Theoretical uncertainty for $0\nu\beta\beta$ decay from chiral EFT

Toño Coello Pérez
in collaboration with Jordan Melendez and Kyle Wendt
funded by LLNL LDRD 19-LW-039

May 28, 2020

LLNL-PRES-810767
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Outline

Introduction and motivation

Description of our model

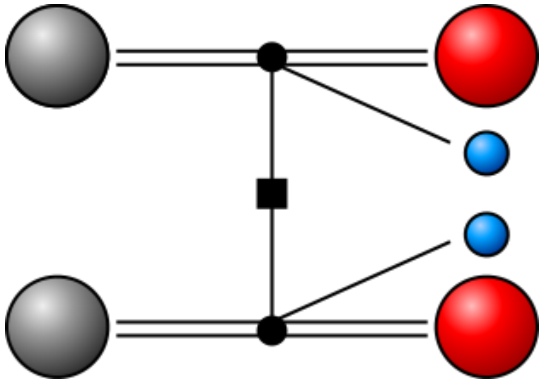
Propagation of the uncertainty in the chiral forces to the matrix element

Distributions for the components of the matrix element

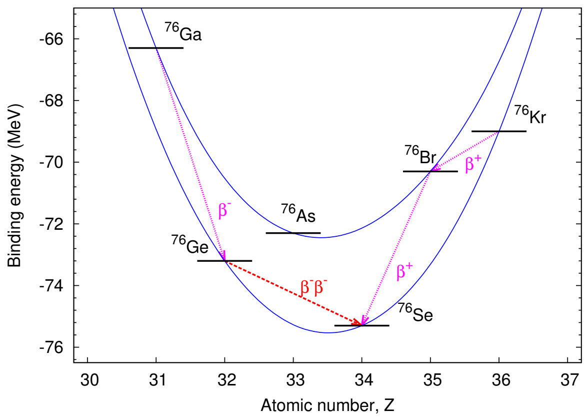
Summary and Outlook

Neutrinoless double-beta decay and its relevance

Decay in which two neutrons are transformed into protons emitting two electrons in the process



Unstable nuclei for which single beta decay is not allowed are candidates



Current experiments have not observed it

Experiment	**Isotope**	$L(T_{1/2})$ **(10^{25} years)**	$S(T_{1/2})$ **(10^{25} years)**
GERDA (this work)	^{76}Ge	9	11
MAJORANA (27)	^{76}Ge	2.7	4.8

M. Agostini et al., Science ***365****, 1445*

If observed:

- It will establish the Majorana nature of neutrinos
- The absolute neutrino mass can be extracted from the half-life
- It may explain the matter-antimatter asymmetry in the Universe

How do we plan future experiments and extract information from them?

Nuclear matrix element

Figure from J. Engel et al., Rep. Prog. Phys. ***80****, 046301*

The number of observed events is related to the exposure and the half-life

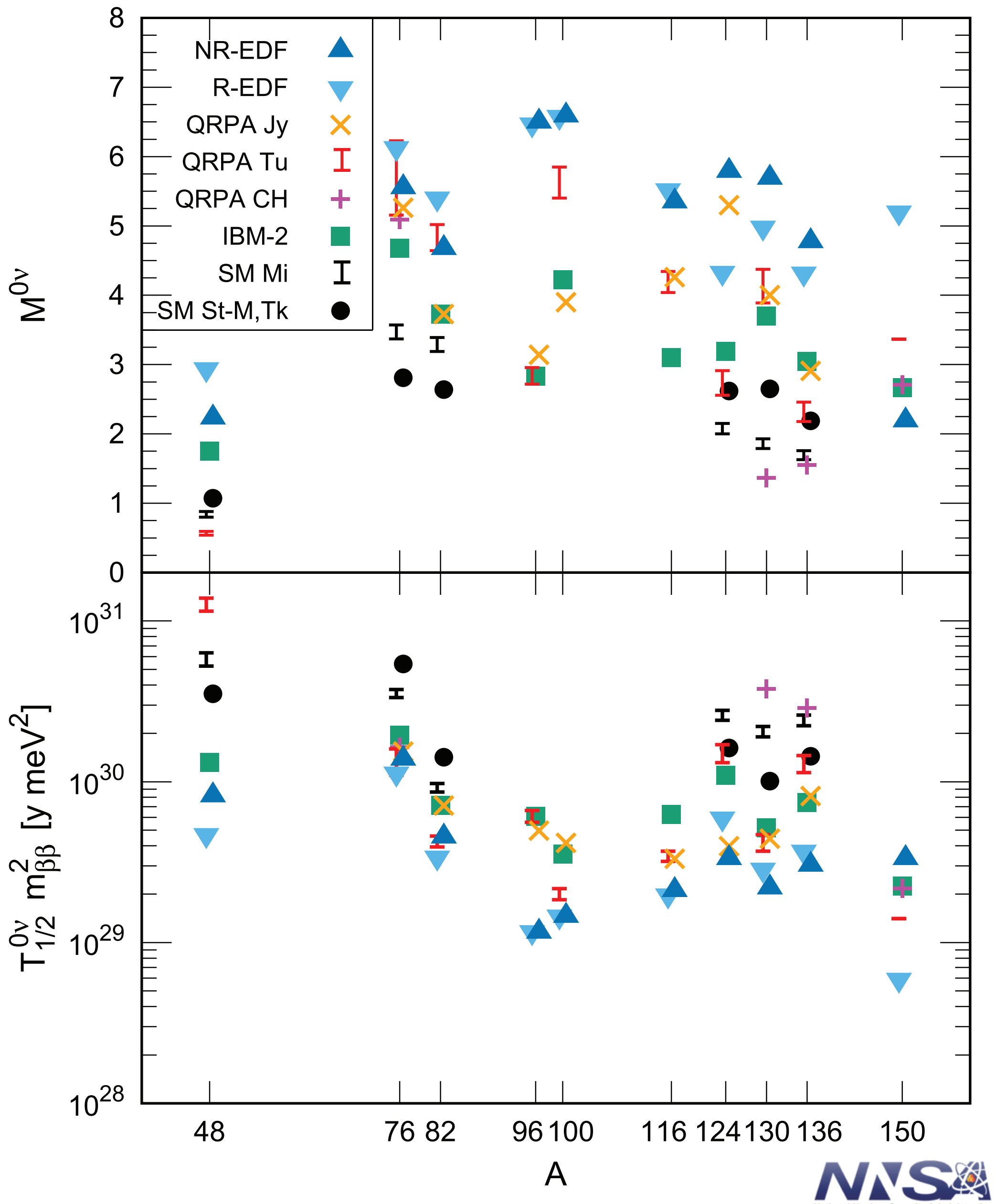
$$N^{0\nu\beta\beta} \propto \frac{Mt}{T_{1/2}^{0\nu\beta\beta}} \qquad \frac{1}{T_{1/2}^{0\nu\beta\beta}} = g_A^4 G_{01} \left|\frac{m_{\beta\beta}}{m_e}\right|^2 |\mathcal{M}_\nu|^2$$

Calculations of the matrix element by diverse nuclear models disagree by factors from two to three:

- Order of magnitude difference in amount of material or time to observe the decay
- Unprecise extraction of the neutrino mass

Calculation of the matrix element with ab-initio methods is computationally expensive

GOAL: Study by means of a simple model how the uncertainty from chiral EFT propagates to the nuclear matrix element. Are calculations of the matrix element with ab-initio methods worth our time?

