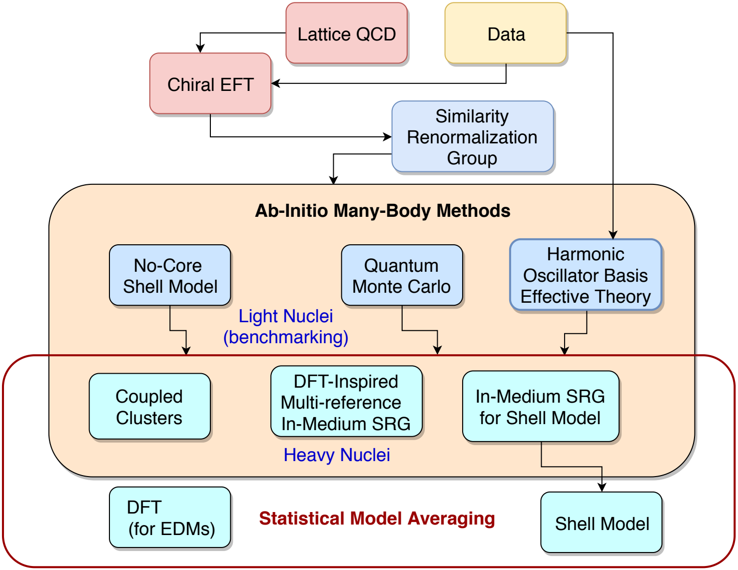
Double-Beta Decay from First Principles

J. Engel

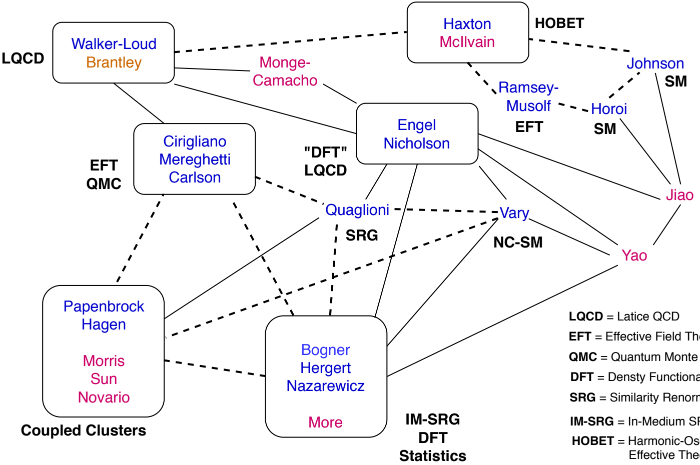
February 26, 2019

CONFERENCE ON NEUTRINO AND NUCLEAR PHYSICS 2020

DBD Topical Theory Collaboration



DBD Topical Theory Collaboration



LQCD = Latice QCD

EFT = Effective Field Theory

QMC = Quantum Monte Carlo

DFT = Densty Functional Theory

SRG = Similarity Renormilazation Group

IM-SRG = In-Medium SRG

HOBET = Harmonic-Oscillator-Based Effective Theory

NC-SM = No-Core Shell Model

SM = Shell Model

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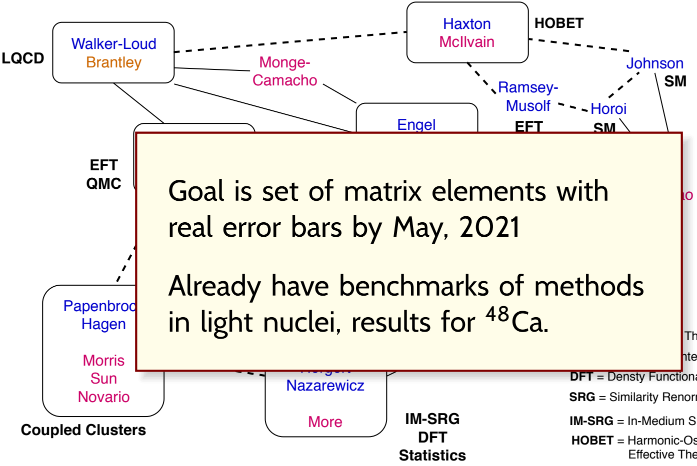

Goal is set of matrix elements with real error bars by May, 2021

Already have benchmarks of methods in light nuclei, results for ^{48}Ca.

