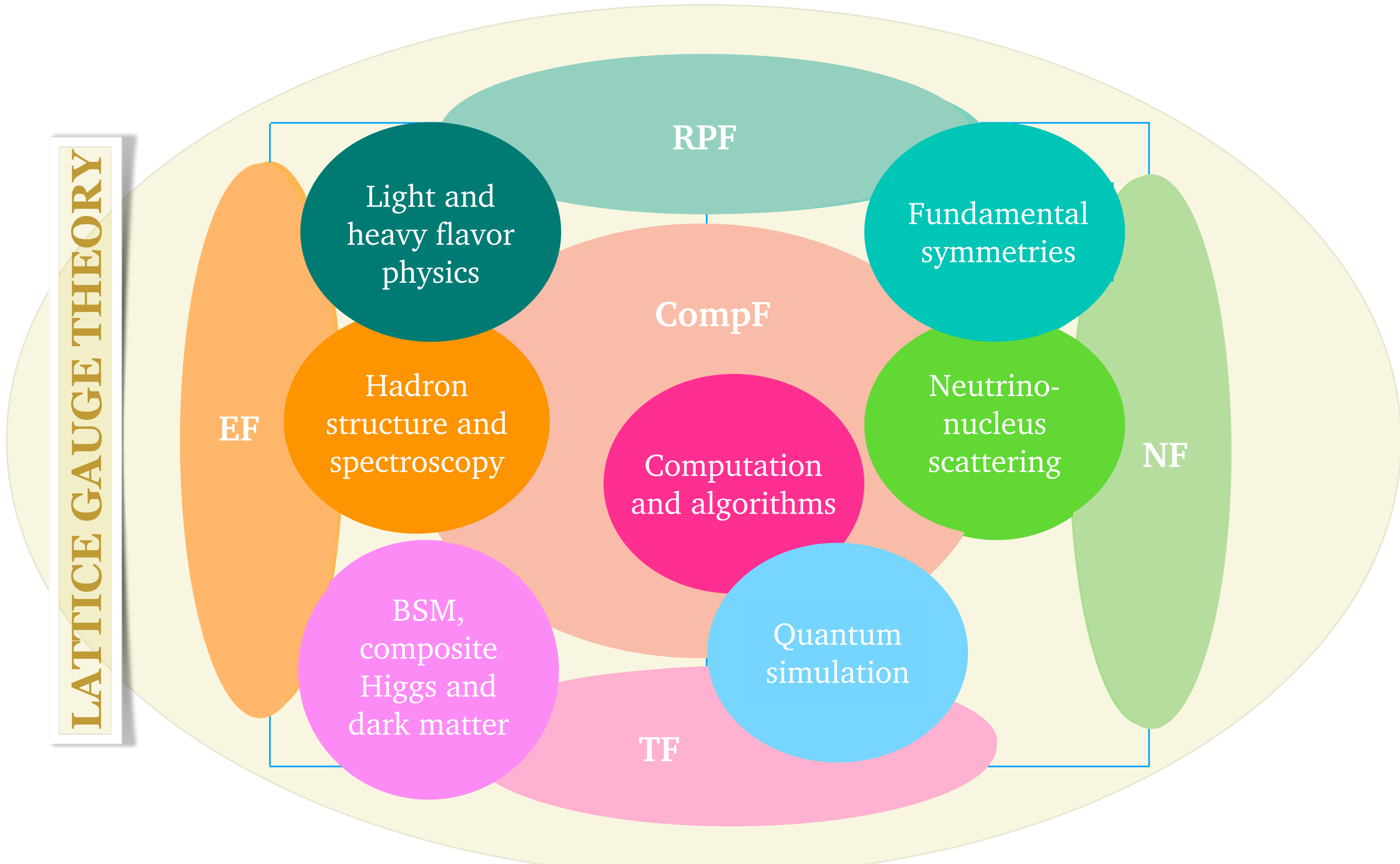
Snowmass Community Summer Study Workshop
July 17-26, 2022, University of Washington, Seattle

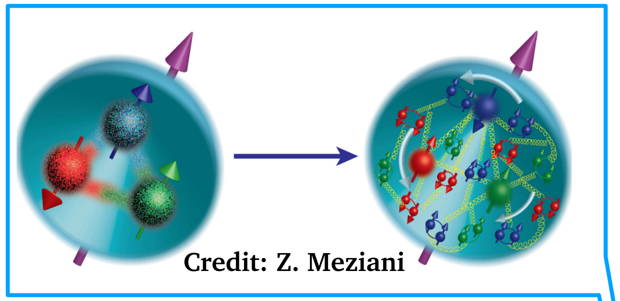


UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI WITH LATTICE QCD

Zohreh Davoudi
University of Maryland, College Park

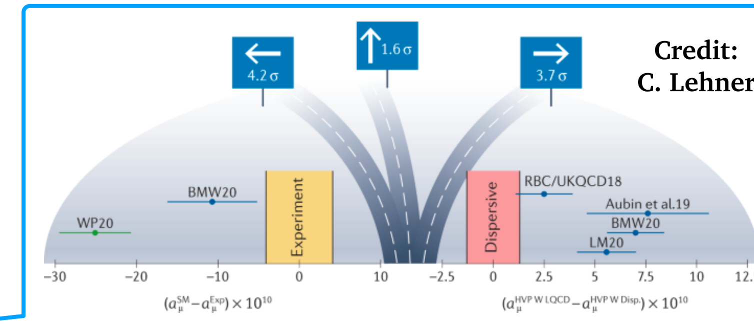
LATTICE QCD TOUCHES ON ALMOST ALL AREAS OF HEP

Parton distribution functions

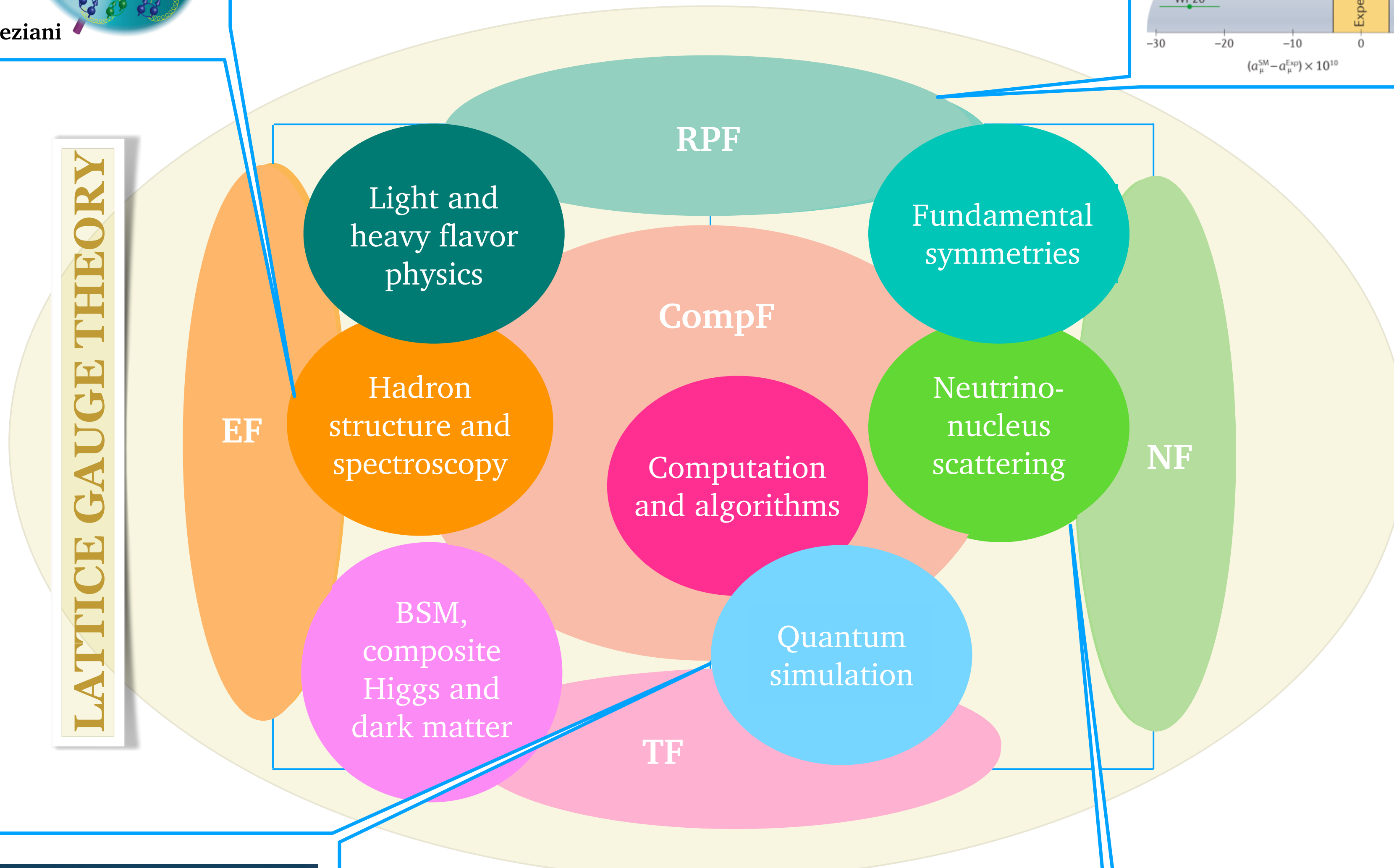


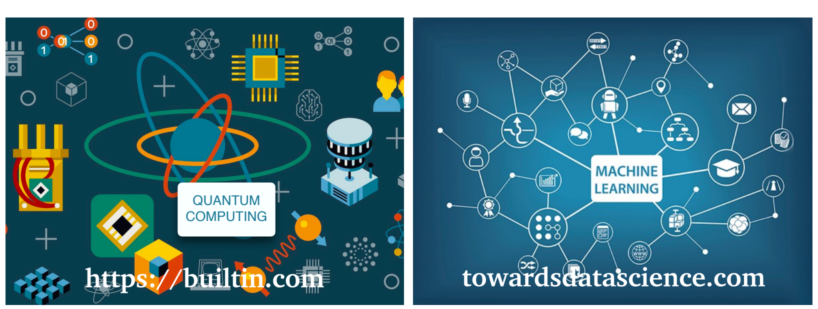
See A. Kronfeld's talk on lattice QCD for precision flavor physics.

Hadronic contributions to muon *g-2*



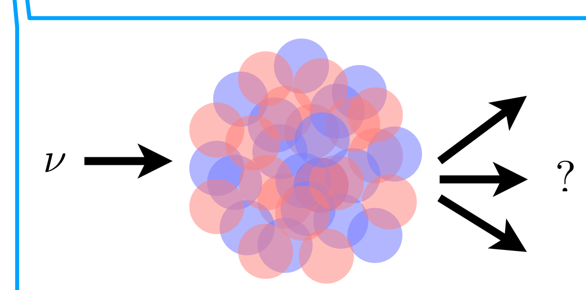
Dedicated parallel session on LGT for HEP on Thursday morning 10:15–12:00.





New strategies in computing and simulation, e.g., machine learning and quantum computing

This talk concerns lattice QCD at the nucleon and nuclear frontiers and more exploratory directions.



Neutrino-nucleus cross sections

GRAND PICTURE OF NEW PHYSICS DISCOVERY IN NUCLEON AND NUCLEI: EXAMPLE OF $0\nu\beta\beta$ decay

$\Lambda > \text{TeV}$

Start with your favorite high-scale model, e.g.:

$\Lambda \sim 10^2$ GeV

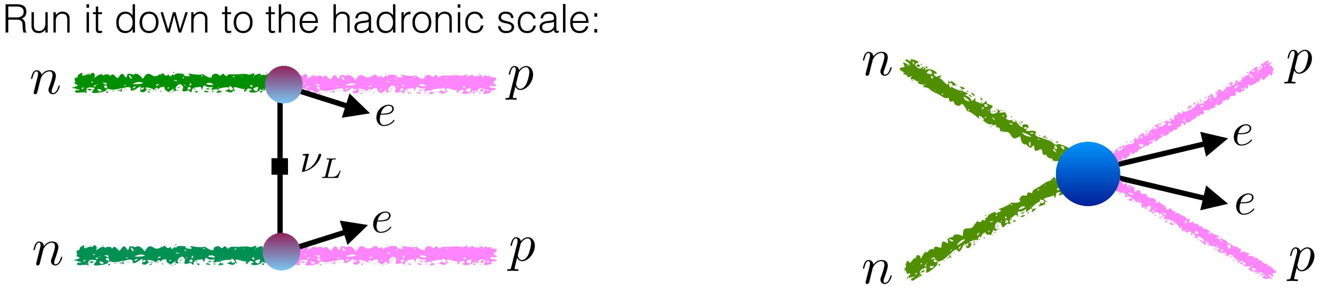
Run it down to the scale where the high-scale physics can be integrated out:

$\Lambda \sim 2$ GeV

Run it down to perturbative quark-level matrix elements:

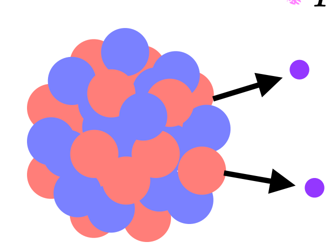
$\Lambda <$ GeV

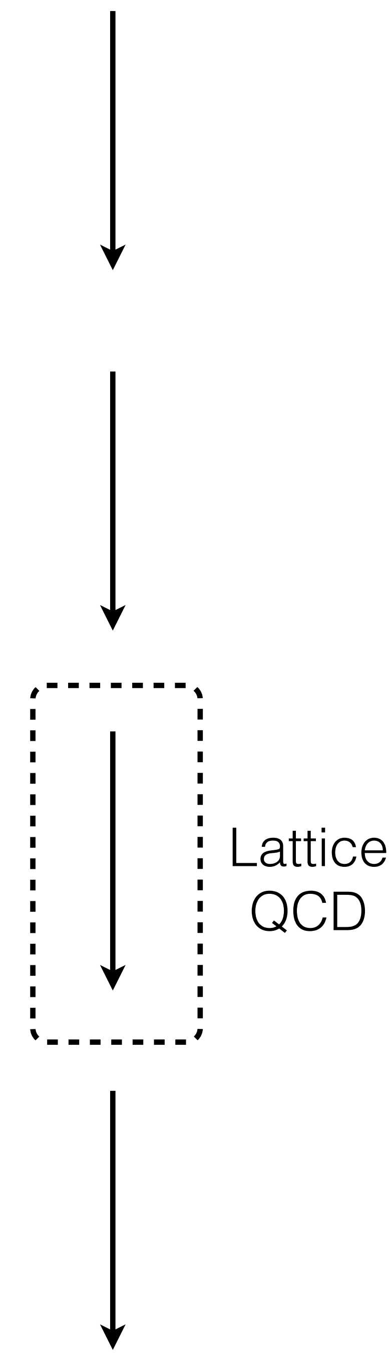
Run it down to the hadronic scale:



$\Lambda <$ MeV

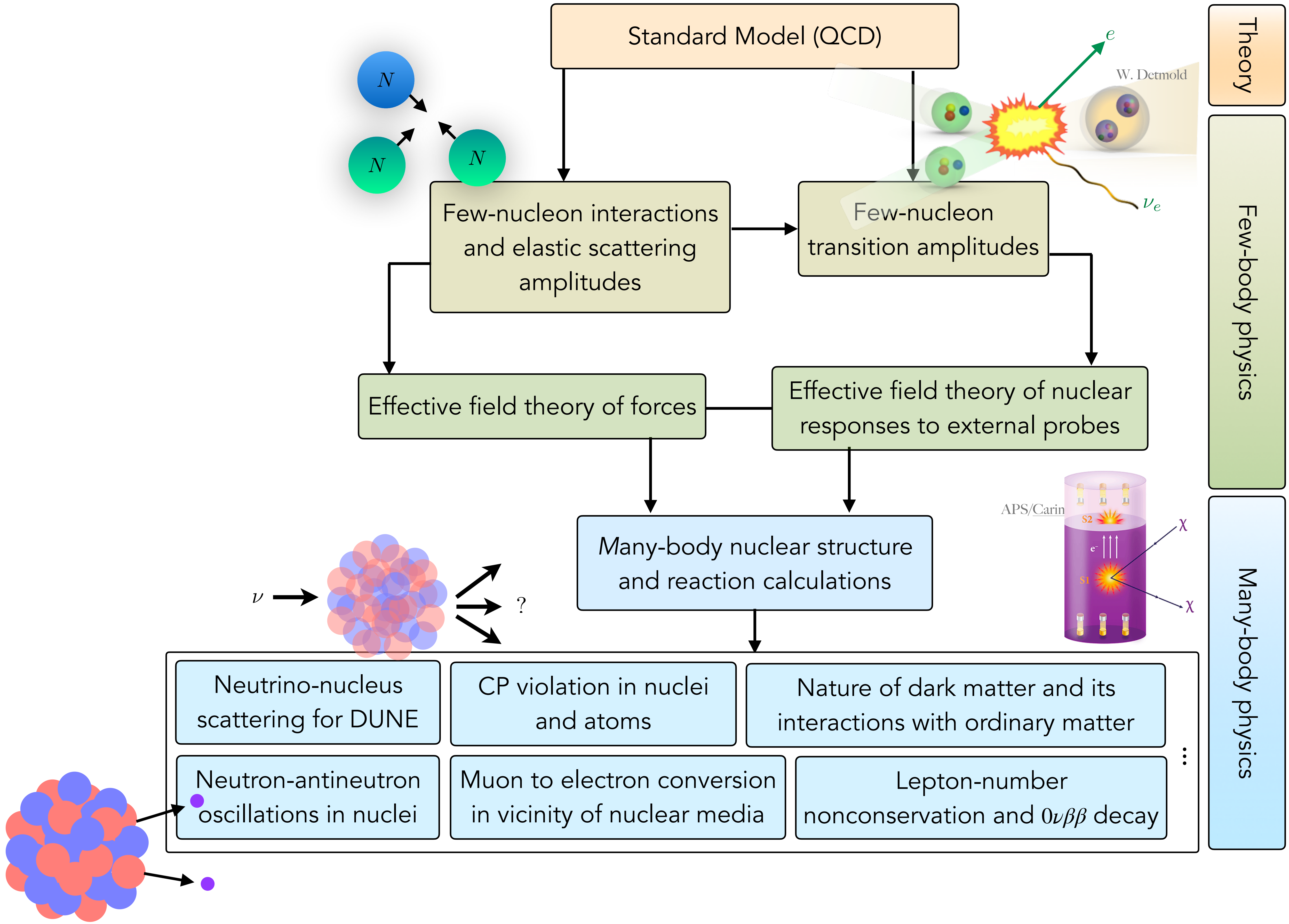
Use nuclear many-body calculation to match it to nuclear matrix elements:





Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197.

MORE DETAILS ON THE ROADMAP FROM QCD TO NUCLEAR OBSERVABLES FOR HEP



UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI

Physics	Target Quantity	Experiments
CP Violation and Neutrino Phenomenology	Neutrino-nucleus Scattering Cross Sections	DUNE, other Long-baseline Neutrino 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

Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197, Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

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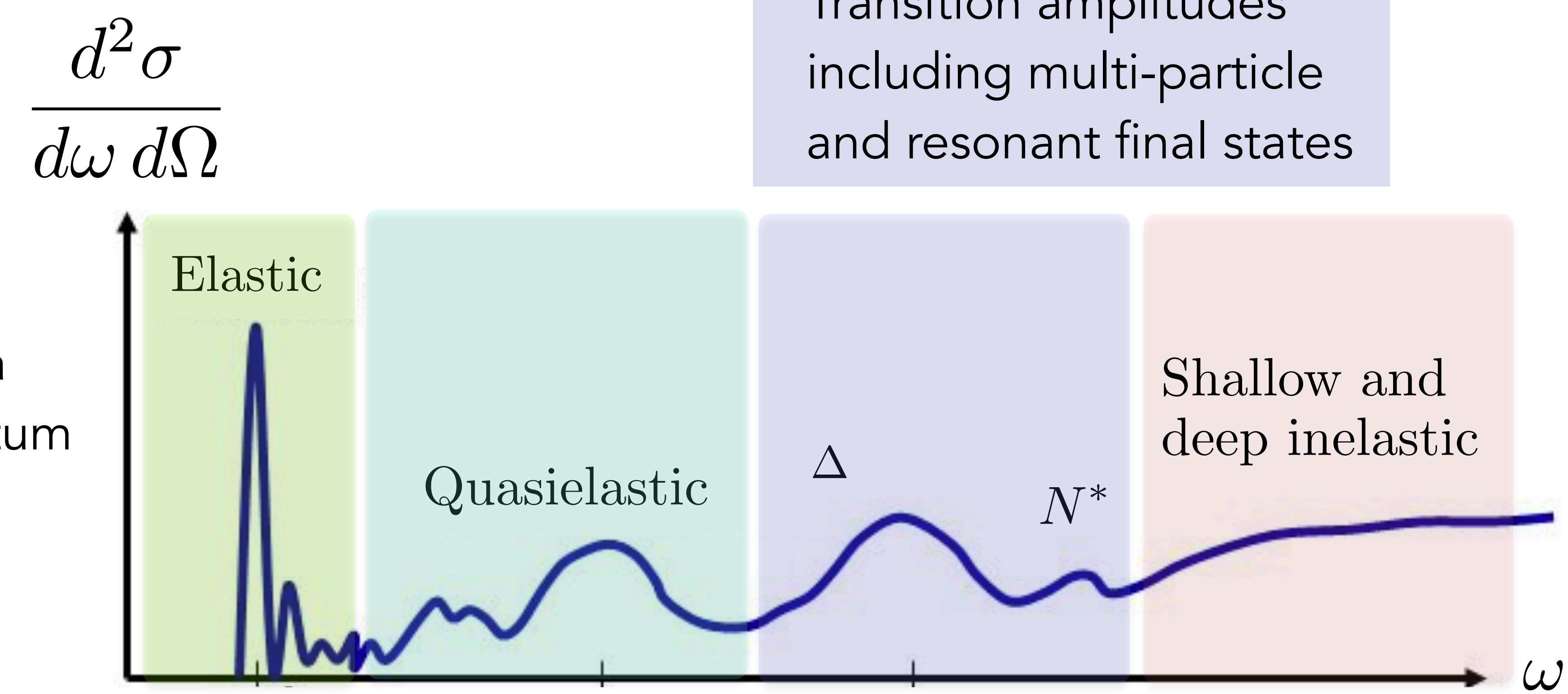
At DUNE, one needs to constrain nuclear response to incoming neutrino of various energy. How can lattice QCD help?

Transition amplitudes including multi-particle and resonant final states

v-nucleus scattering at a fixed momentum transfer

$\nu_\ell A \to \ell^- X$



Forward form factors, radii

Off-forward form factors

Parton distribution functions, hadron tensor

Need to compute various matrix elements in nucleon, multi-hadron states, and (light) nuclei:

$$\langle f|J_\nu|i\rangle, \qquad \langle f|J_\mu^\dagger J_\nu|i\rangle, \qquad \langle f|\mathcal{O}|i\rangle$$

and resort to EFTs to connect to large isotopes in experiments.

Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

Ruso et al, arXiv:2203.09030 [hep-ph].

