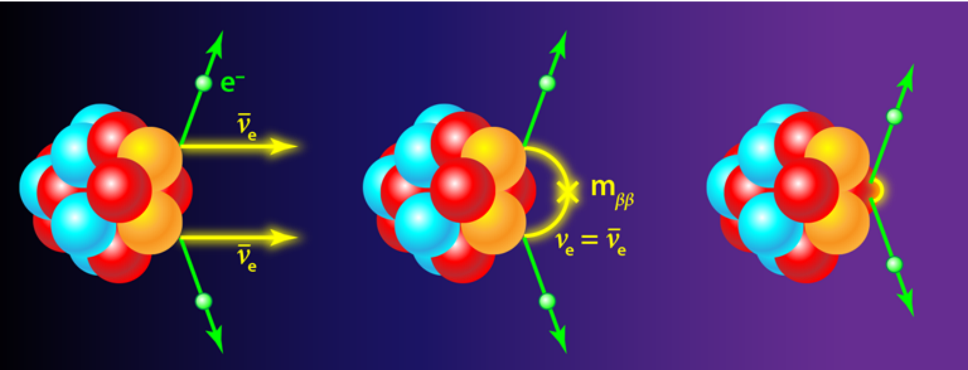
DBD Topical Nuclear Theory Collaboration

Report to NSAC

J. Engel

October 18, 2019



Goal of Collaboration

Improved accuracy and quantifiable error bars in calculations of the nuclear matrix elements affecting:

- the rate of neutrinoless double-beta decay
- atomic electric-dipole moments
- cross sections for scattering of dark-matter particles from nuclei
- parity-violation experiments

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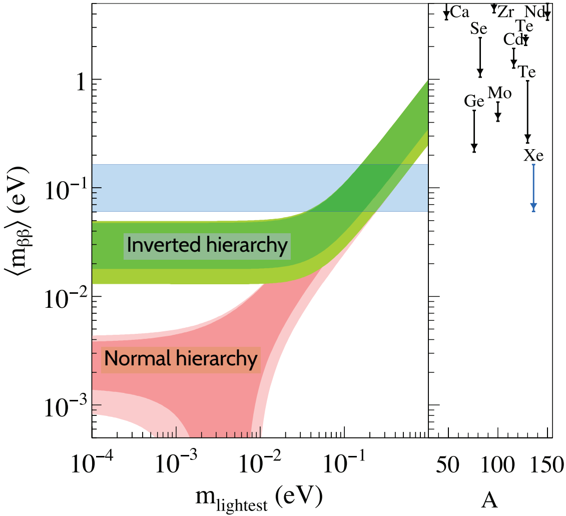
These are all important goals, supporting a variety of experiments, but better matrix elements for double-beta decay are crucial.

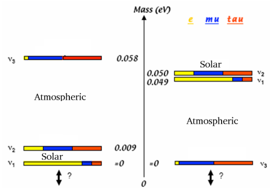
DOE intends to invest a lot of money in one or more “best” $\beta\beta$ experiments.

Neutrino Physics and Neutrinoless $\beta\beta$ Decay

Expected value of effective neutrino mass to be extracted from $\beta\beta$ experiments:



Hierarchy



Normal

Inverted

Large "uncertainties" show why better calculations needed.

Physics of Neutrinoless Double-Beta Decay

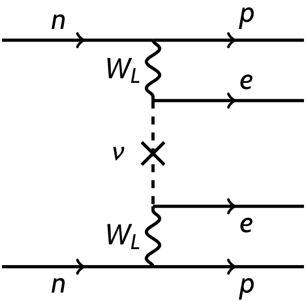


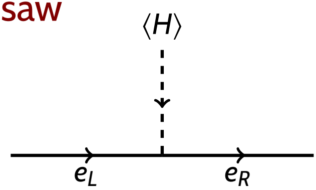
Diagram is proportional to effective Majorana mass of light neutrinos,

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i \,,$$

no matter what the source of the mass.

But the mass must come from somewhere, and the Standard Model by itself doesn't allow it.

Seesaw



This is the way charged fermions get mass in the Standard Model. Neutrinos cannot because the ones we know about seem to be left handed only.

