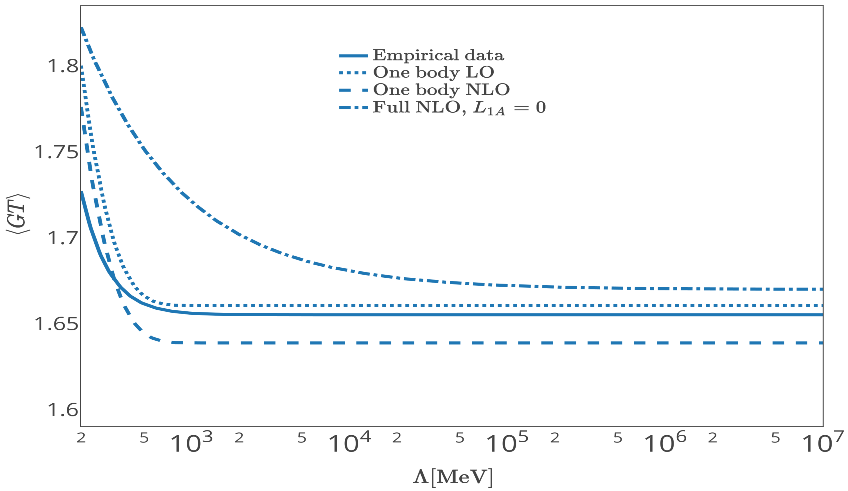


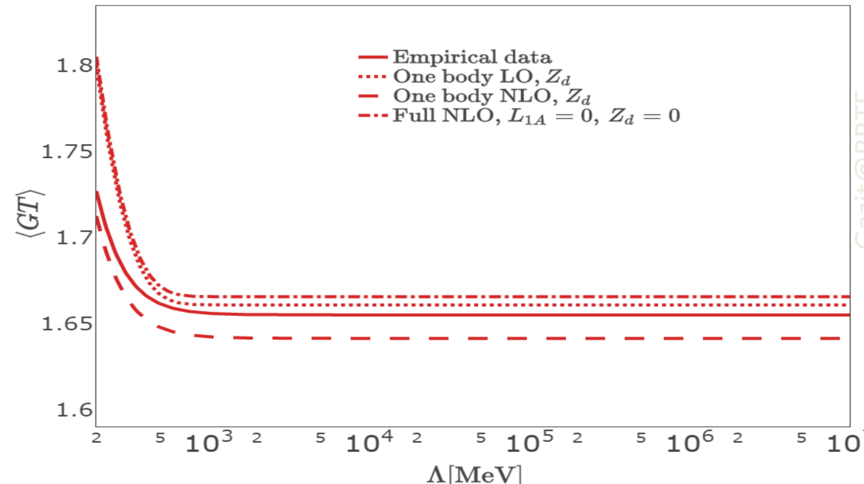
Adding the NLO 1-body contributions

Triton decay – GT cutoff independence

Rho-parameterization | **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \langle {}^3\mathrm{H} \| \mathcal{V}_\mu^+ \| {}^3\mathrm{He} \rangle \right|^2 + \frac{f_A}{f_V} \left| \langle {}^3\mathrm{H} \| \mathcal{A}_\mu^+ \| {}^3\mathrm{He} \rangle \right|^2 \right]}$$