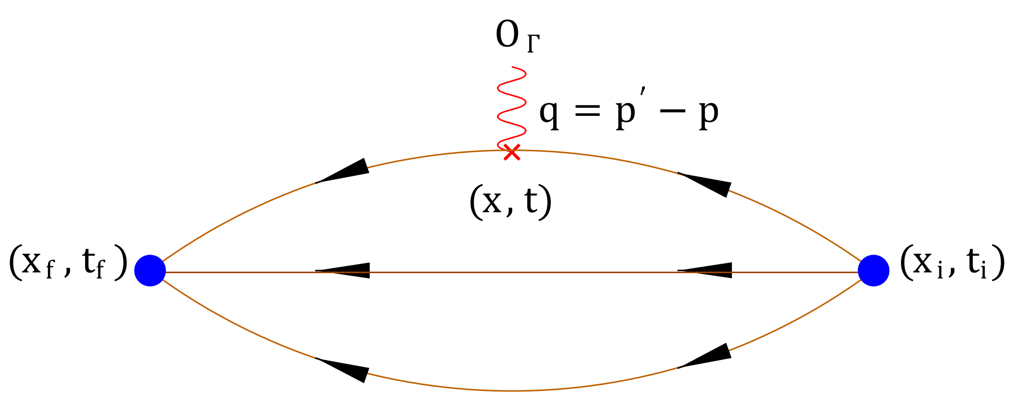
Example: Axial charge and form factors of the nucleon from lattice QCD

$$\langle N(p',s')|\bar{\psi}(x)\,\gamma_\mu\,\gamma_5\,\psi(x)|N(p,s)\rangle = i\left(\frac{m_N^2}{E_N(\mathbf{p}')E_N(\mathbf{p})}\right)^{1/2}\bar{u}_N(p',s')\left[G_A(q^2)\gamma_\mu\gamma_5 + \frac{q_\mu\gamma_5}{2m_N}G_p(q^2)\right]u_N(p,s)$$

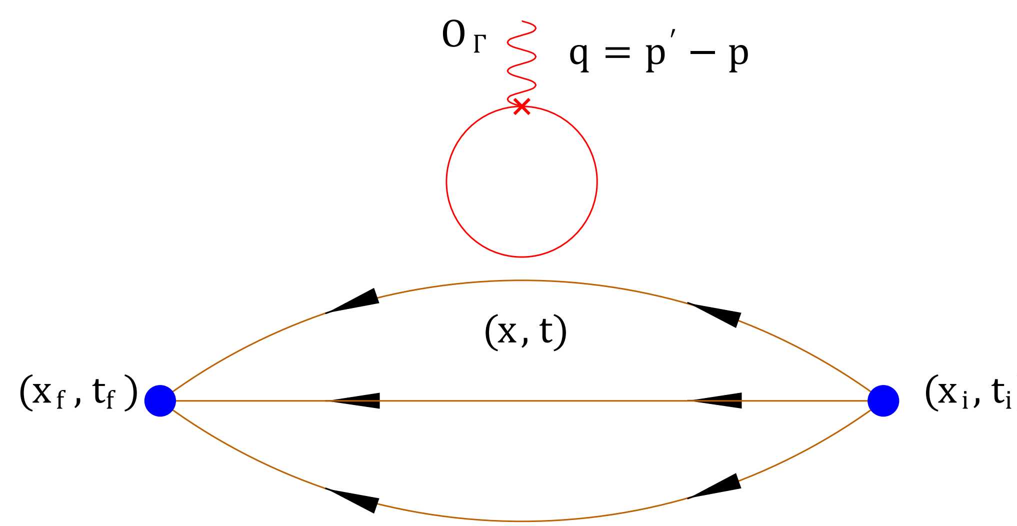
Axial-vector current

Nucleon spinor

Axial and pseudo scalar form factors
$G_A(0) = g_A$



Connected contribution

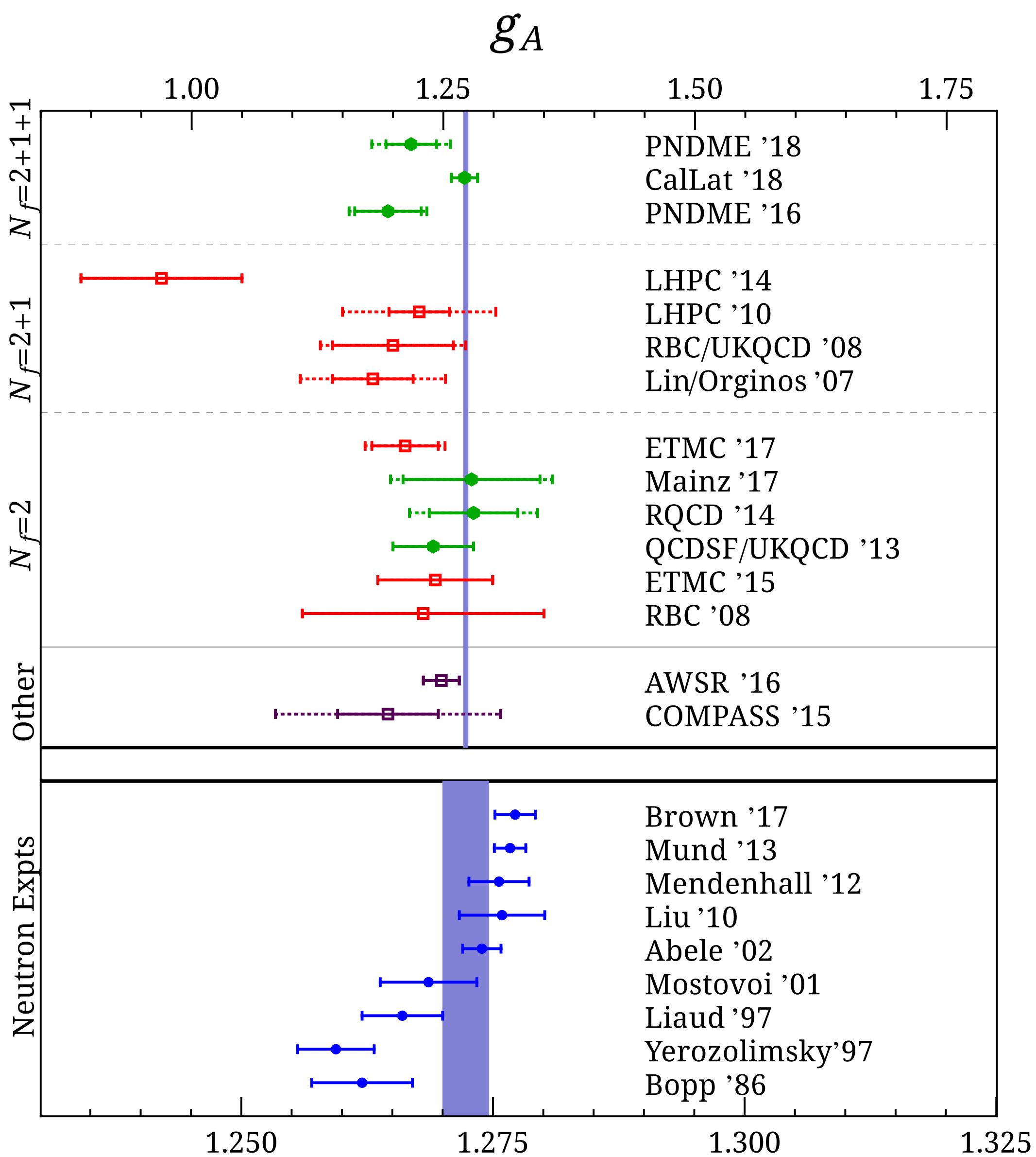


Disconnected contribution (vanishes at isospin limit for isovector quantities)

Constantinou, arXiv:1411.0078 [hep-lat].

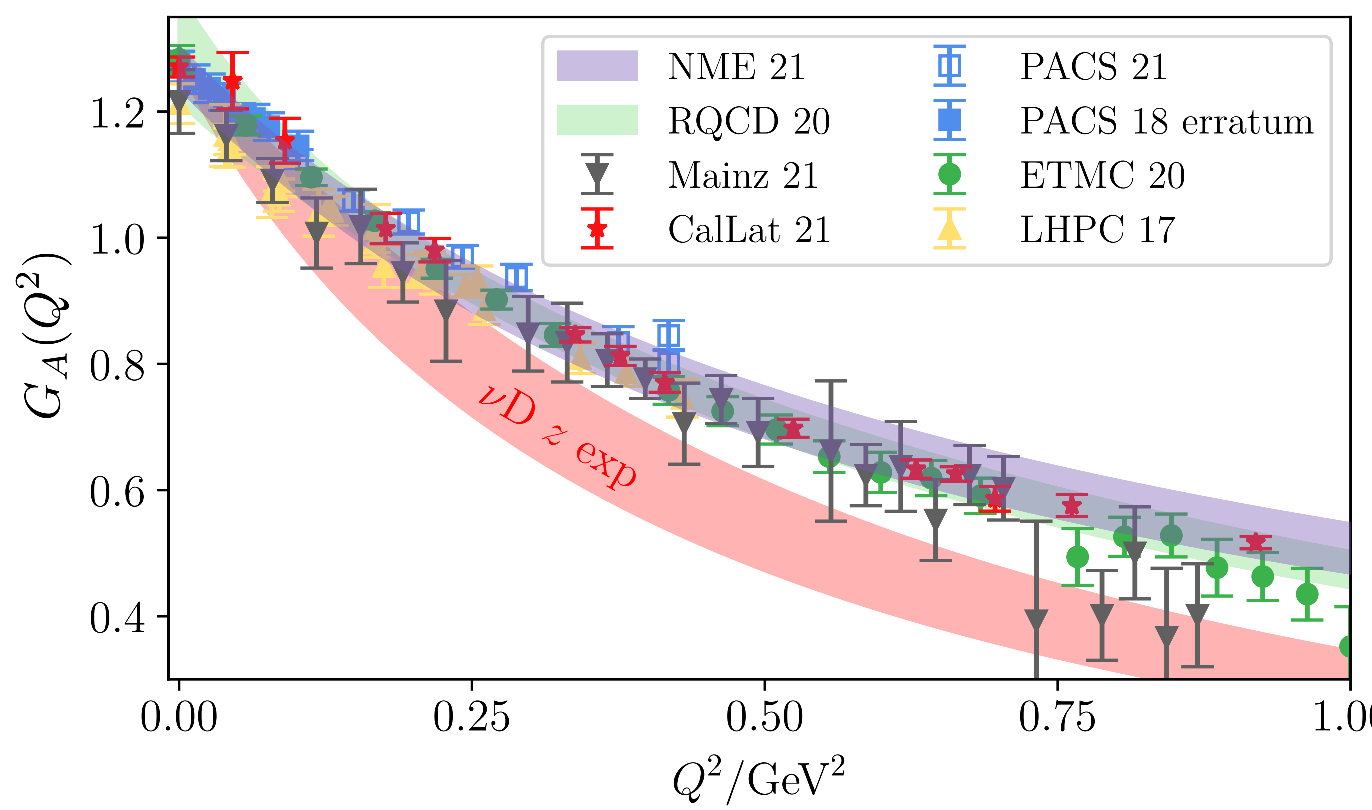
Example: Axial charge and form factors of the nucleon from lattice QCD

FLAG Review (2019), EPJC 80, 113 (2020).



Compilation of results

Meyer, Walker-Loud, and C. Wilkinson, arXiv:2201.01839 [hep-lat].



Isovector axial form factor results

For the status and future of multi-hadron spectroscopy and transitions from lattice QCD, see: Bulava et al, arXiv: 2203.03230 [hep-lat].

For the status and future of parton distribution functions from lattice QCD, see: Constantinou et al, arXiv: 2202.07193 [hep-lat].

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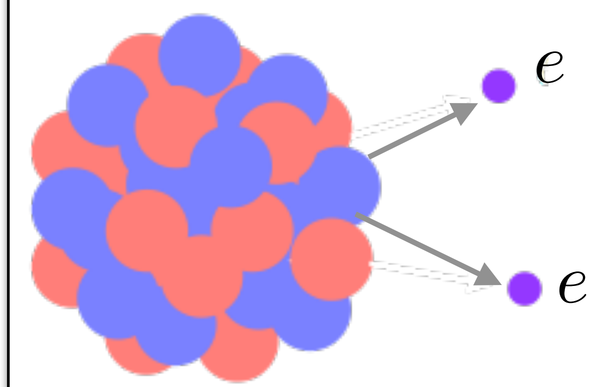


MOTIVATION AND TARGET OBSERVABLES

- Tonne-scale experiment planned in the U.S., design and interpretation of the results requires nuclear matrix elements in various scenarios.

- LNV from dimension-5 operator (light Majorana neutrino exchange)

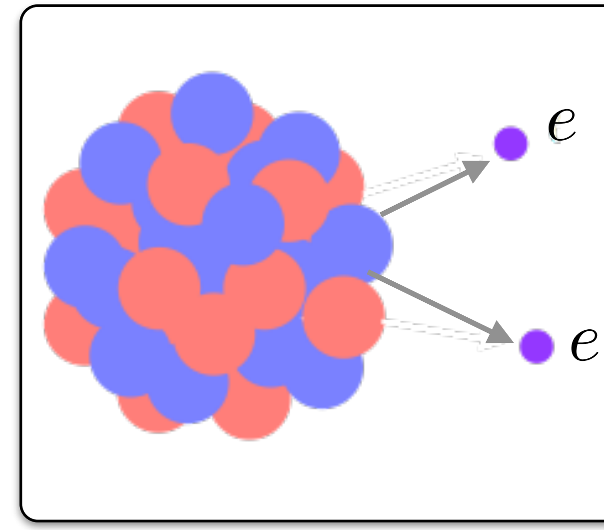
$$\langle \pi^+ | S_{NL} | \pi^- \rangle,\ \langle p\pi^+ | S_{NL} | n \rangle,\ \langle pp | S_{NL} | nn \rangle$$

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

- LNV from dimension-9 operators ("short-distance" mechanisms). Requires matrix elements of 4-quark charge-changing operators

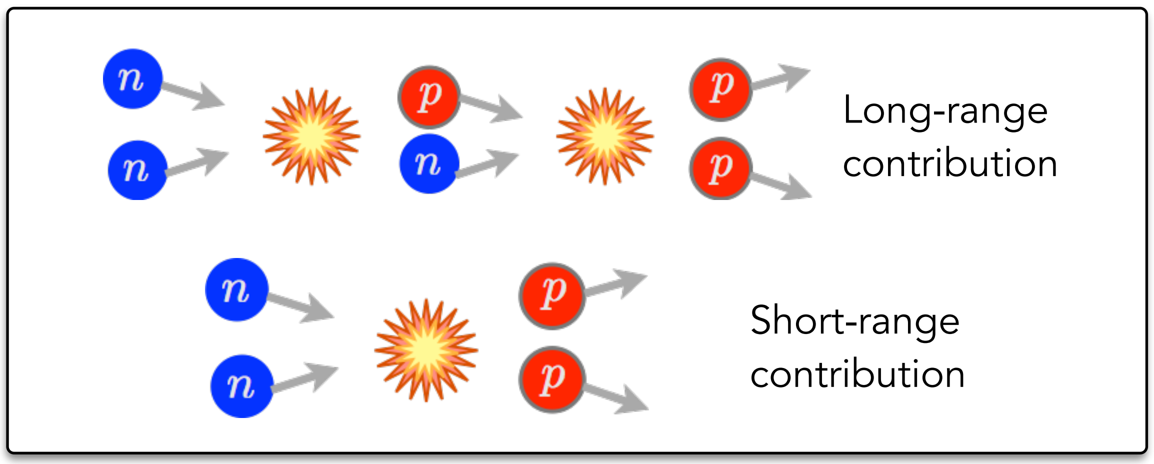
$$\langle \pi^+ | O_i | \pi^- \rangle, \langle p\pi^+ | O_i | n \rangle,\ \langle pp | O_i | nn \rangle$$

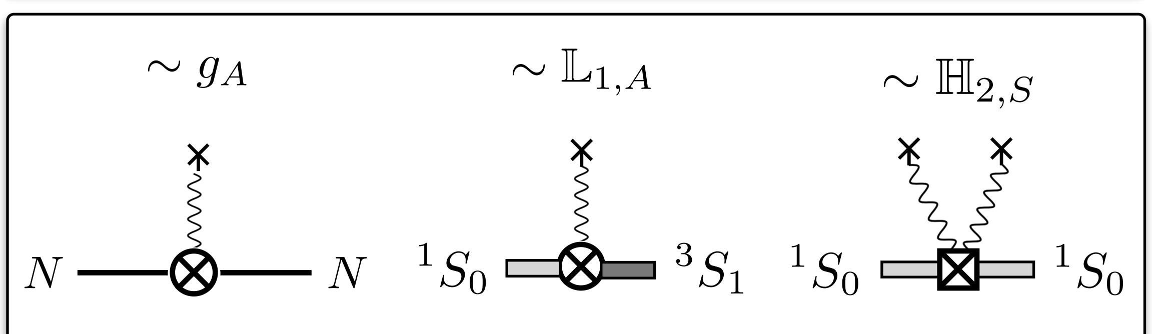
CURRENT STATUS



2νββ DECAY OF TWO NEUTRONS

$$nn \rightarrow pp\, ee\, \overline{\nu}_e \overline{\nu}_e$$



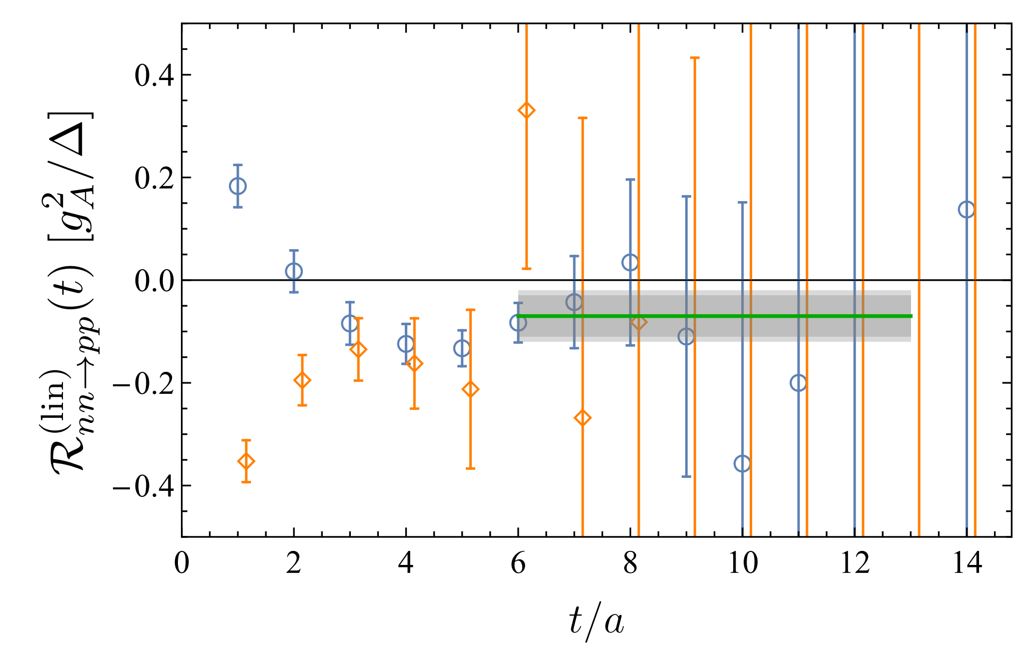


$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \text{fm}$$

@ $m_\pi \approx 800$ MeV

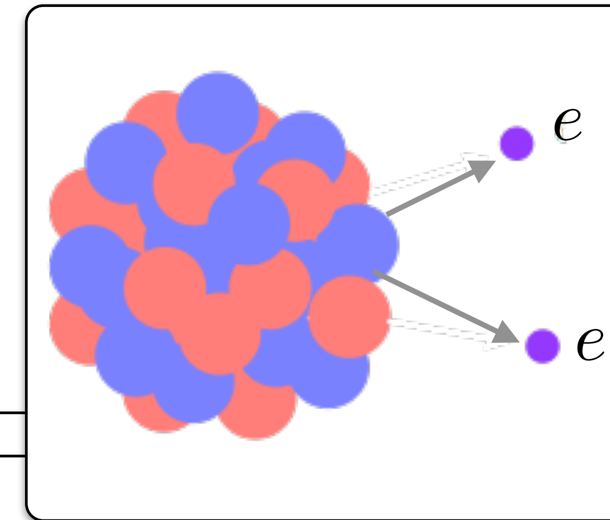
Constraint on the new short-range LEC.