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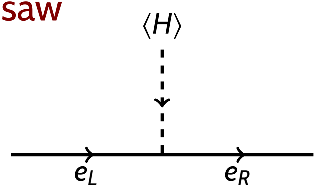

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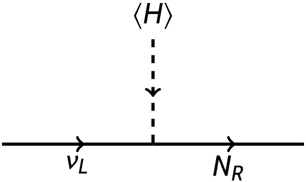
But if there are heavy right-handed neutrinos, then an off-diagonal version of the same diagram operates:



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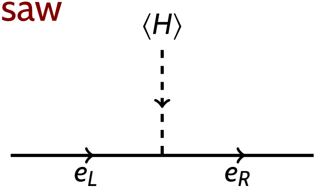

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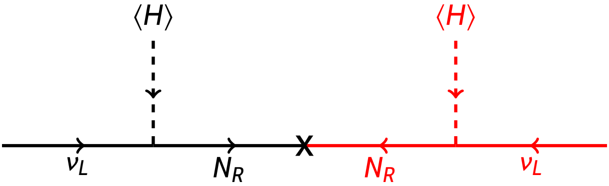

…and the left-handed neutrino gets a Majorana mass from the concatenation of two such diagrams.

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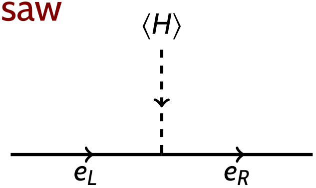

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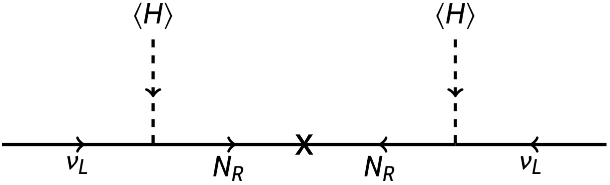
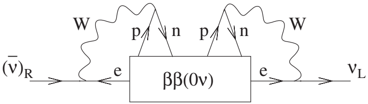


…and the left-handed neutrino gets a Majorana mass from the concatenation of two such diagrams.

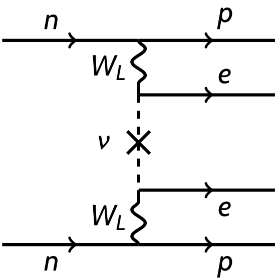
ν_L is light ($\approx m_e^2/m_R$) because of the two electron-mass-like vertices and the heavy-neutrino propagator.

New Physics Can Contribute Directly to $\beta\beta$ Decay

If neutrinoless decay occurs then ν's are Majorana, no matter what:



but high-scale physics can contribute directly alongside light-neutrino exchange:



$$\langle q^2 \rangle_\nu \approx 10^4 \text{ MeV}^2$$

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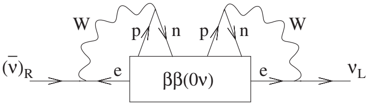

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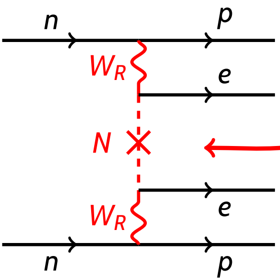

Exchange of heavy right-handed neutrino in left-right symmetric model.

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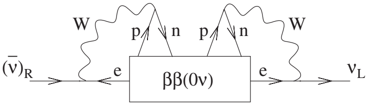

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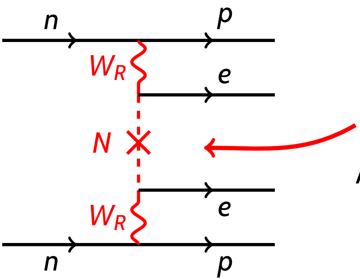

Exchange of heavy right-handed neutrino in left-right symmetric model.

$\langle q^2 \rangle_\nu \approx 10^4 \text{ MeV}^2$

Amplitude of heavy-particle process:

$$\frac{Z_{0\nu}^{\text{heavy}}}{Z_{0\nu}^{\text{light}}} \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{\langle q^2 \rangle_\nu}{m_{\beta\beta}\, m_N}\right)$$

$$\approx \mathbf{1} \quad \text{if} \quad m_N \approx m_{W_R} \approx 1 \text{ TeV}$$

$$\text{and} \quad m_{\beta\beta} \approx \sqrt{\Delta m^2_{\text{atm}}}$$

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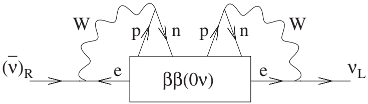
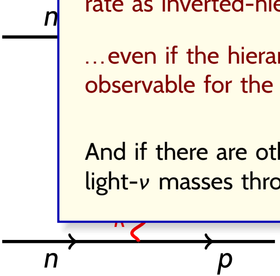


but high-scale physics can contribute directly alongside light



So heavy-particle exchange can occur with roughly the same rate as inverted-hierarchy light-ν exchange would...