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SRG = Similarity Renormilazation Group

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HOBET = Harmonic-Oscillator-Based Effective Theory

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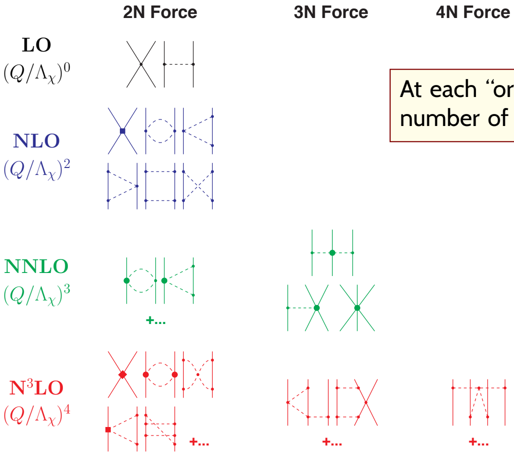
Ab Initio Nuclear Structure

Often starts with chiral effective-field theory

Nucleons, pions sufficient below chiral-symmetry breaking scale.
Expansion of operators in powers of Q/Λ_χ.

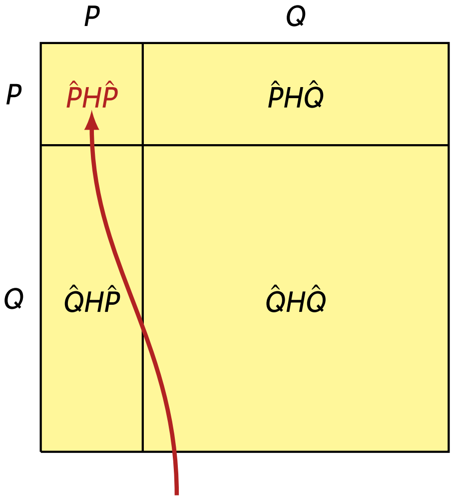
$Q = m_\pi$ or typical nucleon momentum.



At each "order," only a finite number of operators exist.

Ab Initio Many-Body Methods

Partition of Full Hilbert Space



Simpler calculation done here.

P = subspace you want
Q = the rest

Task: Find unitary transformation to make H block-diagonal in P and Q, with H_{eff} in P reproducing most important eigenvalues.

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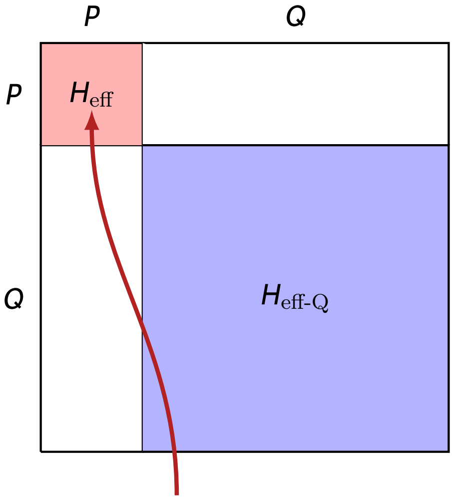

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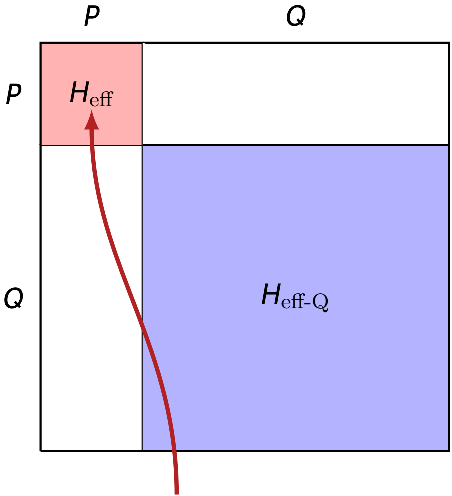

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Must must apply same unitary transformation to transition operator.

Ab Initio Many-Body Methods

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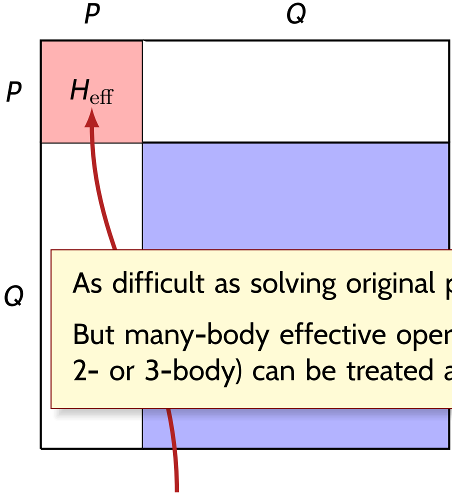

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...ly same unitary ... to transition operator.