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

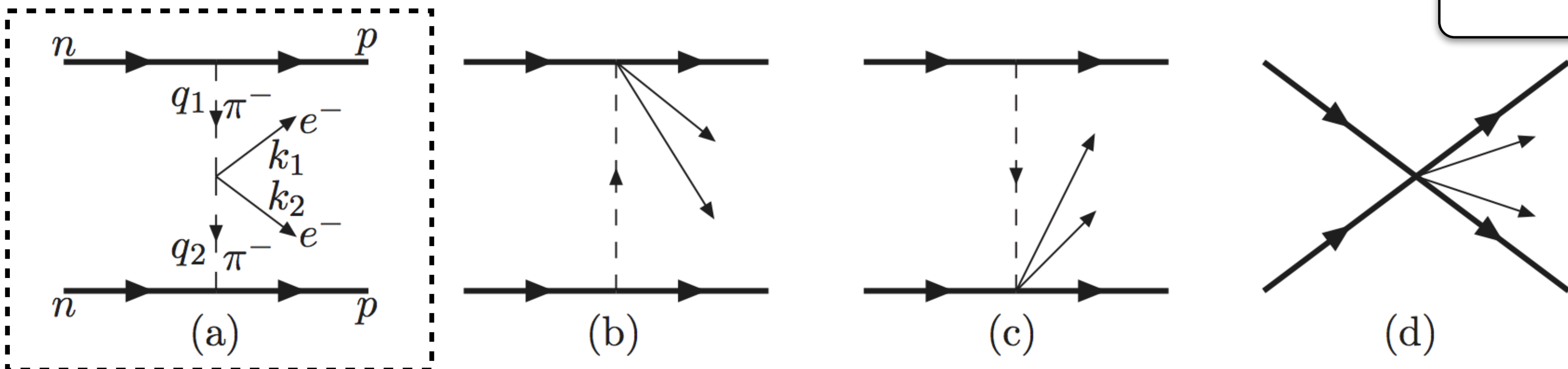


NPLQCD collaboration, Phys. Rev. Lett. 119, 062003 (2017), Phys. Rev. D 96, 054505 (2017). See also Feng et al, Phys. Rev. Lett. 122, 022001 (2019), and Detmold et al, arXiv:1811.05554 [hep-lat] for the $0\nu\beta\beta$ *decay of the pion.*

CURRENT STATUS

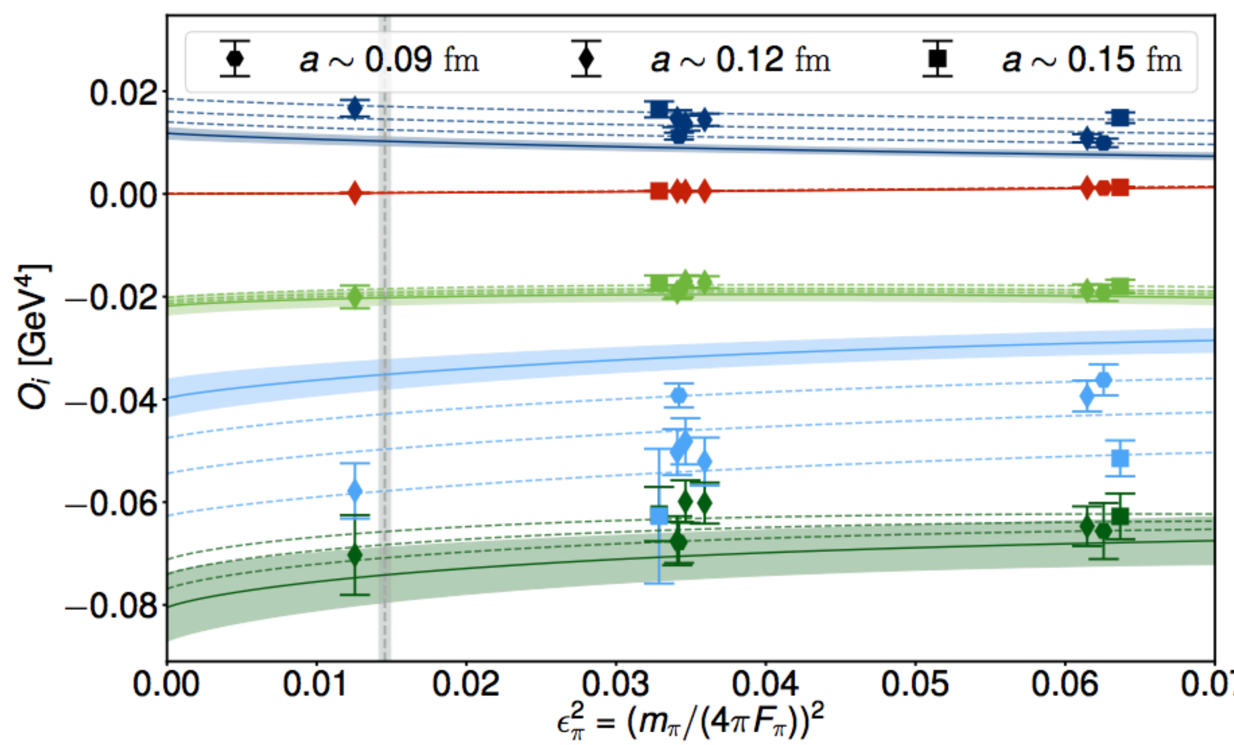


0νββ DECAY OF PIONS

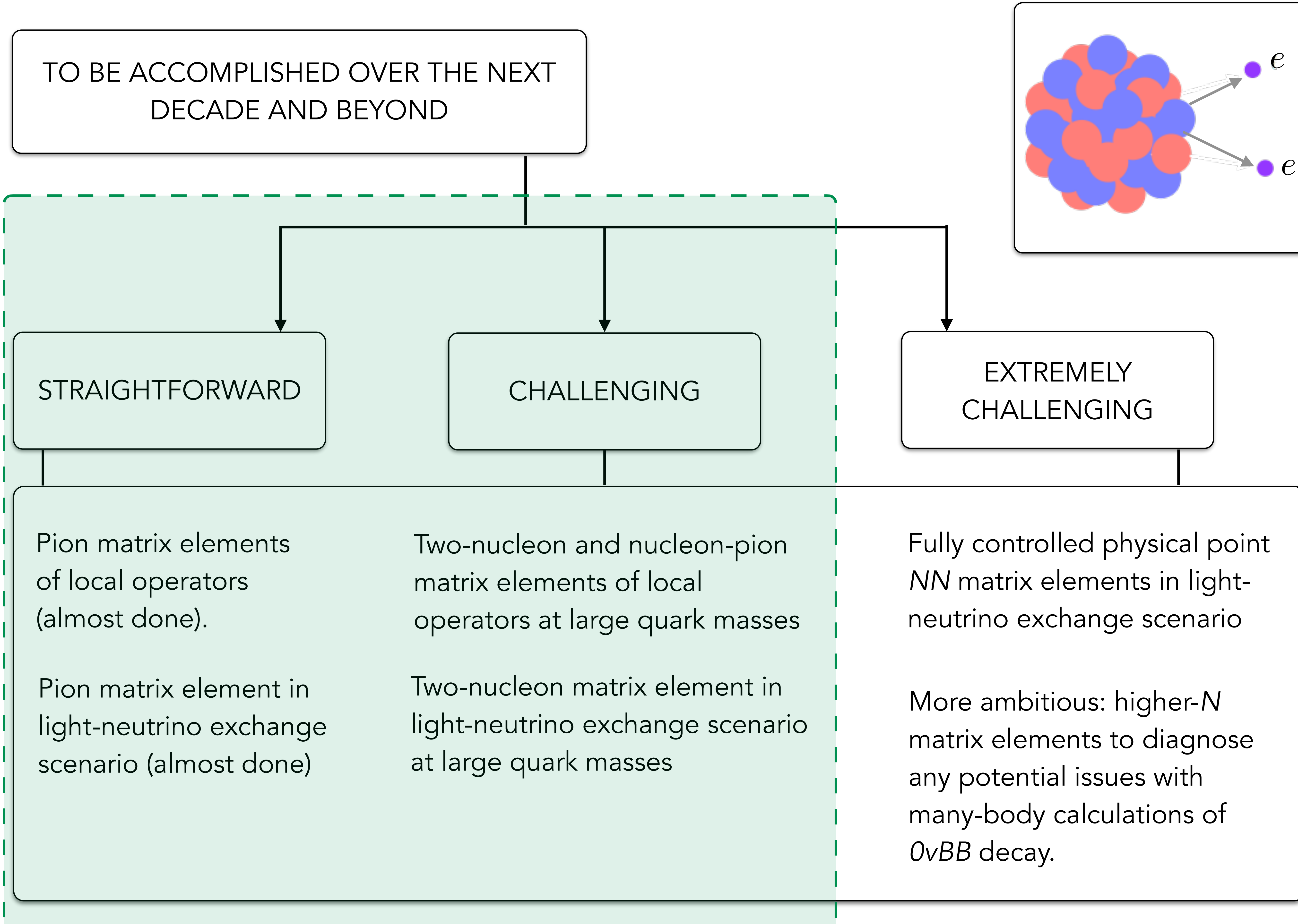


$$\langle \Omega | \Pi^+(t_f, \mathbf{p}_f) \mathcal{O}(0) \Pi^+(t_i, \mathbf{p}_i) | \Omega \rangle$$

$$\pi^- \to \pi^+ ee$$



Nicholson et al (CalLatt), Phys. Rev. Lett. 121, 172501 (2018).


TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND
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STRAIGHTFORWARD
CHALLENGING
EXTREMELY CHALLENGING
Pion matrix elements of local operators (almost done).
Pion matrix element in light-neutrino exchange scenario (almost done)
Two-nucleon and nucleon-pion matrix elements of local operators at large quark masses
Two-nucleon matrix element in light-neutrino exchange scenario at large quark masses
Fully controlled physical point NN matrix elements in light-neutrino exchange scenario
More ambitious: higher-N matrix elements to diagnose any potential issues with many-body calculations of 0vBB decay.

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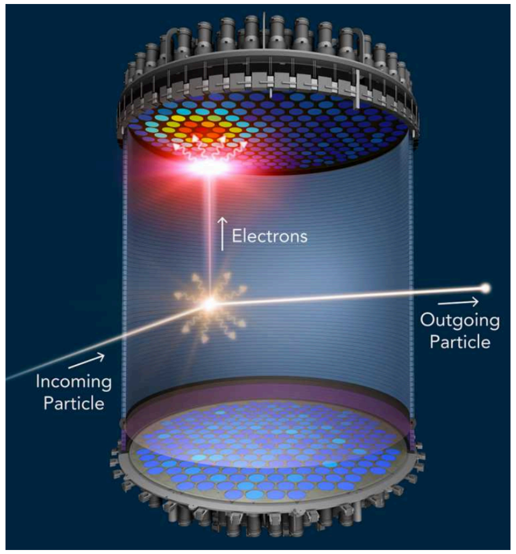
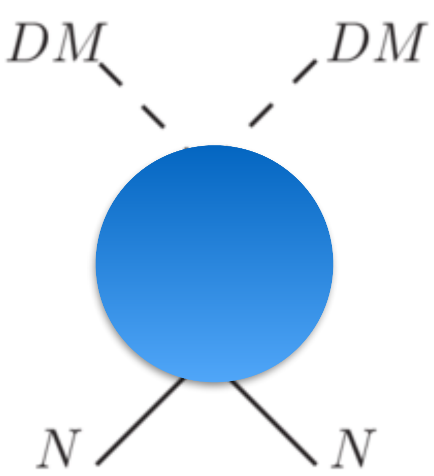
MOTIVATION AND TARGET OBSERVABLES



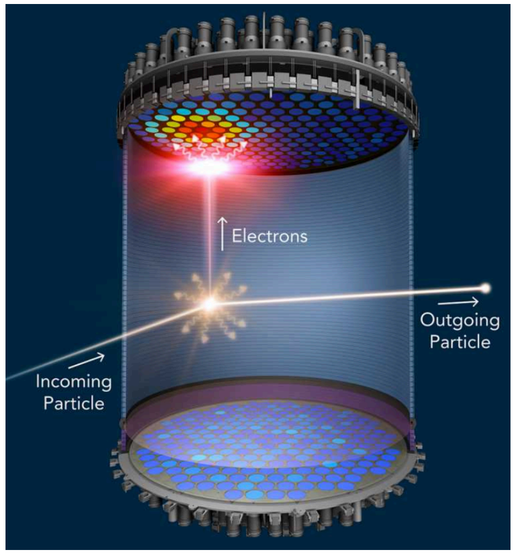
- Standard Model input is necessary to interpret the results of DM searches and translate these into limits on DM models.



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

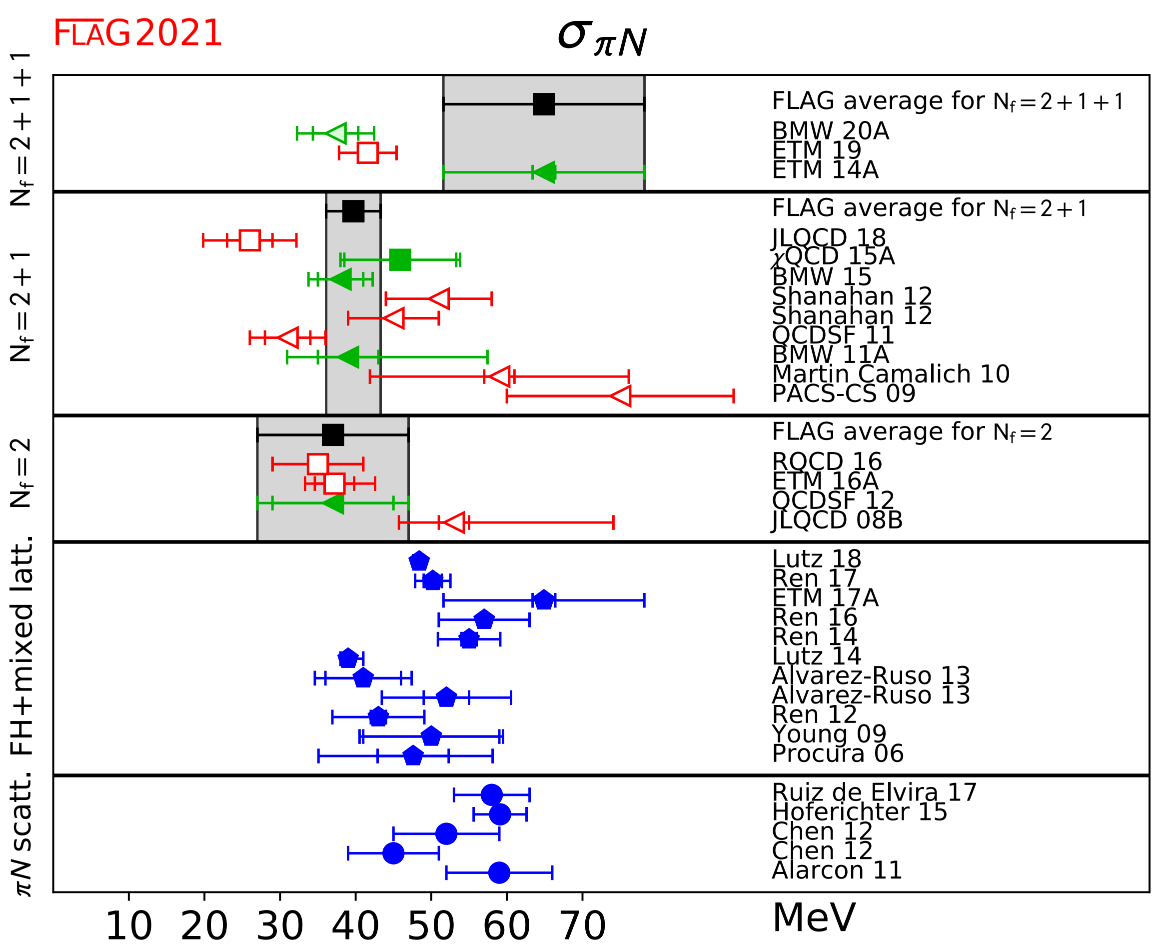
CURRENT STATUS

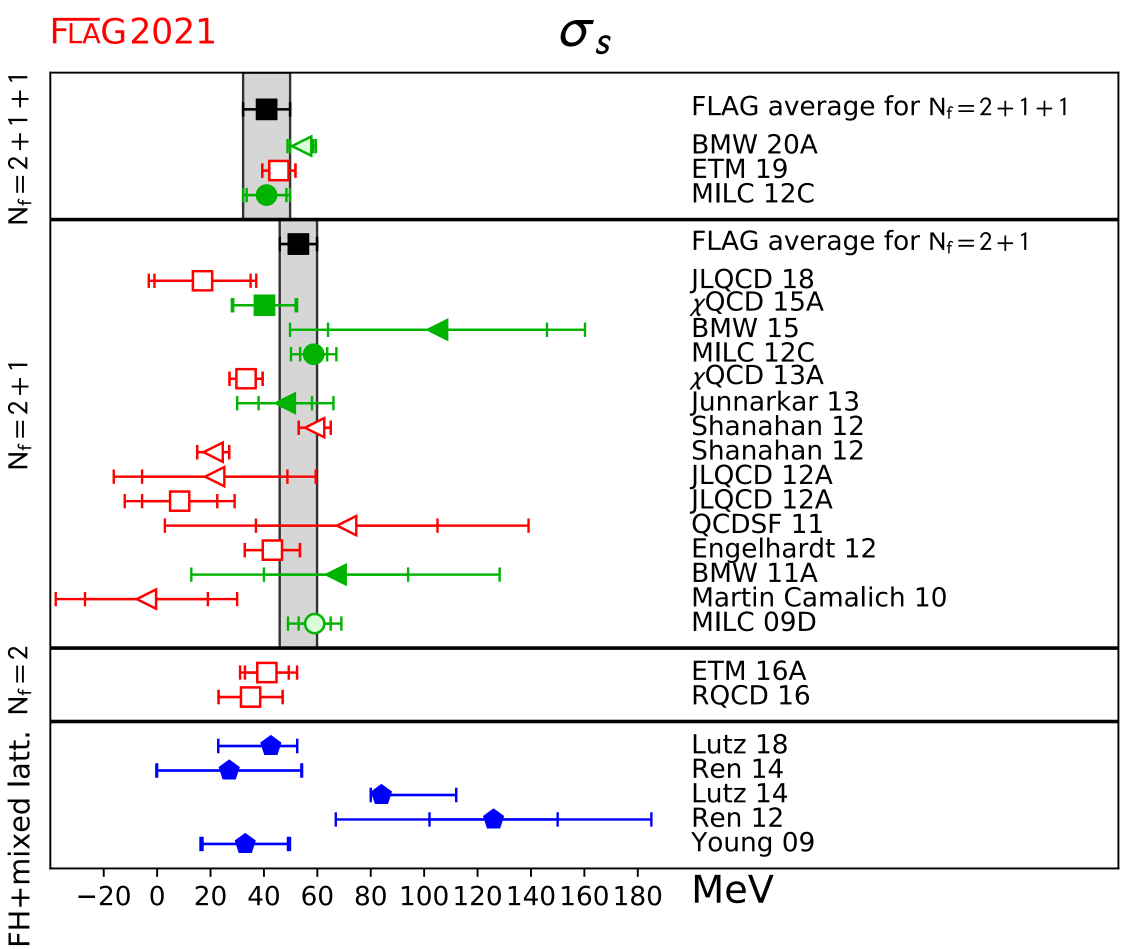
SIGMA TERMS IN NUCLEON



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

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

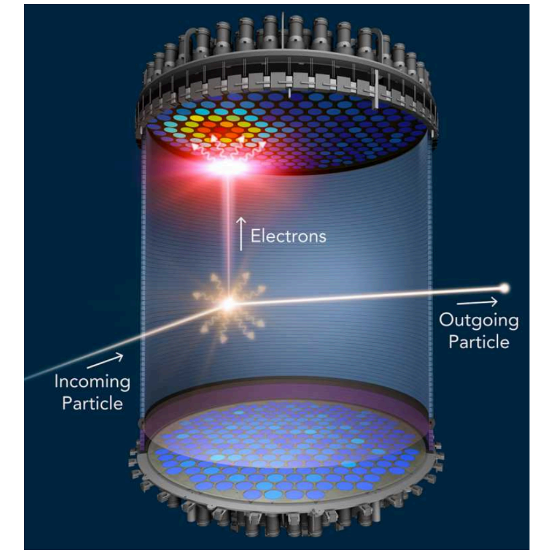




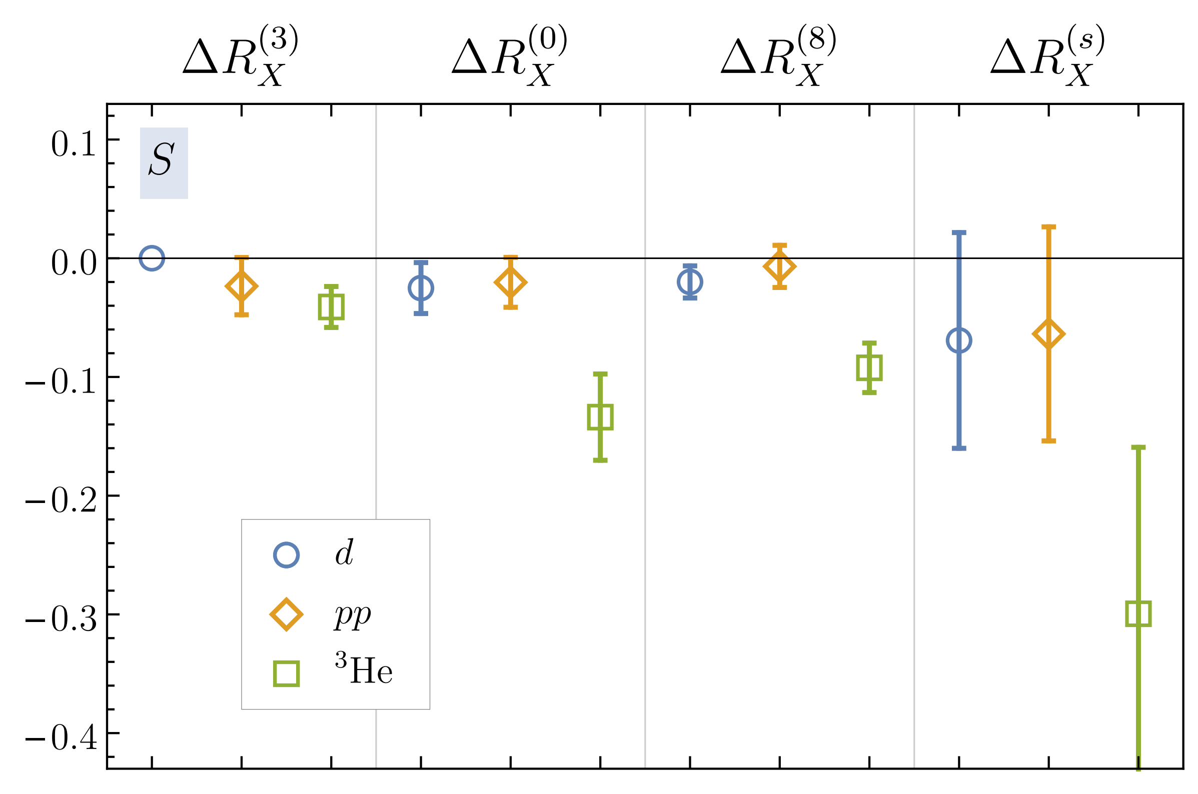
Aoki et al (Flavor Lattice Averaging Group), FLAG Review (2021).

CURRENT STATUS

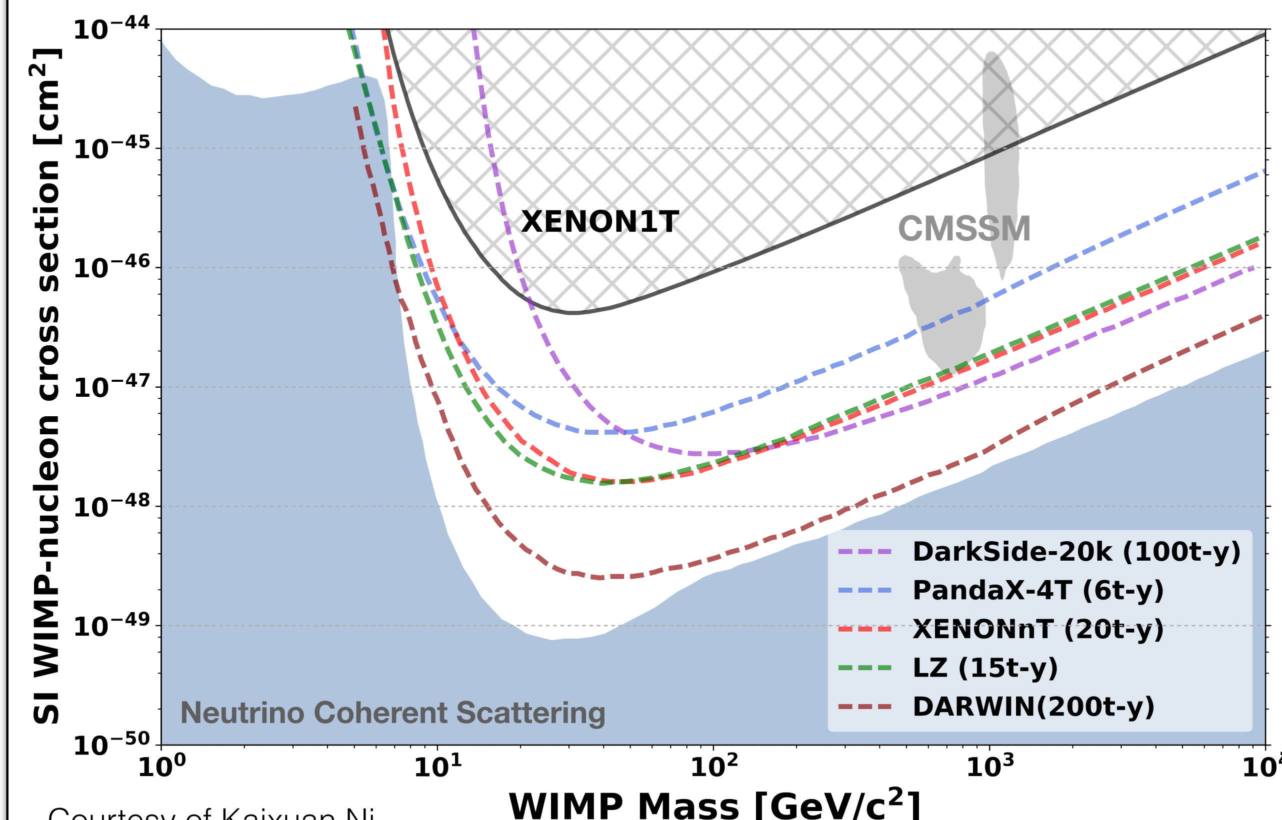
SCALAR RESPONSE OF LIGHT NUCLEI



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

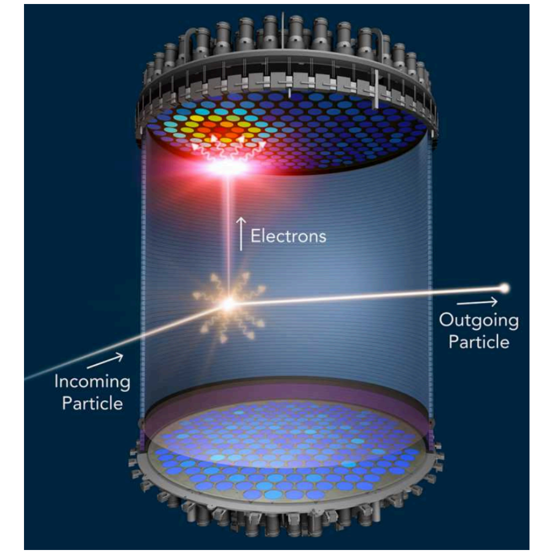


Status of direct detection of WIMP by 2025



Courtesy of Kaixuan Ni

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



TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND

STRAIGHTFORWARD

Few-percent precision on nucleon matrix elements

Spin-dependent interactions, PDF of nucleons, etc.