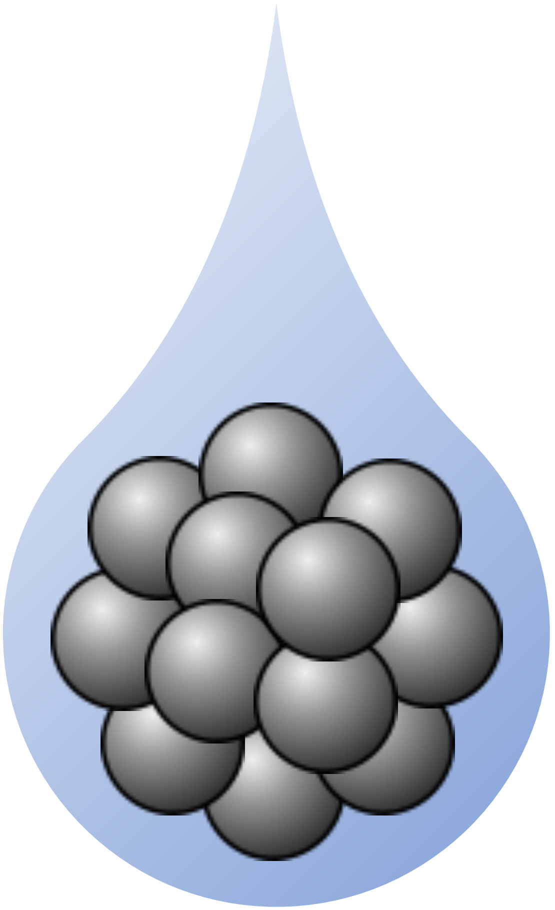


Nucleon droplet

We employed nucleon droplets to mimic the kinematics of the valence nucleons

$$H = T_{\text{val}} + U + V_{\chi\text{EFT}}$$

- The properties of the nucleon droplet can be calculated fast and precisely
- We expect the distribution around a mean to behave similar to that of more involved calculations
- Nuclear observables tend to have a strong systematic behavior



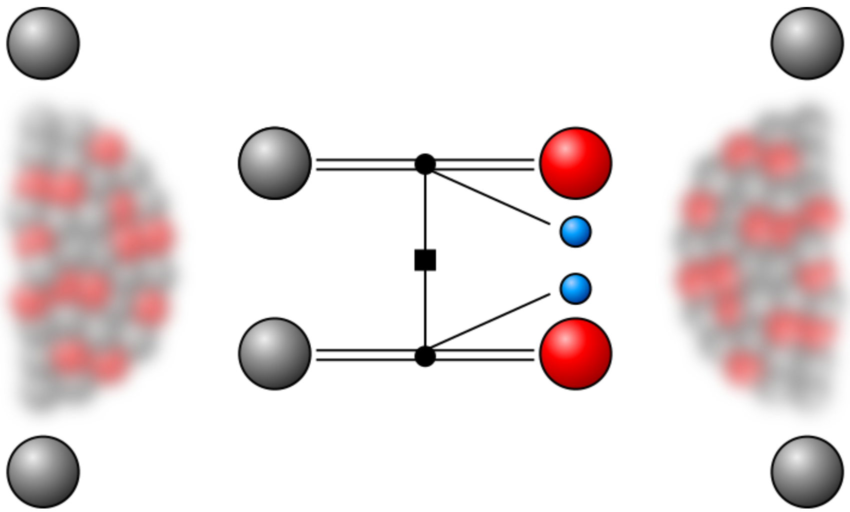
Study case: ^{76}Ge

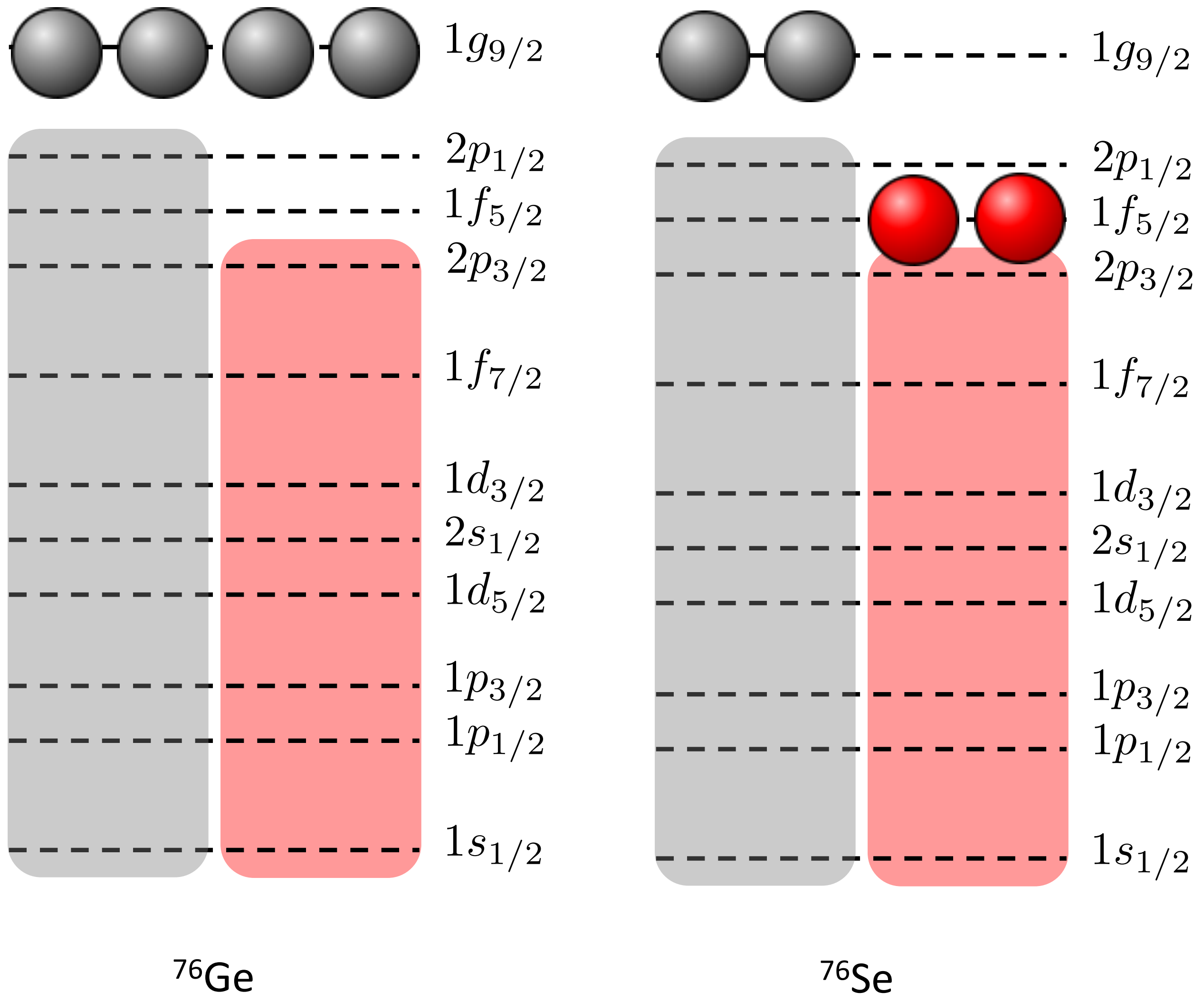
Antisymmetrized HO basis written in Jacobi coordinates