...even if the hierarchy is normal and light-ν exchange is un-observable for the time being.

And if there are other new particles, they can contribute to light-ν masses through other kinds of seesaws.

left-

ess:

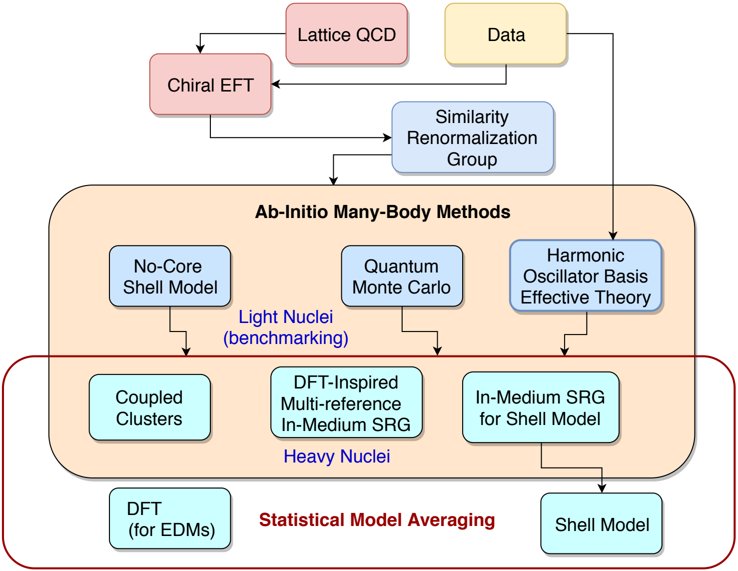
$$\frac{Z^{\text{heavy}}_{0\nu}}{Z^{\text{light}}_{0\nu}} \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{\langle q^2\rangle_\nu}{m_{\beta\beta}\, m_N}\right)$$

$\langle q^2\rangle_\nu \approx 10^4\ \text{MeV}^2$

$\approx \mathbf{1}$ if $m_N \approx m_{W_R} \approx 1\ \text{TeV}$

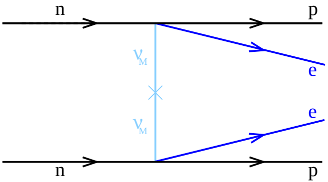
and $m_{\beta\beta} \approx \sqrt{\Delta m^2_{\text{atm}}}$

Integrated Approach to This Kind of Problem



New Physics at Hadronic Level

Light-ν exchange:

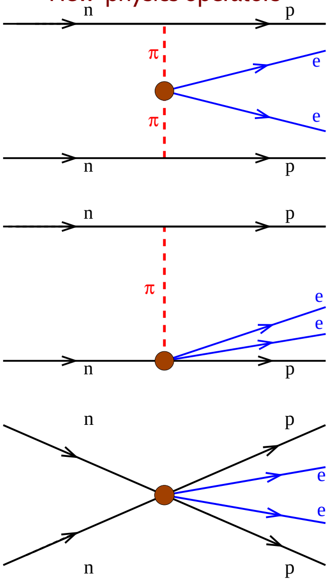


+ higher-order corrections

Effective field theory lists pion-nucleon-level operators and determines their importance.

(There have been some surprises in light-ν exchange...)

New-physics operators



New physics inside blobs

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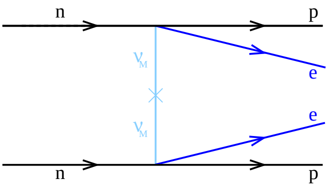

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Lattice QCD can then compute dependence of blobs on new particle masses and couplings.

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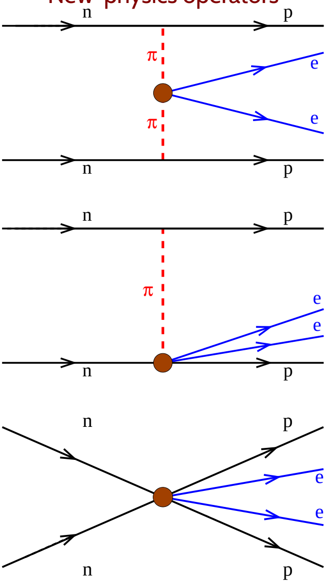

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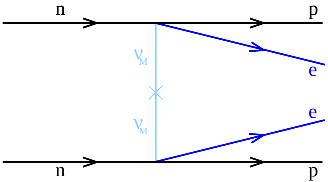