CHALLENGING

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

EXTREMELY CHALLENGING

Direct evaluation in larger nuclei

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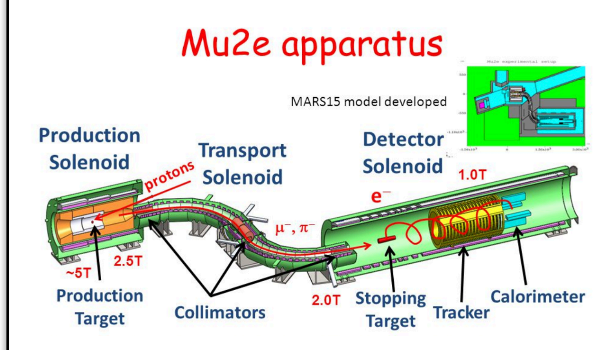
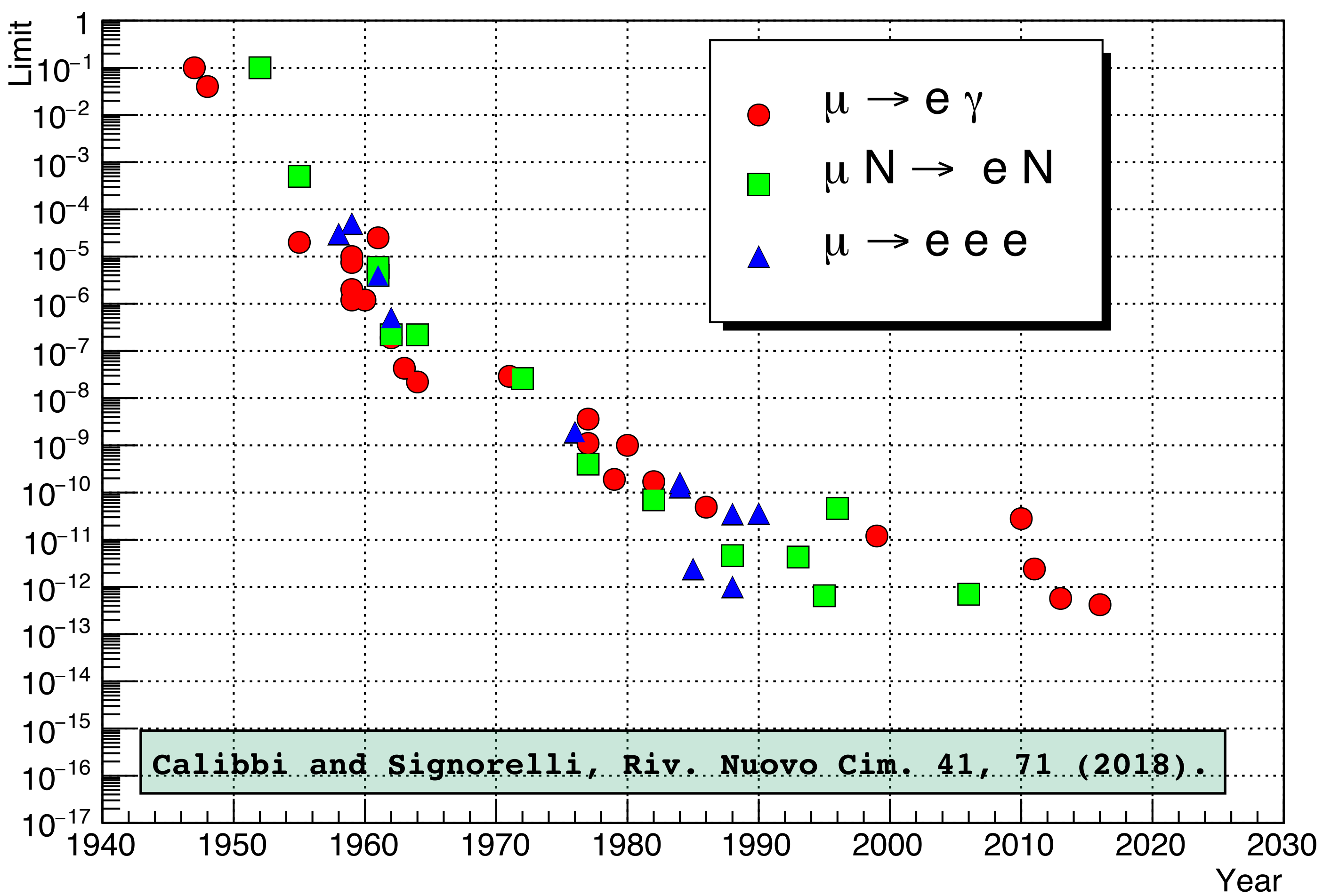
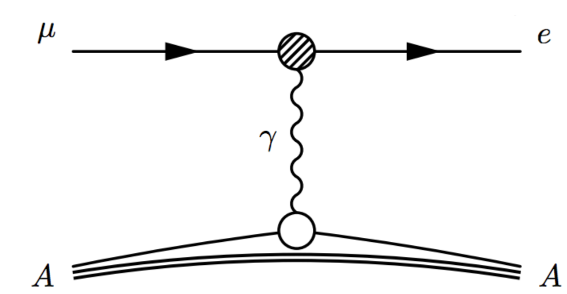


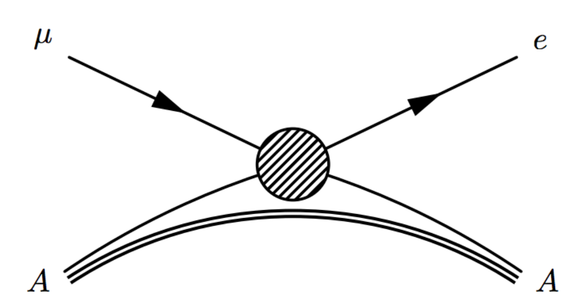
MOTIVATION AND TARGET OBSERVABLES

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



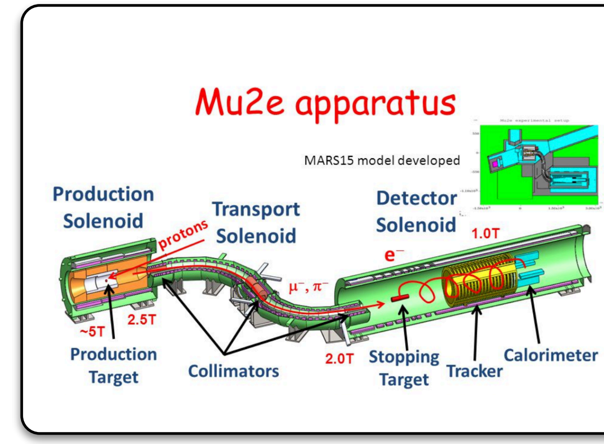


$$\mathcal{L}_d \sim \frac{1}{\Lambda^2} m_\mu \overline{\mu}_L \sigma_{\mu\nu} e_R F^{\mu\nu}$$



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

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

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.

CHALLENGING

Few-percent precision on nucleon form factors

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

EXTREMELY CHALLENGING

Directly evaluating matrix elements in larger nuclei

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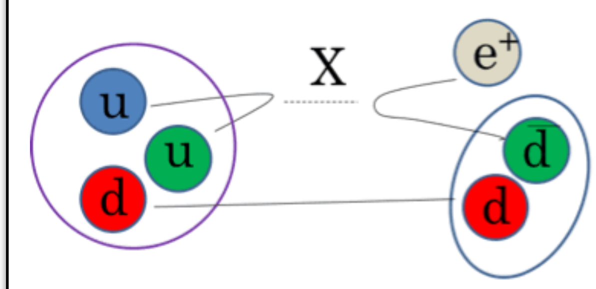
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197, Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

MOTIVATION AND TARGET OBSERVABLES

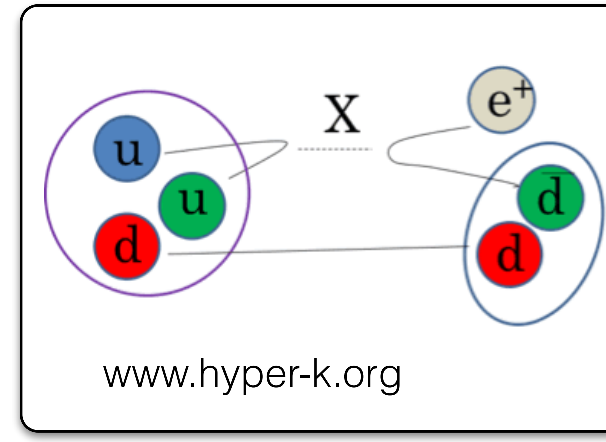


- GUT and SUSY-GUT constraints require $p \to$ meson matrix elements. Some models predict suppression of p decay matrix elements due to nonperturbative dynamics.

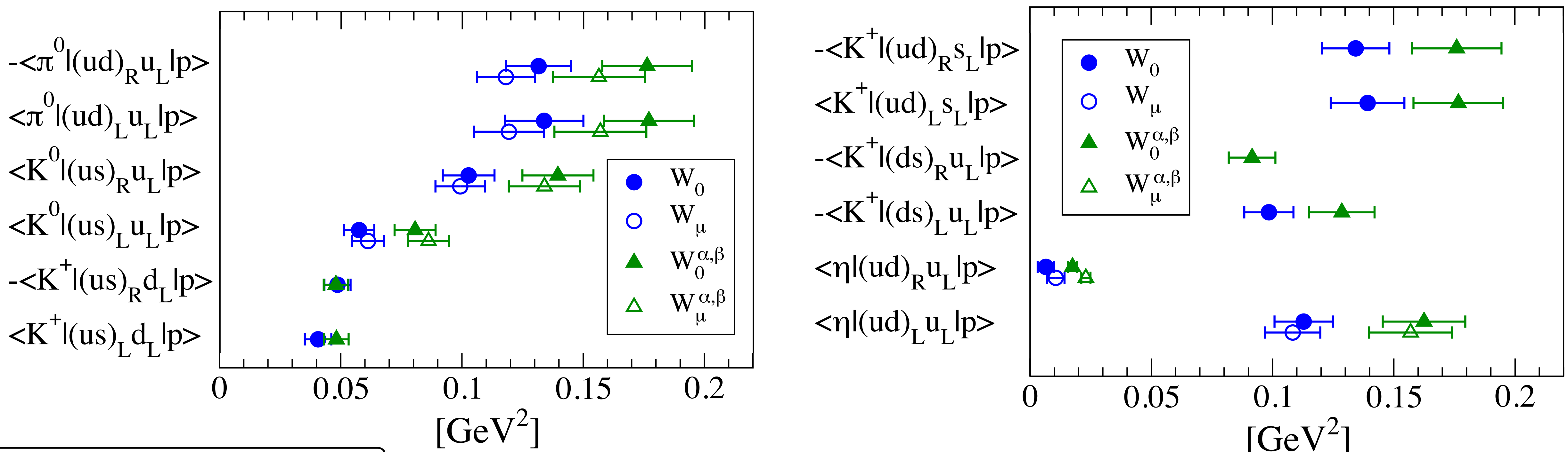
- Upcoming DUNE will examine $p \to Kl\nu$ and $p \to \pi\pi e^+$ decays with better precision, future hyper-K will further improve p-decay constraints.

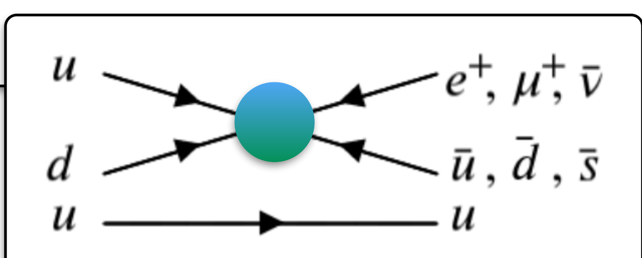
$$\langle \pi^0 | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L u^k | p \rangle$$
$$\langle \pi^+ | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L d^k | p \rangle$$

CURRENT STATUS



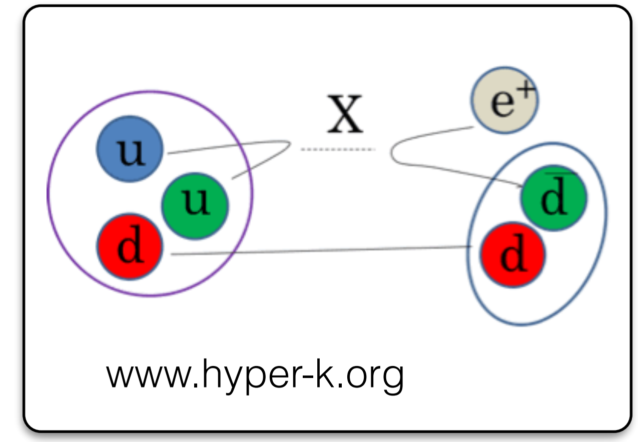
Form factors parametrizing the shown normalized matrix elements at given values of momentum transfer:





Y. Aoki et al (RBC-UKQCD), Phys. Rev. D 96, 014506 (2017).

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

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

CHALLENGING

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

EXTREMELY CHALLENGING

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

UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI

Physics	Target Quantity	Experiments
CP Violation and Neutrino Phenomenology	Neutrino-nucleus Scattering Cross Sections	DUNE, other Long-baseline Neutrino 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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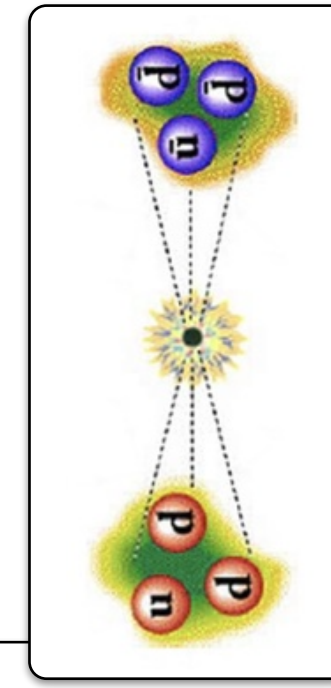
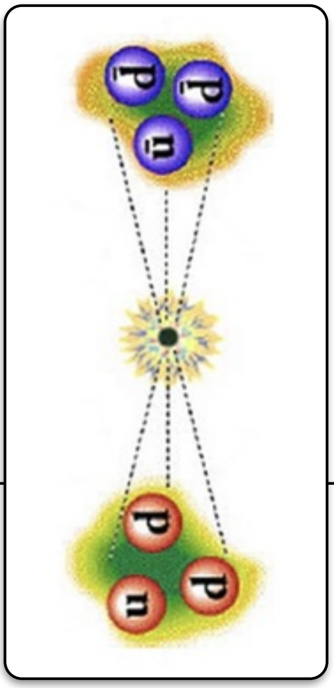
MOTIVATION AND TARGET OBSERVABLES



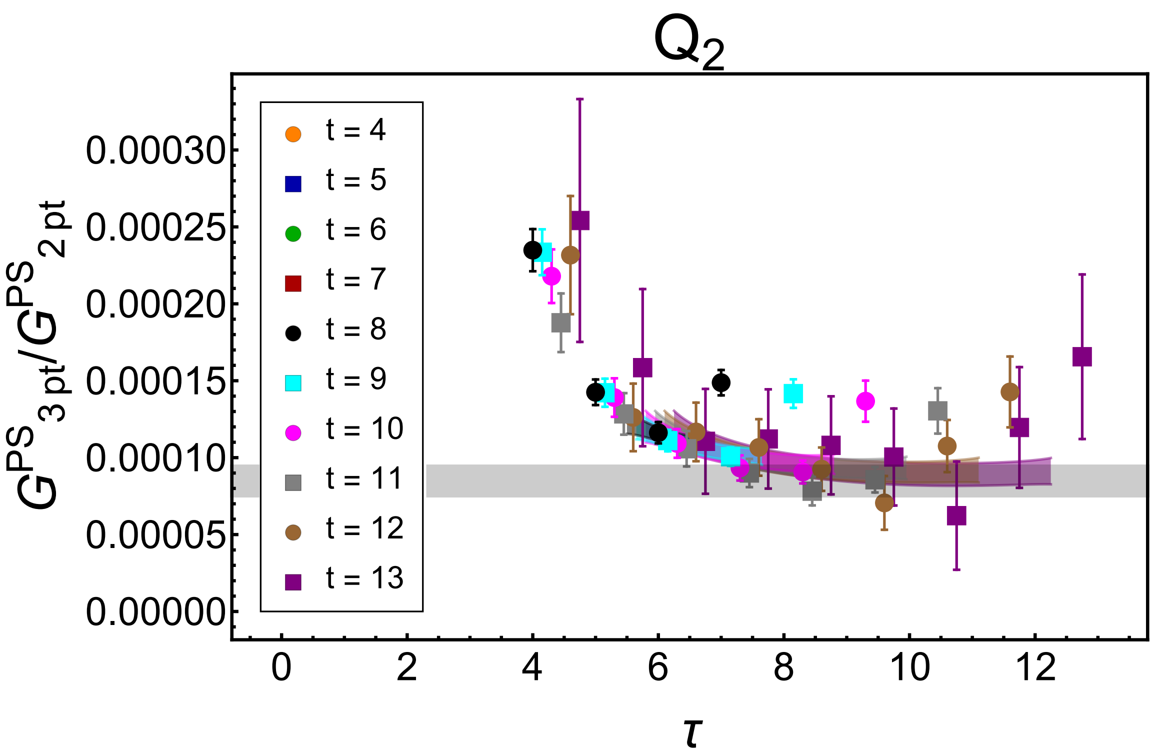
- Some models of B-L violation do not allow the proton decay, therefore, neutron-antineutron oscillation bounds can provide powerful constraints.
- Two types of experiments: slow neutron beams and oscillation in nuclear medium with a distinct 5-pion final state.
- Theoretical uncertainties in neutron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

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

CURRENT STATUS



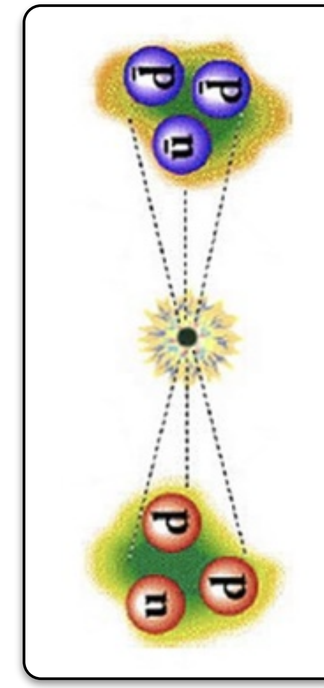
Normalized six-quark operators matrix elements obtained from lattice QCD at the physical point:



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

Rinaldi et al., Phys. Rev. Lett. 122, 162001 (2019).

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD	CHALLENGING	EXTREMELY CHALLENGING
Precision single-neutron matrix elements (sensitive to discretization, chiral symmetry is important). MEs of 6-quark operators including EM current insertions	Neutron-antineutron annihilation matrix element	Neutron-antineutron annihilation matrix element in nuclei (deuteron?) for SNO Multi-nucleon contributions for DUNE/super-K

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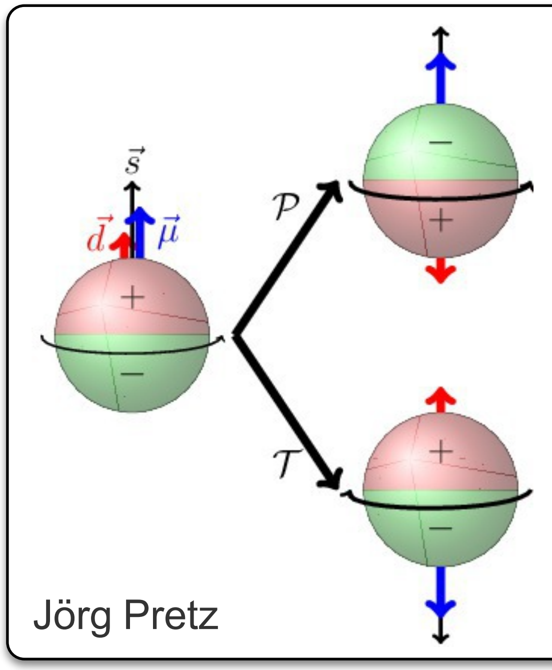
MOTIVATION AND TARGET OBSERVABLES

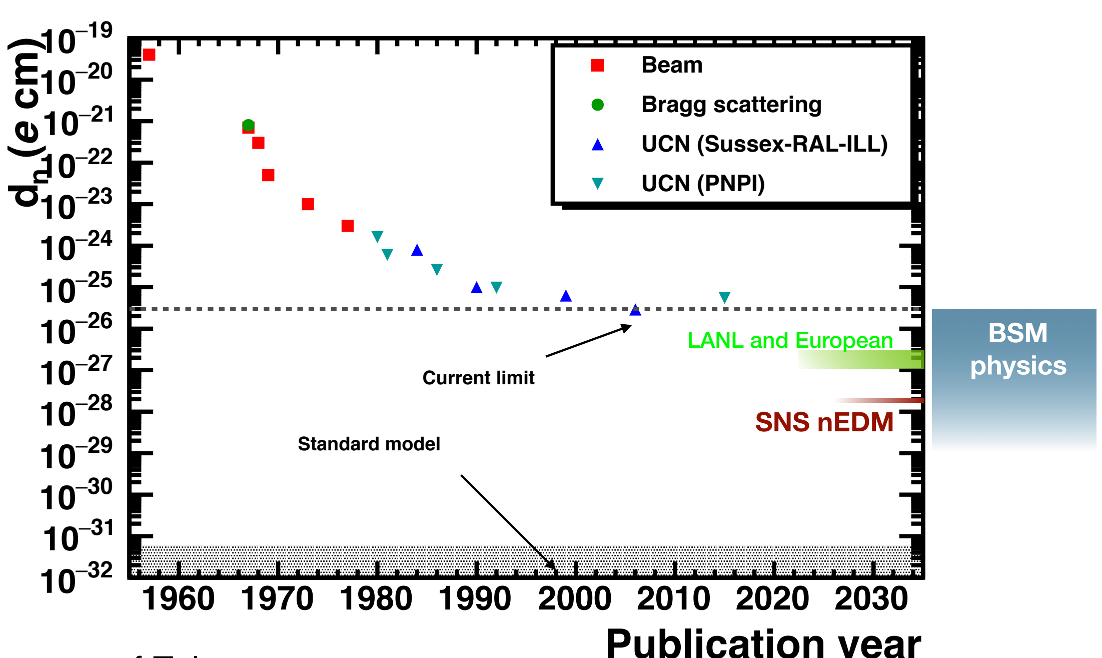


- Permanent EDM of protons, neutrons and nuclei would be the best evidence for CP violation beyond the SM.