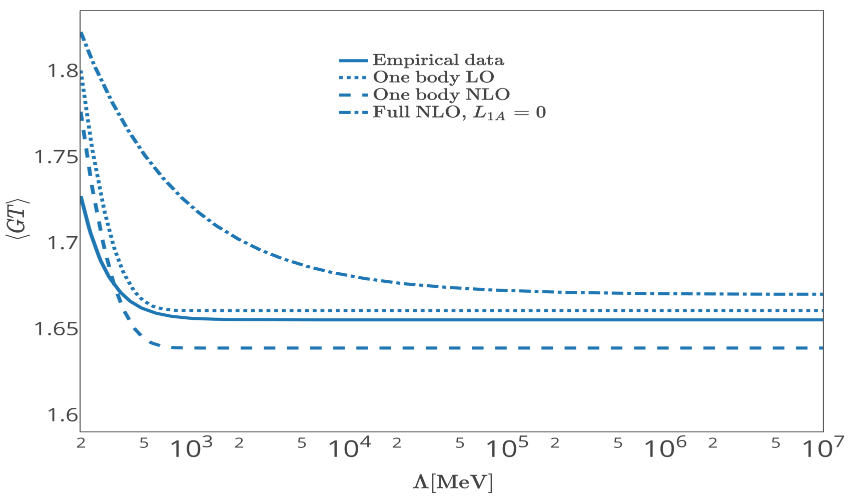
Adding all contribution, but L_{1A}

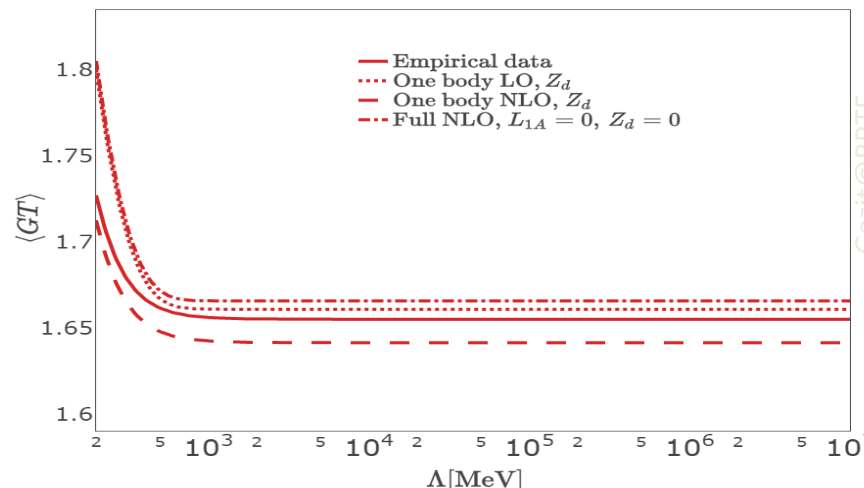
1st estimate of theoretical uncertainty:
All NLO contributions are of the same order (1-2%),
one can estimate higher order effects as the NLO contribution.

Triton decay – GT cutoff independence

Rho-parameterization | **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \left\| \mathcal{V}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \left\| \mathcal{A}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$





Adding all contributi

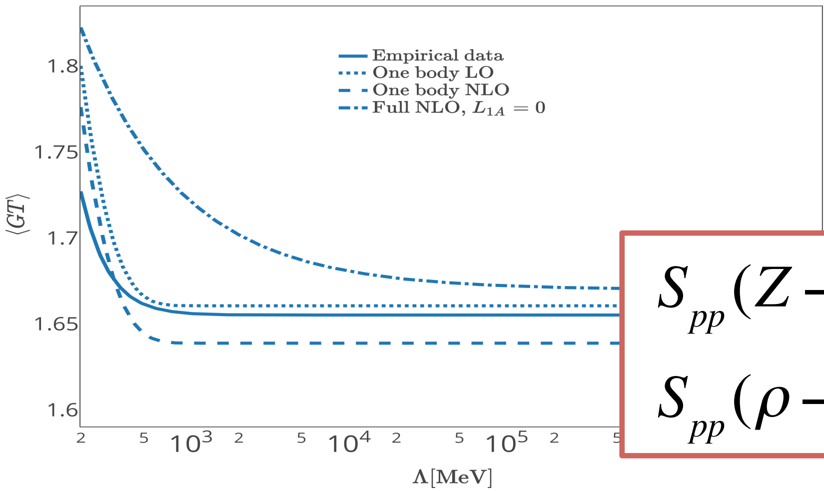
Translates to ±2% difference in pp fusion

