SCIENCE TALK 3: FUNDAMENTAL SYMMETRIES

ZOHREH DAVOUDI

UNIVERSITY OF MARYLAND AND RIKEN FELLOW

Broken symmetry
by Robert Wilson
Fermilab, IL

Proposal to Extend the LQCD Research Program to the Next Five-Year Period, 2020-2024

DOE Scientific Review

July 9-10, 2019, rockville, MD

HIGH ENERGIES AND
NATURAL-SIZE COUPLINGS

INTERMEDIATE ENERGIES
AND FEEBLE COUPLINGS

HIGH ENERGIES AND NATURAL-SIZE COUPLINGS

(Benefits from an effective field theory description)

Physics	Target Quantity	Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
CP Violation and Baryon Asymmetry in Universe	Electric Dipole Moment	Hg, Ra, *n* EDM at SNS and LANL
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

Cornell University

the Sim

arXiv.org > hep-lat > arXiv:1904.09704

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High Energy Physics – Lattice

The Role of Lattice QCD in Searches for Violations of Fundamental Symmetries and Signals for New Physics

Vincenzo Cirigliano, Zohreh Davoudi, Tanmoy Bhattacharya, Taku Izubuchi, Phiala E. Shanahan, Sergey Syritsyn, Michael L. Wagman

(Submitted on 22 Apr 2019)

This document is one of a series of whitepapers from the USQCD collaboration. Here, we discuss opportunities for Lattice Quantum Chromodynamics (LQCD) in the research frontier in fundamental symmetries and signals for new physics. LQCD, in synergy with effective field theories and nuclear many-body studies, provides theoretical support to ongoing and planned experimental programs in searches for electric dipole moments of the nucleon, nuclei and atoms, decay of the proton, n–$\bar{n}$ oscillations, neutrinoless double-β decay of a nucleus, conversion of muon to electron, precision measurements of weak decays of the nucleon and of nuclei, precision isotope-shift spectroscopy, as well as direct dark matter detection experiments using nuclear targets. This whitepaper details the objectives of the LQCD program in the area of Fundamental Symmetries within the USQCD collaboration, identifies priorities that can be addressed within the next five years, and elaborates on the areas that will likely demand a high degree of innovation in both numerical and analytical frontiers of the LQCD research.

Comments: A whitepaper by the USQCD Collaboration, 30 pages, 9 figures

Subjects: **High Energy Physics – Lattice (hep-lat)**; High Energy Physics – Experiment (hep-ex); High Energy Physics – Phenomenology (hep-ph); Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)

Cite as: arXiv:1904.09704 **[hep-lat]**

(or arXiv:1904.09704v1 **[hep-lat]** for this version)

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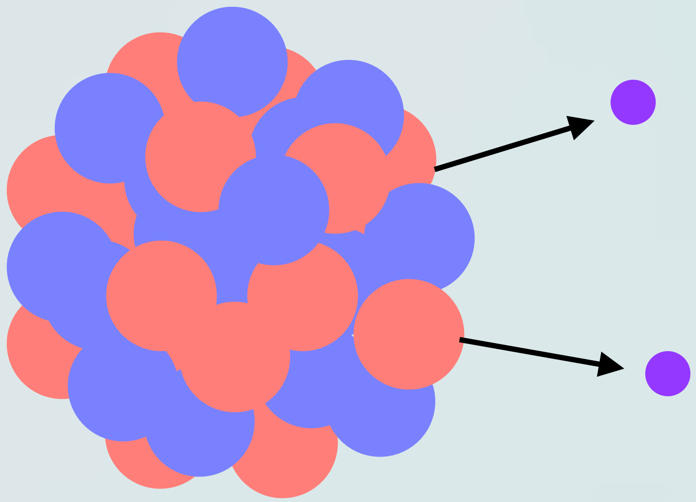
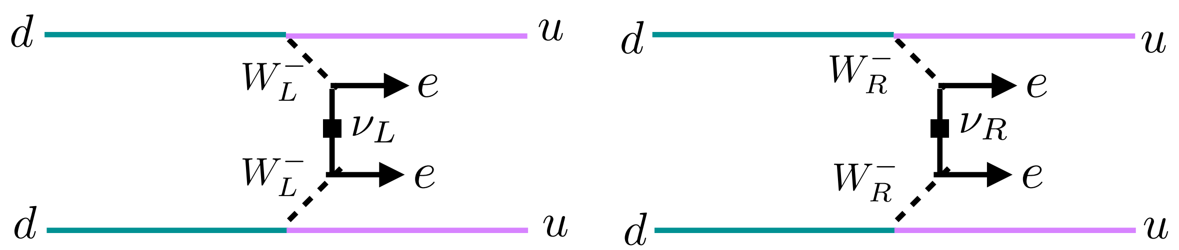
THE ROADMAP FOR *0vBB* DECAY



Addresses if neutrinos are Majorana fermions (P5)

$\Lambda > \text{TeV}$

START WITH A GIVEN HIGH-SCALE MODEL, e.g., LEFT-RIGHT SYMMETRIC MODEL:



RUN IT DOWN TO THE SCALE WHERE THE HIGH-SCALE PHYSICS CAN BE INTEGRATED OUT:

$\Lambda > \text{TeV}$

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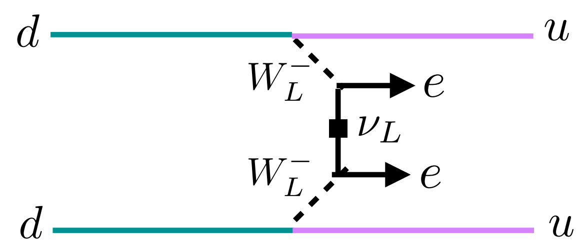

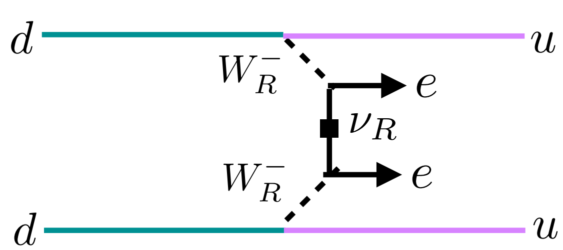

$\Lambda \sim 10^2$ GeV

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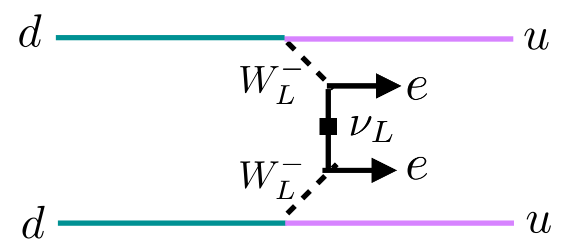

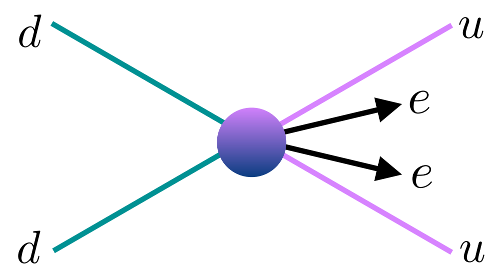

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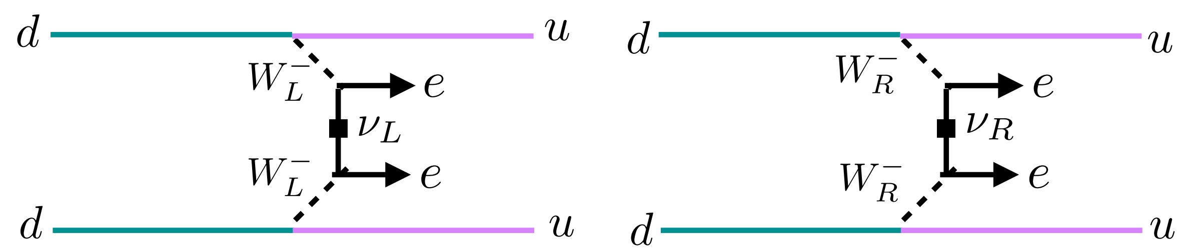

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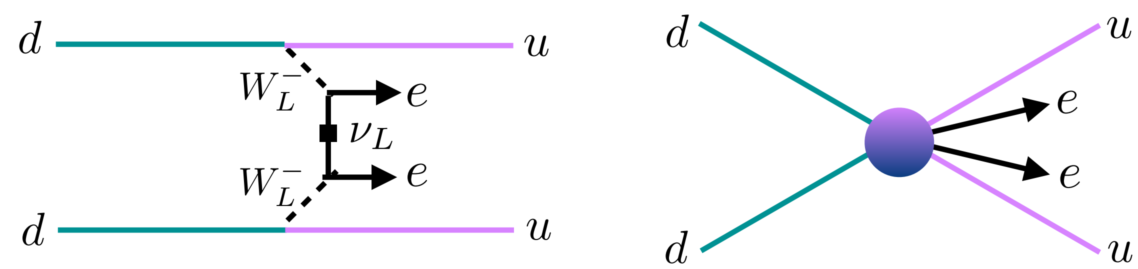

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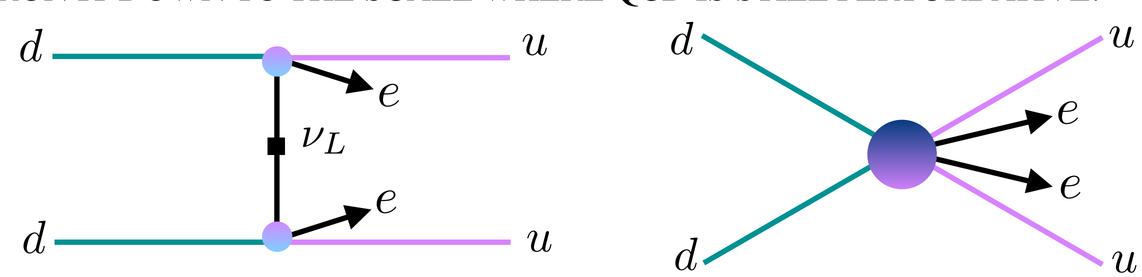
RUN IT DOWN TO THE SCALE WHERE QCD IS STILL PERTURBATIVE:



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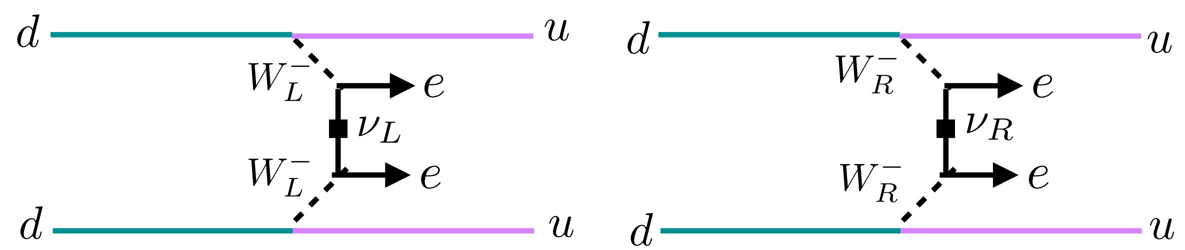

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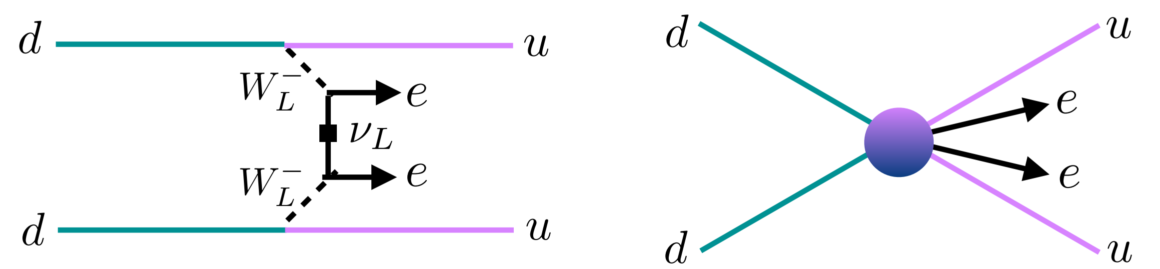

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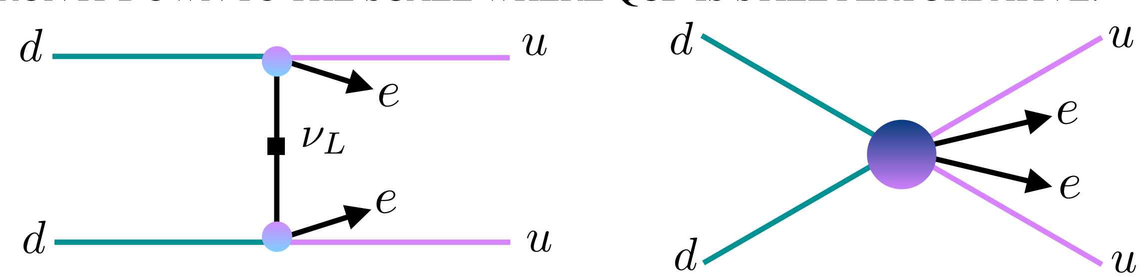
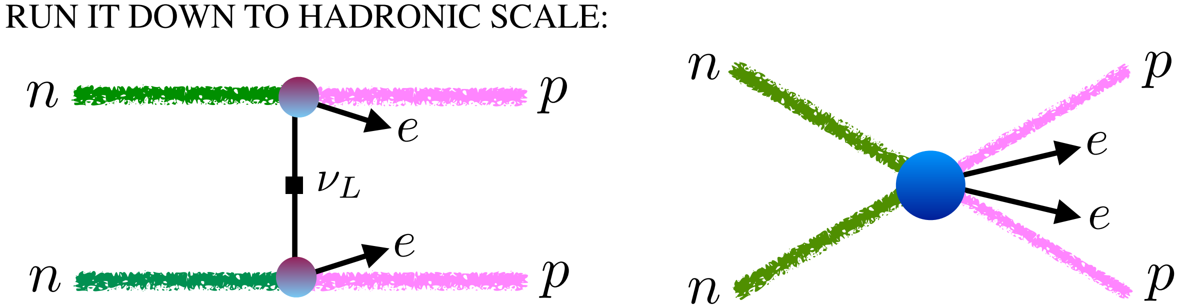


$\Lambda < \text{GeV}$

RUN IT DOWN TO HADRONIC SCALE:



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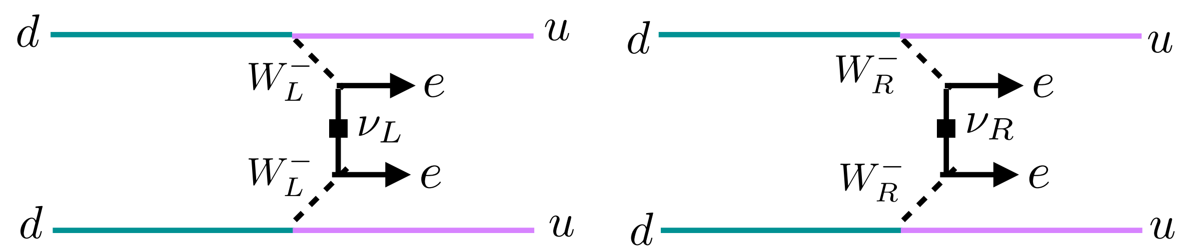