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

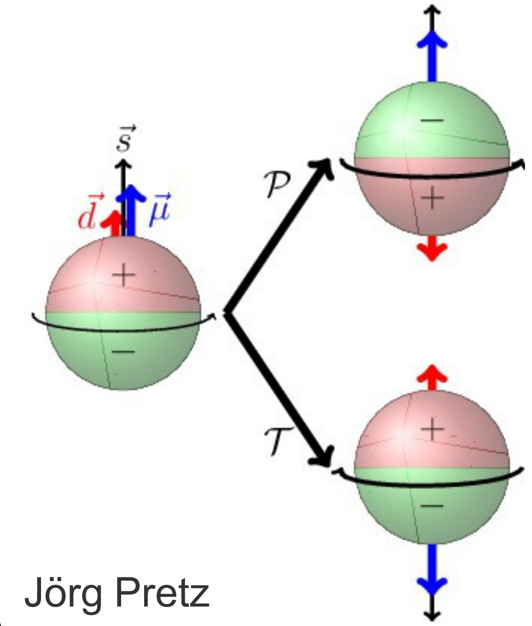
	Current	SM
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
n	10^{-26}	10^{-31}
p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
^{129}Xe	10^{-27}	10^{-33}
^{225}Ra	10^{-23}	10^{-33}

Experimental landscape



Plot courtesy of T. Ito.

MOTIVATION AND TARGET OBSERVABLES



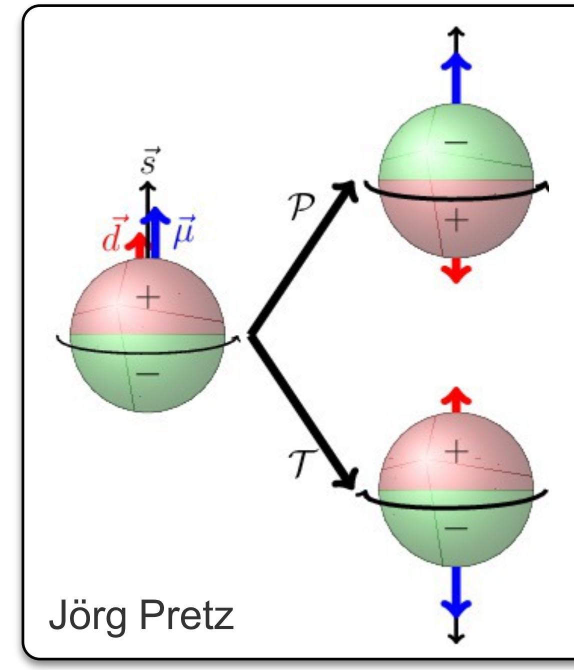
- Constraining BSM requires combining different non-zero EDM results and matching between nuclear-level EDM and quark/gluon effective CP violating operators.
- Quark EDM and tensor charges essentially done, more on isoscalar and strange/charm to be done. the rest of EDM contributions yet unconstrained.

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

See e.g., Bhattacharya et al, Phys. Rev. Lett. 115, 212002.

Alarcon et al, arXiv:2203.08103 [hep-ph].

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

- θ_{QCD}-induced *p*/*n*EDM at large quark masses
- Isovector *q*chromo-EDM-induced *n*EDM at the physical point
- Weinberg *GGG*-induced *p*/*n*EDM at large quark masses

CHALLENGING

- θ_{QCD}-induced *p*/*n*EDM at physical point
- Isoscalar *q*chromo-EDM-induced *n*EDM at the physical point, requires subtraction of the first item
- Weinberg *GGG*-induced *p*/*n*EDM at the physical point, again mixing with the first item

EXTREMELY CHALLENGING

- 4-quark-induced *p*/*n*EDM requires 4pt functions, and often disconnecteds contb.
- πNN and *NNNN* CP-violating interactions
- EDM in deuteron and light nuclei

EXPECTATIONS FOR THE NEXT DECADE

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

Single-nucleon
Multi-nucleon

Kronfeld at al, USQCD Snowmass whitepaper (2022).

EXPECTATIONS FOR THE NEXT DECADE

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Nucleon	Nucleon g_A^{u-d}	1%*	Neutron lifetime puzzle
matrix	Nucleon g_T^{u-d}	1%	UCNB, Nab
elements	Nucleon g_S^{u-d}	3%	UCNB, Nab
	$\sigma_{\pi N}$, σ_s	5%	Mu2e, LZ, CDMS
	Nucleon r_E, r_A	5%	DUNE, MicroBooNE, NOvA, T2K
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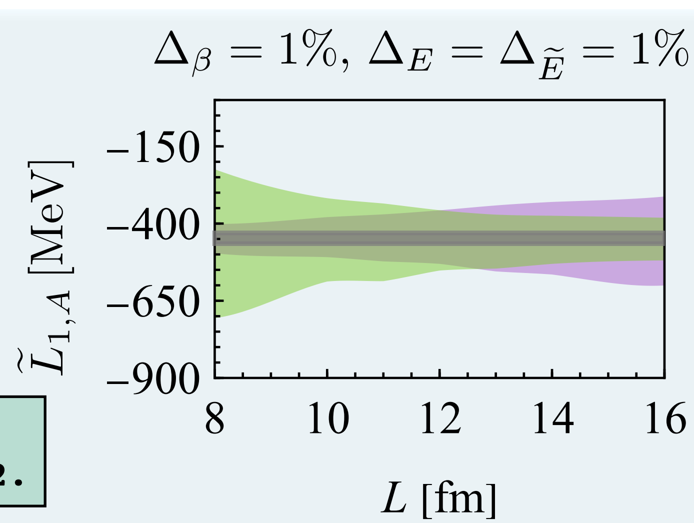
Single-nucleon
Multi-nucleon

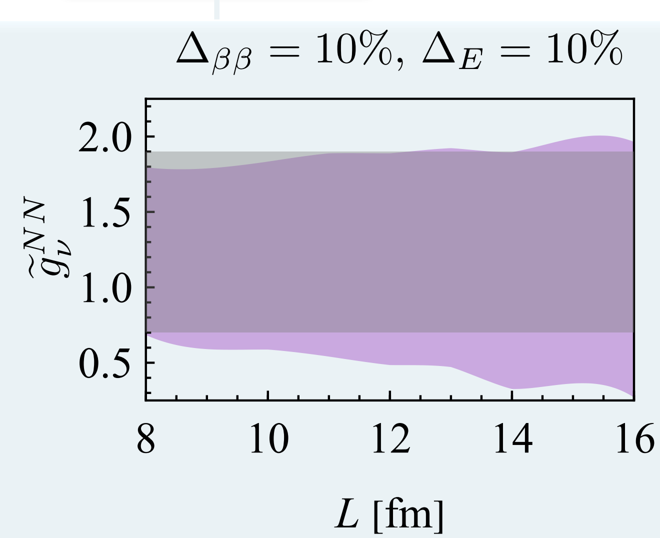
Kronfeld at al, USQCD Snowmass whitepaper (2022).

Need more resource assessments and sensitivity analysis using synthetic data for nuclear matrix elements.

Leading-order two-nucleon correlated axial coupling



ZD, Kadam, Phys. Rev. D 105 (2022) 9, 094502.



Leading-order $0\nu\beta\beta$ coupling with light Majorana neutrinos

Three features make lattice QCD calculations of nuclei hard:

i) The complexity of systems grows rapidly with the number of quarks.

Detmold and Orginos, Phys. Rev. D 87, 114512 (2013).

See also: Detmold and Savage, Phys.Rev.D82 014511 (2010). Doi and Endres, Comput. Phys. Commun. 184 (2013) 117.

ii) Excitation energies of nuclei are much smaller than the QCD scale.

Beane at al (NPLQCD), Phys.Rev.D79 114502 (2009).
Beane, Detmold, Orginos, Savage, Prog. Part. Nucl. Phys. 66 (2011).
Junnakar and Walker-Loud, Phys.Rev. D87 (2013) 114510.
Briceno, Dudek and Young, Rev. Mod. Phys. 90 025001.

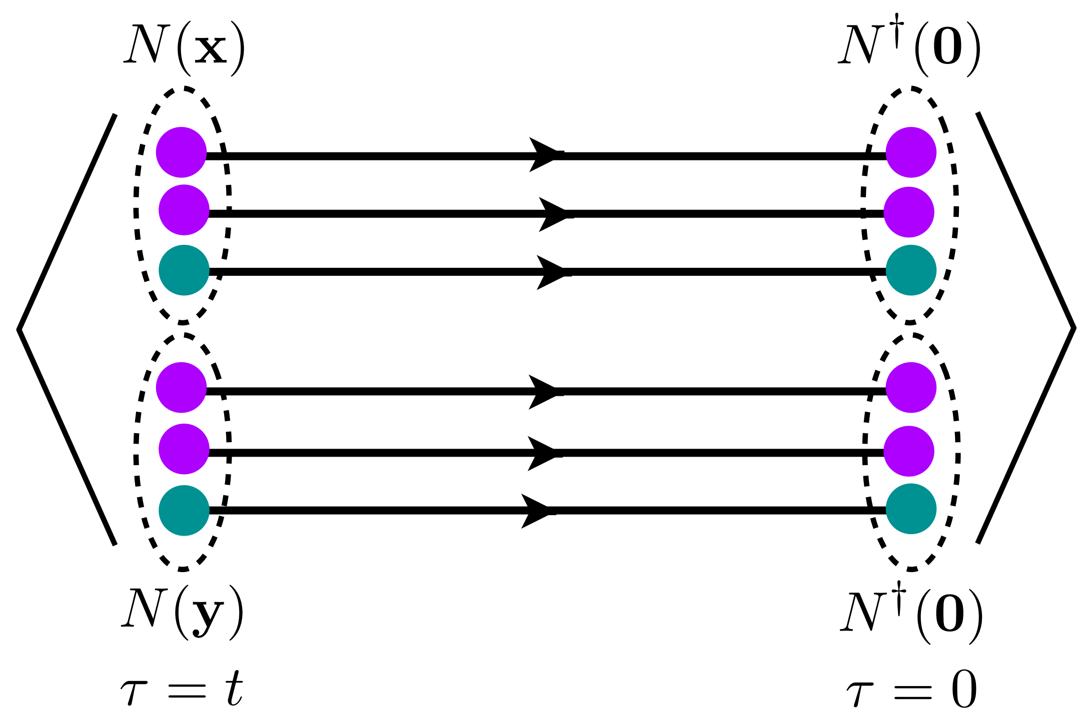
iii) There is a severe signal-to-noise degradation.

Paris (1984) and Lepage (1989).

Wagman and Savage, Phys. Rev. D 96, 114508 (2017).
Wagman and Savage, arXiv:1704.07356 [hep-lat].

i) The complexity of systems grows rapidly with the number of quarks.

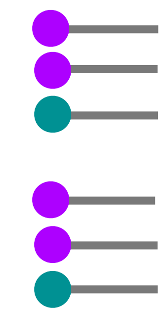
$$C(\mathbf{P};t) = \sum_{\mathbf{p}_1+\mathbf{p}_2=\mathbf{P}} \sum_{\mathbf{x},\mathbf{y}} e^{i\mathbf{p}_1\cdot\mathbf{x}+i\mathbf{p}_2\cdot\mathbf{y}} \times$$



Complexities of quark-level interpolating fields

Complexities of quark contractions

A quark-level nuclear interpolating field: $\bar{\mathcal{N}}^h = \sum_{\mathbf{a}} w_h^{a_1,a_2\cdots a_{n_q}} \bar{q}(a_1)\bar{q}(a_2)\cdots\bar{q}(a_{n_q})$



All possibilities for quark quantum numbers in the interpolating operator

Naive weights

which naively has $\frac{N!}{n_q!(N-n_q)!}$ terms! But many of the terms are zero by symmetries.

Example: deuteron at a single site

$$924 \quad \rightarrow \quad 21$$

Detmold and Orginos (2013),
Endres and Doi (2013).

Complexities of quark-level interpolating fields

Naively the number of quark contractions for a nucleus goes as:

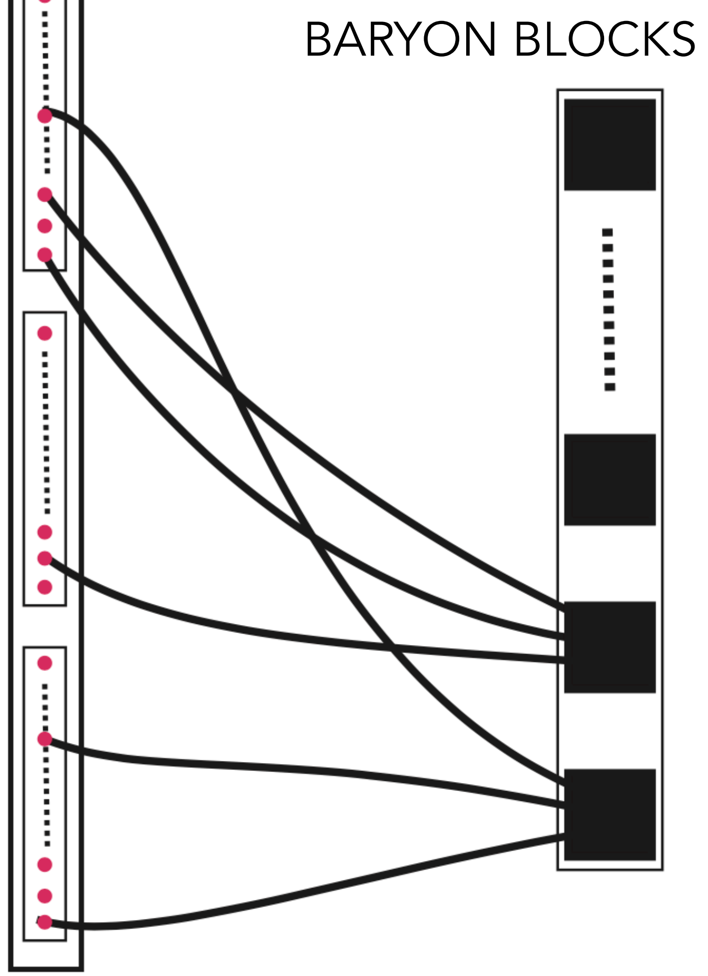
$$(2N_p + N_n)!\ (N_p + 2N_n)!$$

How bad is this?

Example: Consider radium-226 isotope.
The number of contractions required is ~ 10^{1425}

Complexities of quark contractions

An example of a more efficient algorithm:

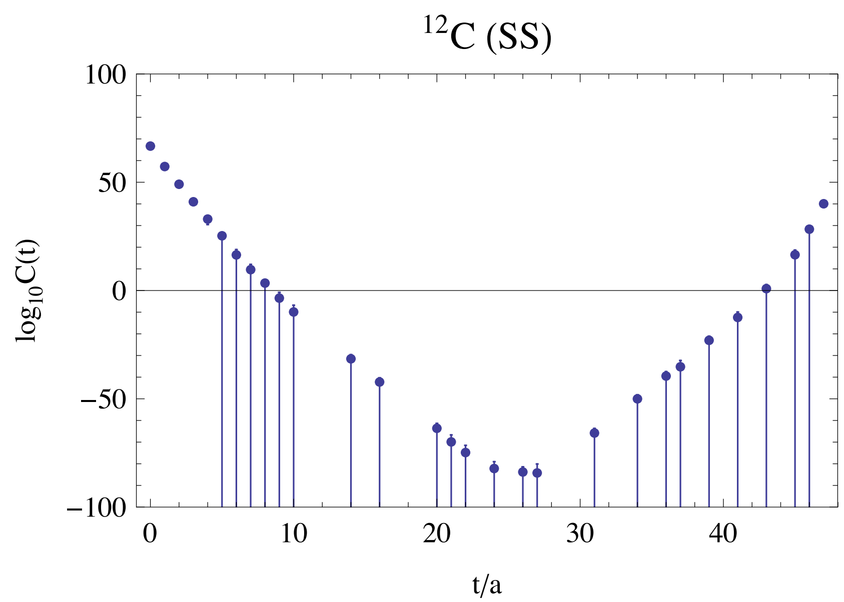


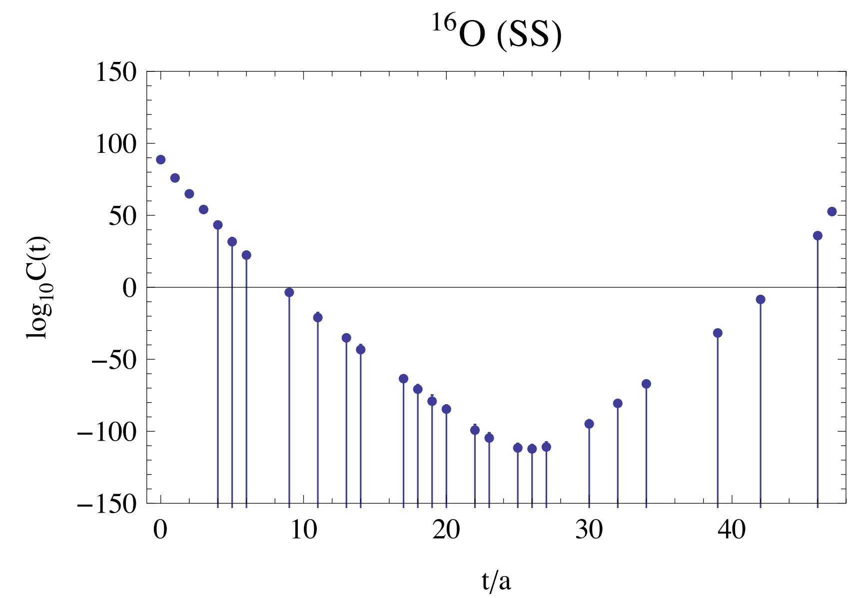
The new scaling is: $M_w \cdot N_w \cdot \frac{(3A)!}{(3!)^A}$

M_w: Number of terms in the sink

N_w: Number of terms in the source

Detmold and Orginos (2013).

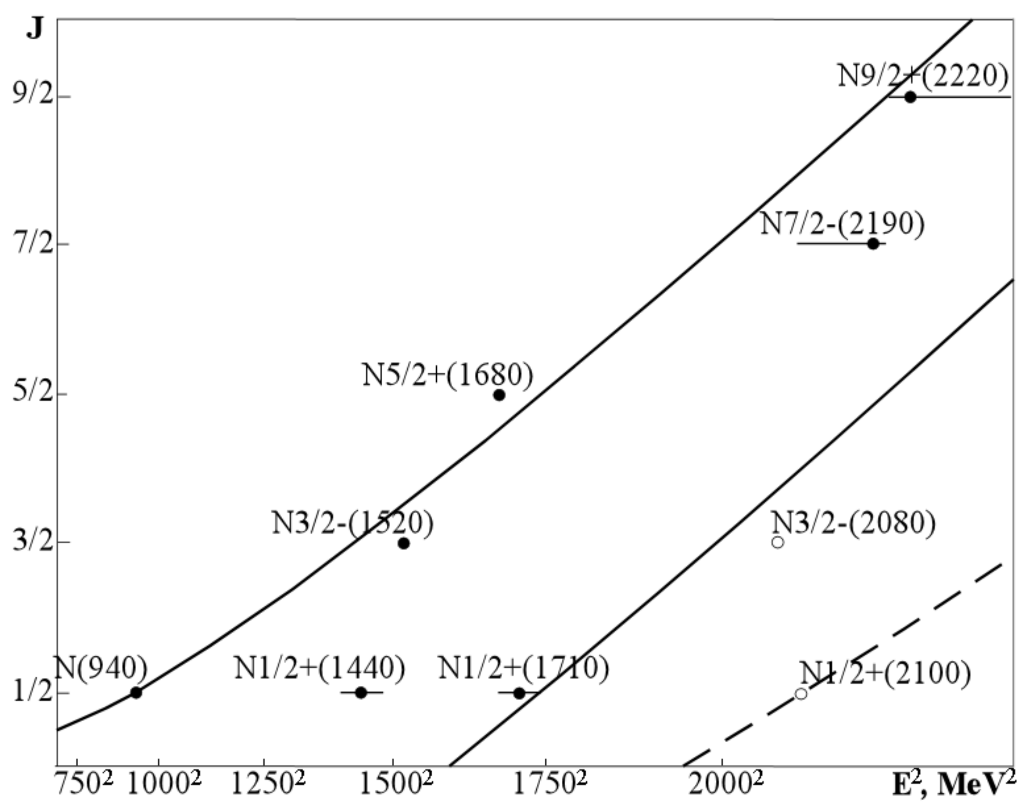




Complexities of quark contractions

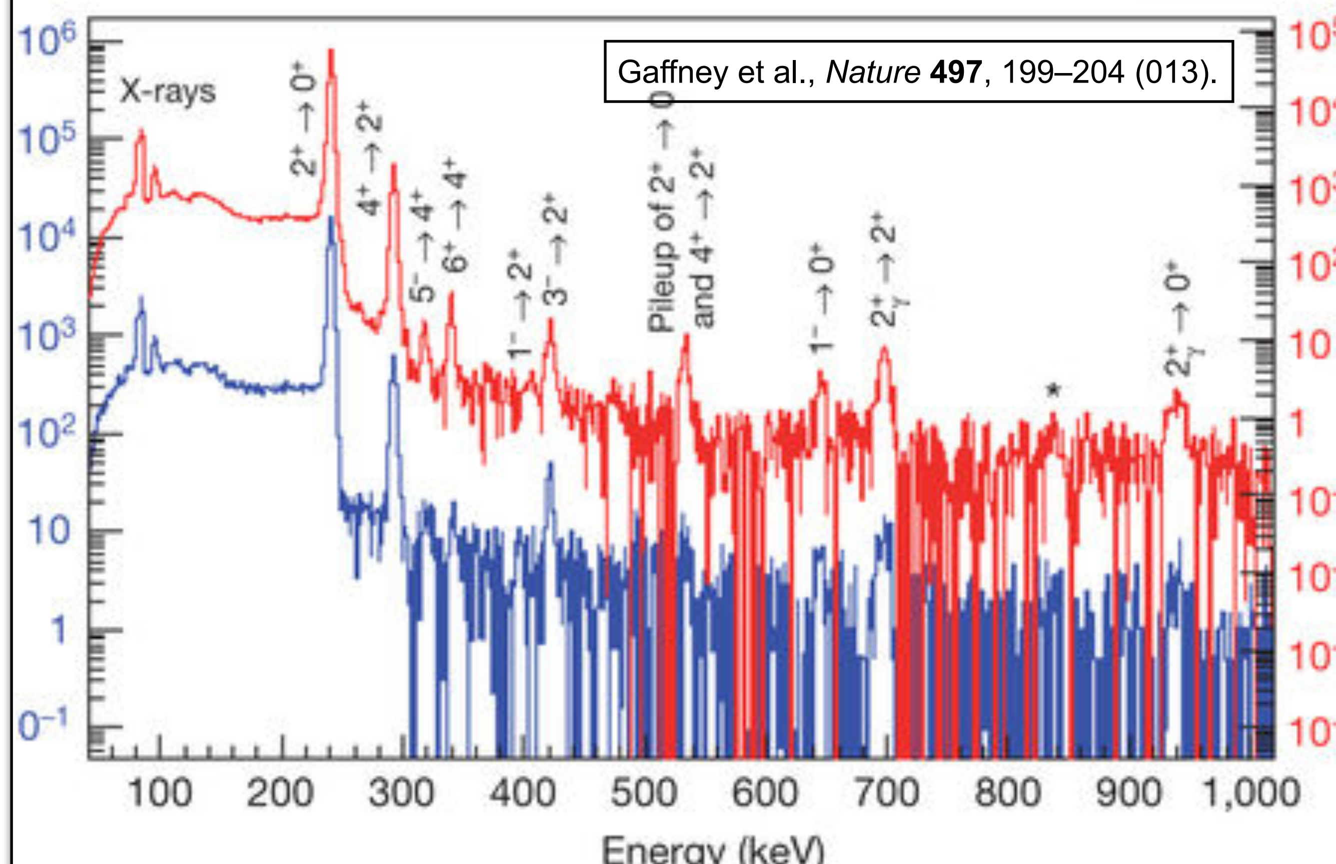
ii) Excitation energies of nuclei are much smaller than the QCD scale.