As difficult as solving original problem.

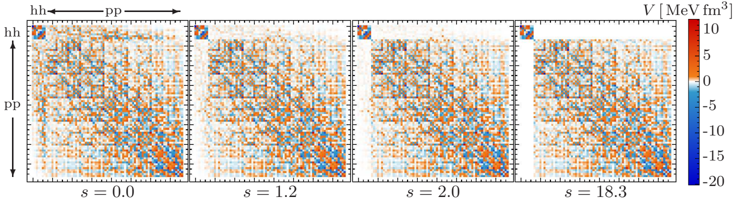
But many-body effective operators (beyond 2- or 3-body) can be treated approximately.

Simpler calculation done here.

In-Medium Similarity Renormalization Group

One way to determine the transformation

Flow equation for effective Hamiltonian.
Gradually decouples selected set of states.



from H. Hergert

Trick is to keep all 1- and 2-body terms in *H* at each step *after normal ordering* (approximate treatment of 3-, 4-body …terms).

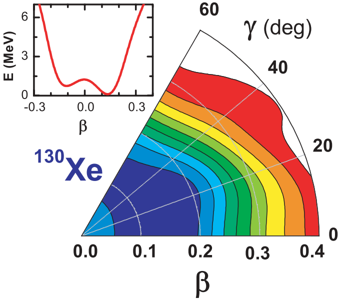
If selected set contains just a single state, approach yields ground-state energy. If it contains a typical valence space, result is effective shell-model interaction and operators.

New Idea: Reference State with Collective Correlations

Background: Generator Coordinate Method

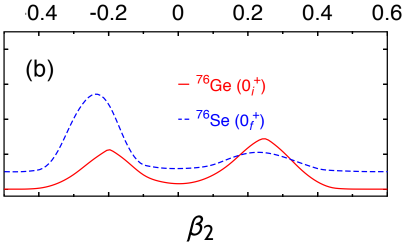
Construct set of mean fields by constraining coordinate(s), e.g. quadrupole moment $\langle Q_0 \rangle$. Then diagonalize H in space of symmetry-restored quasiparticle vacua with different $\langle Q_0 \rangle$.

Potential energy surface



Li et al.: Potential energy surface for ^{130}Xe

Collective wave functions

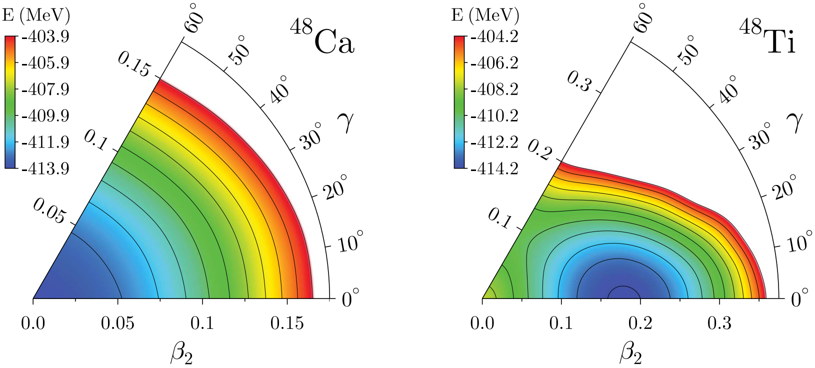


Rodríguez and Martínez-Pinedo: Wave functions in ^{76}Ge,Se peaked at two different deformed shapes.

In-Medium GCM for Decay of ^{48}Ca

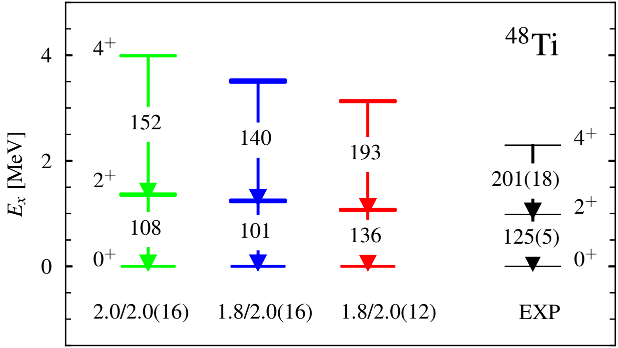
GCM Reference States for IMSRG

Potential Energy Surfaces



^{48}Ca is spherical and ^{48}Ti is weakly deformed.