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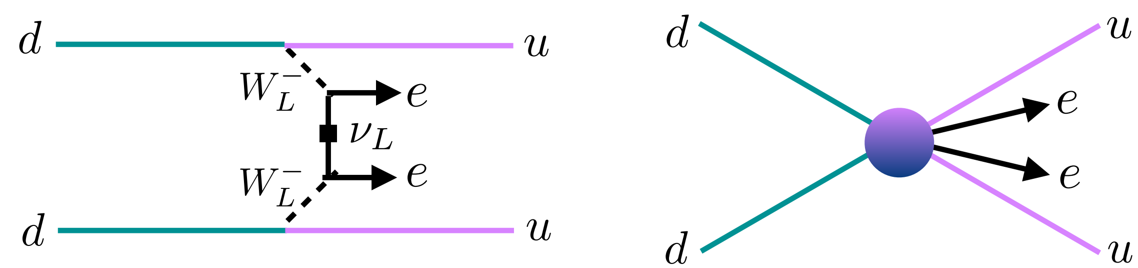

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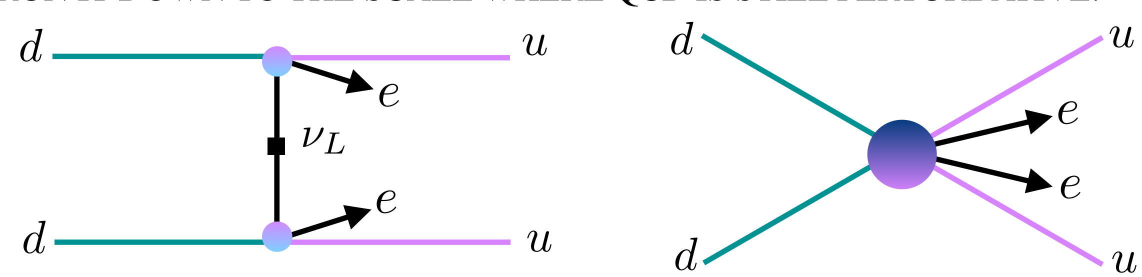

$\Lambda <$ GeV

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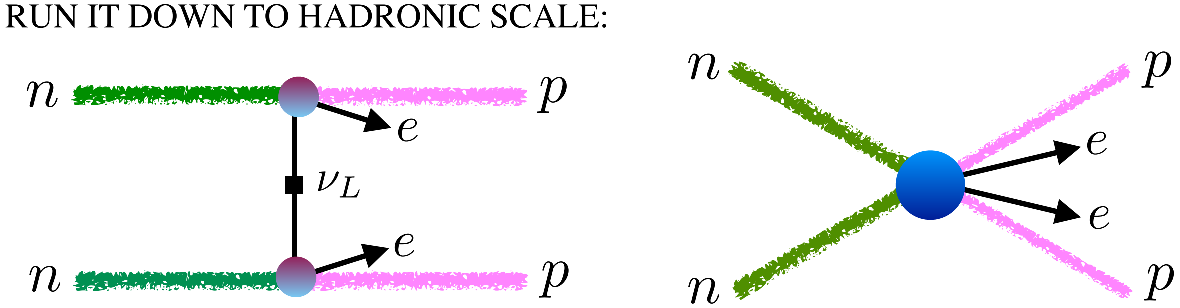
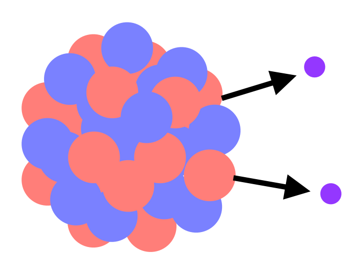


$\Lambda <$ MeV

USE AB INITIO NUCLEAR MANY-BODY CALCULATIONS TO MATCH TO NUCLEAR MATRIX ELEMENTS:



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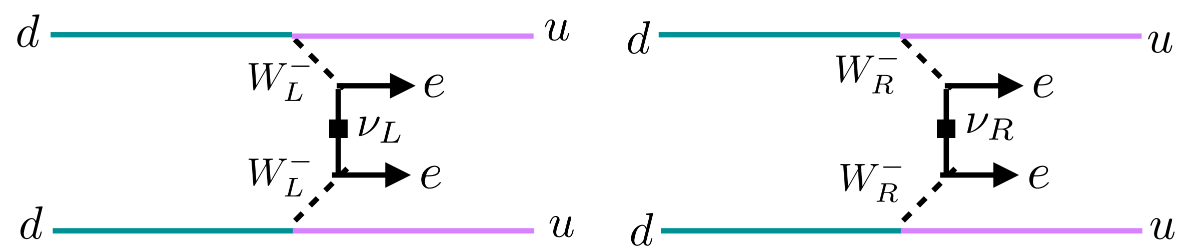

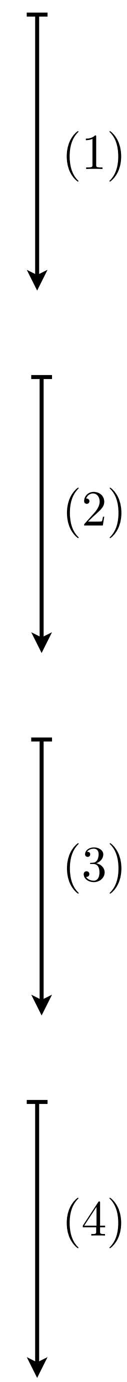

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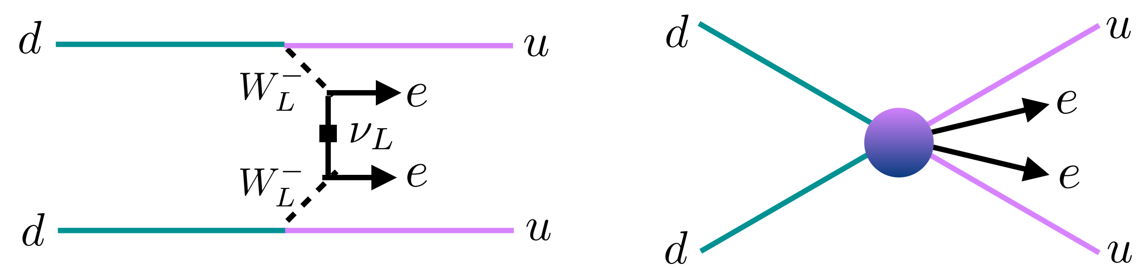

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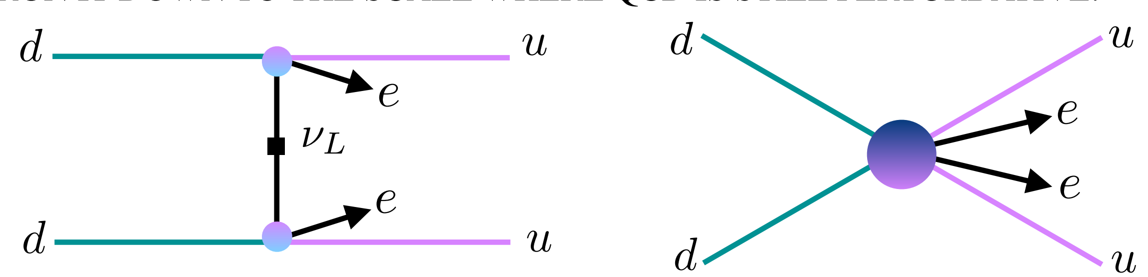

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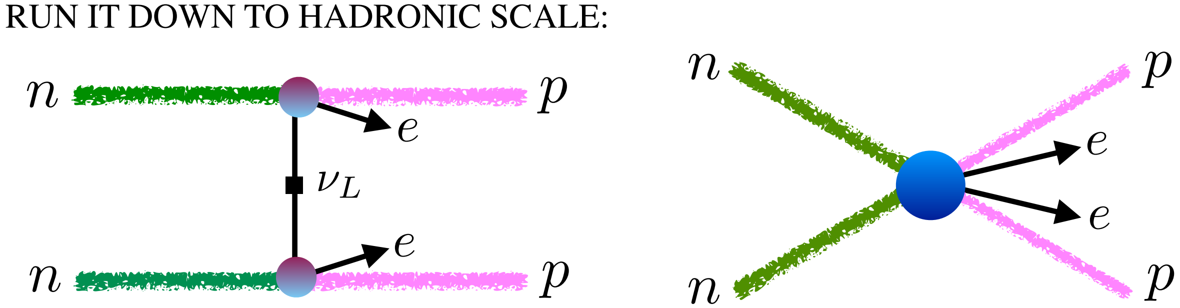
RUN IT DOWN TO HADRONIC SCALE:



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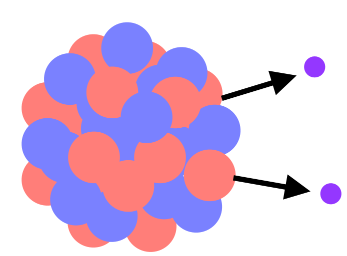
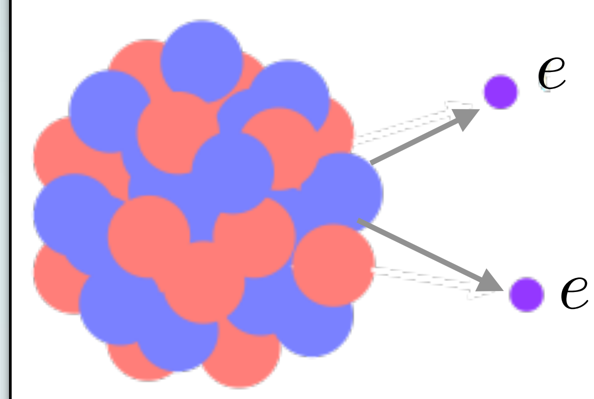


MOTIVATION AND TARGET OBSERVABLES



- Tonne-scale experiment planned in the U.S., design and interpretation of the results requires nuclear MEs in various scenarios.
- LNV from dimension-5 operator (light Majorana neutrino exchange)
- LNV from dimension-9 operators (“short-distance” mechanisms). requires MEs of 4-quark charge-changing operators

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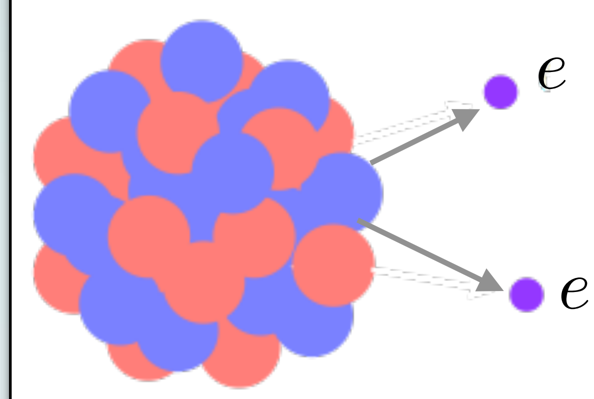

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$$\langle \pi^+ | S_{NL} | \pi^- \rangle, \ \langle p\pi^+ | S_{NL} | n \rangle, \ \langle pp | S_{NL} | nn \rangle$$

$$S_{NL} = \int dx\, dy\, S_0(x-y)\; T\left(J_\alpha^+(x) J_\beta^+(y)\right)\; g^{\alpha\beta}$$

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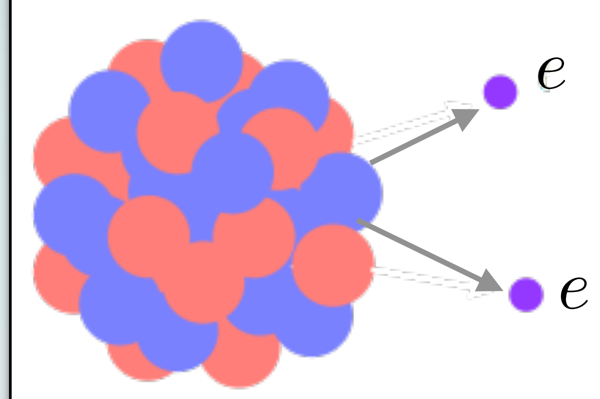

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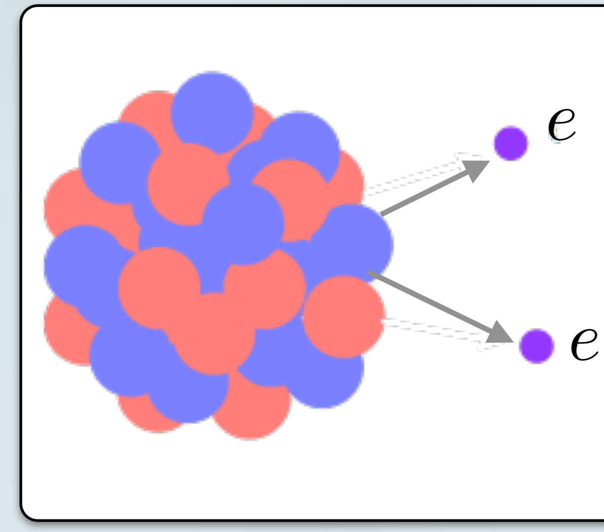
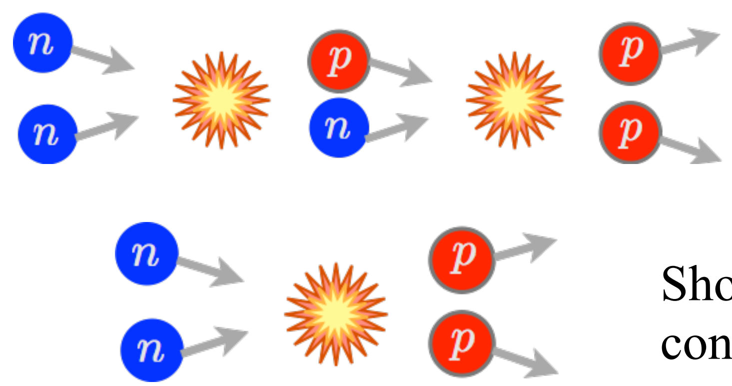
$$\langle \pi^+ | O_i | \pi^- \rangle, \langle p\pi^+ | O_i | n \rangle, \ \langle pp | O_i | nn \rangle$$