Nucleon excitations



Kulikov, Dmitry A. et al., Central Eur.J.Phys. 11 (2013) .

Nuclear excitations of two pear-shaped nuclei (radium and radon)

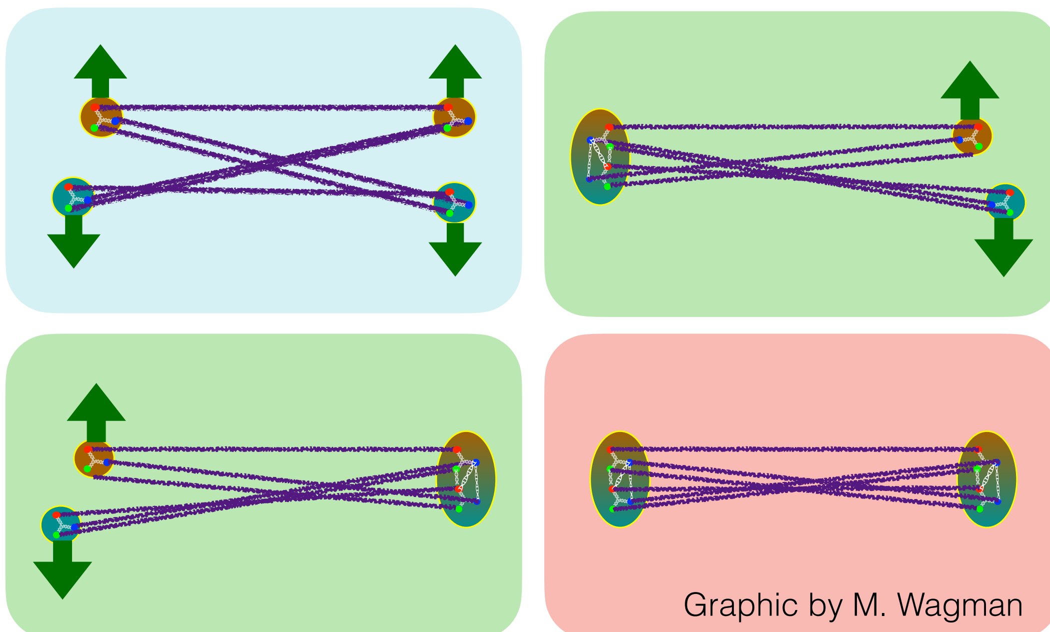


Gaffney et al., *Nature* **497**, 199–204 (013).

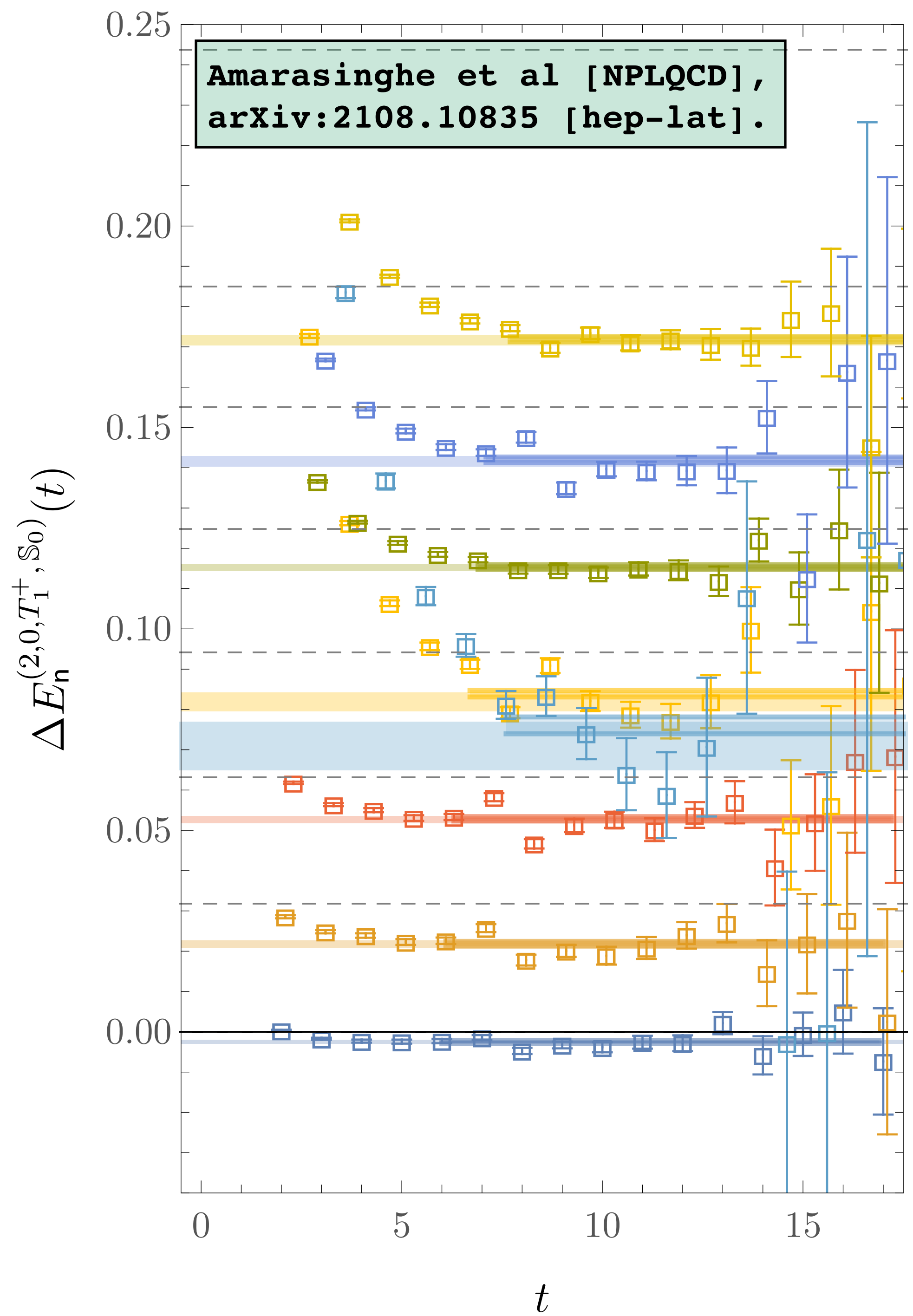
Getting radium directly from QCD will remain challenging for a long time! One should first compute A = 2, 3, 4 systems well. This is till not that easy: $B_d \approx 2\ \mathrm{MeV}$!

The small excitation gaps require more sophisticated techniques to discern the spectrum, such as variational approaches with a large and diverse operator set. Example: Deuteron channel at $m_\pi \approx 800$ MeV.

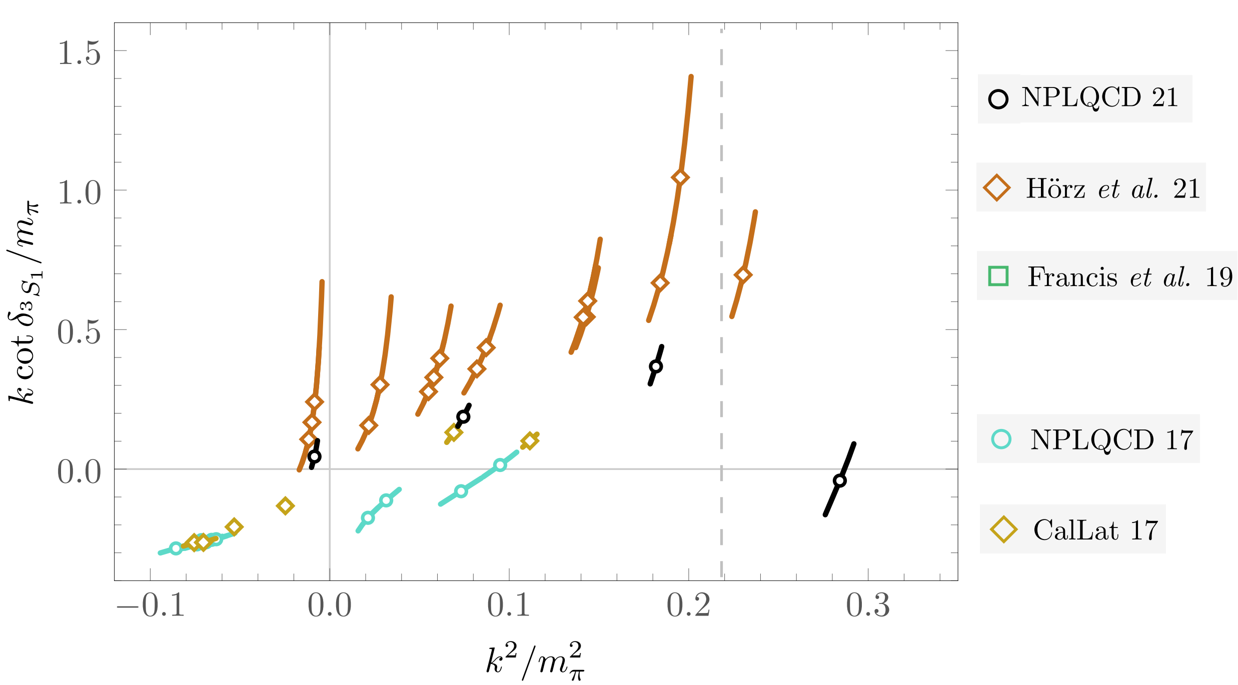
A symmetric correlation function of many types of operators at source and sink…



leads to identification of upper bounds on finite-volume eigenenergies…



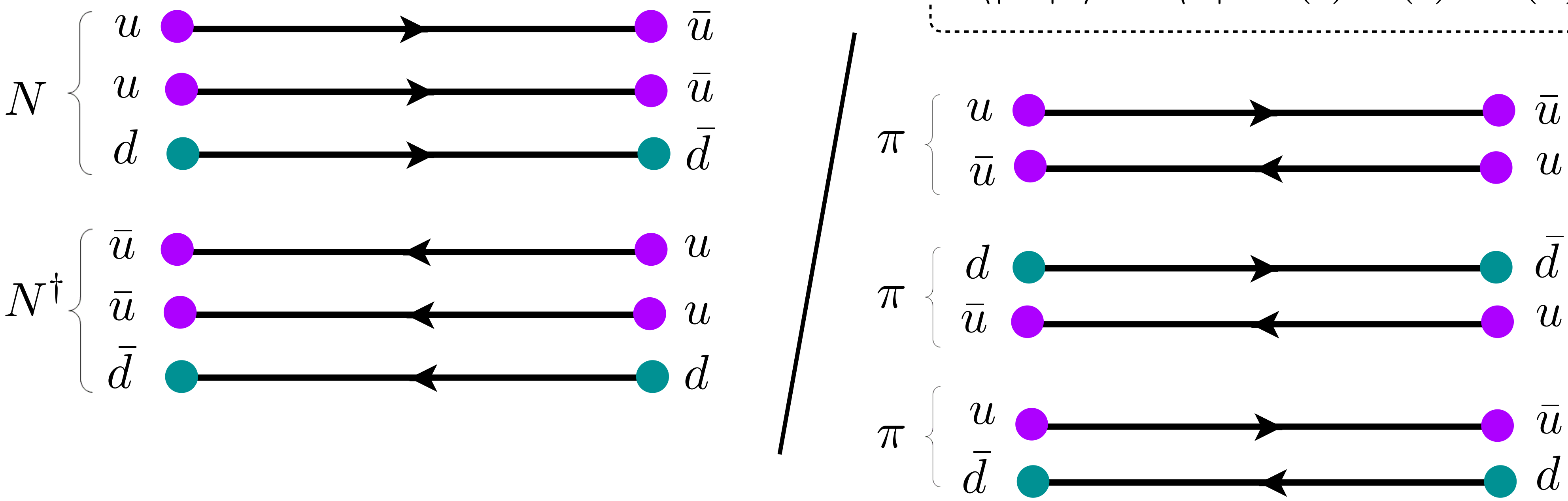
which gives access to low-energy scattering phase shifts.



iii) There is a severe signal-to-noise degradation.

The origin of noise

$$\langle |C|^2 \rangle = \langle 0 | N^\dagger(t) N(t) N^\dagger(0) N(0) | 0 \rangle$$



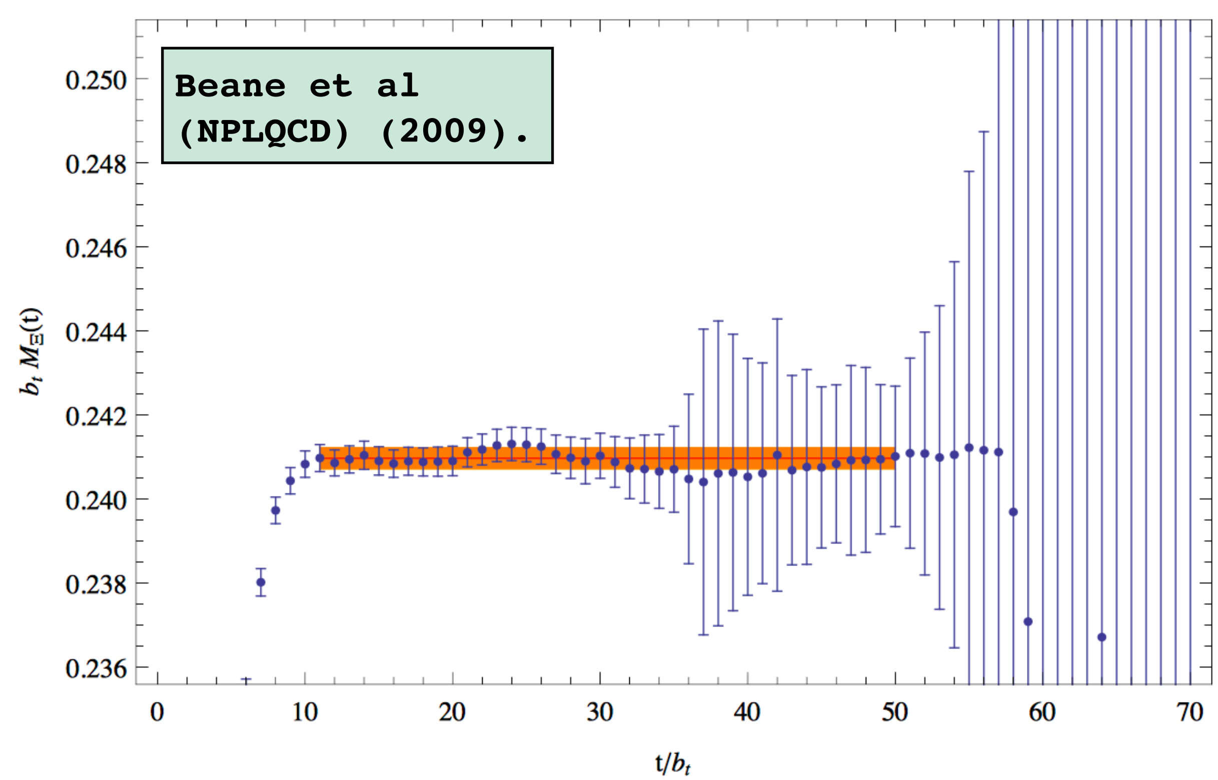
The ground-state of the variance correlator is three pions and not two nucleons:

$$\mathrm{StN}(C_i) \sim \frac{\langle C_i \rangle}{\sqrt{\langle |C_i|^2 \rangle}} \sim e^{-(M_N - \frac{3}{2} m_\pi)t}.$$

Parisi (1984) and Lepage (1989).

Wagman and Savage (2016,2017).

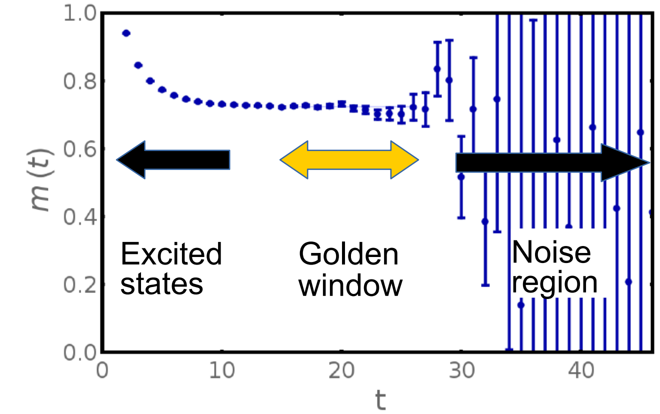
Similar arguments explain why boosted hadron correlation functions are noisy too.



Ideas to combat signal-to-noise problem include:

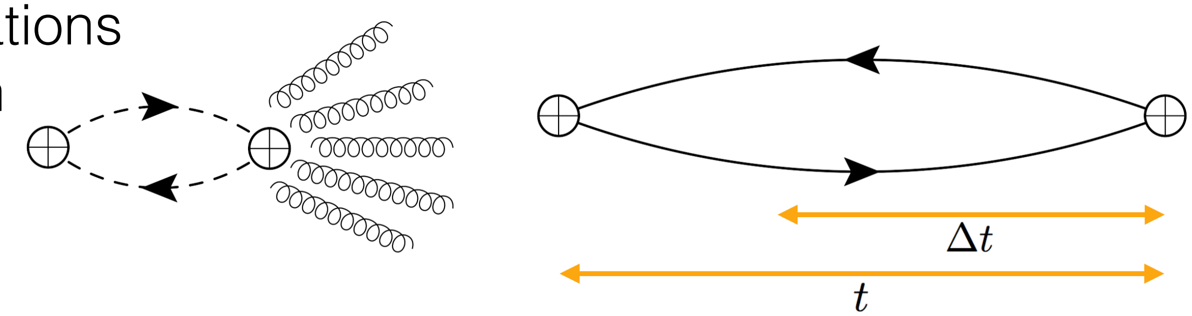
i) Enhancing the signal by operator-overlap optimizations (heuristically or systematically)

Endres and Detmold (2014).

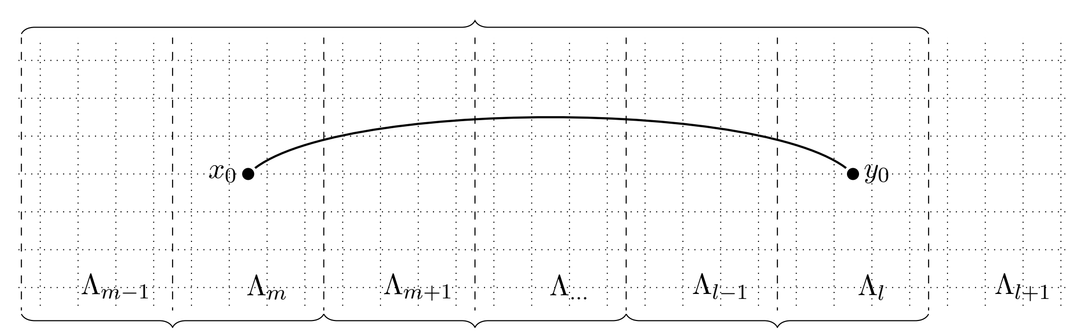


ii) A phase reweighting method to allow extrapolations by systematically changing the noise contribution

Savage and Wagman (2016-2017).