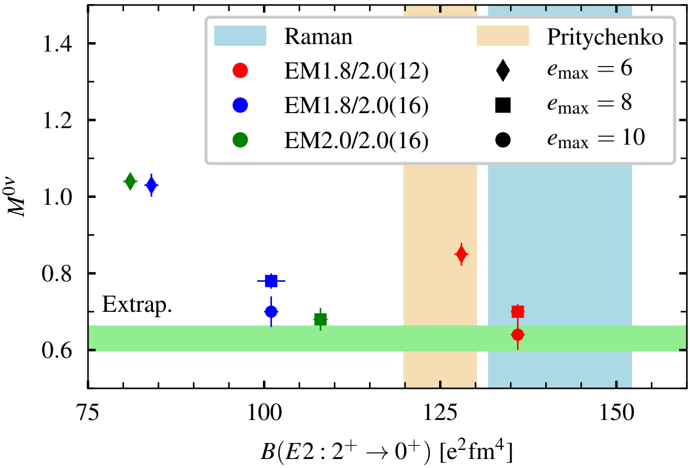
Spectrum in ^{48}Ti



In 9 shells

Smaller $\hbar\omega$ gives a bit more collectivity.

Variation with BE2 and Summary of Results

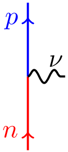


The green band is our best guess for the matrix element.

Axial Weak Current in Chiral EFT

β Decay (simplified) with electron lines omitted

Leading order:



g_A

Usual β-decay current

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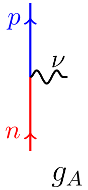
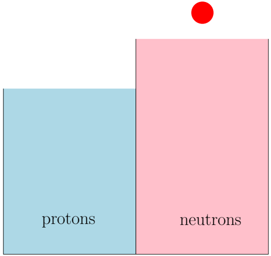


Usual β-decay current

Consider very simple wave function



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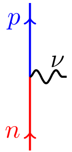

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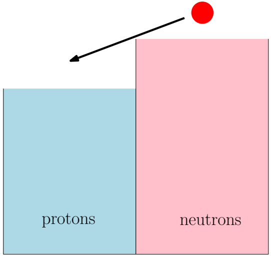

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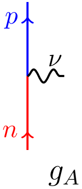

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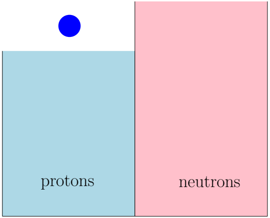

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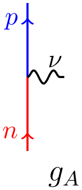

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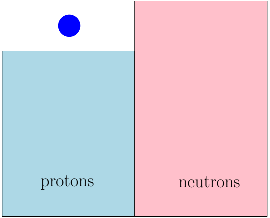
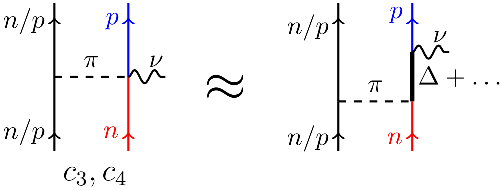


Higher order:



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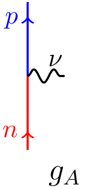

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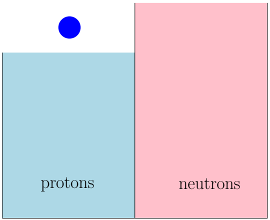

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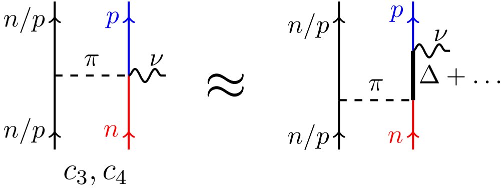

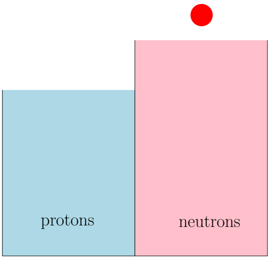

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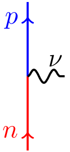