PROGRESS REPORT

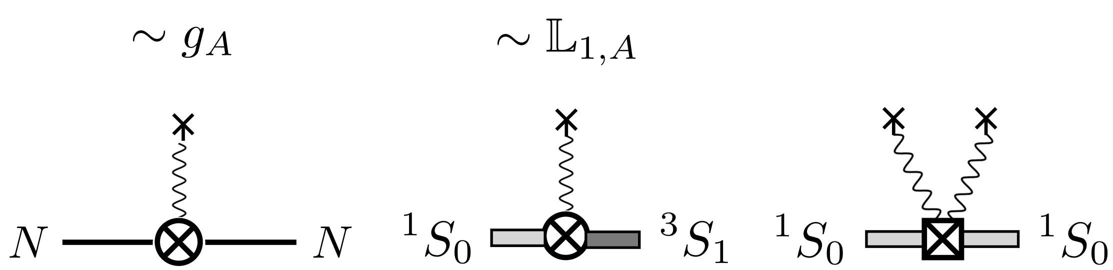


2νββ DECAY



Long-range contribution

Short-range contribution

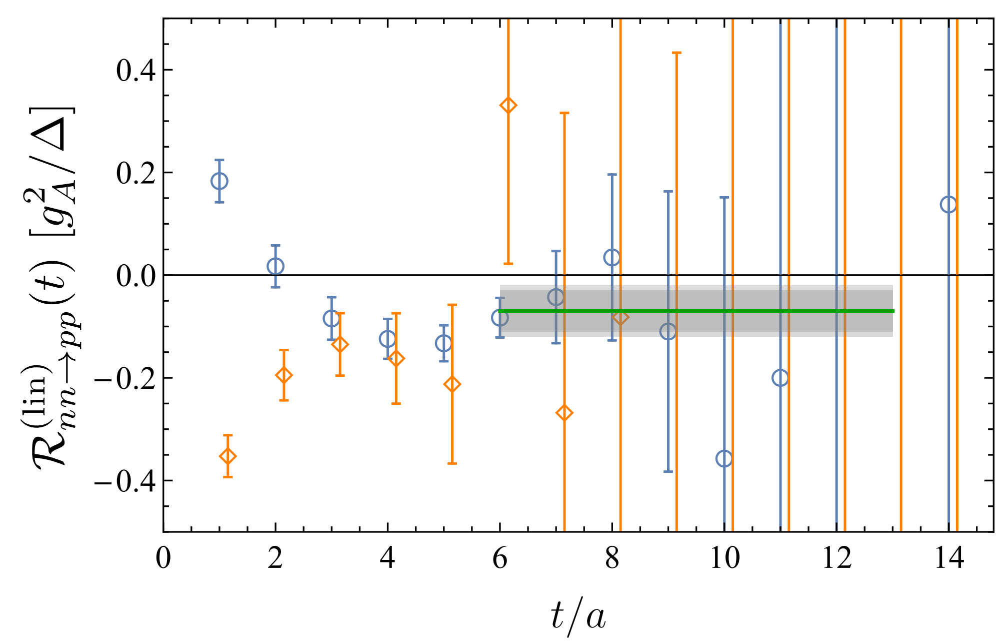


$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \text{fm}$$

$@\ m_\pi \approx 800$ MeV

Constraint on the new short-range LEC.

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

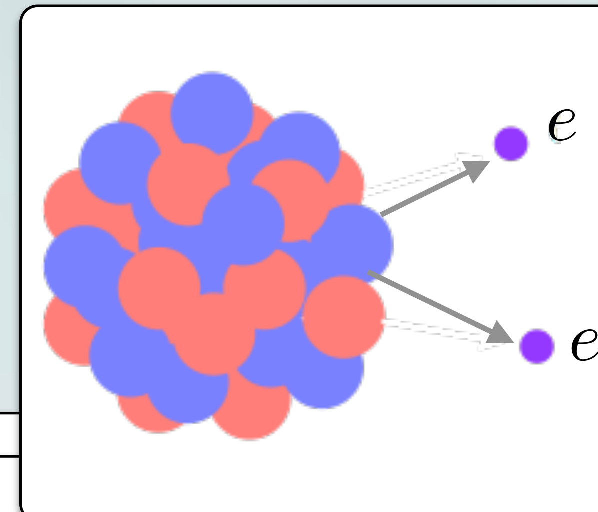


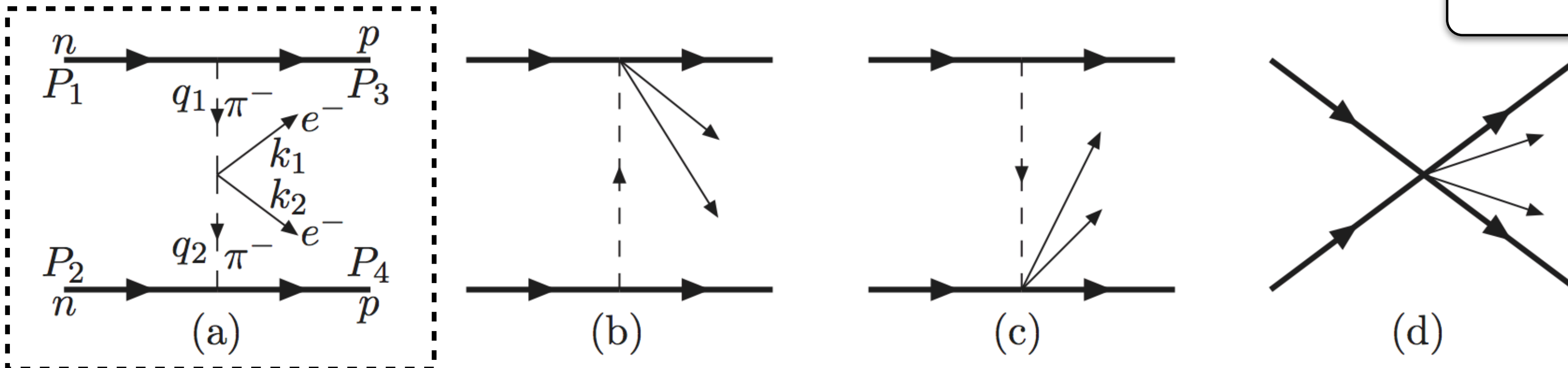
STATE OF THE ART: NPLQCD collaboration, Phys.Rev.Lett. 119, 062003 (2017), Phys.Rev.D 96, 054505 (2017).

See also Feng et al arXiv:1809.10511 [hep-lat] and Detmold et al, arXiv:1811.05554 [hep-lat] for the initial steps towards neutrinoless *BB decay of the pion.*

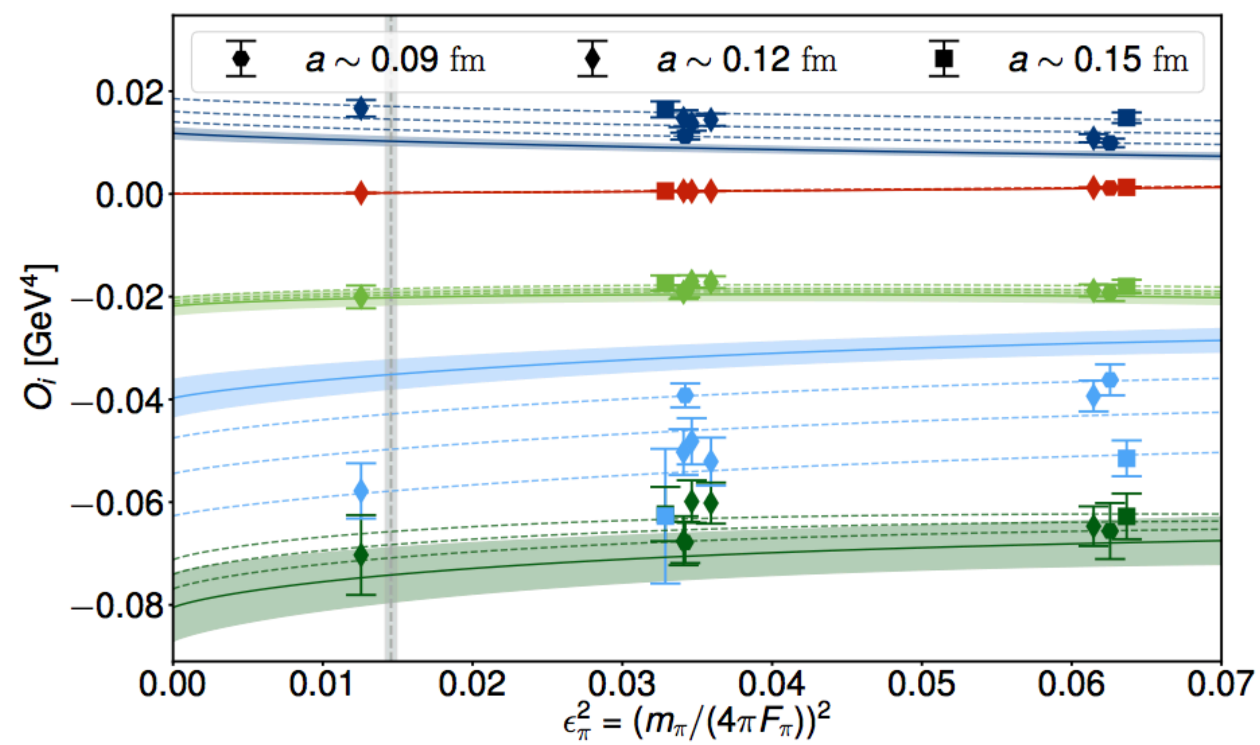
PROGRESS REPORT

0νββ DECAY

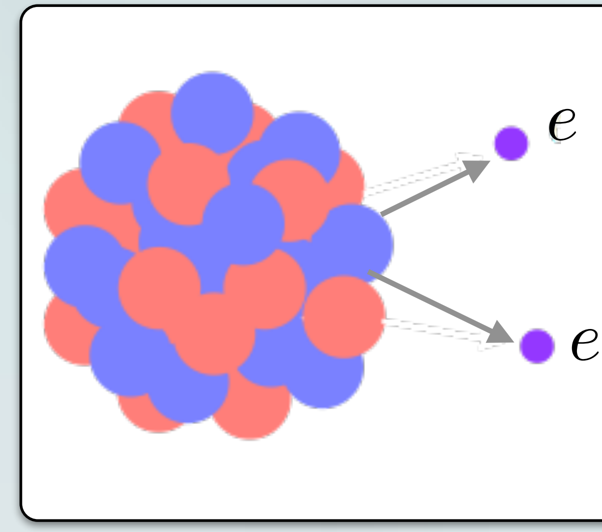




$$\langle \Omega | \Pi^+(t_f, \mathbf{p}_f)\, \mathcal{O}(0)\, \Pi^+(t_i, \mathbf{p}_i) | \Omega \rangle$$



STATE OF THE ART: CALLATT collaboration, Phys. Rev. Lett. 121, 172501 (2018).



TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND

STRAIGHTFORWARD CALCULATIONS

Pion matrix elements of local operators (almost done).

CHALLENGING CALCULATIONS

Two-nucleon and nucleon-pion matrix elements of local operators.

Pion matrix element in light *v* exchange scenario

Two-nucleon matrix element in light *v* exchange scenario at large quark masses

EXTREMELY CHALLENGING CALCULATIONS

Fully controlled physical point *NN* matrix elements in light *v* exchange scenario

More ambitious: higher-*n* matrix elements to diagnose any potential issues with many-body calculations of *0vBB* decay.

TO BE ACCOMPLISHED WITHIN LQCD
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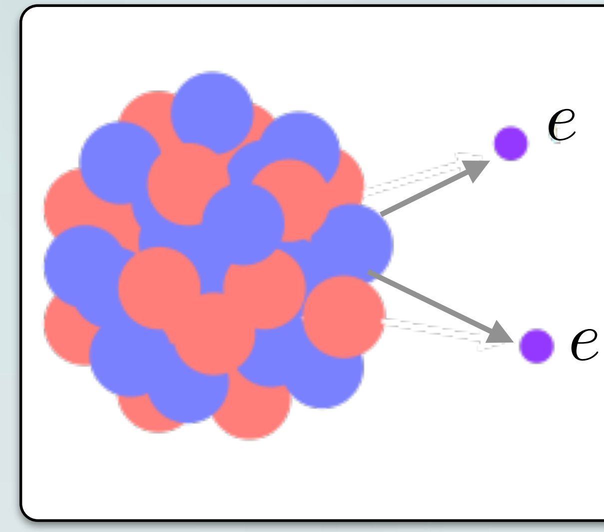

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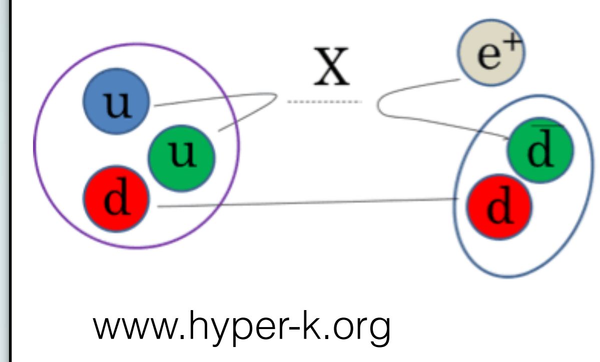
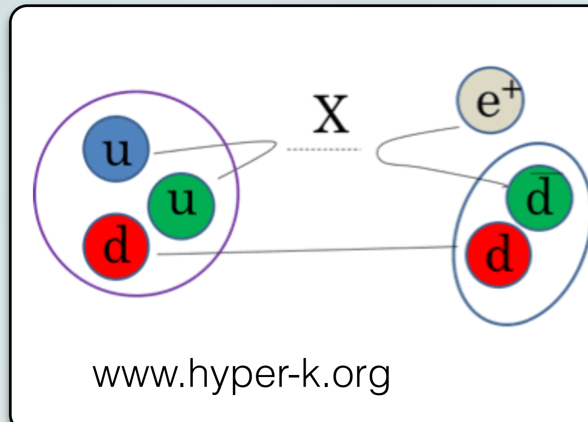


- GUT and SUSY-GUT constraints require $p \to$ meson MEs. Some models predict suppression of p decay MEs due to nonperturbative dynamics.

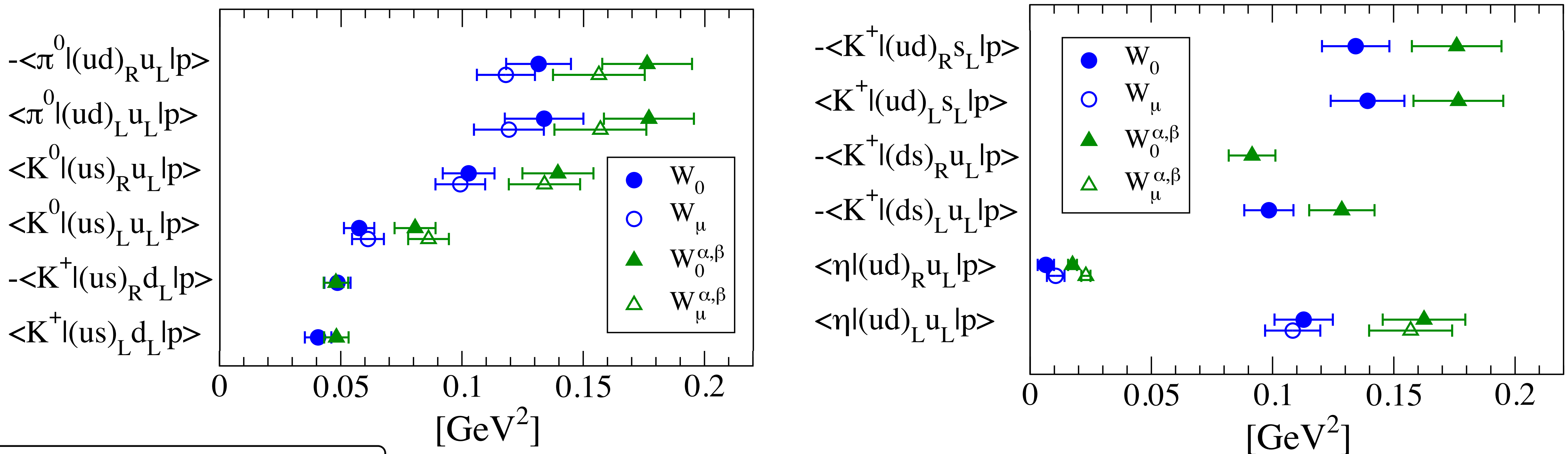
- Upcoming DUNE will examine $p \to Kl\nu$ and $p \to \pi\pi e^+$ decays with better precision, future hyper-K will further improve p-decay constraints.