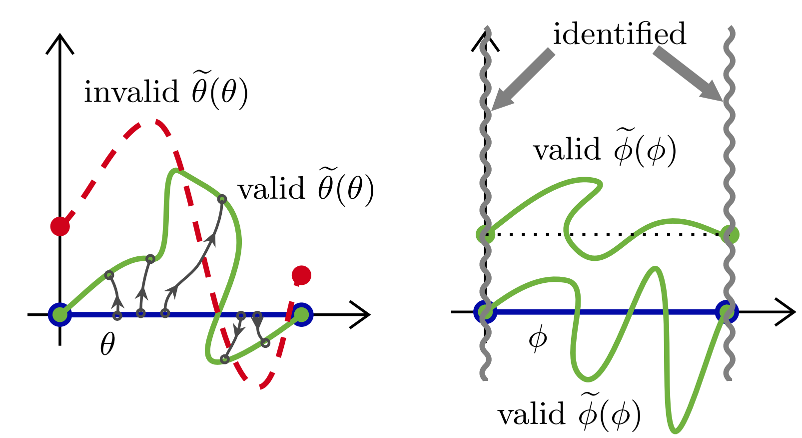


iii) Exploiting decorrelation between spacetime subvolumes (multilevel integrals and domain decomposition) **Ce, Giusti and Schaefer (2016-2018).**

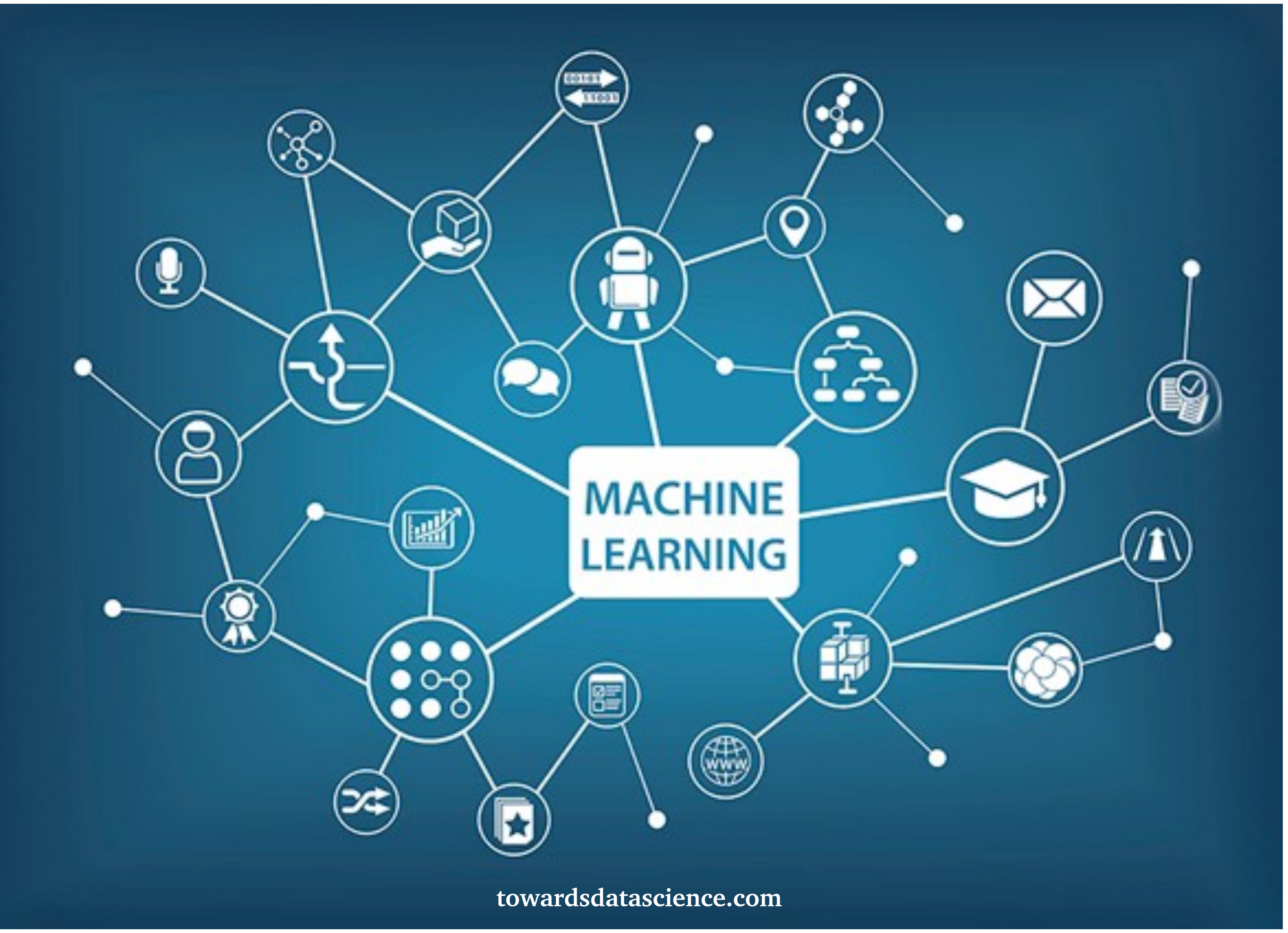


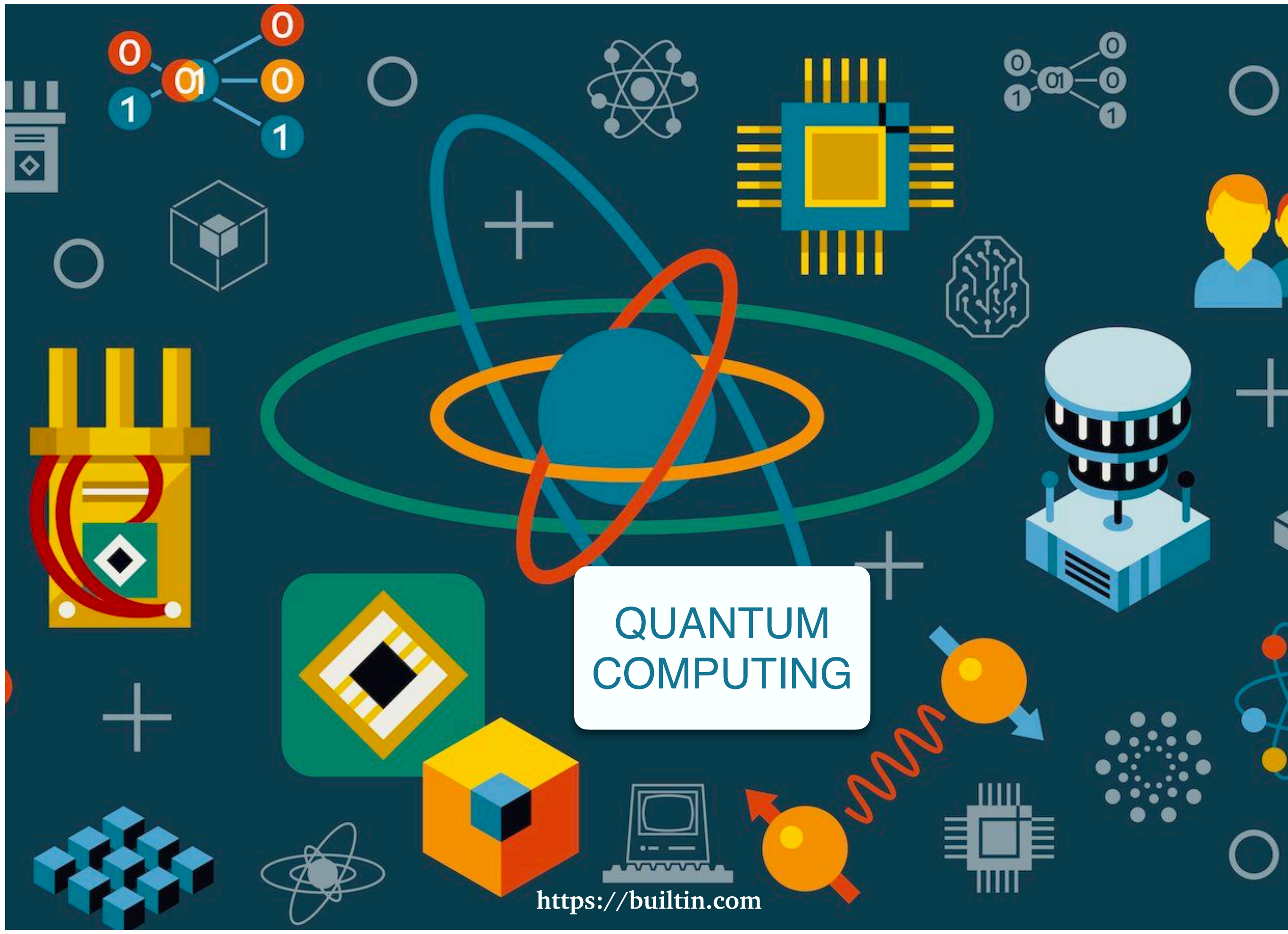
iv) Path integral contour deformations for observables

Detmold, Kanwar, Lamm, Wagman, Warrington (2021).

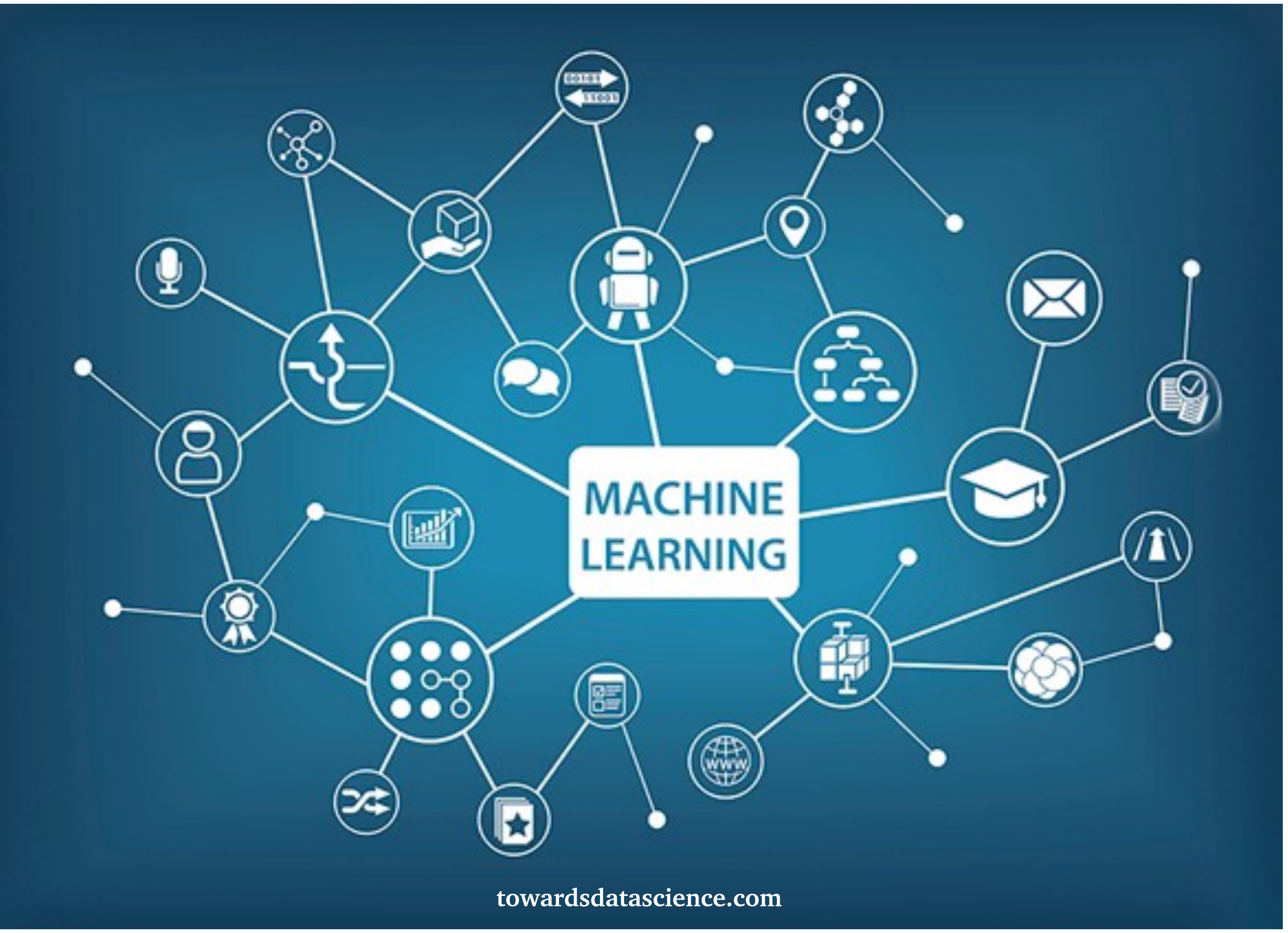


CAN WE COMBAT SIGNAL-TO-NOISE AND SIGN PROBLEMS IN MONTE CARLO LATTICE QCD SIMULATIONS WITH NEW COMPUTATIONAL PARADIGMS?





CAN WE COMBAT SIGNAL-TO-NOISE AND SIGN PROBLEMS IN MONTE CARLO LATTICE QCD SIMULATIONS WITH NEW COMPUTATIONAL PARADIGMS?



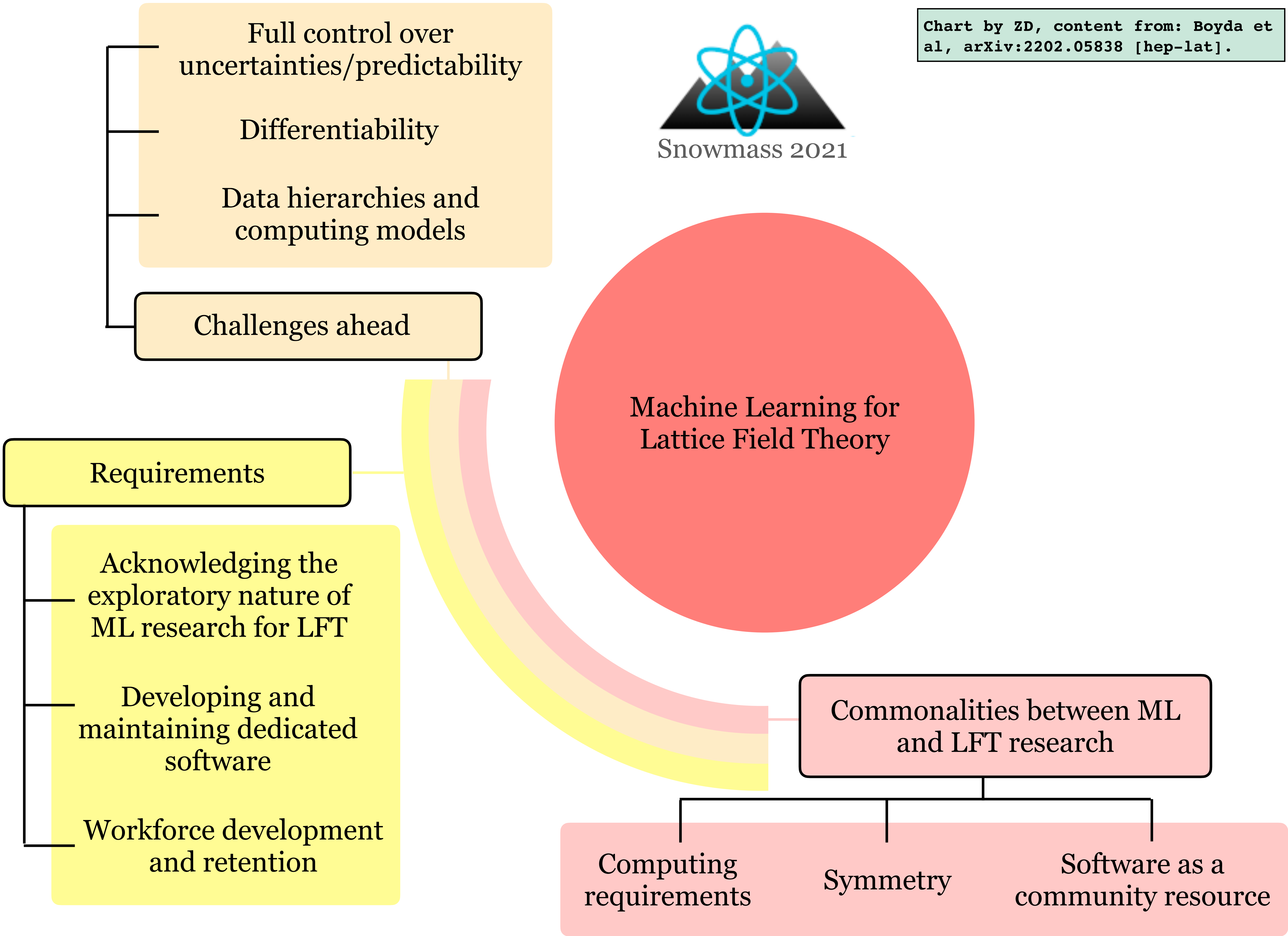
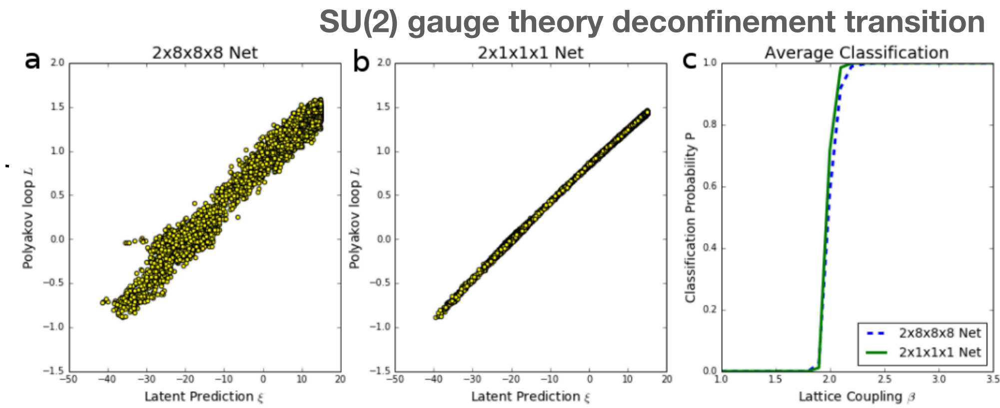


Chart by ZD, content from: Boyda et al, arXiv:2202.05838 [hep-lat].
Snowmass 2021
Machine Learning for Lattice Field Theory
Challenges ahead
Full control over uncertainties/predictability
Differentiability
Data hierarchies and computing models
Requirements
Acknowledging the exploratory nature of ML research for LFT
Developing and maintaining dedicated software
Workforce development and retention
Commonalities between ML and LFT research
Computing requirements
Symmetry
Software as a community resource

APPLICATIONS OF ML ON LATTICE FIELD THEORY TO DATE

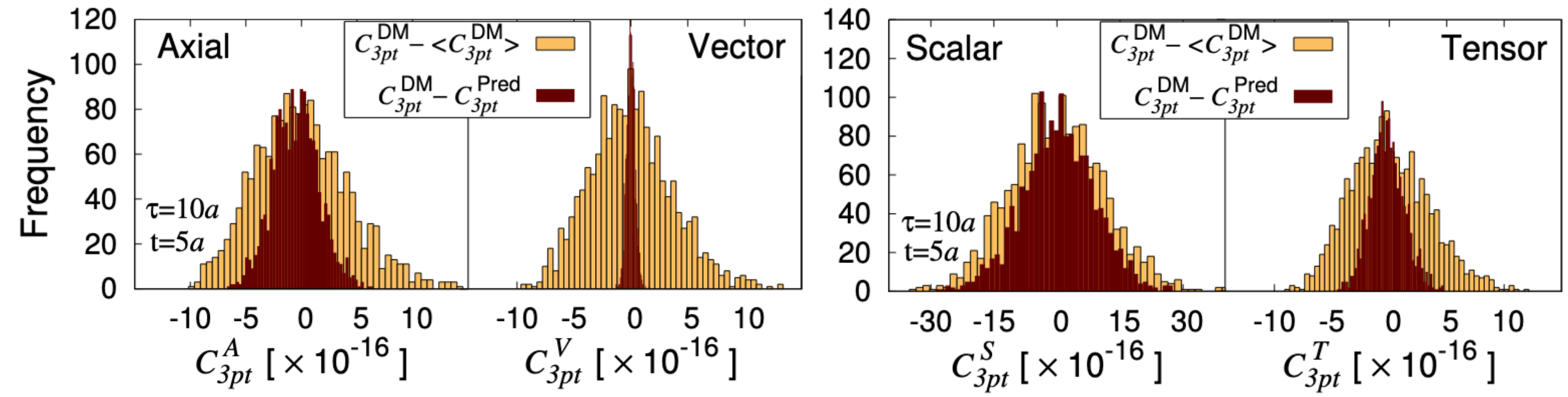
i) Classifying lattice field theory phases

e.g., Wetzel et al, Phys. Rev. B 96, 184410 (2017).



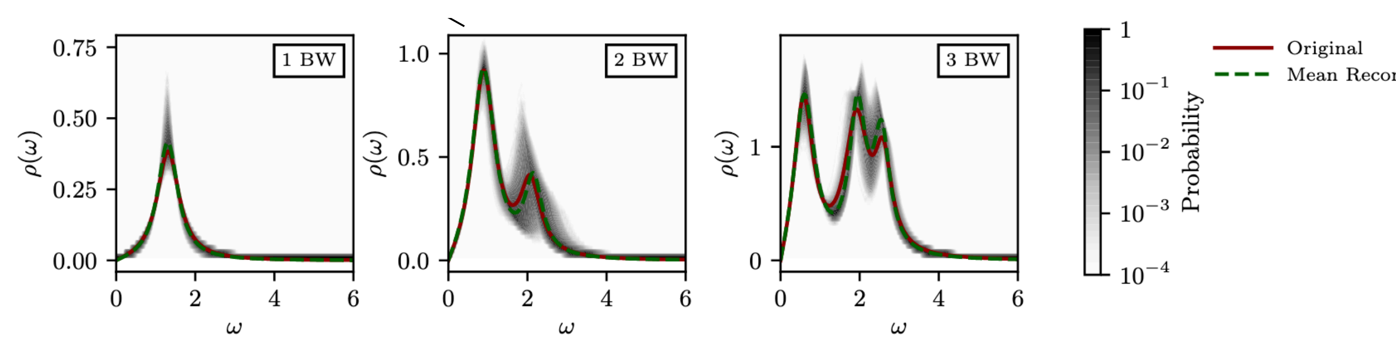
ii) Estimating observables

e.g., Yoon+ Phys. Rev. D 100, 014504 (2019).



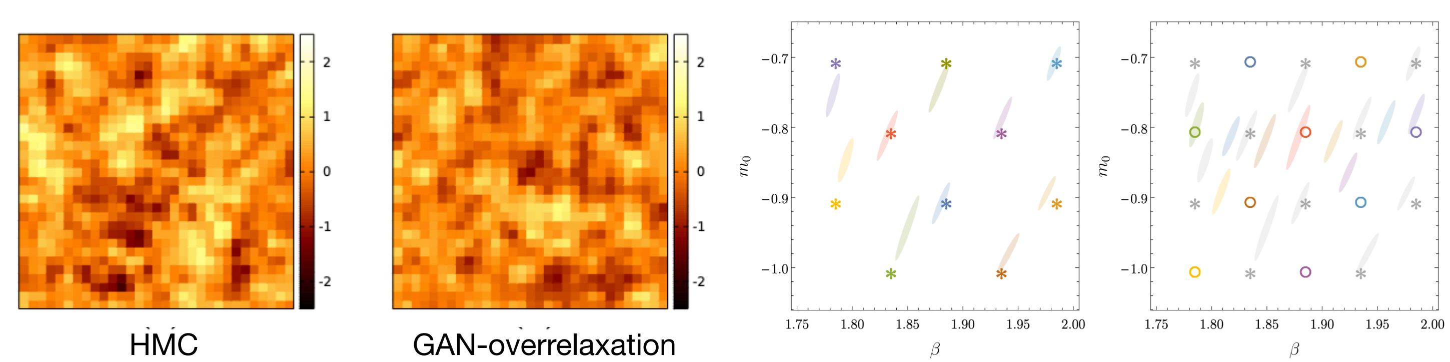
iii) Reconstructing spectral functions

e.g., Kades+ Phys. Rev. D 102, 096001 (2020).



iv) Gauge ensemble genenration and action parameter regression

e.g., Shanahan+ Phys. Rev. D 97, 094506 (2018), Pawlowski and Urban, ML: Sci. and Tech. 1 (2020) 045011.



And many more references e.g., in K. Kanwar's EuroPLEX 2022 Lectures and a Snowmass whitepaper by Boyda et al, arXiv:2202.05838 [hep-lat].