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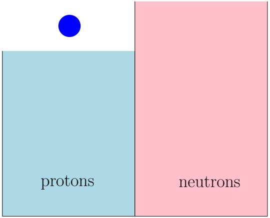

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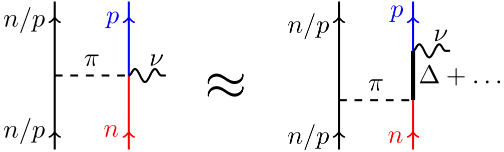
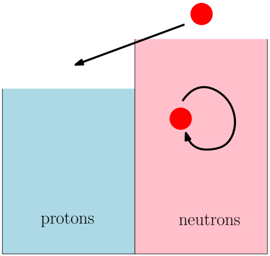


c_3, c_4



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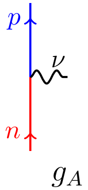

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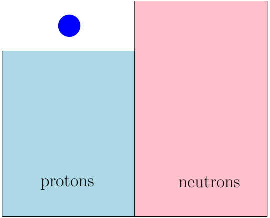

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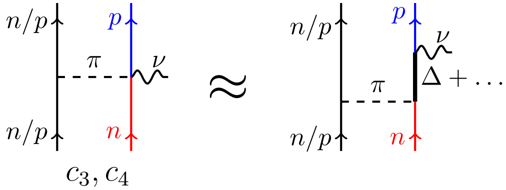
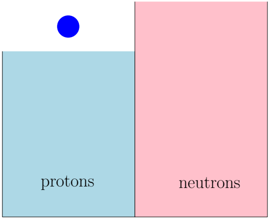
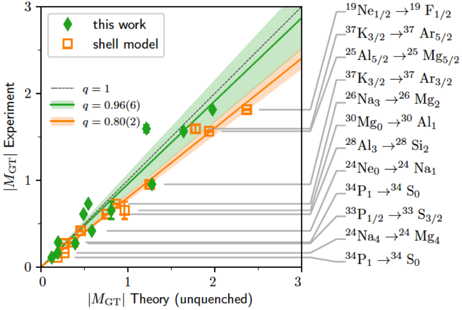
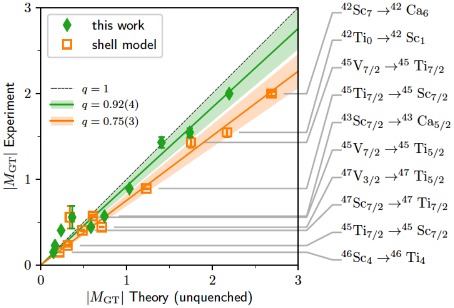




Quenching in the *sd* and *pf* Shells





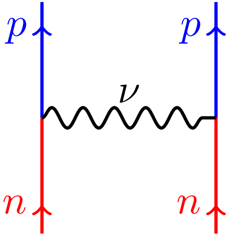
IMSRG calculation, Holt et al

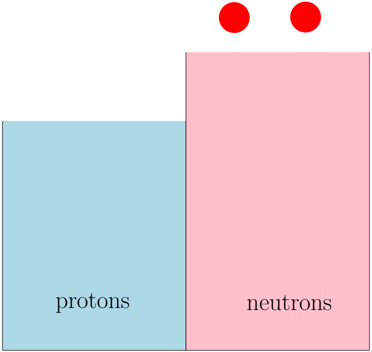
Some quenching from correlations omitted by the shell model.

But a lot comes from the two-body current.

What about in $\beta\beta$ Decay

Usual leading-order process





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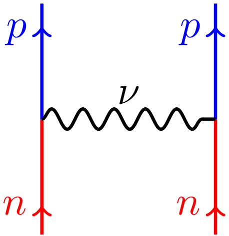