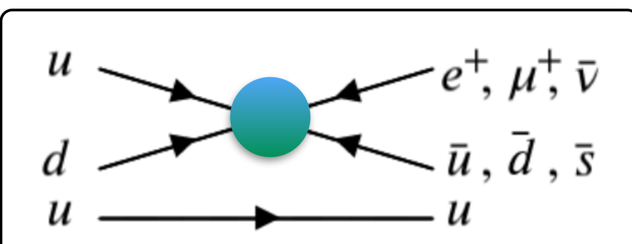
$$\langle \pi^0 | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L u^k | p \rangle$$
$$\langle \pi^+ | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L d^k | p \rangle$$

PROGRESS REPORT



Form factors parametrizing the shown normalized matrix elements at given values of momentum transfer:





STATE OF THE ART RBC collaboration, Y. Aoki et al., Phys. Rev. D 96, 014506 (2017).

TO BE ACCOMPLISHED WITHIN LQCD
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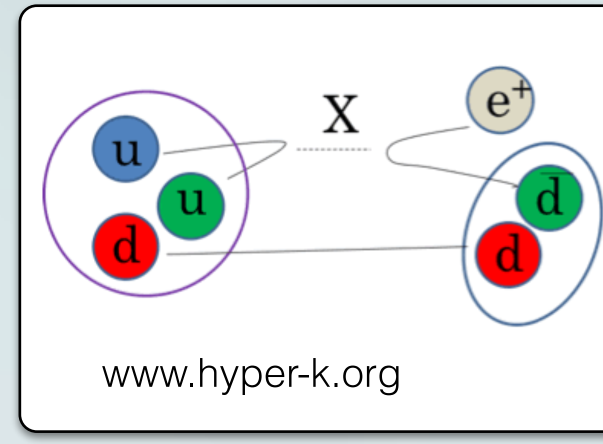


STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

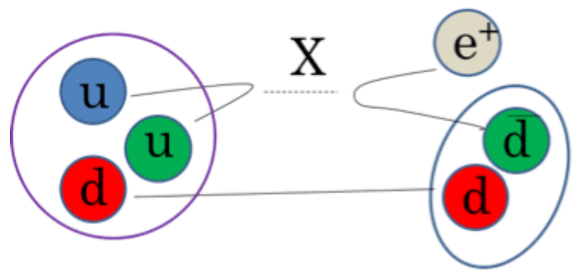
EXTREMELY CHALLENGING CALCULATIONS

Physical-point calculations with controlled systematic (multiple volumes, lattice spacing, etc.)

MEs for $p \to \pi\pi e^+$ at a range of quark masses and at the physical point

Proton decay in nuclear medium, i.e., $NN \to NP$ with P being the pseudo-scalar meson.

TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND



www.hyper-k.org

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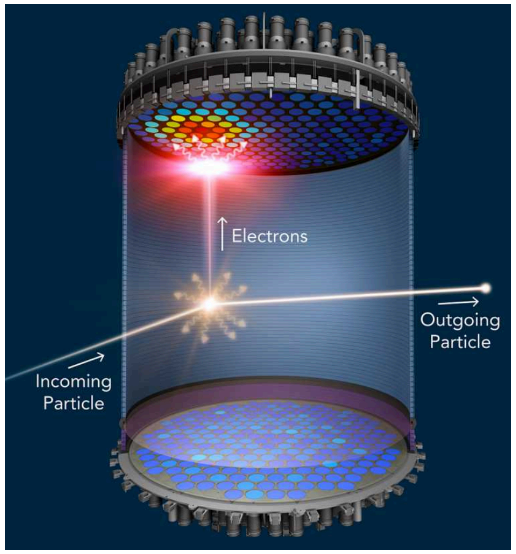
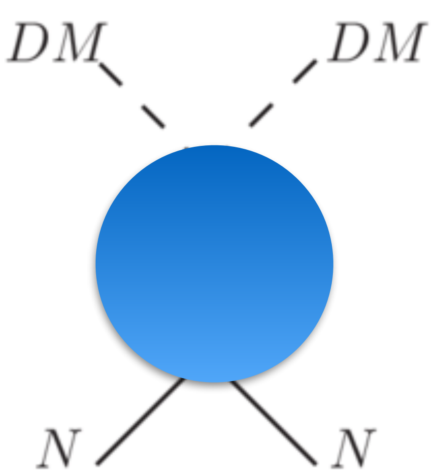


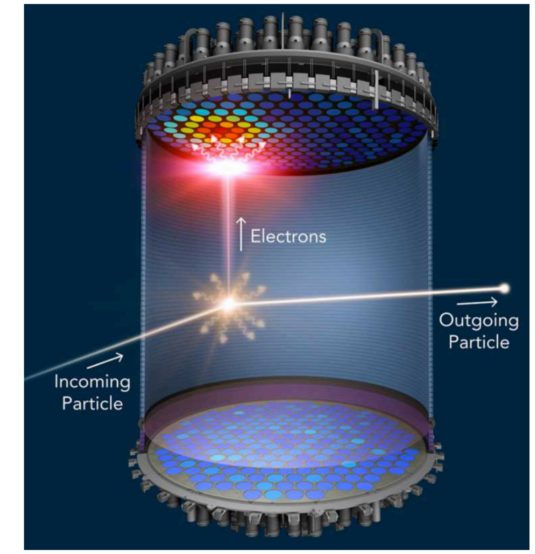
MOTIVATION AND TARGET OBSERVABLES

- Standard Model input is necessary to interpret the results of DM searches and translate these into limits on DM models.



- The low-energy limit of a generic spin-independent interaction is scalar coupling to any quark flavor.
- LQCD is the key tool to obtain the strange contributions.
- Spin-dependent couplings and other interactions require knowledge of parton structure of nuclei.

PROGRESS REPORT

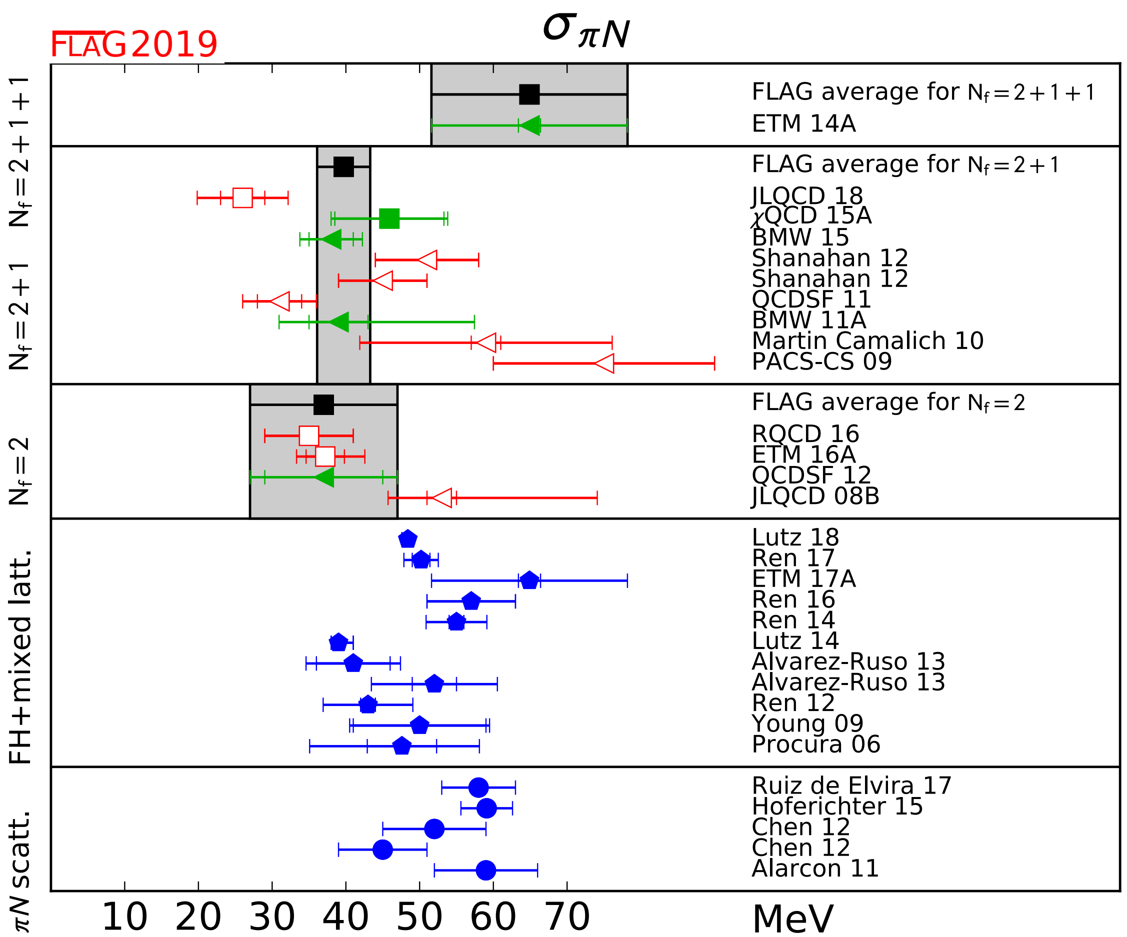


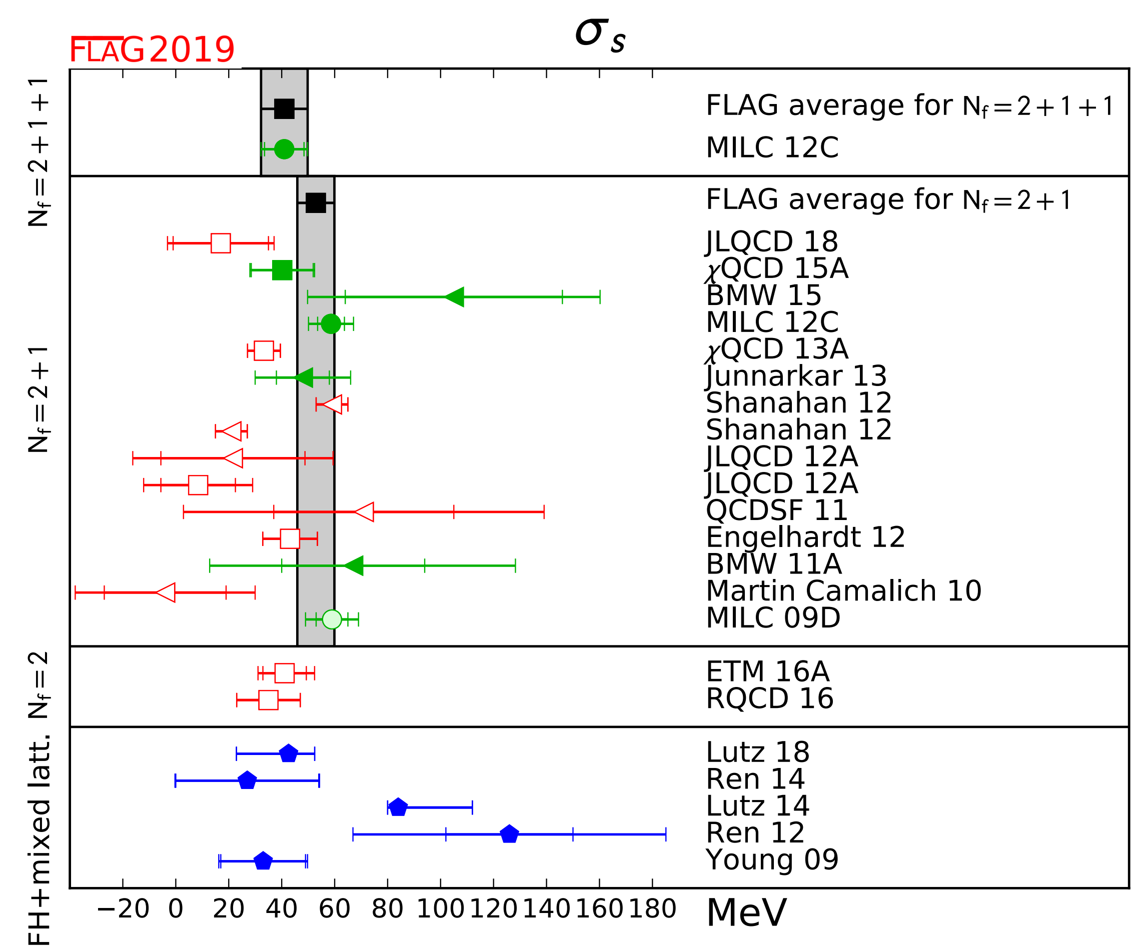
SIGMA TERMS IN NUCLEON

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle$$

χQCD
MILC

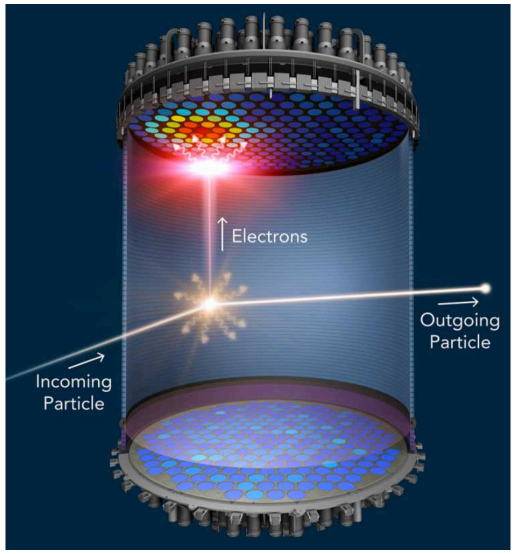
$$\sigma_s = m_s\langle N|\bar{s}s|N\rangle$$