- $N_{max} = 24$

Number of quanta constrained from below due Pauli blocking

- For ^{76}Ge: $N_{min} = 16$
- For ^{76}Se: $N_{min} = 14$





Chiral EFT interactions

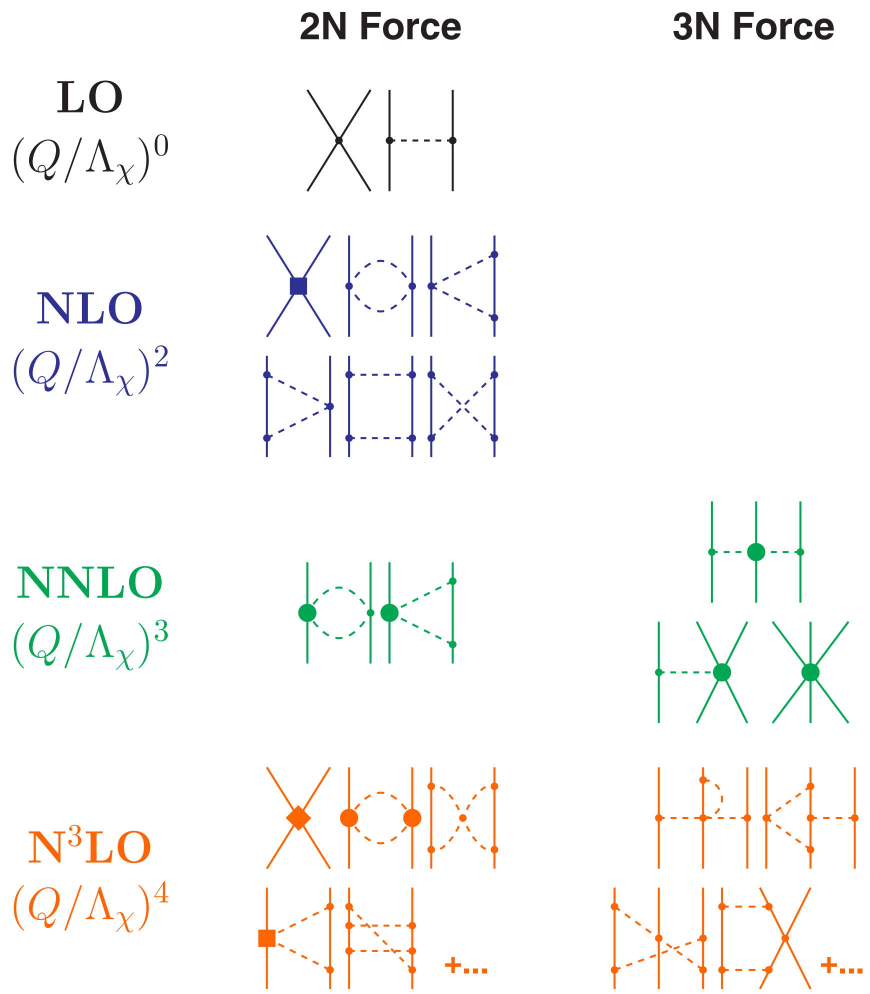


*Figure from D. R. Entem et al., Phys. Rev. C **96**, 024004*

The nucleons interact via forces from chiral EFT

- Constructed order-by-order
- Quantities of interest are expected to behave as series

$$O(q) = O_{\text{ref}}(q) \sum_{\nu} c_\nu(q) x^\nu$$

- At order ν

$$O(q) = O^{(\nu)}(q) + O_{\text{ref}}(q) \sum_{i=\nu+1}^{\infty} c_i(q) x^i$$

- The expression for the residual can be employed to derive a theoretical covariance

*J. A. Melendez et al., Phys. Rev. C **96**, 024003*

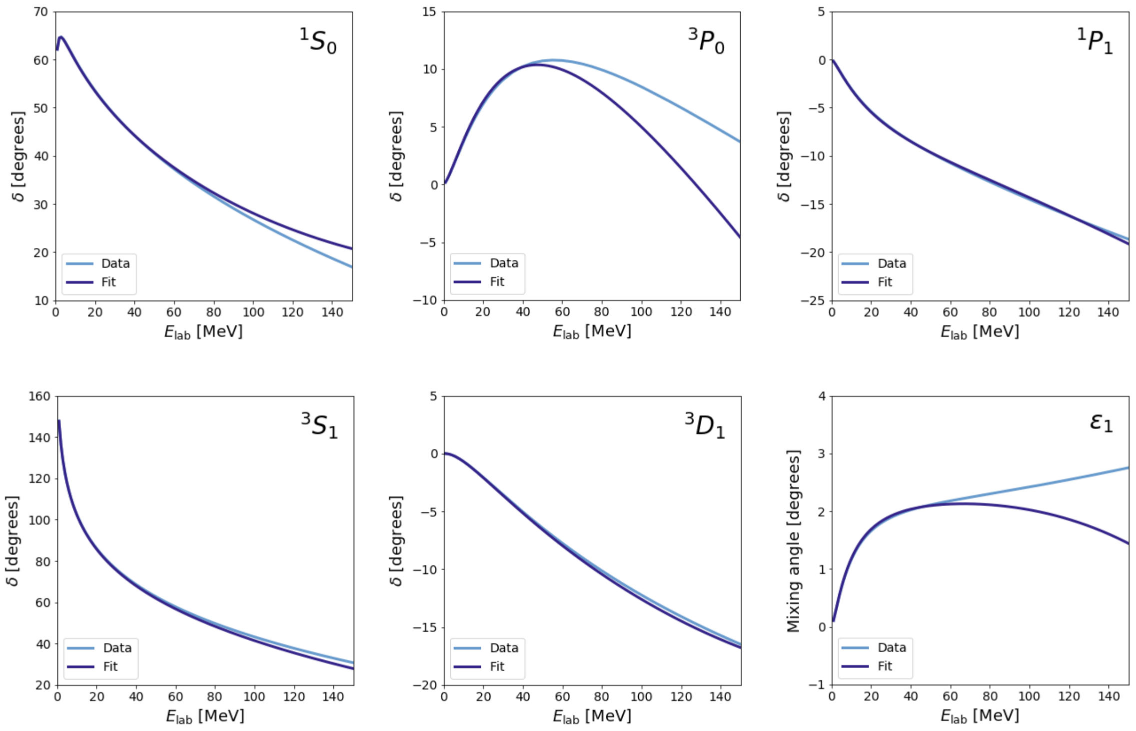
We considered chiral forces up to N3LO

We considered diverse regulator cutoffs

Parameters of the chiral EFT interaction

2N forces fitted to nucleon-nucleon scattering data

$$\exp\left(-\frac{1}{2}\mathbf{r}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{r}-\frac{1}{2\sigma_C^2}\mathbf{C}^{\mathrm{T}}\mathbf{C}\right) \qquad \Sigma=\Sigma_{\mathrm{exp}}+\Sigma_{\mathrm{th}}$$



The objective function considered:

- Experimental uncertainties
- Truncation of the chiral expansion
- Size of the parameters

S. Wesolowski et al., J. Phys. G: Nucl. Part. Phys. ***46****, 045102*

3N forces fitted the energies and radii of ^{3}H and ^{4}He

	^{3}H	^{4}He
E [MeV]	8.482	28.296
r_{ch} [fm]	1.759 (36)	1.675 (3)