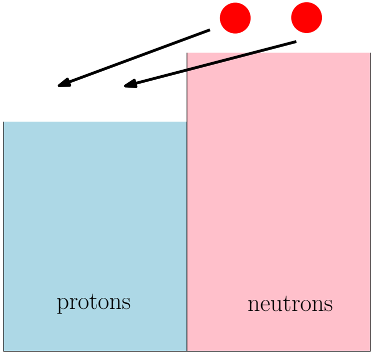

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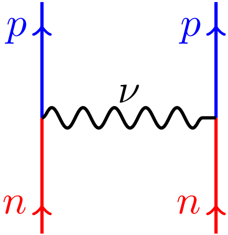
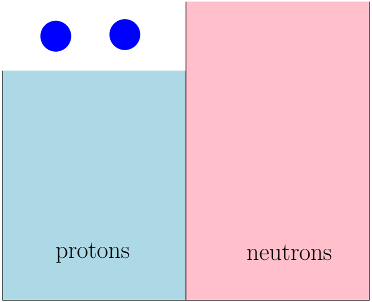
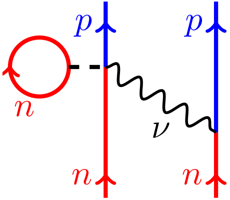


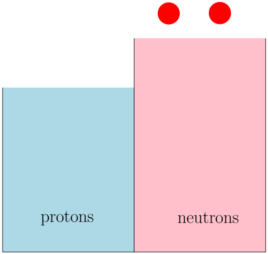


Leading Corrections

Example of diagram included by Klos, Menéndez, Schwenk,Gazit:



Effective two-body operator



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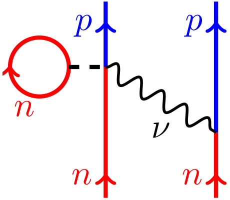

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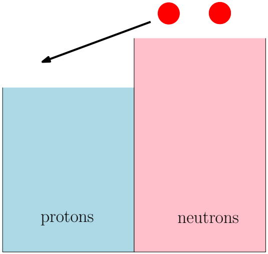
One-body current acts first.



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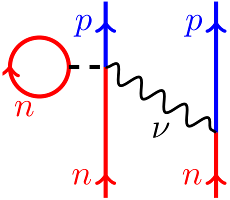

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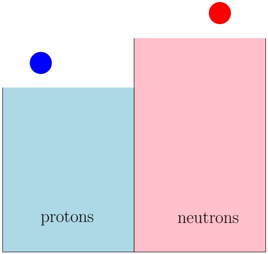

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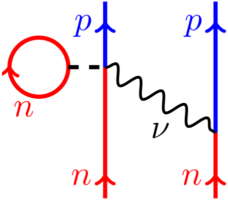

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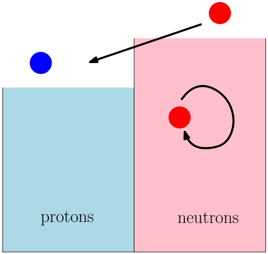

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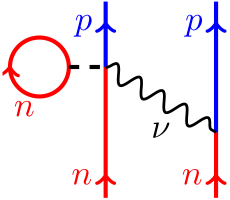

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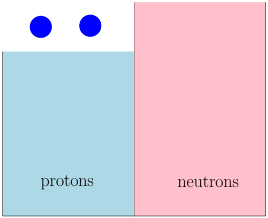

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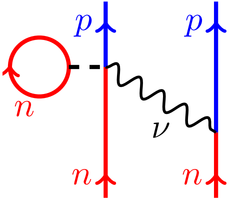

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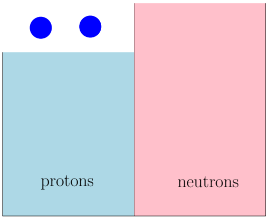

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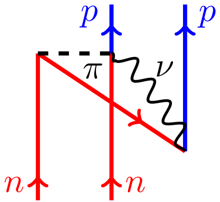

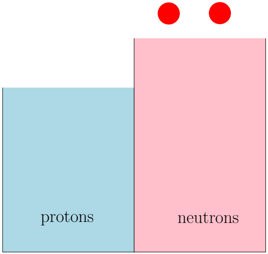

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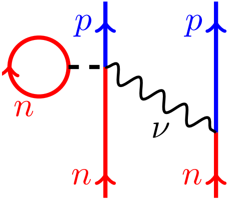

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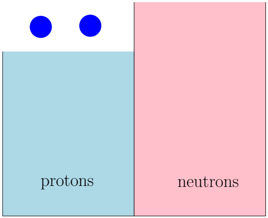