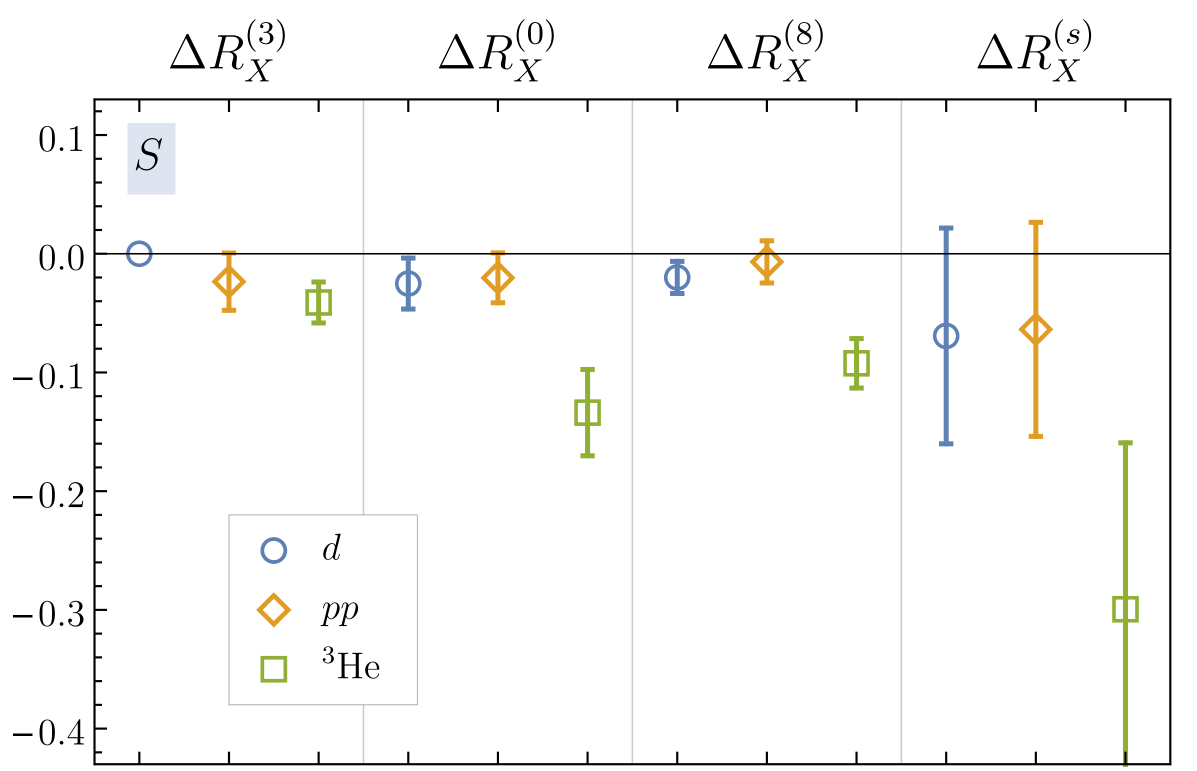
STATE OF THE ART: 10%-15% UNCERTAINTY ON SCALAR MEs IN NUCLEON, e.g., YANG et al., Phys. Rev. D 94, 054503 (2016).

PROGRESS REPORT

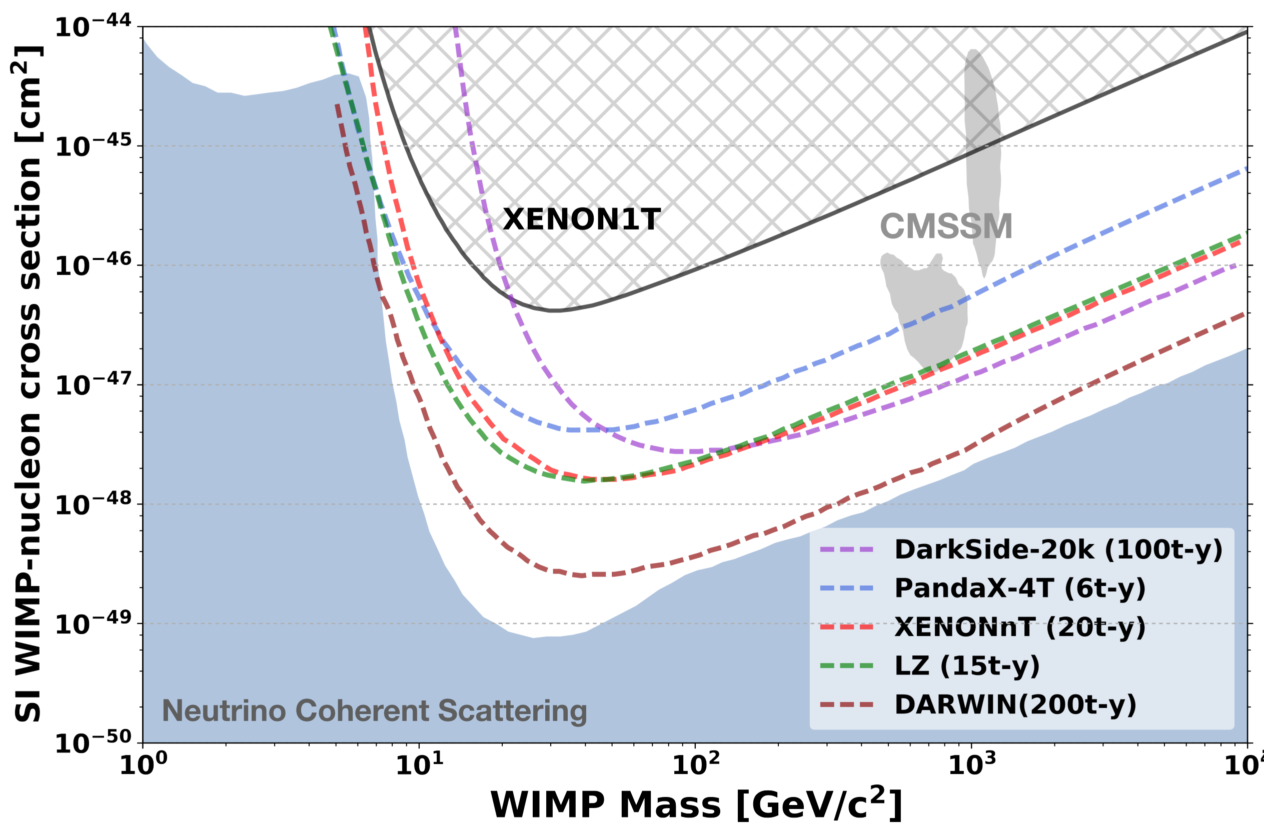


SCALAR RESPONSE OF LIGHT NUCLEI

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

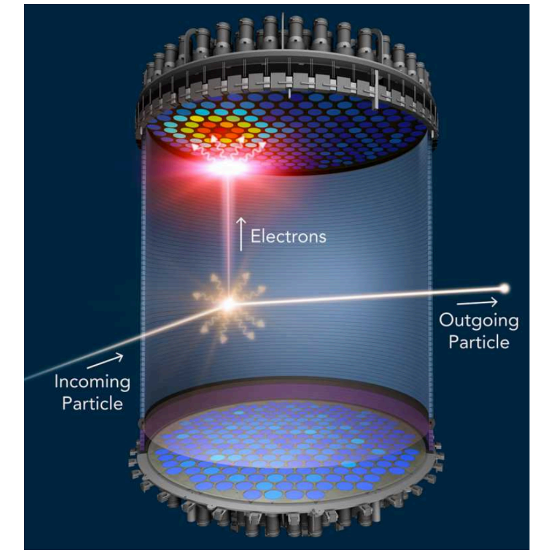


Direct detection of WIMP by 2025?



Courtesy of Kaixuan Ni

Chang et al, NPLQCD collaboration, Phys. Rev. Lett. 120, 152002 (2018).



TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND

STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

EXTREMELY CHALLENGING CALCULATIONS

Few-percent precision on nucleon matrix elements

Spin-dependent interactions, PDF of nucleons, etc.

Fully controlled 2 and 3 nucleon matrix elements (disconnected, multiple lattice spacings, volumes, chiral extrapolation). Scalar MEs are the priority.

Direct evaluation in larger nuclei

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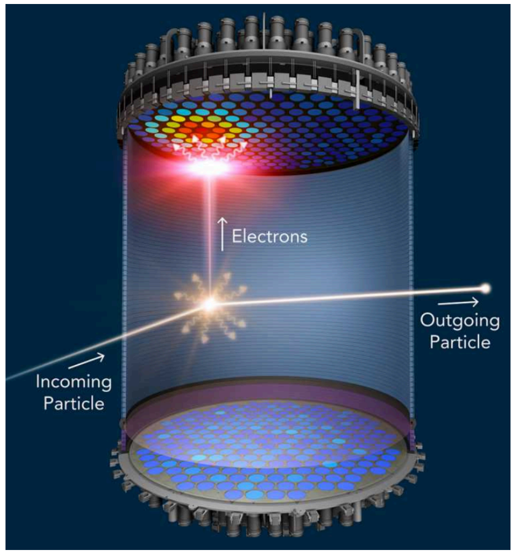

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Direct evaluation in larger nuclei

PROJECTED UNCERTAINTY ON NUCLEON AND NUCLEAR MATRIX ELEMENTS WITHIN LQCD EXT-III

Nucleon g_A^{u-d}	1%*	$F_A(q^2)$	Neutron lifetime puzzle
Nucleon g_T^{u-d}	1%	1.5%	UCNB, Nab
Nucleon g_S^{u-d}	3%	1.5%	UCNB, Nab
$\sigma_{\pi N}$, σ_s	5%	2%	Mu2e, LZ, CDMS
Nucleon r_E, r_A	5%	$F_A(q^2)$	DUNE, MicroBooNE, NOvA, T2K
Nucleon $F_A(q^2)$	8%	15%	DUNE, MicroBooNE, NOvA, T2K
Nucleon tensor	20%	3%	DUNE, MicroBooNE, NOvA, T2K
Nucleon PDFs	12%*	15%	ATLAS, CMS, DUNE
Proton decay	10%	–	DUNE, HyperK
$nn \to pp$	50%*	4%	EXO, other $0\nu\beta\beta$ experiments
Nucleon EDM	10%*	3.5%	Neutron, proton EDM experiments
$g_{A,T,S}$, $A \leq 4$	20%*	3%	All neutrino, DM, EDM, ...

Single-nucleon
Multi-nucleon

THE PATH TO TOWARD EXPERIMENTAL QUANTITIES IN THIS PROGRAM

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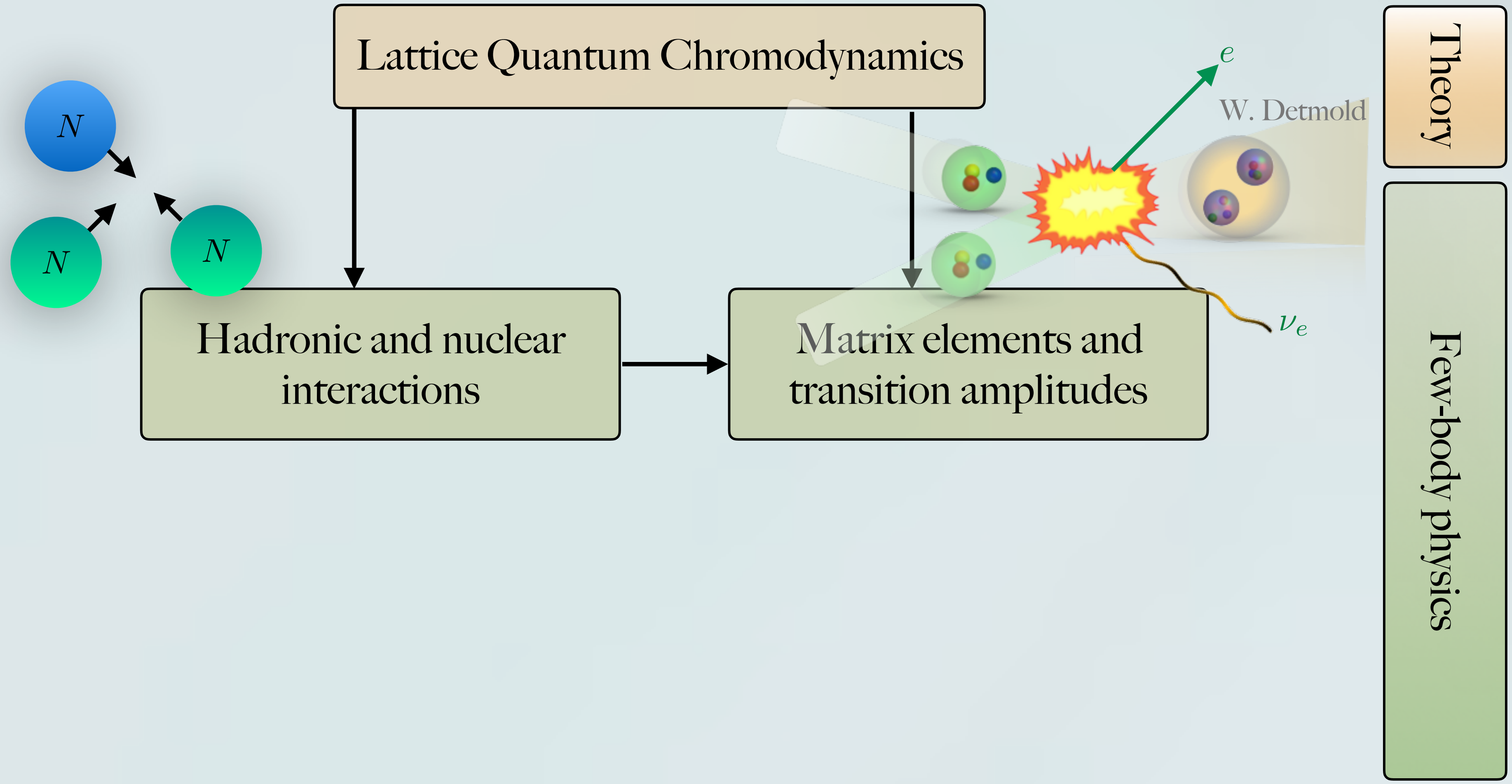
Lattice Quantum Chromodynamics