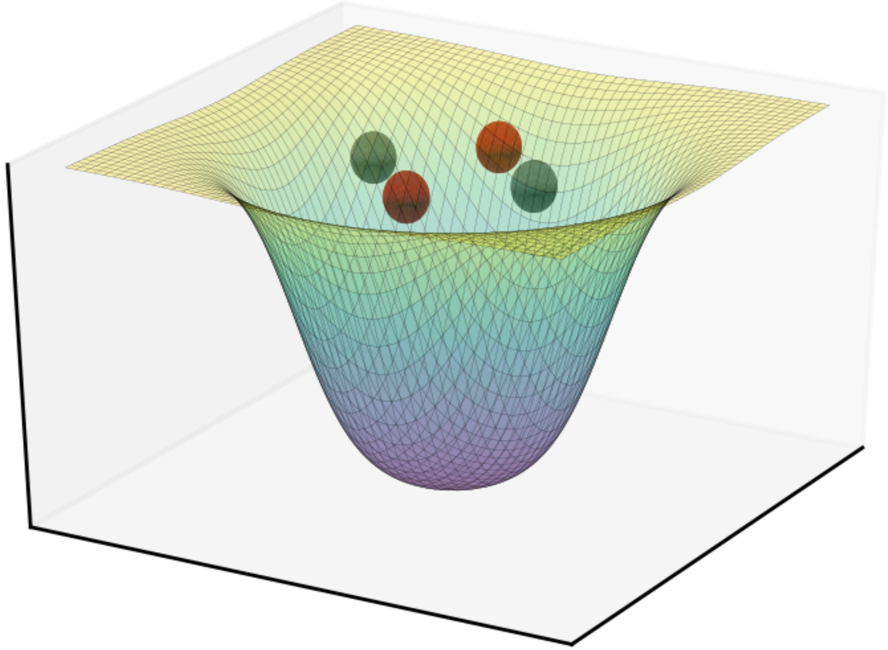
One-body potential

The one-body potential contains central and spin-orbit parts

$$U = v_{\mathrm{C}} + v_{\mathrm{LS}} \boldsymbol{L} \cdot \boldsymbol{S}$$

For this study we employ a Woods-Saxon potential

$$v_{\mathrm{C}} = -\frac{V_0}{1 + e^{-(r-R)/a}} \qquad v_{\mathrm{LS}} = v_{\mathrm{LS}}^{(0)} \left(\frac{R}{\hbar}\right)^2 \frac{1}{r} \left[\frac{d}{dr} \frac{1}{1 + e^{-(r-R)/a}}\right]$$



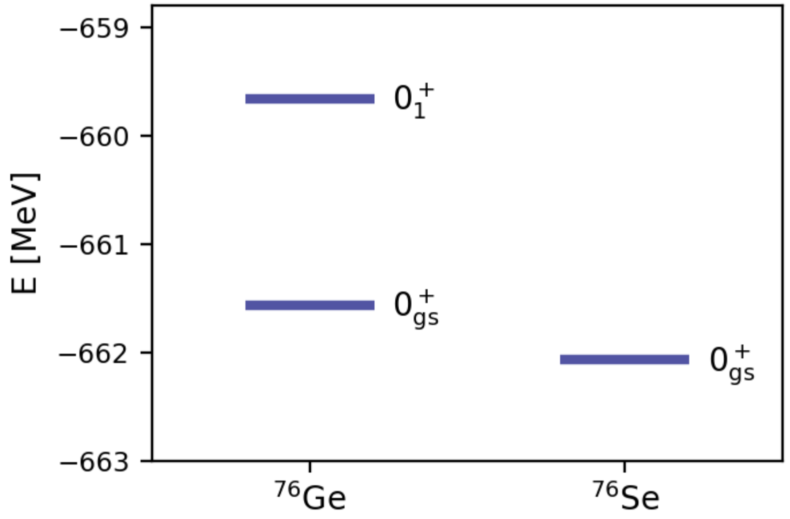
The parameters of the form factor *R* and *a* remain fixed

We chose the parametrization

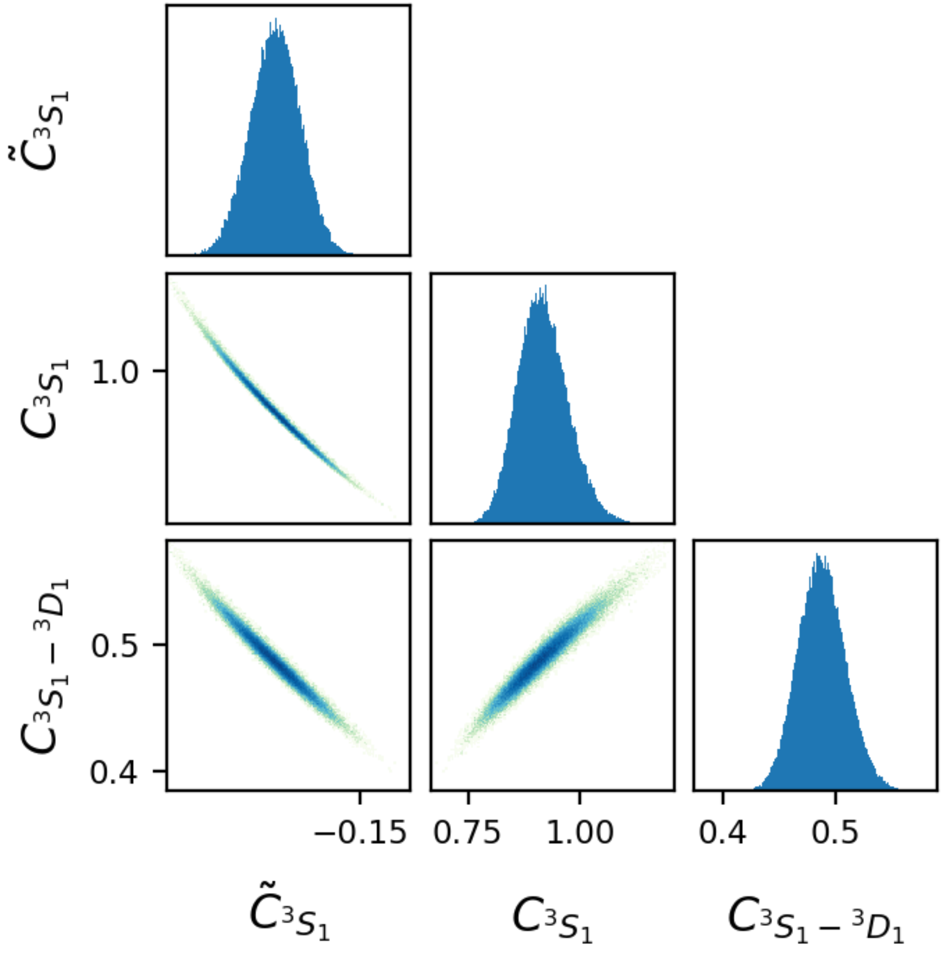
$$v_{\mathrm{LS}}^{(0)} = \lambda V_0$$

V_0 an isospin-dependent parameter

These parameters are fit to the binding energies of the nuclei of interest



Sampling the parameters in the chiral EFT interaction



We sampled many LEC sets from the posterior distribution

$$\exp\left(-\frac{1}{2}\mathbf{r}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{r}-\frac{1}{2\sigma_C^2}\mathbf{C}^{\mathrm{T}}\mathbf{C}\right) \qquad \Sigma=\Sigma_{\mathrm{exp}}+\Sigma_{\mathrm{th}}$$