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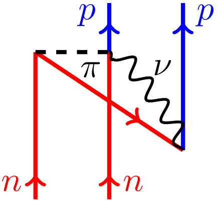
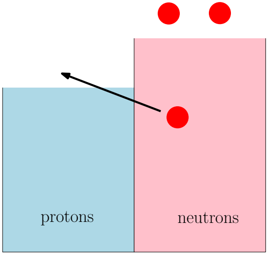
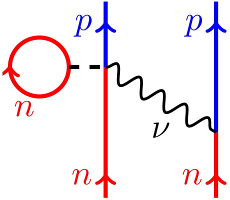


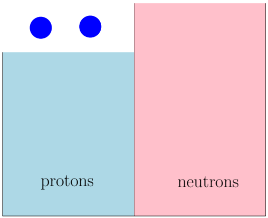


Leading Corrections

Example of diagram included by Klos, Menéndez, Schwenk,Gazit:

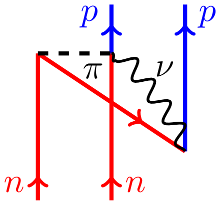


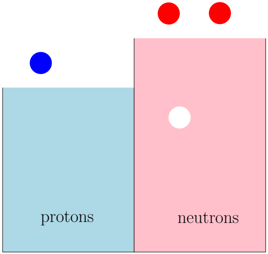
One-body current acts first.



Effective two-body operator

Example of corrections:





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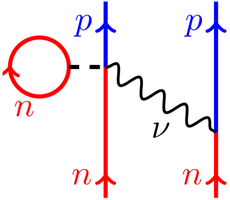

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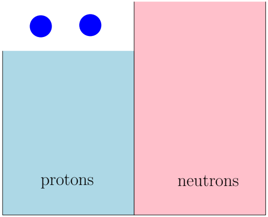

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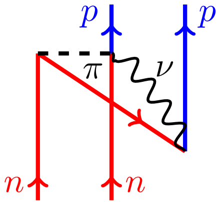

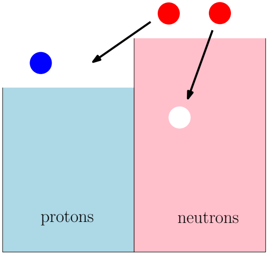

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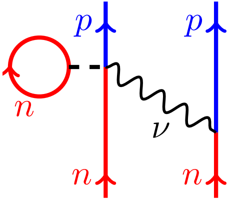

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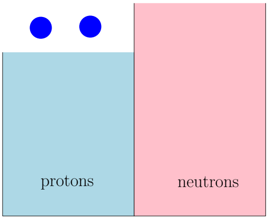

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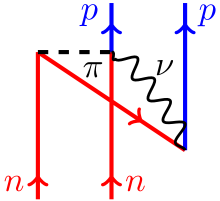

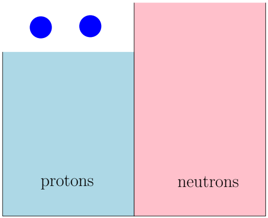

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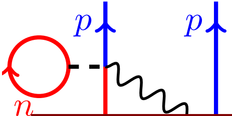
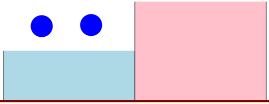


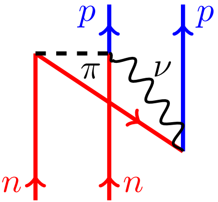


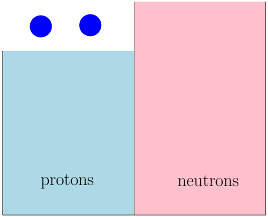
The bottom contributions

1. don't affect single-β decay
2. make quenching of $0\nu\beta\beta$ decay less important.

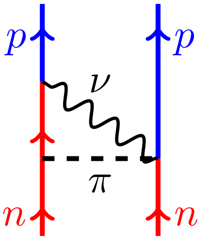
Eff

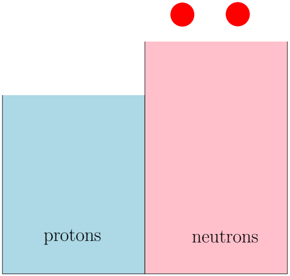
Example of corrections:





Divergent Contributions





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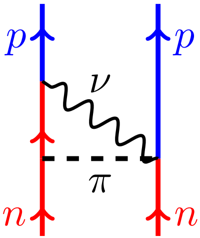