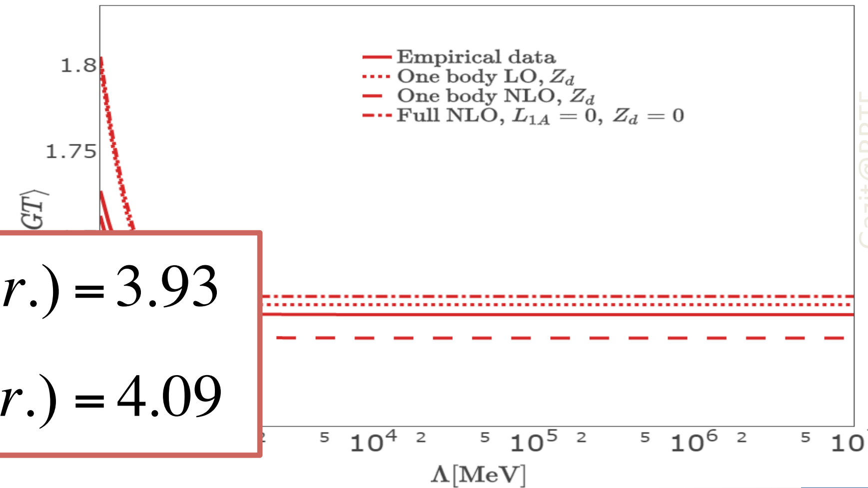
1st estimate of theoretical uncertainty:
All NLO contributions are of the same order (1-2%),
one can estimate higher order effects as the NLO contribution.

Triton decay – GT cutoff independence

Rho-parameterization | **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \left\| \mathcal{V}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \left\| \mathcal{A}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$





$$S_{pp}(Z-par.) = 3.93$$

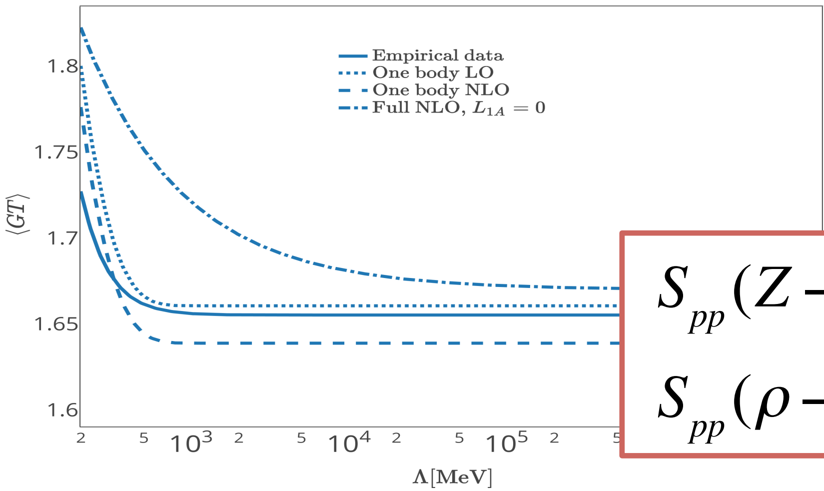
$$S_{pp}(\rho-par.) = 4.09$$

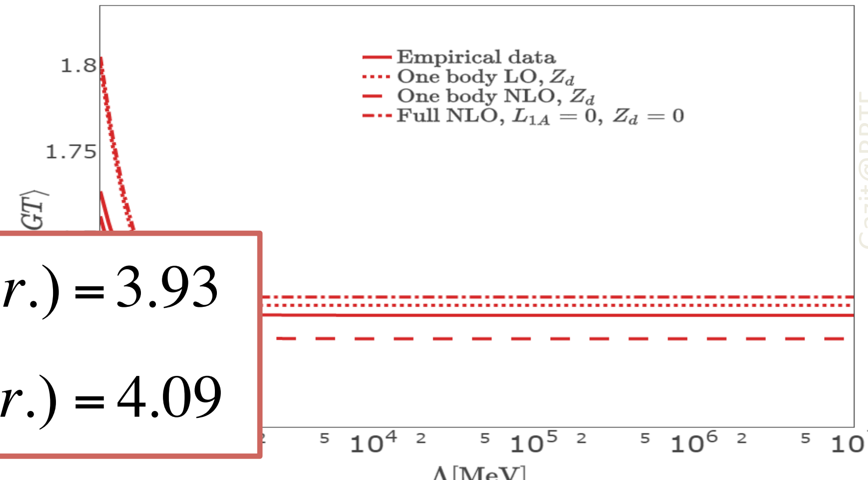
2nd estimate of theoretical uncertainty:
difference between Zed and Rho Paramerizations.