Theory

THE PATH TO TOWARD EXPERIMENTAL QUANTITIES IN THIS PROGRAM



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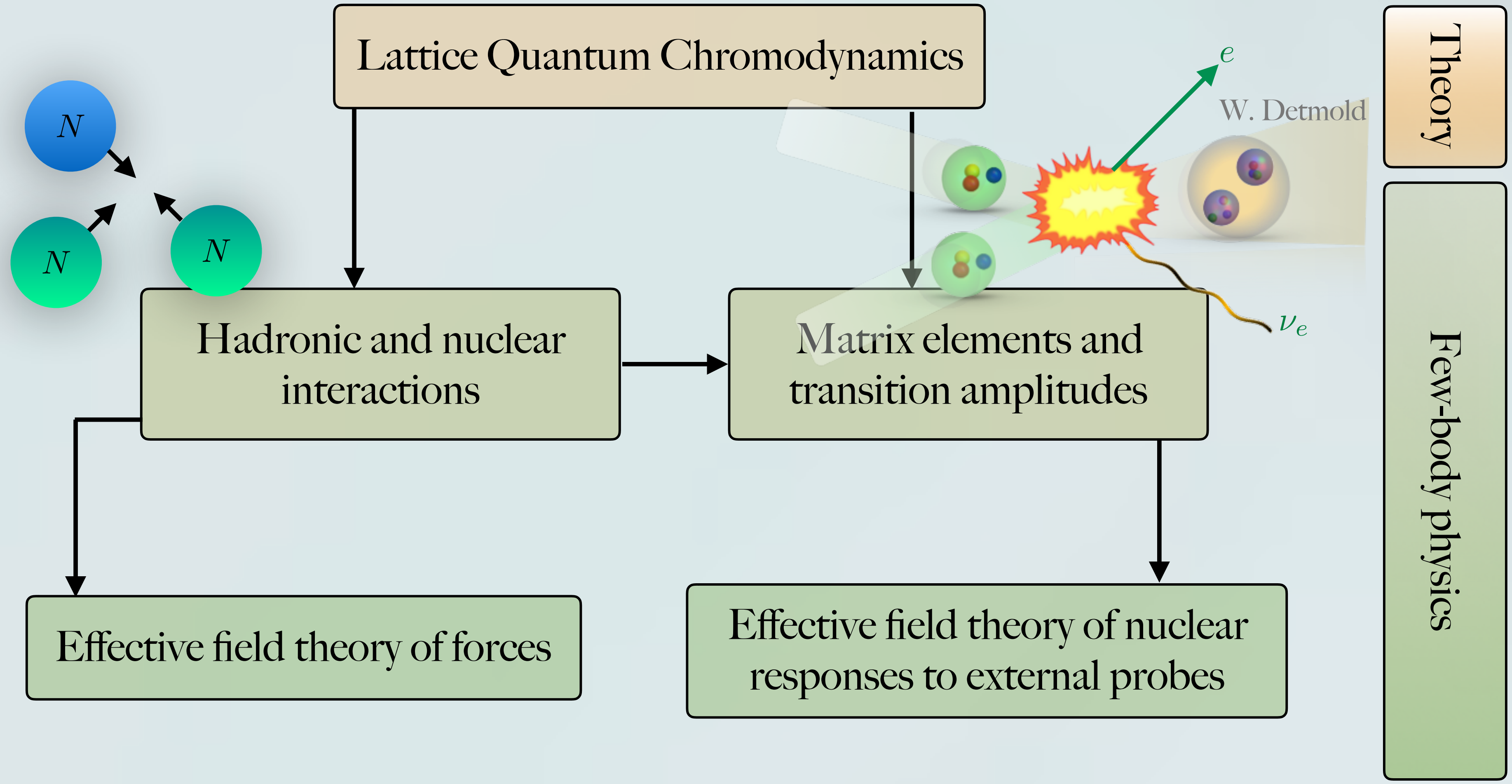

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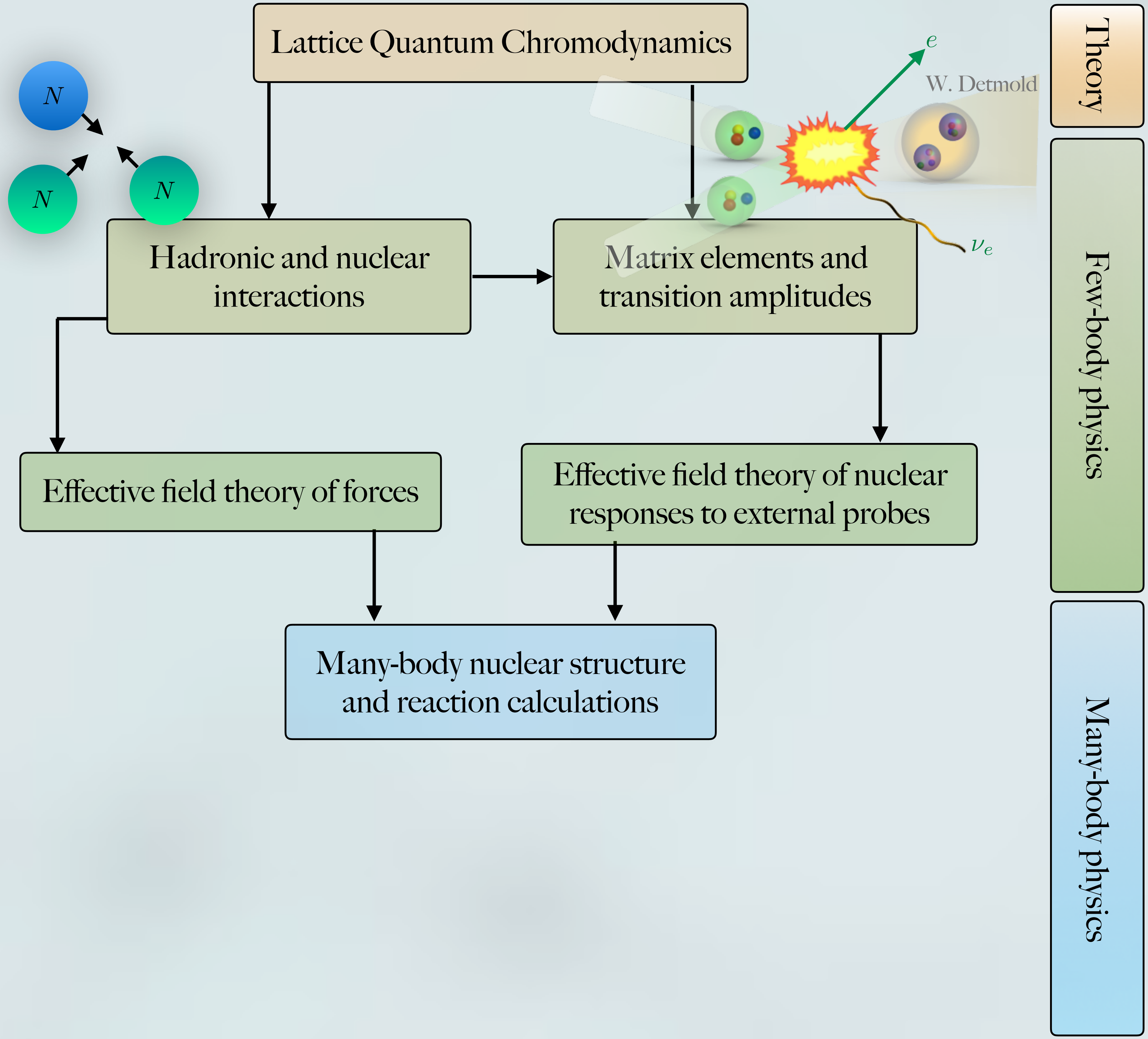

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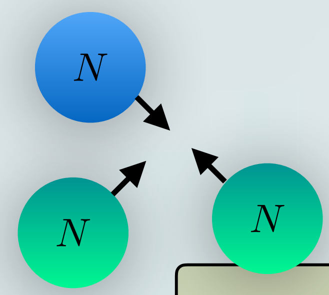
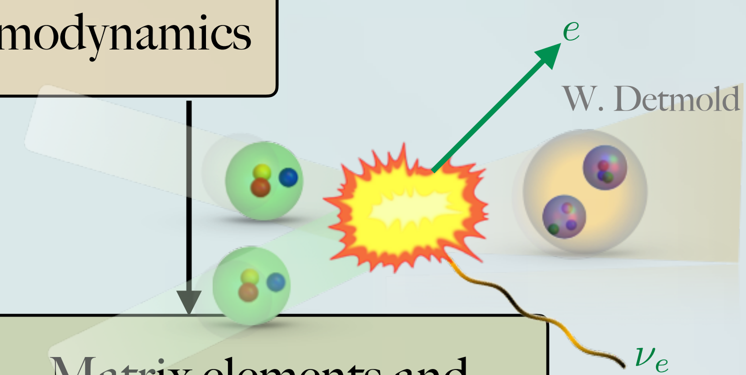
Lattice Quantum Chromodynamics





Hadronic and nuclear interactions

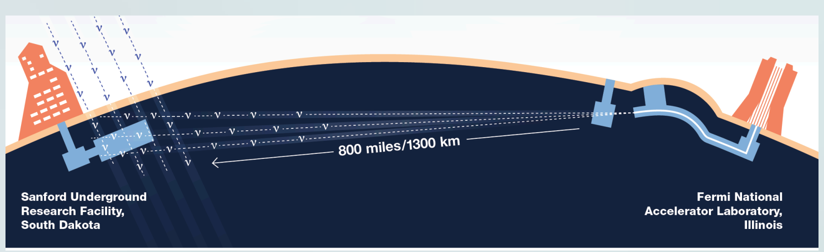
Matrix elements and transition amplitudes

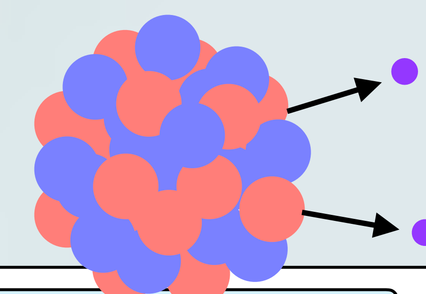
Effective field theory of forces

Effective field theory of nuclear responses to external probes

Many-body nuclear structure and reaction calculations

https://news.fnal.gov/





- Neutrino-nucleus scattering for DUNE
- CP violation in nuclei and atoms
- Lepton-number nonconservation and neutrinoless *BB* decay
- Neutron-antineutron oscillations in nuclei
- muon to electron conversion near nuclear media
- Nature of dark matter and its interactions with ordinary matter
- ⋮

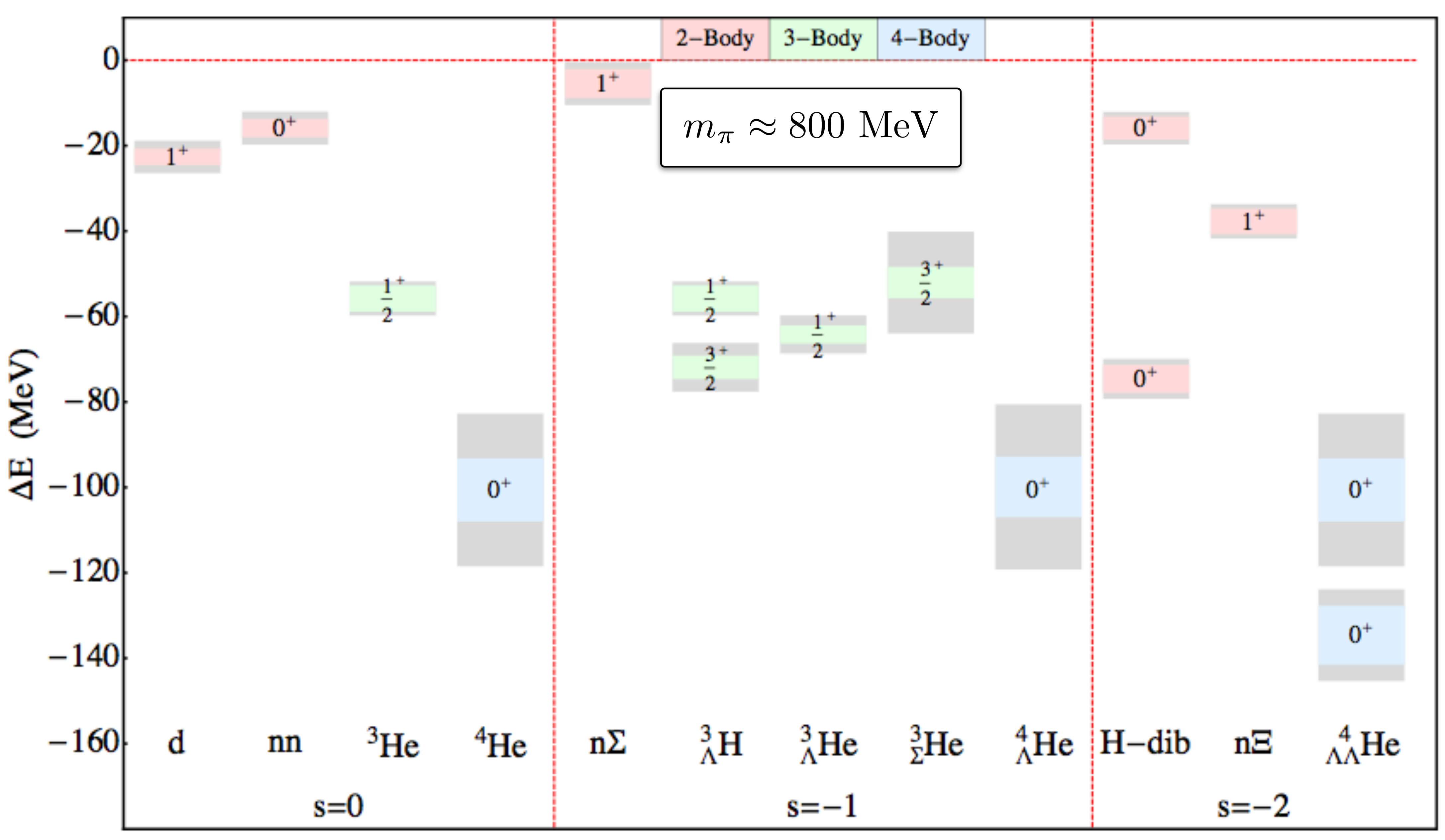
Theory

Few-body physics

Many-body physics

NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS

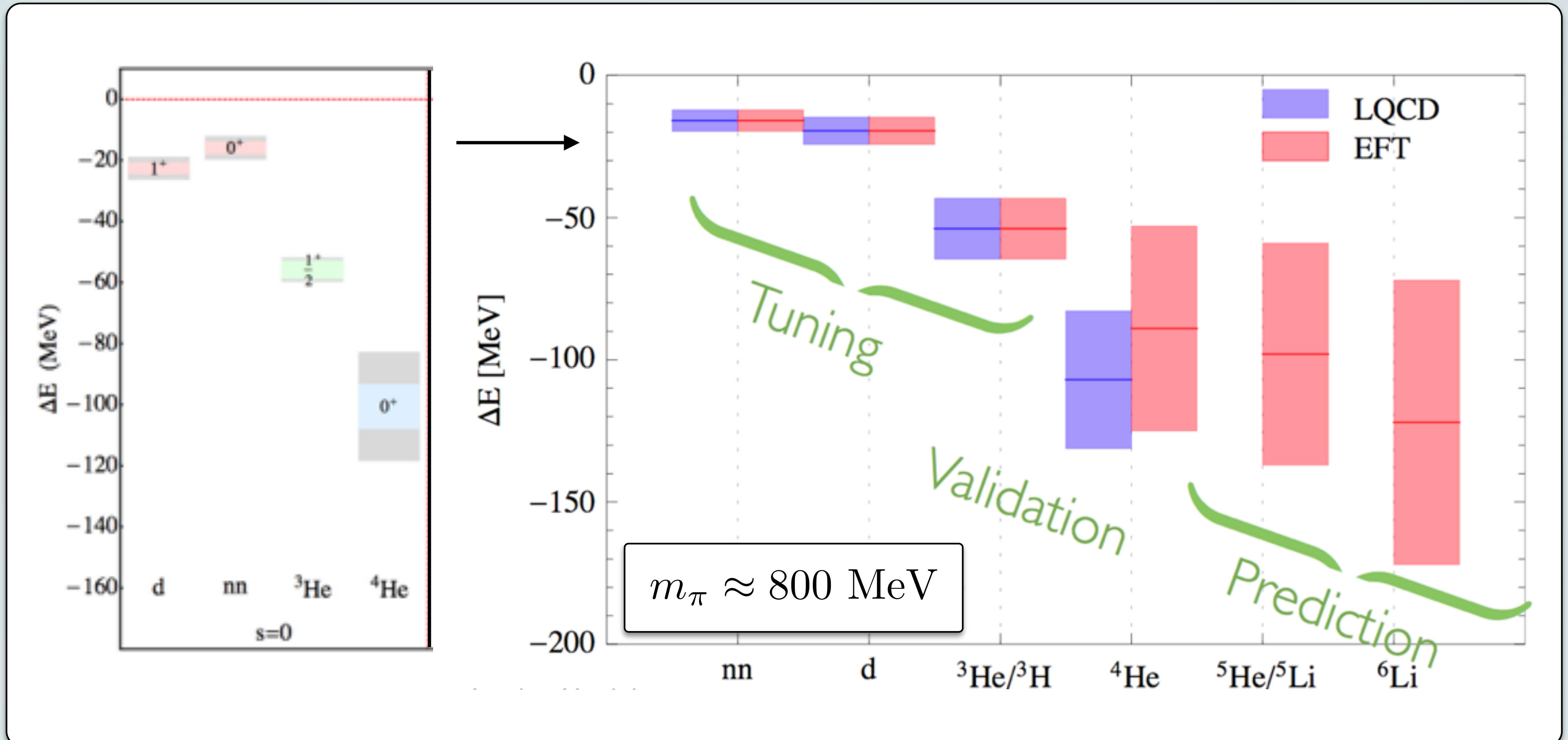
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



NPLQCD collaboration, Beane, et al., Phys.Rev. D87 (2013), Phys.Rev. C88 (2013)

See also USQCD's recent whitepaper on Hadrons and Nuclei.