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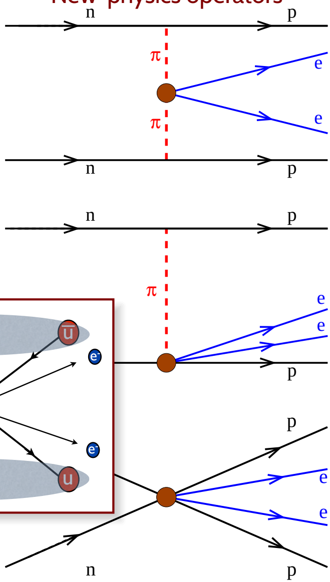

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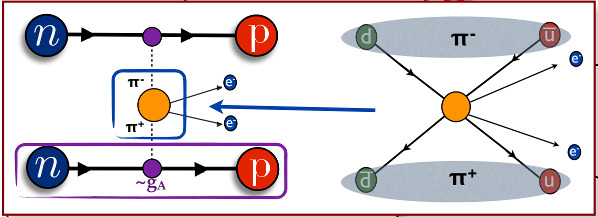

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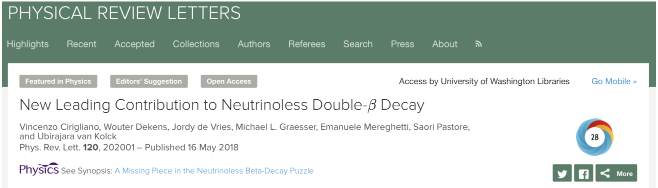
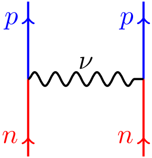
Discovery/Issue

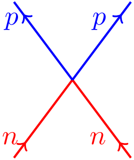


Even the usual light neutrino exchange:

(electron lines removed)



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



Coefficient of this term is unknown.

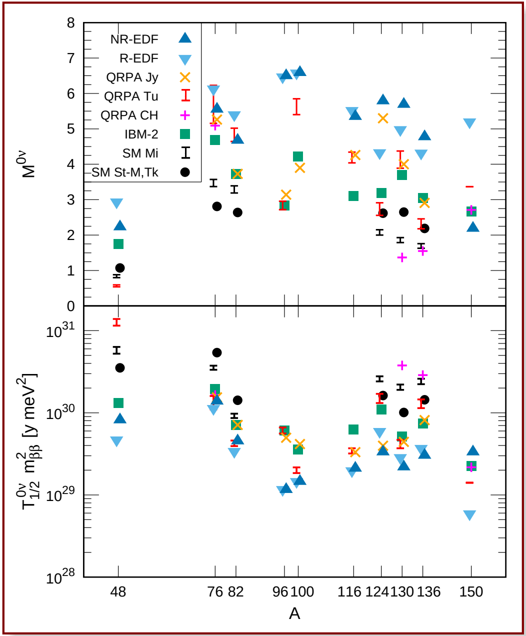
We're working to determine it.

Nuclear Level

Matrix Elements Pre-TC

Significant spread. And all the models may miss important physics.

Uncertainty can't be quantified.



Improving Nuclear Structure: Ab Initio Methods

Use most accurate methods:
No-Core Shell Model, Quantum Monte Carlo

in light nuclei to verify other methods:
Coupled Clusters, RG-based techniques

that are not quite as accurate but better able to treat heavy nuclei.

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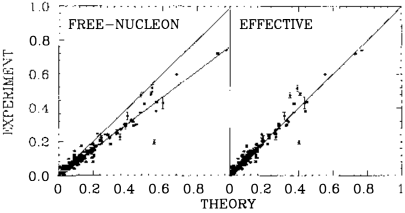
Practitioners have come together to explain most of the "g_A quenching" in ordinary β decay!



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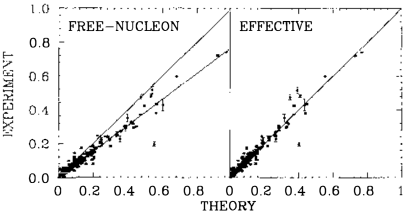