Triton decay – GT cutoff independence

Rho-parameterization **Z-parameterization**

$$ft = \frac{K}{G_F^2 V_{ud}^2 \left[\left| \left\langle {}^3\mathrm{H} \left\| \mathcal{V}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 + \frac{f_A}{f_V} \left| \left\langle {}^3\mathrm{H} \left\| \mathcal{A}_\mu^+ \right\| {}^3\mathrm{He} \right\rangle \right|^2 \right]}$$





$$S_{pp}(Z-par.) = 3.93$$

$$S_{pp}(\rho-par.) = 4.09$$

Translates to ±2% difference in pp fusion

2nd estimate of theoretical uncertainty:
difference between Zed and Rho Paramerizations.

So… is 3% too big to be called precision physics?

$$S_{pp}(g_A = 1.2701) = 4.01 \pm 0.08 \pm 0.07 \pm 0.04$$

$$S_{pp}(g_A = 1.275) = 4.12 \pm 0.08 \pm 0.07 \pm 0.04$$

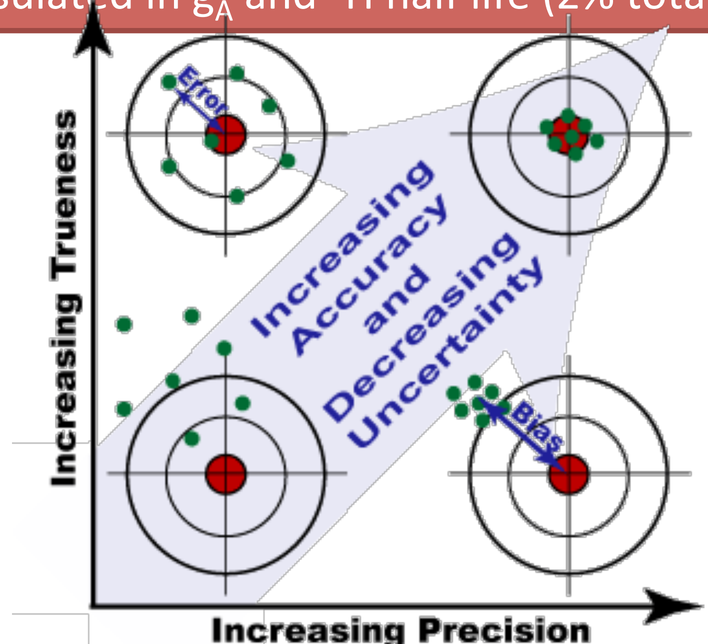
g_A systematic uncertainty

theoretical uncertainty

g_A stat. unc.

^3H halflife syst. unc.

i.e., theoretical uncertainty of the same order of systematic experimental error encapsulated in g_A and ^3H half life (2% total).



Summary

- Pionless EFT reproduces low-energy electroweak observables to a very good precision (~1%), even at NLO, and allows reliable uncertainty estimates.
- Theoretical uncertainty estimated from:
  - (Natural) Size of NLO contribution (all NLO contributions are of the same order of magnitude).
  - Difference between Zed and Rho parameterizations.
  - Both error estimates lead to about 2% uncertainty.
- EM sector confirms calculation procedure.
- Lattice QCD for nuclei is a new front for $\not\pi$EFT
- Based on the EM sector, a theoretical prediction for pp fusion:

$$S_{pp}(g_A = 1.2701) = 4.01 \pm_{theory} 0.08 \pm_{g_A(1\sigma)} 0.07 \pm_{^3\text{H half life}} 0.04$$

$$S_{pp}(g_A = 1.275) = 4.12 \pm_{theory} 0.08 \pm_{g_A(1\sigma)} 0.07 \pm_{^3\text{H half life}} 0.04$$

- Better determination of g_A is necessary!
- (^{3}H half life is also an open exp. issue).