…MATCHED TO EFTs TO REACH LARGER NUCLEI.



QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

Ground-State Properties of 4He and 16 O Extrapolated from Lattice QCD with Pionless EFT Contessi et al., arXiv:1701.06516.

Effective Field Theory for Lattice Nuclei, Barnea et al, Phys.Rev.Lett. 114 (2015) no.5, 052501.

Physics
Baryon Number Violation and Grand Unified Theories
Baryon Number minus Lepton Number Violation
Lepton Flavor Violation
Lepton Number Violation
CP Violation and Baryon Asymmetry in Universe
Dark Matter and New Physics Searches

TO SUMMARIZE:

A vibrant experimental program is searching for unambiguous signatures of new physics in violation of fundamental symmetries of nature, in direct dark-matter detections and in precision beta decay and isotope shift spectroscopy. These often use nucleon and nuclear targets.

Theorists supporting this program can be divided into to three categories: high-energy physicists building the high-scale models, QCD physicists matching high-scale models to hadronic-scale quantities, and nuclear physicists matching the hadronic quantities to nuclear-scale quantities for experiment. The synergy among these communities will be essential.

USQCD has long identified the impactful calculations in this area and is a key contributor, and often a leader, in the international effort in exploratory as well as mature full-scale computations of quantities relevant to the Fundamental Symmetries program.

The quantities of interest are a set of local (and bi-local) nucleon and nuclear matrix elements associated with SM or beyond the SM quark- and gluon-level currents. Few percent uncertainties in nucleon matrix elements and <50% uncertainties in few-nucleon matrix elements are achievable goals of this program.

Nuclear physicists have already started developing approaches that take full advantage of matching to the QCD input in such multi-scale problems.

BACK-UP SLIDES

Physics	Target Quantity	Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
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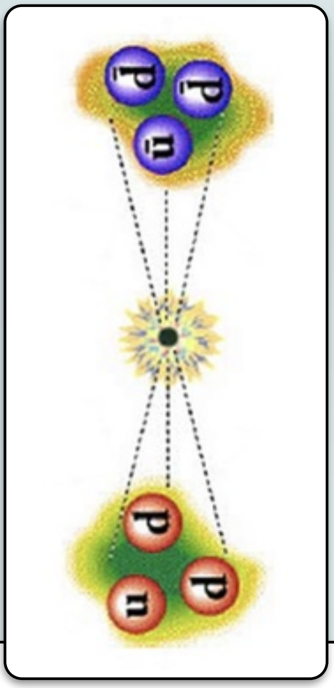
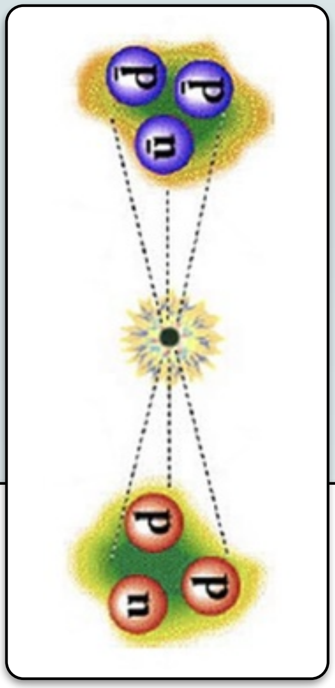
MOTIVATION AND TARGET OBSERVABLES



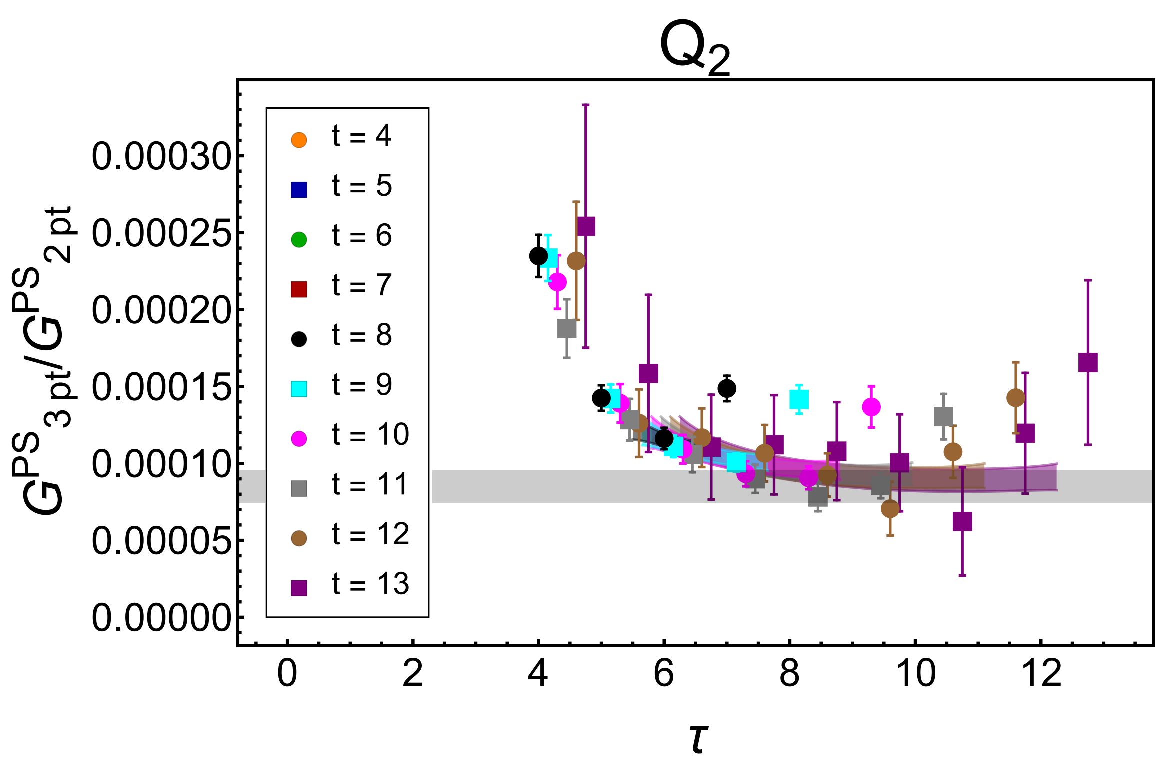
- Some models of B-L violation do not allow the proton decay and neutron-antineutron oscillation bounds can therefore provide powerful constraints.
- Two types of experiments: slow neutron beams and oscillation in nuclear medium with a distinct 5-pion final state.
- Theoretical uncertainties in neutron beam expts easier to control. Bounds could be improved by a factor of 1000 in next experiments.
- LQCD evaluates matrix elements of 6-quark operators that convert a neutron to an antineutron.

$$\frac{1}{\tau_{n\bar{n}}} = \delta m = c_{BSM}(\mu_{BSM}, \mu_W) c_{QCD}(\mu_W, \Lambda_{QCD}) \langle \bar{n} | \mathcal{O} | n \rangle$$

PROGRESS REPORT

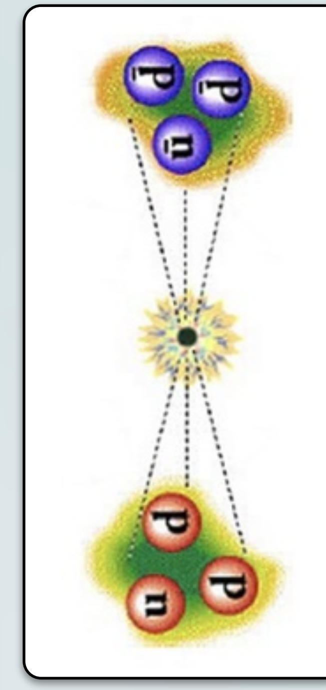


Normalized six-quark operators matrix elements obtained from LQCD at the physical point:



Operator	$\mathcal{M}_I^{\overline{\text{MS}}}$ (2 GeV)	$\mathcal{M}_I^{\overline{\text{MS}}}$ (700 TeV)	$\frac{\mathcal{M}_I^{\overline{\text{MS}}}}{\text{MIT bag A}}$ (2 GeV)	$\frac{\mathcal{M}_I^{\overline{\text{MS}}}}{\text{MIT bag B}}$ (2 GeV)
Q_1	$-46(13)$	$-26(7)$	4.2	5.2
Q_2	$95(17)$	$144(26)$	7.5	8.7
Q_3	$-50(12)$	$-47(11)$	5.1	6.1
Q_5	$-1.06(48)$	$-0.23(10)$	-0.8	1.6

STATE OF THE ART: Rinaldi et al.,arXiv:1809.00246 [hep-lat].



TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND

STRAIGHTFORWARD CALCULATIONS

Precision single-neutron matrix elements (sensitive to discretization, chiral symmetry is important).

MEs of 6-quark operators including EM current insertions

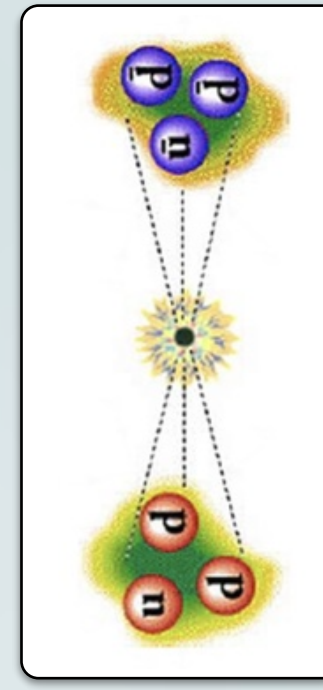
CHALLENGING CALCULATIONS

Neutron-antineutron annihilation matrix element

EXTREMELY CHALLENGING CALCULATIONS

Neutron-antineutron annihilation matrix element in nuclei (deuteron?) for SNO

Multi-nucleon contributions for DUNE/super-K



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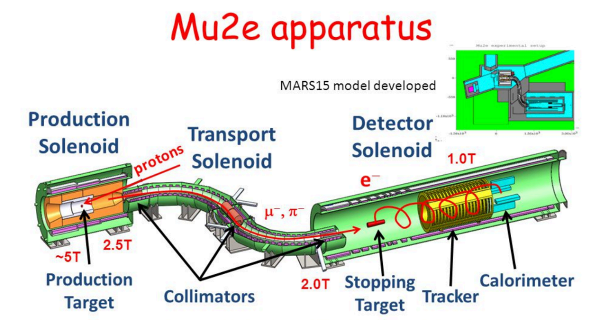
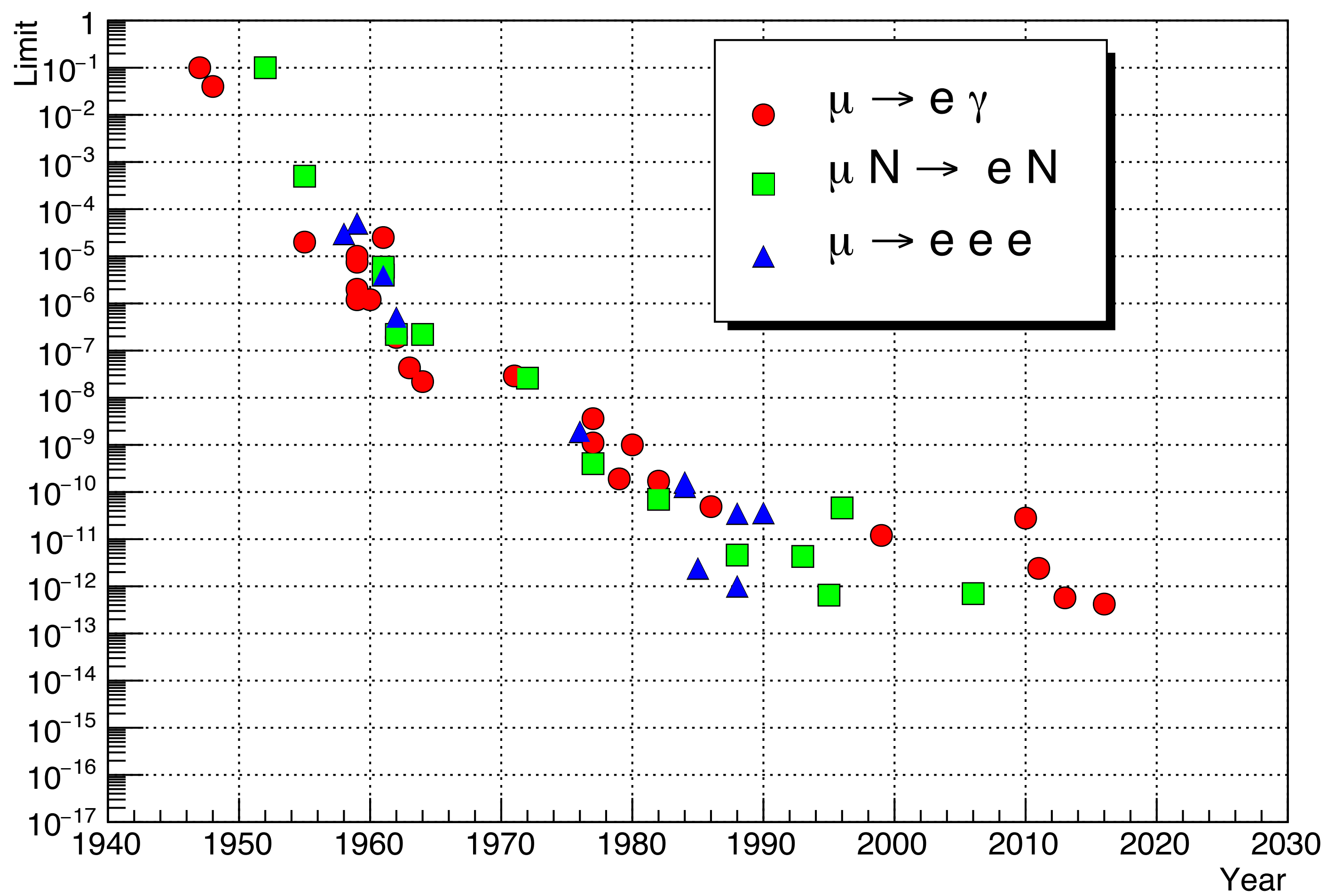
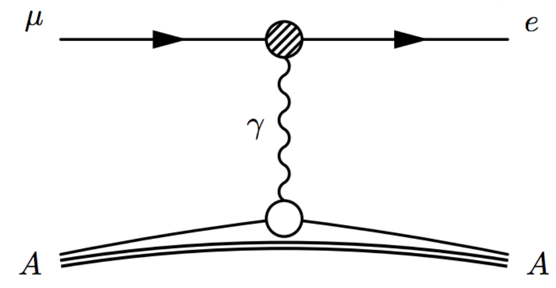
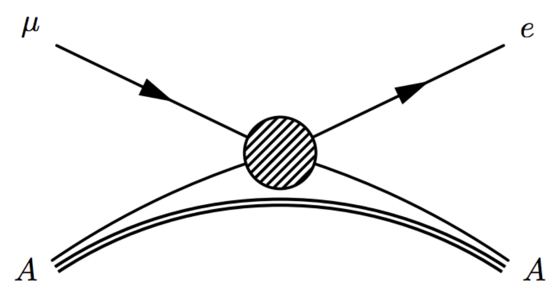


Reliable matrix elements will help establish pattern of LFV signatures in various decay channels depending on the underlying mechanism.