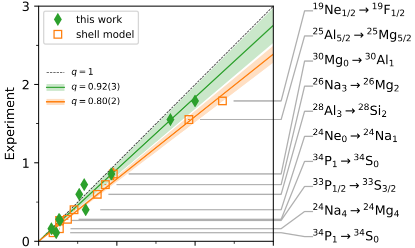

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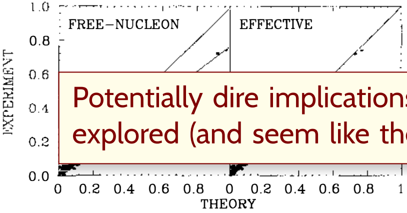
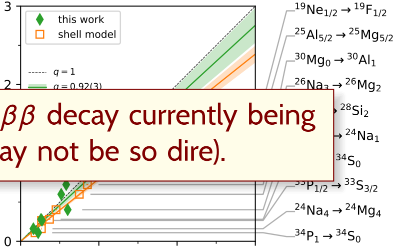
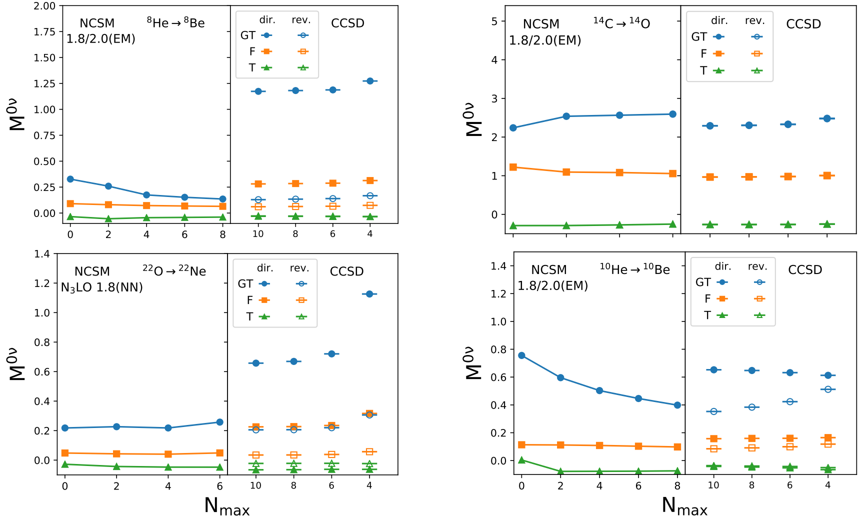




Potentially dire implications for $\beta\beta$ decay currently being explored (and seem like they may not be so dire).

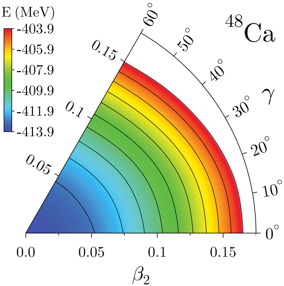
Benchmarking

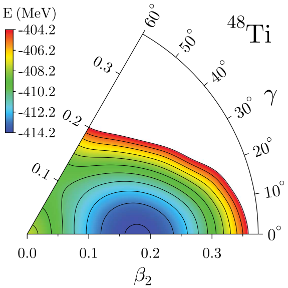


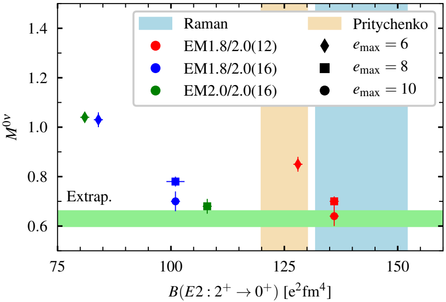
Takeaway: Coupled clusters works well, particularly when final nucleus is the "core." In-medium GCM (RG method) also works well.

Applying Validated Methods to Nuclei of Real Interest

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







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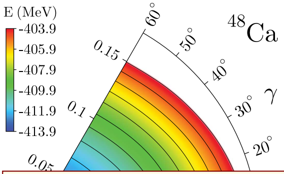
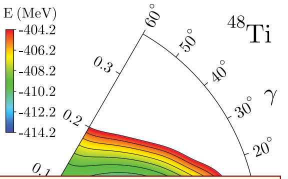
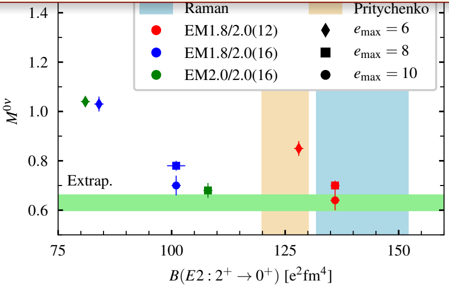




We're now applying this and coupled-clusters theory to ^{76}Ge, ^{130}Te, and ^{136}Xe. The matrix elements for these nuclei are our primary deliverables.