Experimental covariance

$$(\Sigma_{\mathrm{exp}})_{ij}=\sigma_i^2\delta_{ij}$$

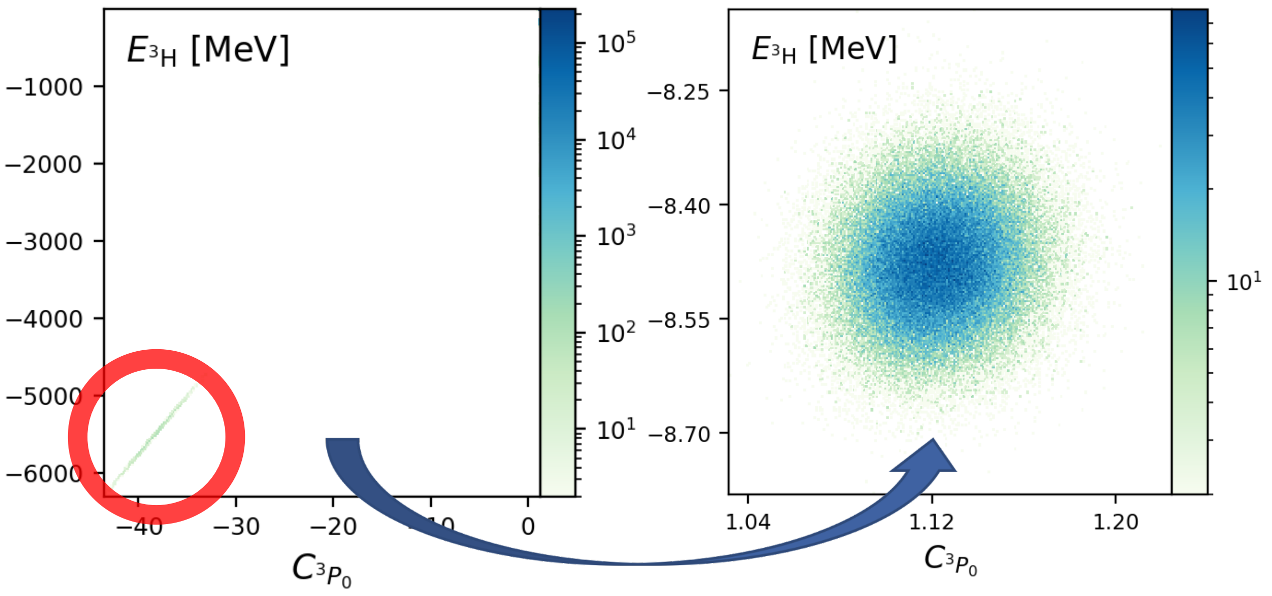
Theoretical covariance

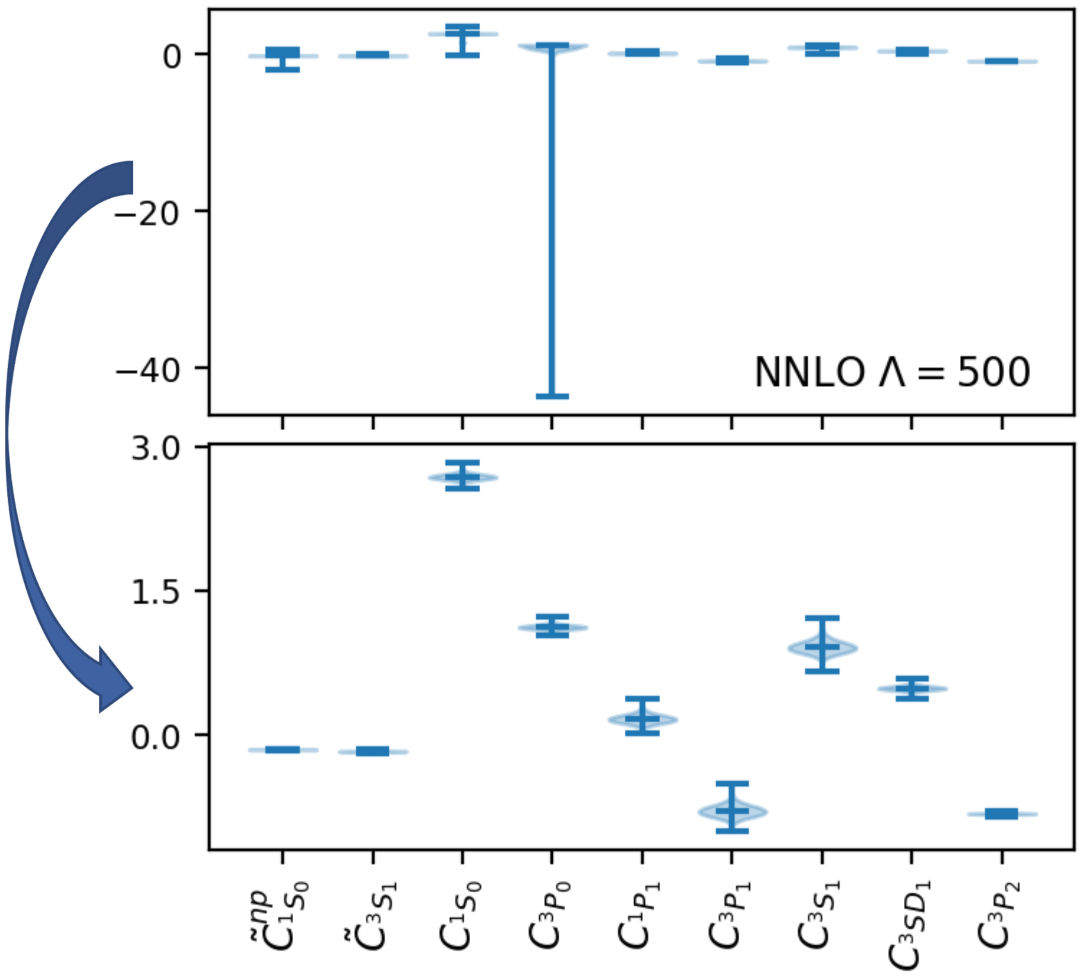
$$(\Sigma_{\mathrm{th}})_{ij}=(y_{\mathrm{ref}})_i(y_{\mathrm{ref}})_j\bar{c}^2\frac{Q_i^{k+1}Q_j^{k+1}}{1-Q_iQ_j}K(Q_i,Q_j)$$

*S. Wesolowski et al., J. Phys. G: Nucl. Part. Phys. **46**, 045102*

*J. A. Melendez et al., Phys. Rev. C **96**, 024003*

Discriminating parameter sets





We discriminate LEC sets:

- LECs of unnatural size
- LECs that yield unnatural energies

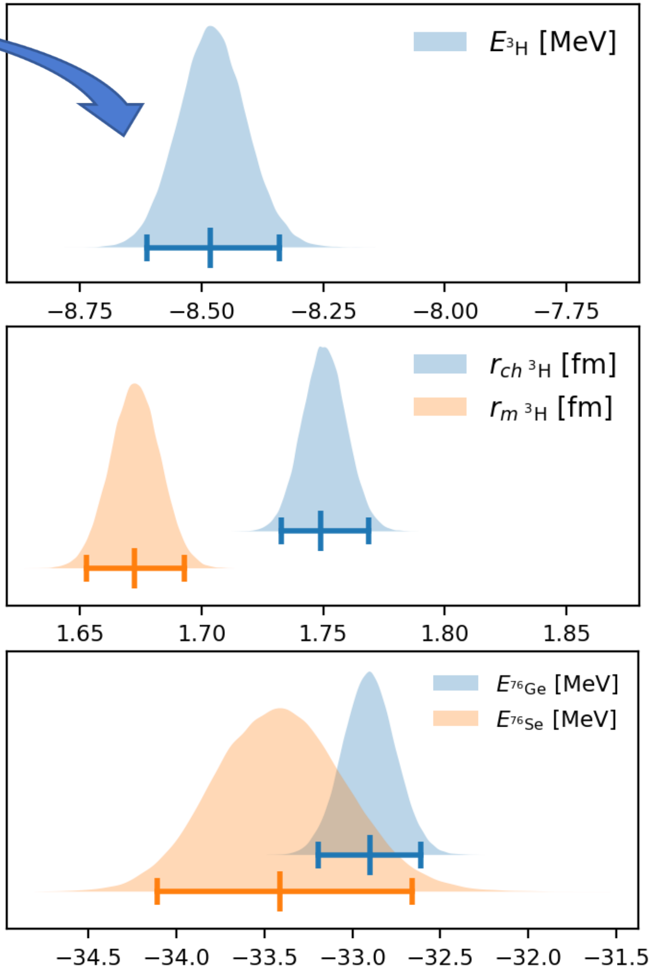
80 % of the sampled sets remain

Remaining LECs are of natural size and well constrained

Few-body results

For models including chiral forces up to N2LO

Observable		Experiment	Λ_χ=450	Λ_χ=500	Λ_χ=550
^{3}H	E [MeV]	8.482	8.486	8.486(+128, -152)	8.486
	r_{ch} [fm]	1.759(36)	1.747	1.747(+19, -18)	1.749
	r_m [fm]		1.669	1.669(+21, -20)	1.672
^{4}He	E [MeV]	28.296	28.290	28.290	28.290
	r_{ch} [fm]	1.675(3)	1.648	1.650	1.657
	r_m [fm]		1.424	1.427	1.434