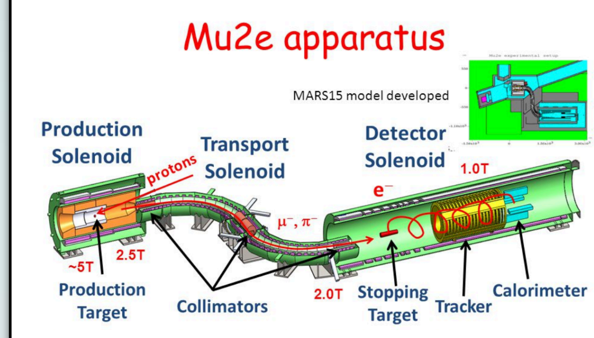


$$\mathcal{L}_d \sim \frac{1}{\Lambda^2} m_\mu \bar{\mu}_L \sigma_{\mu\nu} e_R F^{\mu\nu}$$



$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L \right)$$

TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND



STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

EXTREMELY CHALLENGING CALCULATIONS

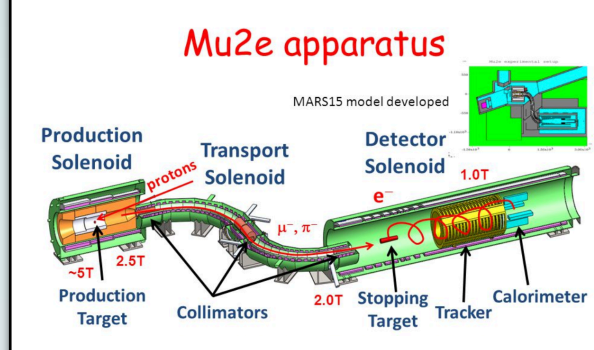
Nucleon form factors (scalar, vector, axial, tensor, pseudoscalar) at $q^2 = m_\mu^2$.

Most relevant is the set of scalar form factors (with *u*, *d*, *s* flavor) and *GG* gluonic operator.

Few-percent precision on nucleon form factors

Going beyond impulse approx: directly evaluating MEs in nuclei (2 and 3 body contributions)

Directly evaluating MEs in larger nuclei



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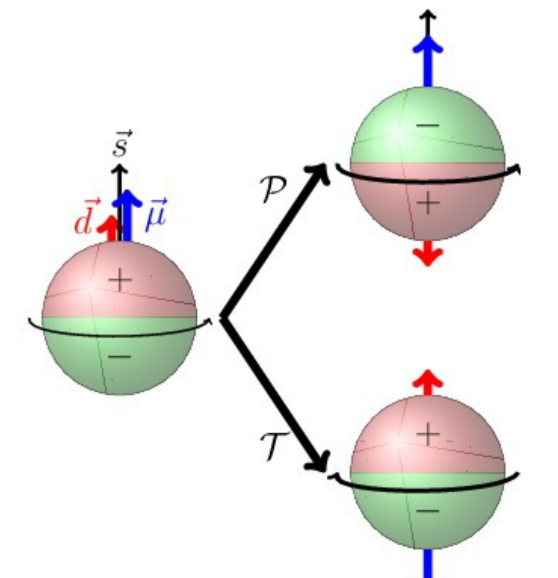


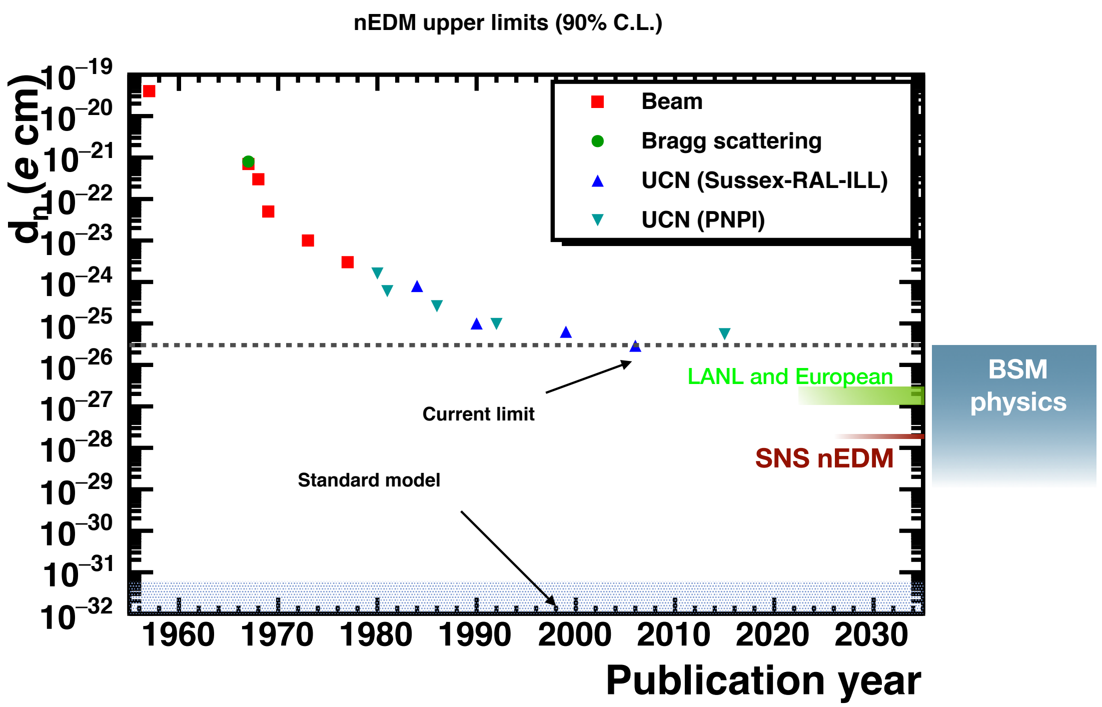
Jörg Pretz

- Permanent EDM of protons, neutrons and nuclei would be the best evidence for CP violation beyond the SM.

- Several neutron EDM experiments are planned (SNS and LANL in the U.S.), improving the limits by 2 orders of magnitude.

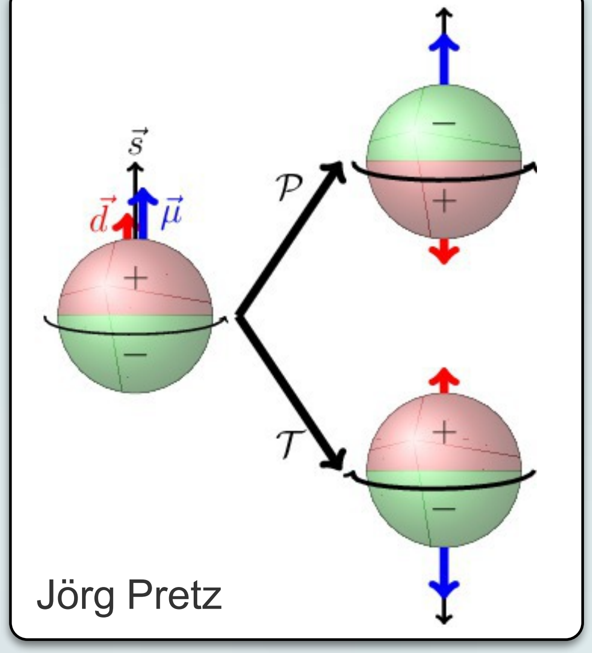
	Current	SM
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
n	10^{-26}	10^{-31}
p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
^{129}Xe	10^{-27}	10^{-33}
^{225}Ra	10^{-23}	10^{-33}

Experimental landscape



STATE OF THE ART: BHATTACHARYA et al., Phys. Rev. Lett. 115, 212002.
IZUBUCHI et al, arXiv:1702.00052 [hep-lat].

MOTIVATION AND TARGET OBSERVABLES



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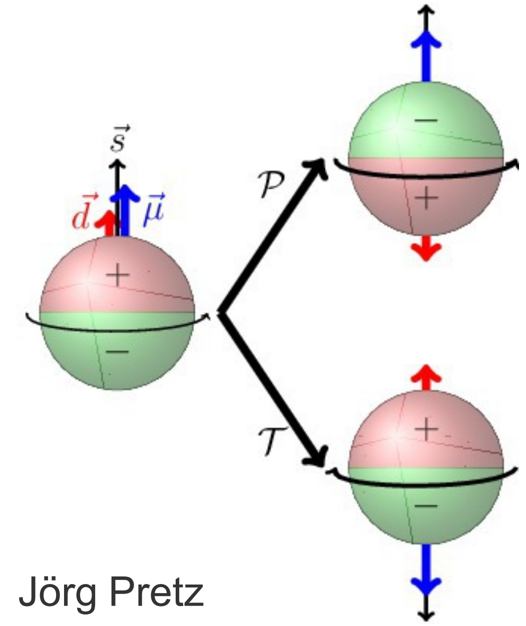

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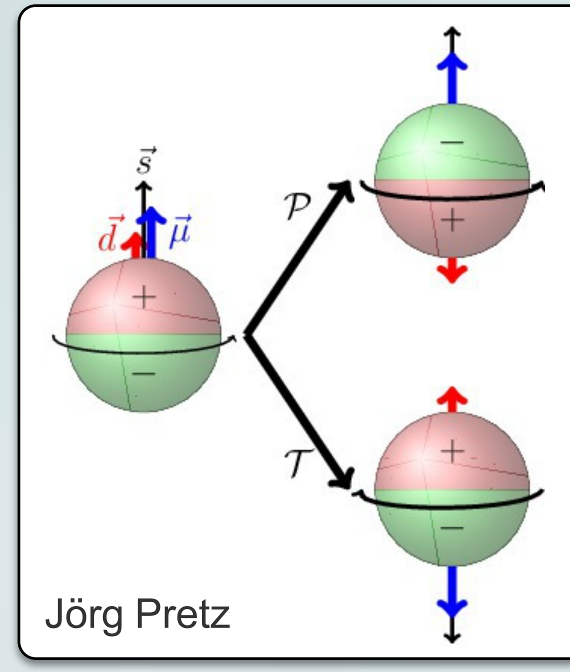
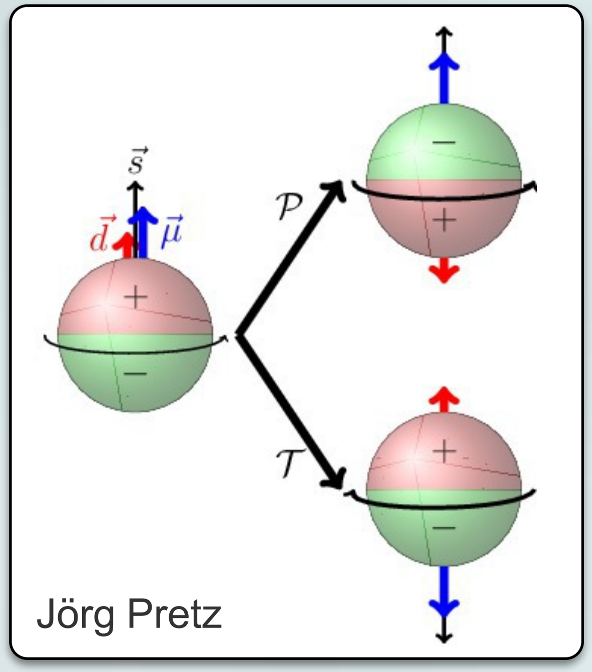
$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma{\cdot}F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma{\cdot}G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

STATE OF THE ART: BHATTACHARYA et al., Phys. Rev. Lett. 115, 212002.
IZUBUCHI et al, arXiv:1702.00052 [hep-lat].



TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND

STRAIGHTFORWARD CALCULATIONS	CHALLENGING CALCULATIONS	EXTREMELY CHALLENGING CALCULATIONS
θ_{QCD} -induced *p*/*n*EDM at large quark masses	θ_{QCD} -induced *p*/*n*EDM at physical point	4-quark-induced *p*/*n*EDM requires 4pt functions, and often disconnecteds contb.
Isovector *q*chromo-EDM-induced *n*EDM at the physical point	Isoscalar *q*chromo-EDM-induced *n*EDM at the physical point, requires subtraction of the first item.	*piNN* and *NNNN* CP violating interactions
Weinberg *GGG*-induced *p*/*n*EDM at large quark masses	Weinberg *GGG*-induced *p*/*n*EDM at the physical point, again mixing with first item	EDM in deuteron and light nuclei



TO BE ACCOMPLISHED WITHIN LQCD EXT-III AND BEYOND

STRAIGHTFORWARD CALCULATIONS	CHALLENGING CALCULATIONS	EXTREMELY CHALLENGING CALCULATIONS
$\theta_{\rm QCD}$ -induced *p*/*n*EDM at large quark masses	$\theta_{\rm QCD}$ -induced *p*/*n*EDM at physical point	4-quark-induced *p*/*n*EDM requires 4pt functions, and often disconnecteds contb.
Isovector *q*chromo-EDM-induced *n*EDM at the physical point	Isoscalar *q*chromo-EDM-induced *n*EDM at the physical point, requires subtraction of the first item.	*piNN* and *NNNN* CP violating interactions
Weinberg *GGG*-induced *p*/*n*EDM at large quark masses	Weinberg *GGG*-induced *p*/*n*EDM at the physical point, again mixing with first item	EDM in deuteron and light nuclei