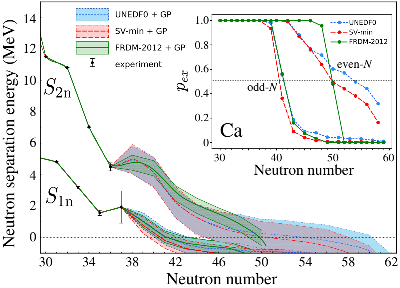
Finally: Error Quantification

PHYSICAL REVIEW LETTERS **122,** 062502 (2019)

Neutron Drip Line in the Ca Region from Bayesian Model Averaging

Léo Neufcourt,[1,2] Yuchen Cao (曹宇晨),[3] Witold Nazarewicz,[4] Erik Olsen,[2] and Frederi Viens[1]
[1]*Department of Statistics and Probability, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*FRIB Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy and NSCL Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics and Astronomy and FRIB Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

(Received 12 September 2018; revised manuscript received 15 November 2018; published 14 February 2019)



Will apply similar techniques to our matrix-element calculations.

EDMs, Dark-Matter, Etc.

Nonzero EDMs for states of particles, nuclei, atoms with good angular momentum imply *CP* violation, from beyond the Standard Model if seen in current or upcoming experiments.

A discovery could help explain the observed matter-antimatter asymmetry. A wide range of experiments are operating or planned.

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Understanding dark matter also pretty important…

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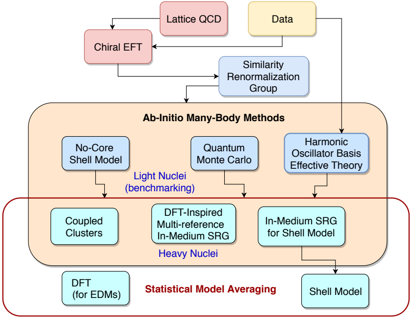
Understanding dark matter also pretty important…

Working out the matrix elements that connect experiment to underlying theory requires the same kinds of steps as in $\beta\beta$ decay:

- lattice QCD to determine pion and nucleon couplings from fundamental physics
- EFT to to construct effective Lagrangian
- nuclear-structure theory to embed Lagrangian in nuclei

Operation of Collaboration



- Parts of the chain above have really worked. The Similarity Renormalization Group, for example has provided softened operators that we use in in nuclear-structure work.
- We meet twice a year, have frequent opportunities to discuss developments and plan joint work.
- Will publish comprehensive Physics Report on state of field and advances by DBD during last year.

Impact

nature
International journal of science

Letter | Published: 30 May 2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

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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

nature physics

Letter | Published: 11 March 2019

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers, G. Hagen, J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt

Physics ABOUT BROWSE PRESS COLLECTIONS

Viewpoint: The Hunt for No Neutrinos

Jonathan Engel, Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, USA
Petr Vogel, Kellogg Radiation Laboratory and Physics Department, California Institute of Technology, Pasadena, CA 91125, USA

March 26, 2018 • *Physics* 11, 30

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Volume 769, 10 | Go to Physics Letters B on ScienceDirect

Neutrinoless double beta decay and chiral *SU*(3)

V. Cirigliano [a], W. Dekens [a, b], M. Graesser [a], E. Mereghetti [a]

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Heavy Physics Contributions to Neutrinoless Double Beta Decay from QCD

A. Nicholson, E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joó, T. Kurth, B. C. Tiburzi, P. Vranas, and A. Walker-Loud

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Reports on Progress in Physics

REVIEW

Status and future of nuclear matrix elements for neutrinoless double-beta decay: a review

Jonathan Engel[1] and Javier Menéndez[2]

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Reports on Progress in Physics, Volume 80, Number 4

Thoughts on Collaboration

- Targeted resources for work particular problems has increased the amount and quality of that work substantially. Before the TC I had a hard time convincing top nuclear-structure and QCD people to prioritize $\beta\beta$ decay.
- We've actually collaborated to advantage:
  - Frequent meetings have allowed us to address new problems as they emerge.
  - Work by some has been used as input for others higher on the particle-physics-to-nuclear-structure chain
  - Benchmarking methods against one another has been essential
  - $\vdots$
- Slight downside: Distribution of resources can be difficult. Participation by members can wax and wane.
- Requires some oversight by organizer(s) to stay on optimal path.

Finally…

For our field, the collaboration has been extremely useful. Has profoundly strengthened the connection between fundamental physics and nuclear theory.

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Thanks very much for your kind attention!