Intervals with 95% DOB in the distributions for the energies:

- For ^{76}Ge ~ 1 MeV
- For ^{76}Se ~ 2 MeV

Neutrinoless double-beta decay in chiral EFT

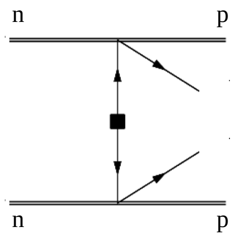
The $0\nu\beta\beta$ decay operator has been written in chiral EFT

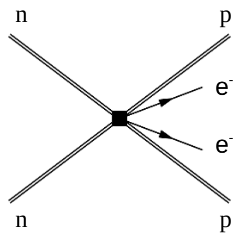
G. Prezeau et al., Phys. Rev. D ***68****, 034016*

V. Cirigliano et al., J. High Energy Phys. ***2018****, 19*

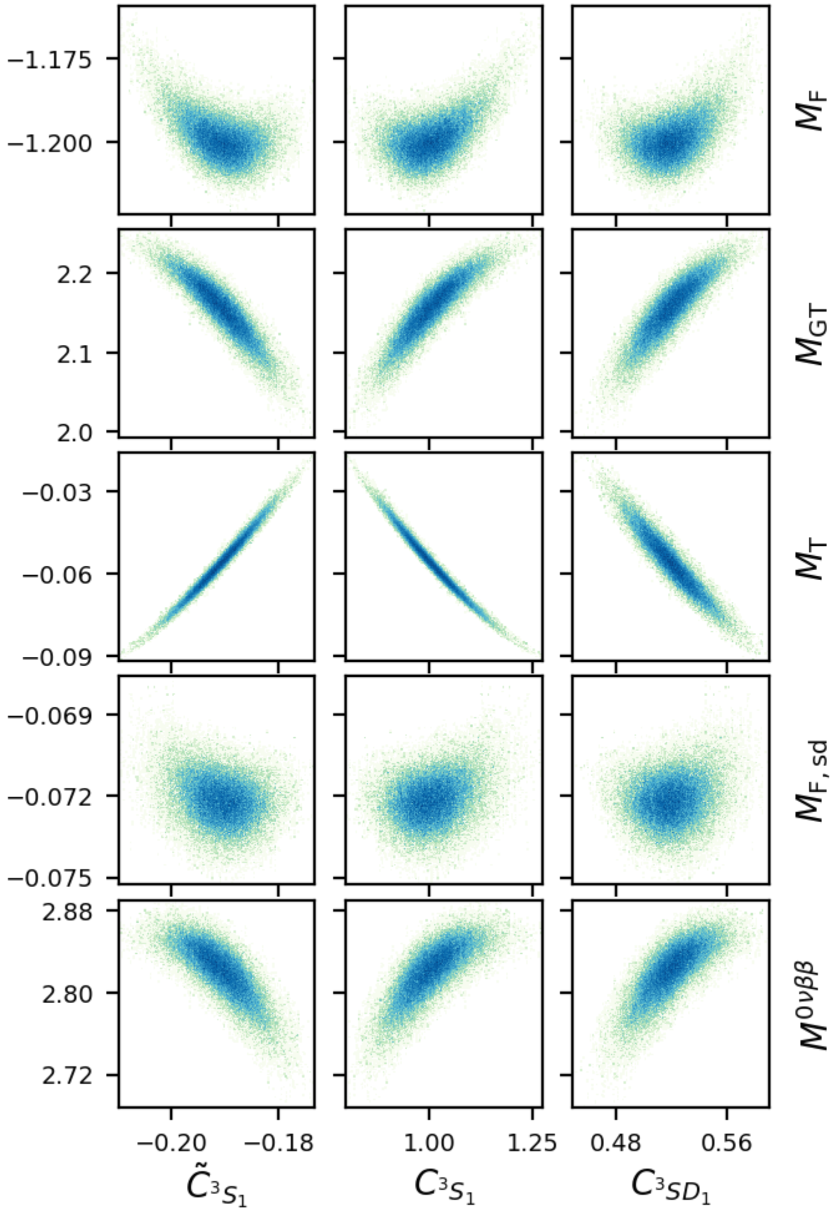
V. Cirigliano et al., Phys. Rev. Lett. ***120****, 202001*