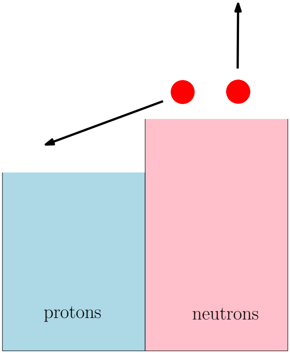

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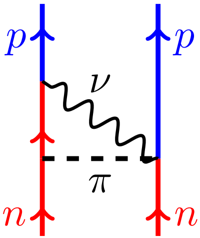

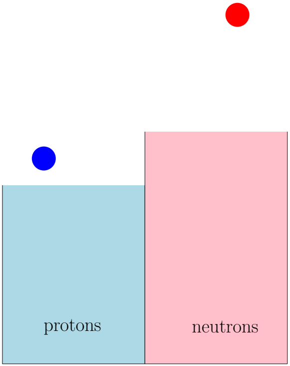

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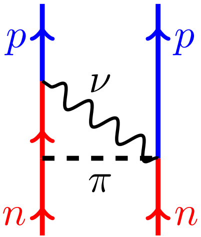

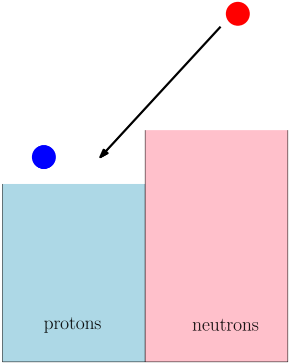

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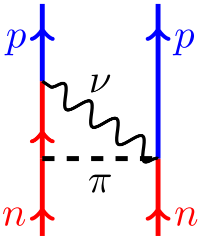

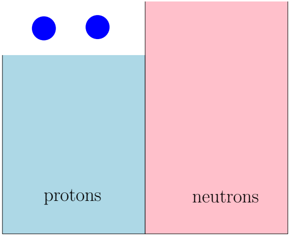

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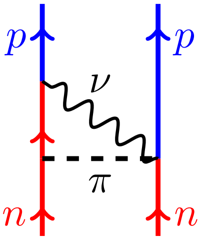

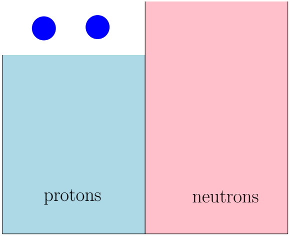

Neutron can be excited to *any* empty level.

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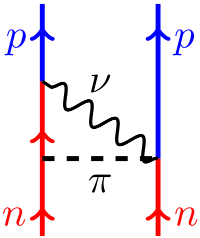
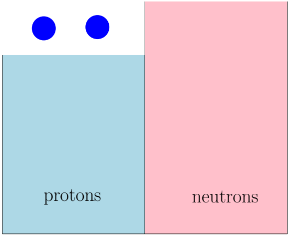
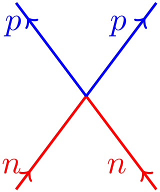


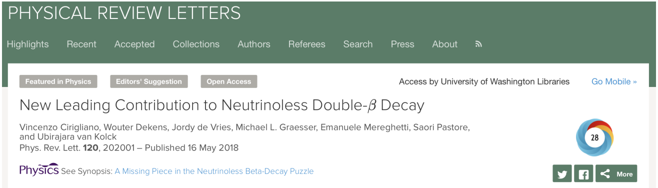


Neutron can be excited to *any* empty level.

Can "tame" the divergence with form factors, but effective field theory says that there is a short-range contribution *beyond* what is usually considered in nuclear models. Appears as contact counter-term with coefficient that is unknown.



More on Counter-Terms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New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck

Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

Physics See Synopsis: A Missing Piece in the Neutrinoless Beta-Decay Puzzle

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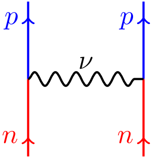
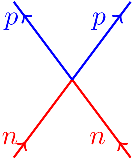
More

Usual light neutrino exchange:



must be supplemented, even at leading order in chiral EFT, by short-range operator (representing high-energy ν exchange):



Coefficient of this leading-order term is also unknown. Results in uncertainty of order 100%

Collaboration members are to estimating it.

So, to Sum Up…

1. Chiral EFT + new many-body methods are the tools required to compute matrix elements with controlled uncertainty. We currently have results for ^{48}Ca, working on ^{76}Ge.

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   ed

That's all; thanks.

3. ge
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