At LO a contact term yields a short-distance contribution

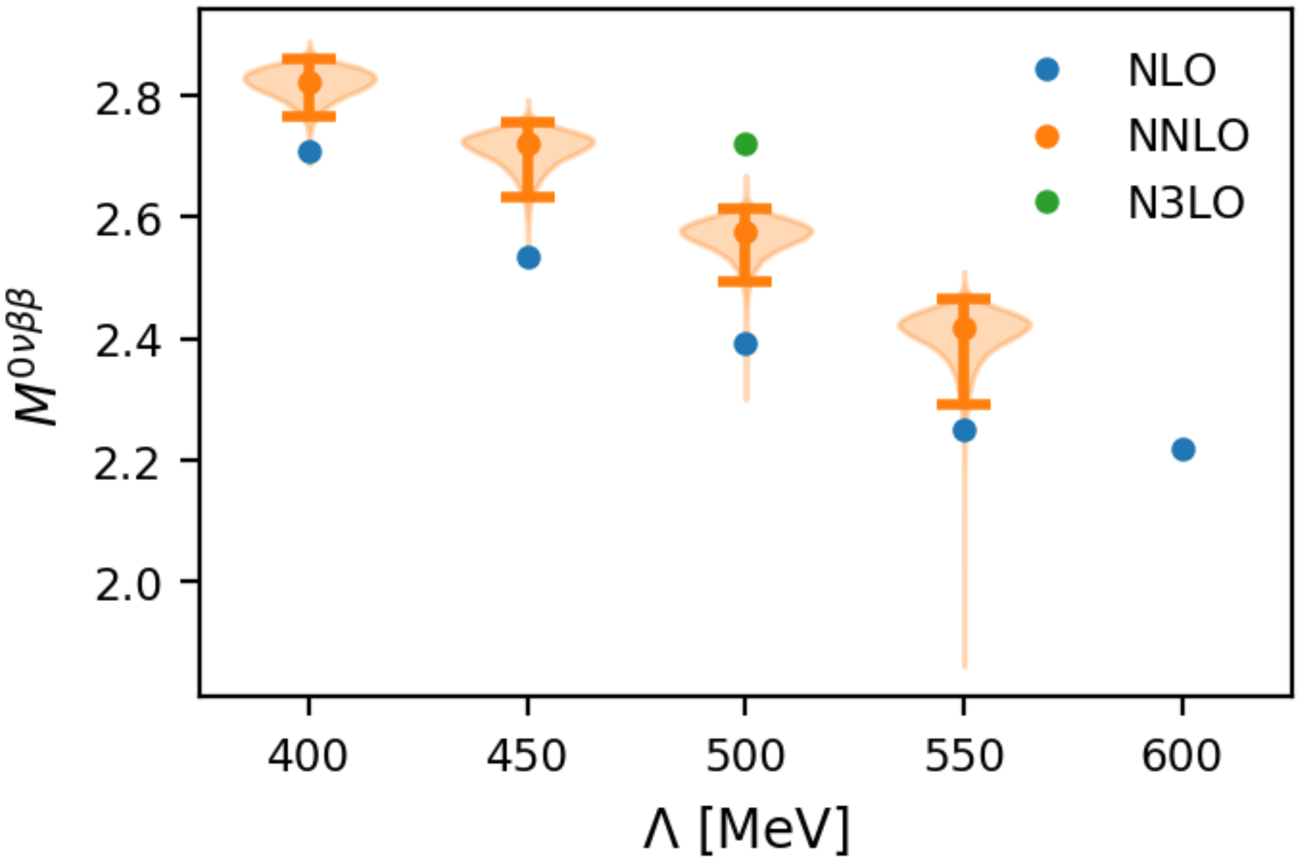




$$V(q^2) \propto \frac{1}{q^2}\left[-\frac{1}{g_A^2}h_F(q^2) + \boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)}h_{GT}(q^2) + S^{(12)}h_T(q^2)\right] + \frac{2m_\pi^2 g_\nu^{NN}}{g_A^2}h_F(q^2)$$



Uncertainty from the chiral NN interaction

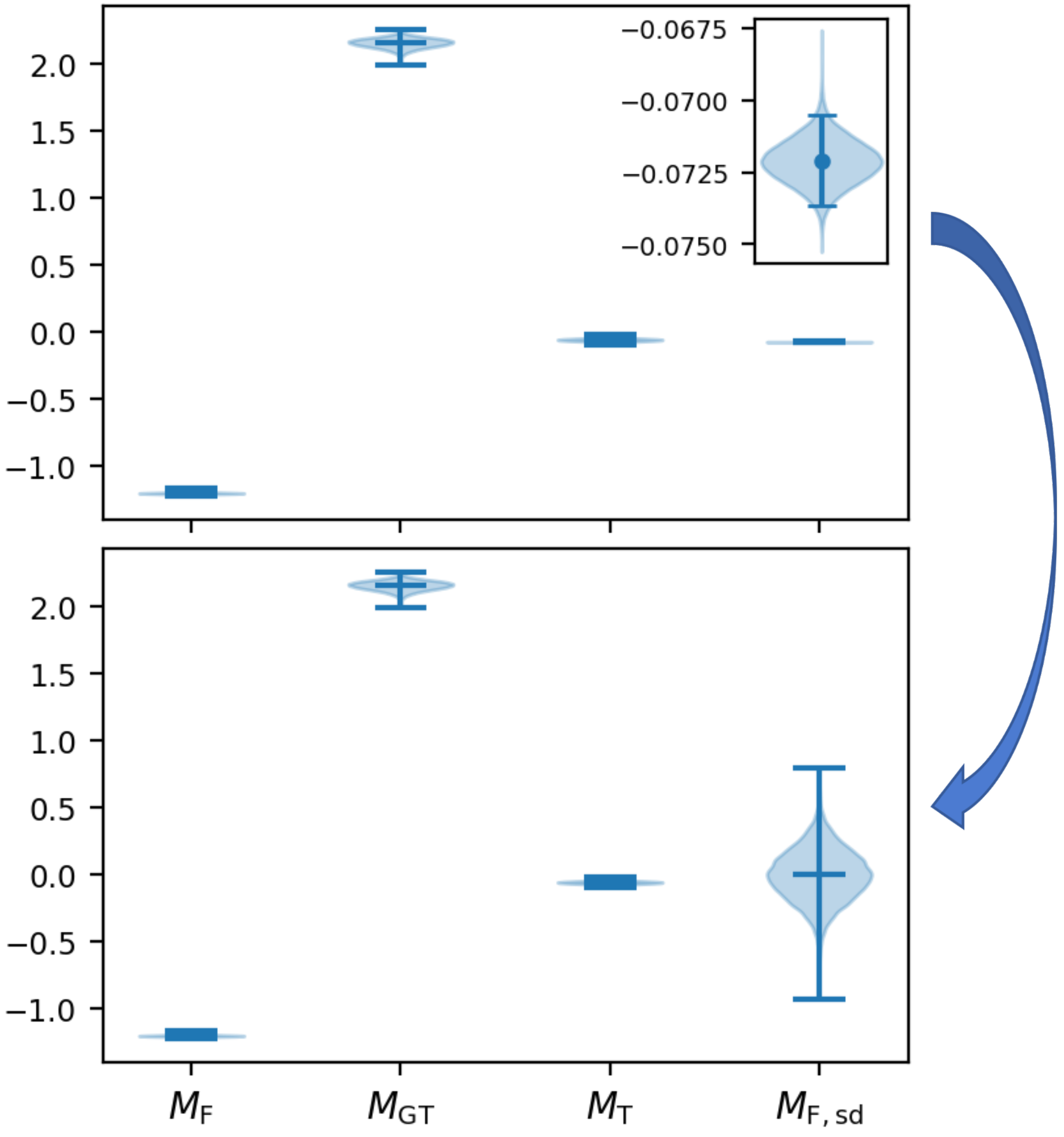


Matrix elements in our model from chiral forces at different orders with different regulator cutoffs

- Means (circles) do not include the short-distance contribution
- Distributions at NNLO arise from propagating the uncertainty from the chiral NN forces
- Distributions show dependence on the regulator cutoff
- At NNLO intervals with 95% DOB are at most 0.2 wide

How bad does the inclusion of the short-distance contribution mess up these distributions?

Sampling the short-distance parameter



The Fermi and Gamow-Teller components are of order one

The tensor component is small

To take this contribution into account the short-distance contribution we must sample g_ν^{NN}:

- Factor out the estimated scale

$$\tilde{g}_\nu^{NN} = f_\pi^2 g_\nu^{NN}$$

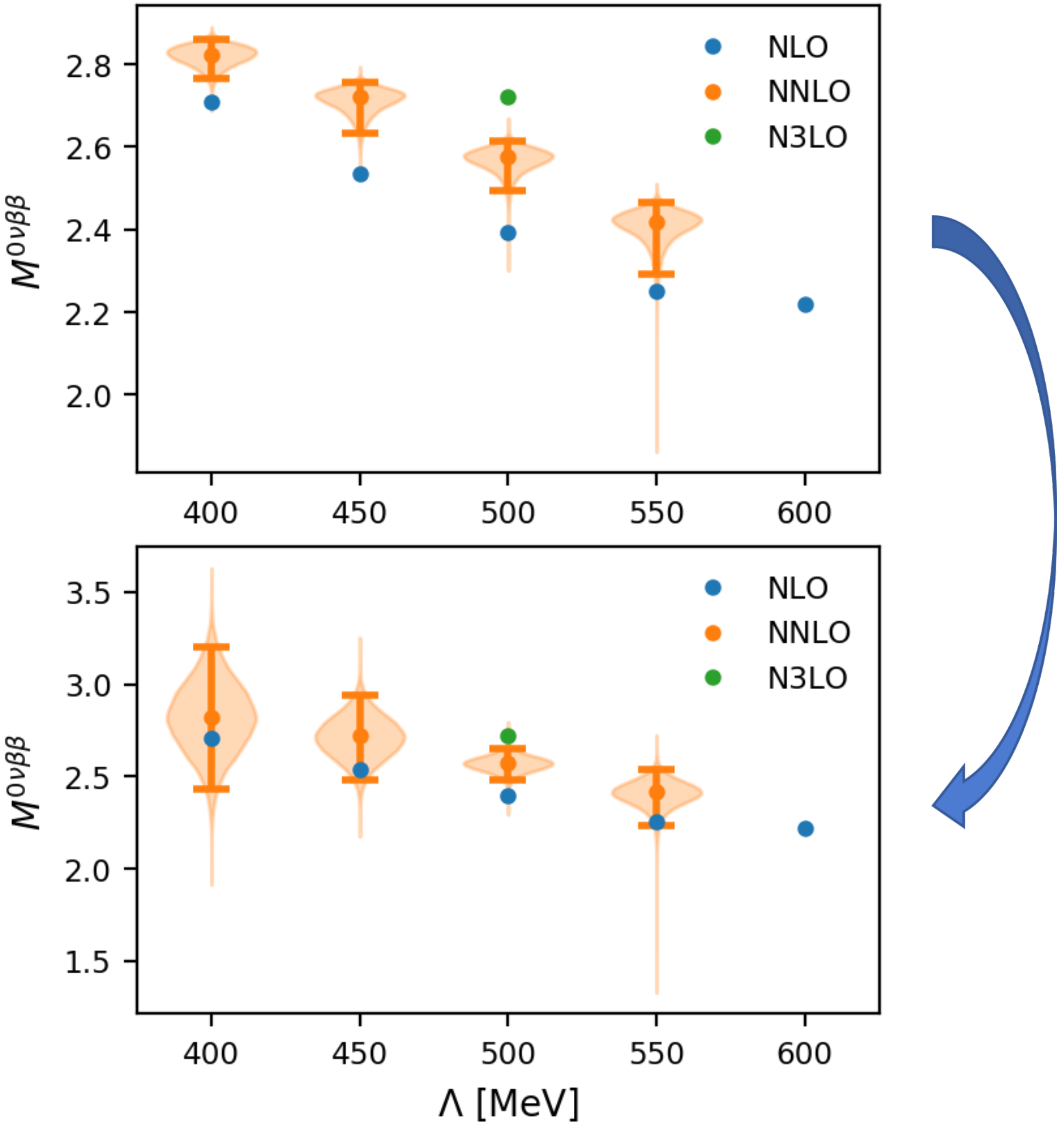
V. Cirigliano et al., Phys. Rev. Lett. ***120****, 202001*

- Assume $\tilde{g}_\nu^{NN}$ is normally distributed

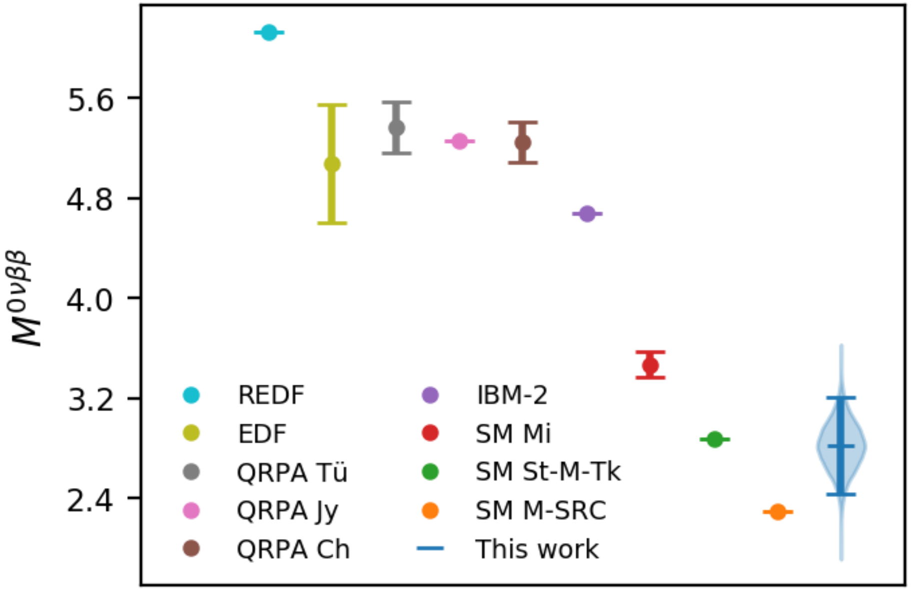
$$\mathrm{pr}(\tilde{g}_\nu^{NN}|\mu,\sigma) \propto \exp\left(-\frac{(\tilde{g}_\nu^{NN}-\mu)^2}{2\sigma_C^2}\right)$$

$$\sigma_C = 3 \qquad \mu = 0$$

Uncertainty from the short-distance contribution



- The distribution labeled “This work” results from the uncertainty from the chiral NN forces and the sampling the short-distance parameter
- The truncation error can be included once N3LO calculations are completed
- The width of the interval with 95% DOB is smaller than the spread from the diverse nuclear models

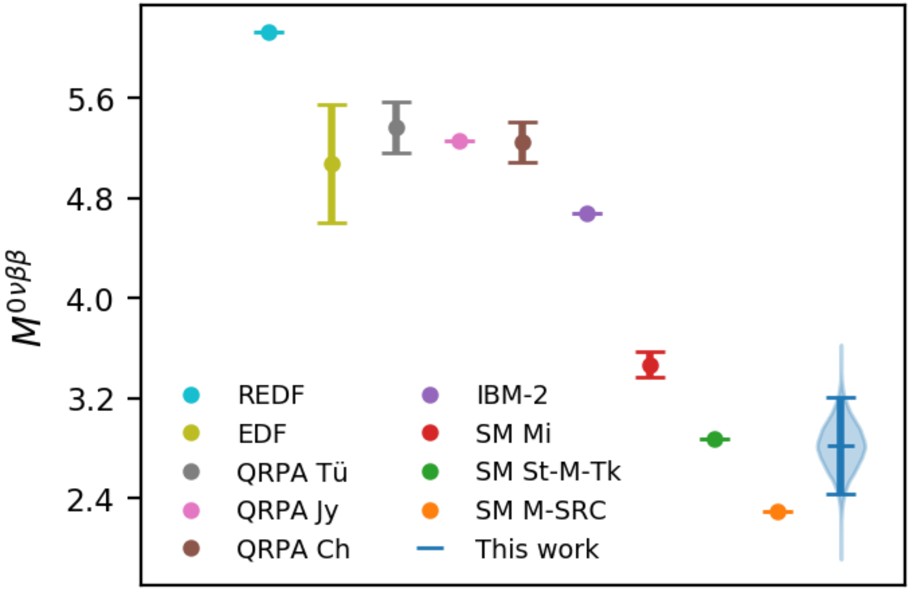


Summary and Outlook

- We employ four-nucleon droplets to simulate the valence nucleons in ^{76}Ge and ^{76}Se. These nucleons interact via chiral EFT forces
- The parameters of the chiral interaction are fitted to scattering data by means of an objective function that considers experimental uncertainties, the truncation of the chiral expansion and the size of the parameters
- We sampled the parameters of the chiral force and generate a large number of wave functions from were distributions for diverse quantities are obtained
- We obtained distributions for the components of the matrix element required to quantify the uncertainty for the $0\nu\beta\beta$ decay

- Push our calculations up to N4LO for the interaction
- Study the approximate independence of the distribution with the one-body potential
- Study other $0\nu\beta\beta$ decay candidates (^{136}Xe)

THANKS FOR YOUR ATTENTION!



Lawrence Livermore National Laboratory