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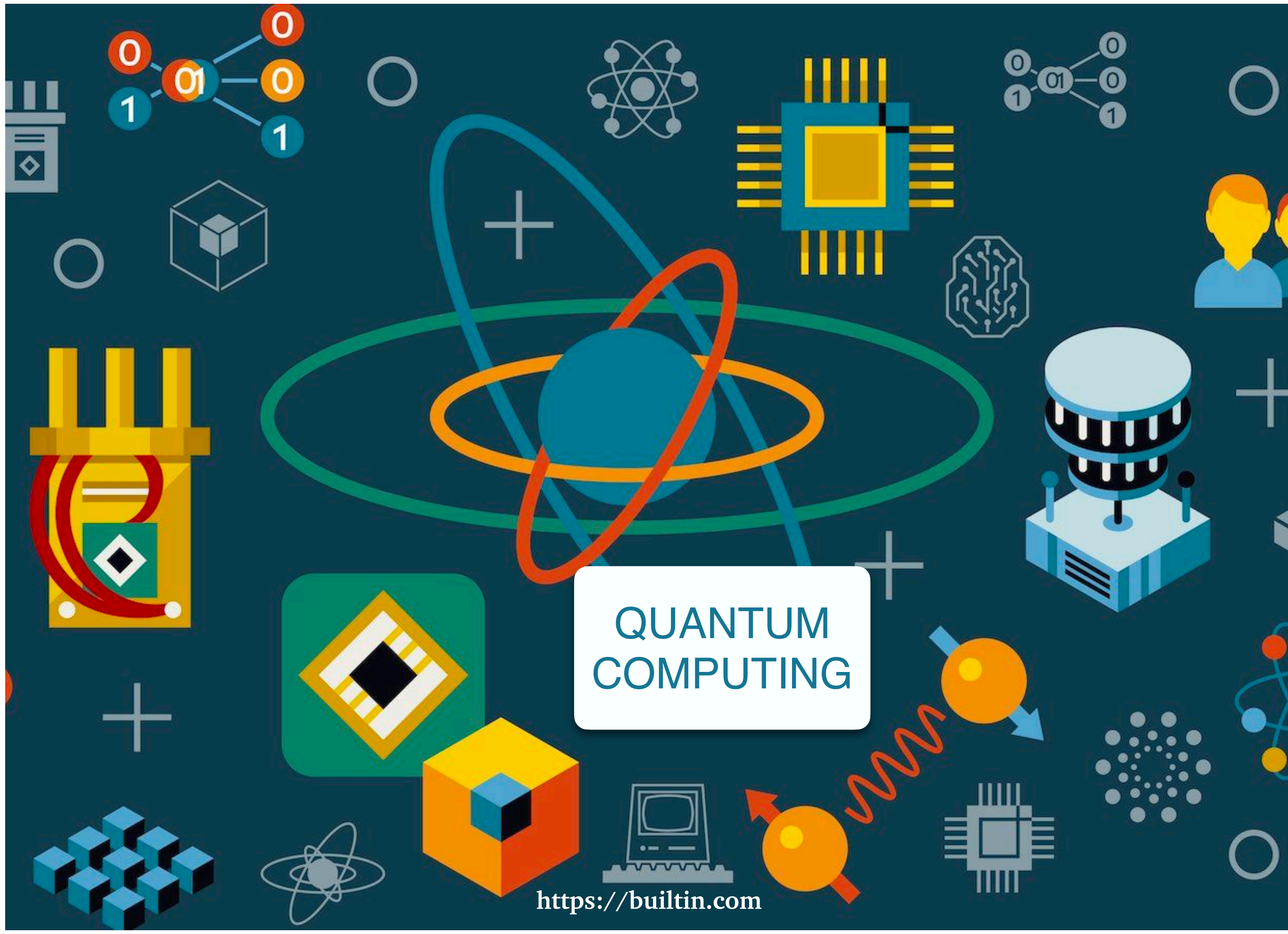
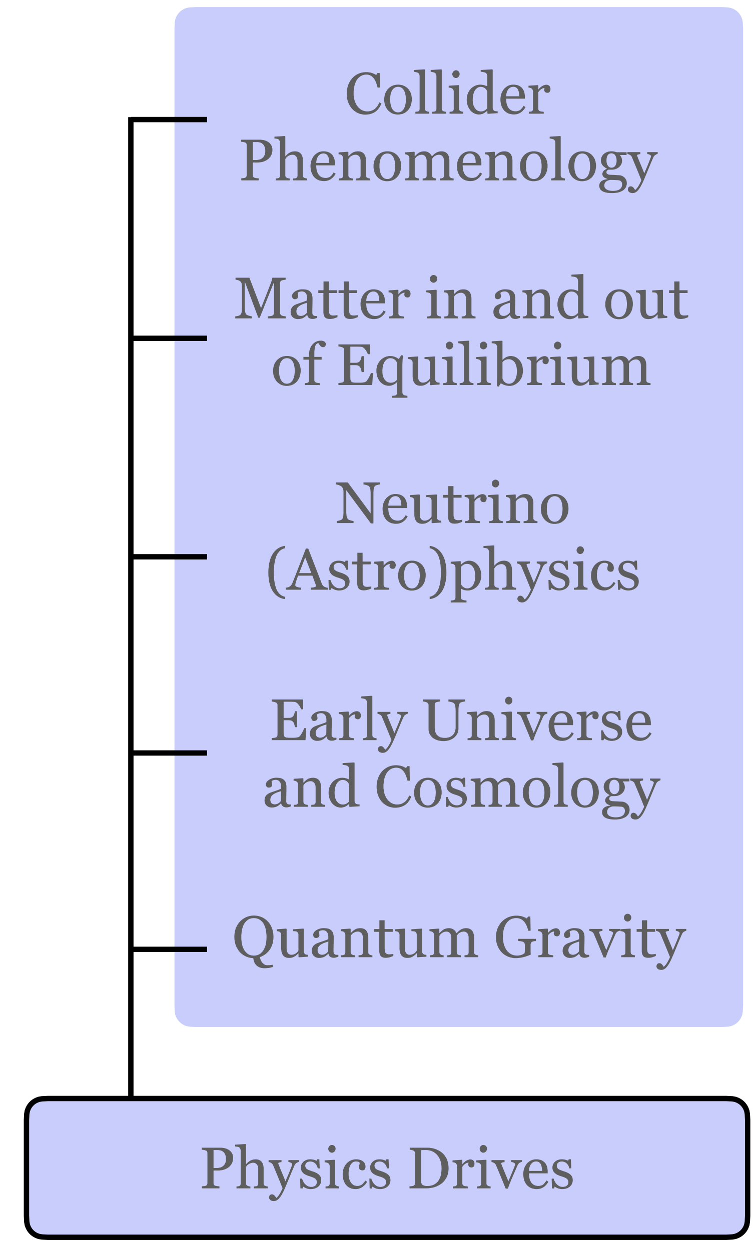
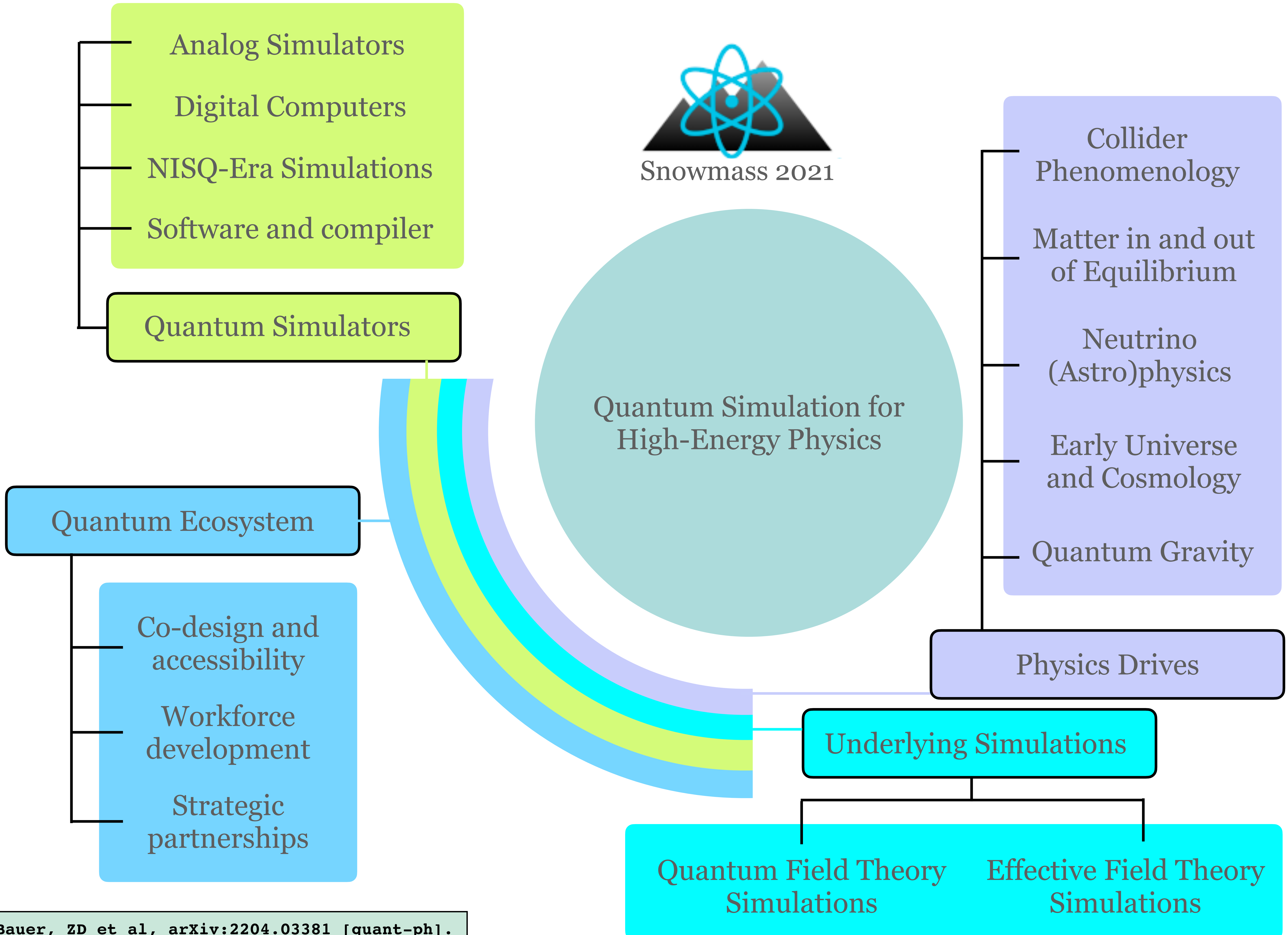


MANY INTRACTABLE QUESTIONS IN NUCLEAR AND HIGH ENERGY PHYSICS REMAIN ILLUSIVE…

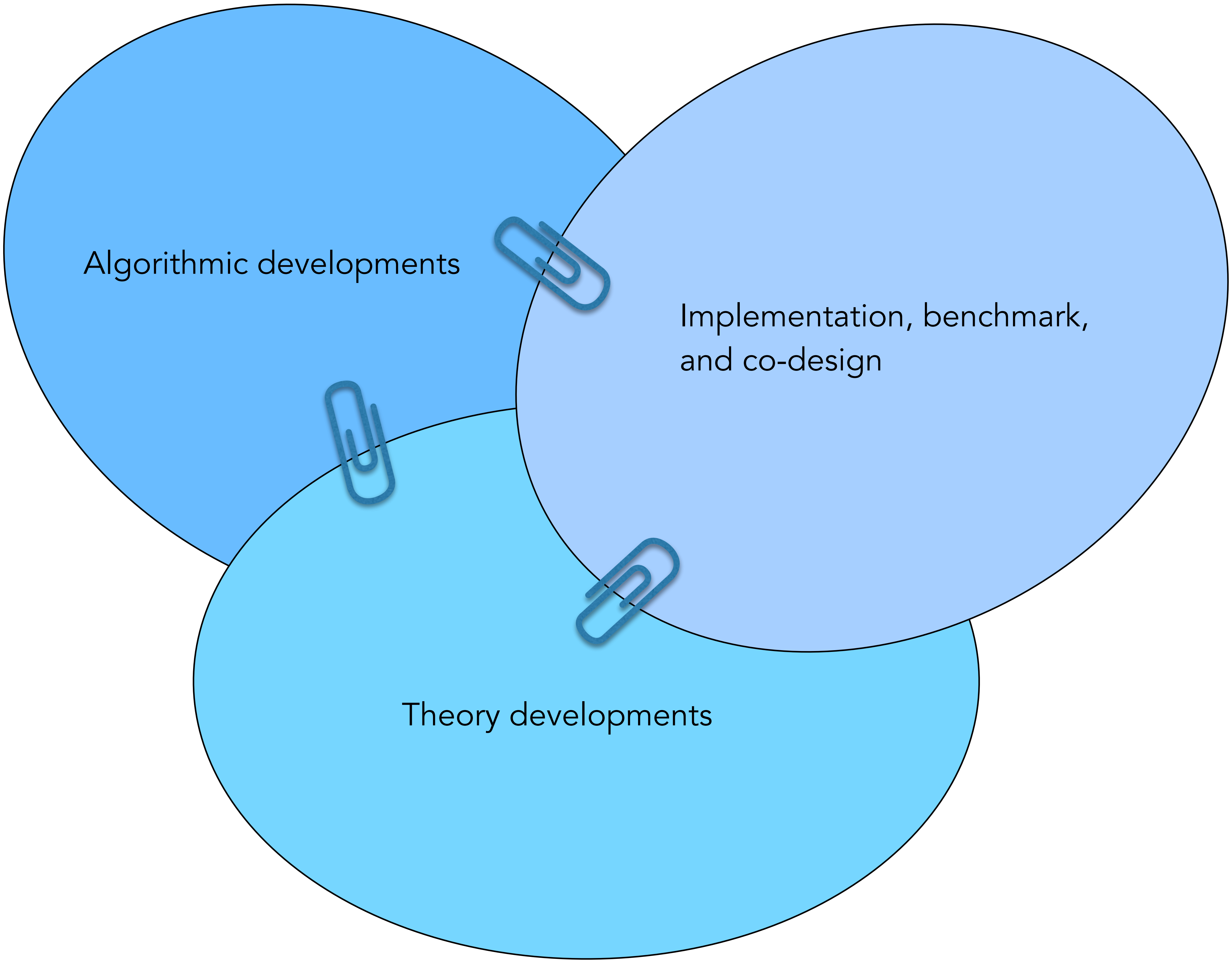


Bauer, ZD et al, arXiv:2204.03381 [quant-ph].



Bauer, ZD et al, arXiv:2204.03381 [quant-ph].

A QUANTUM-SIMULATION-BASED LATTICE FIELD THEORY CAMPAIGN WILL BE MULTI PRONG AS HAS BEEN THE CASE WITH THE CONVENTIONAL PROGRAM…



How to formulate QCD in the Hamiltonian language?

What are the efficient formulations? Which bases will be most optimal toward the continuum limit?

How to preserve the symmetries? How much should we care to retain gauge invariance?

How to quantify systematics such as finite volume, discretization, boson truncation, time digitization, etc.?

Theory developments

Algorithmic developments

- Near- and far-term algorithms with tight bounded errors and resource requirement for gauge theories?
- Can given formulation/encoding reduce qubit and gate resources?
- How do we do state preparation and compute observables like scattering amplitudes?
- Can non-Abelian gauge theories and higher dimensional theories be realized in an analog simulator?
- Can we robustly bound the errors in the analog simulation? What quantities are more robust to errors?

Implementation, benchmark, and co-design

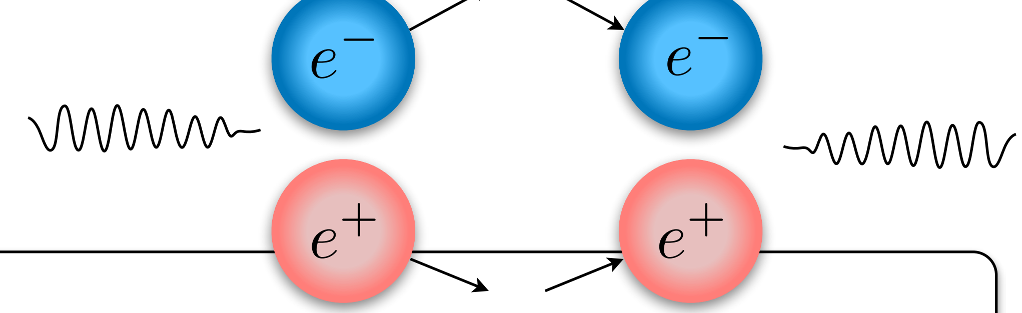
What is the capability limit of the hardware for gauge-theory simulations so far?

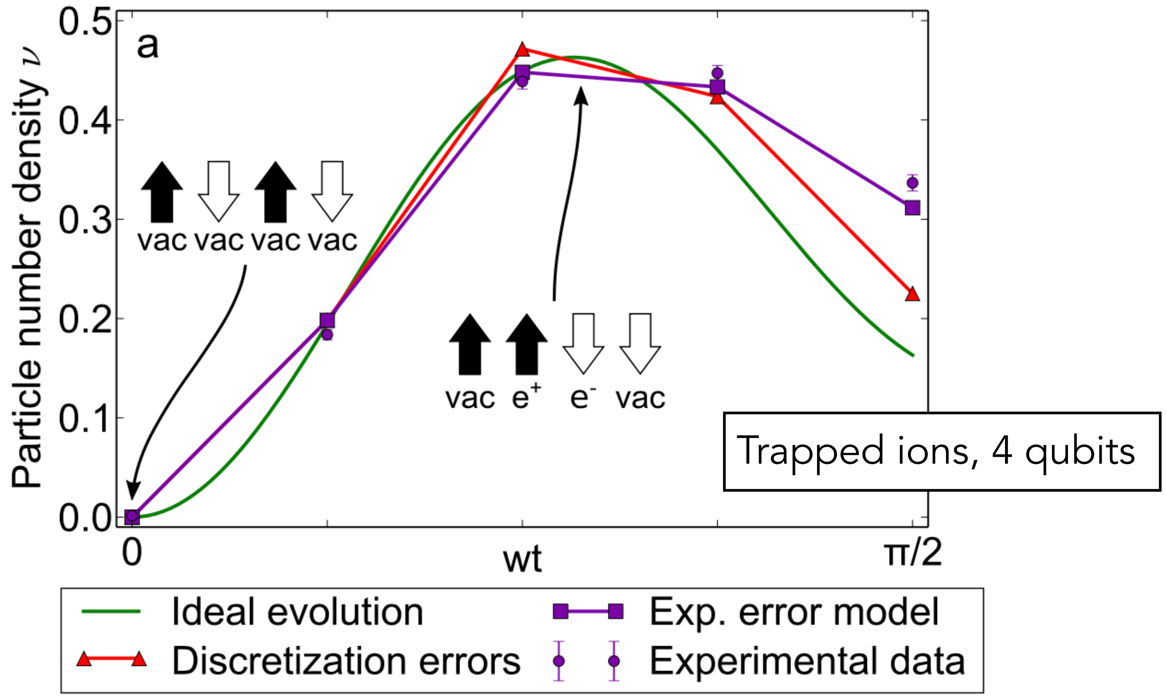
What is the nature of noise in hardware and how can it best be mitigated?

Can we co-design dedicated systems for gauge-theory simulations?

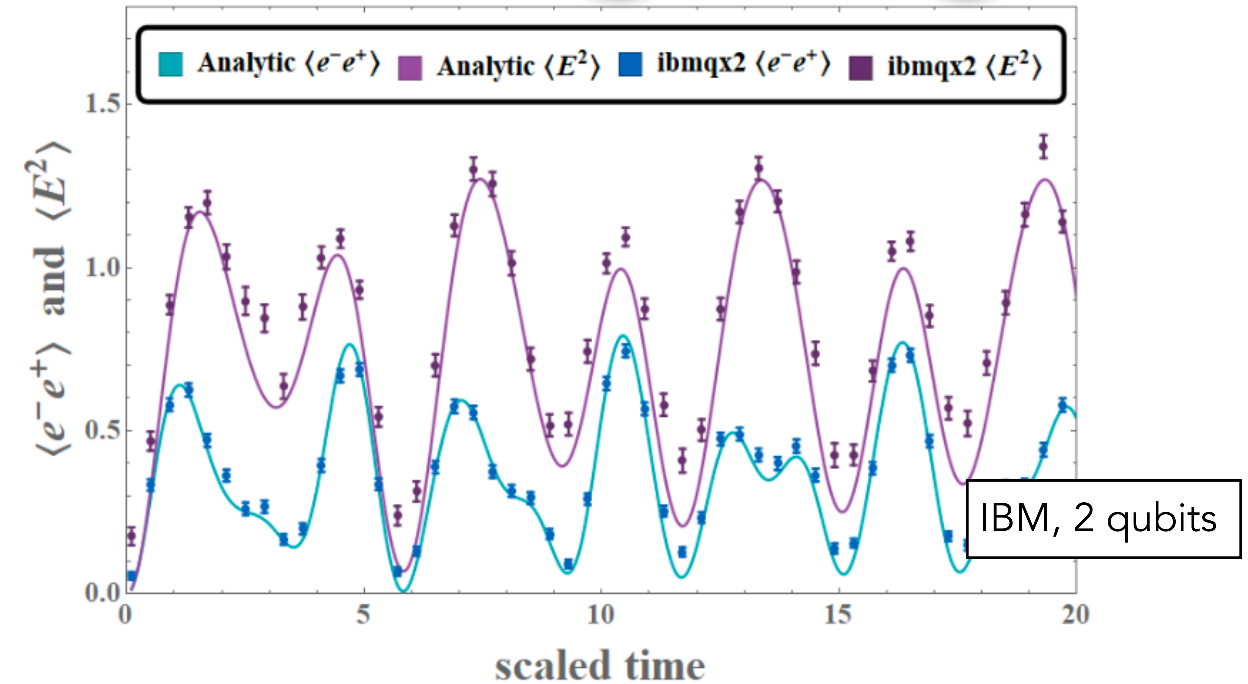
Can digital and analog ideas be combined to facilitate simulations of field theories?

DIGITAL EXAMPLES FOR AN ABELIAN 1+1D MODEL

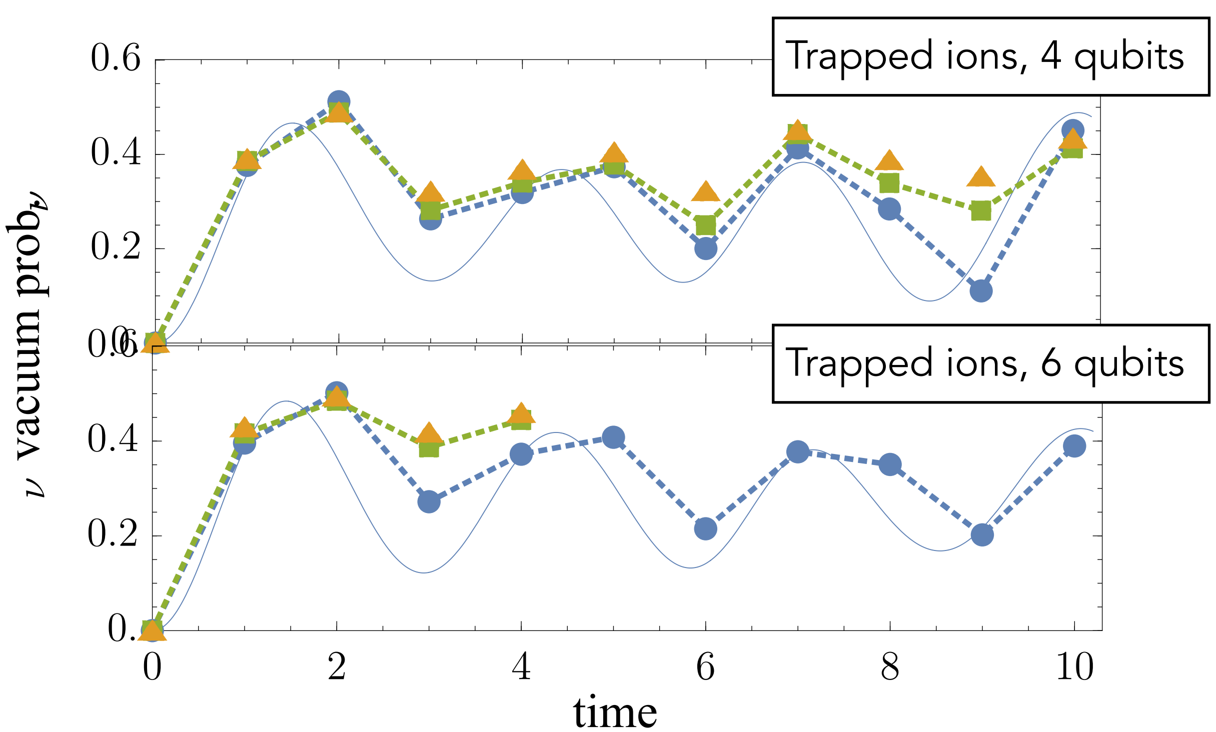




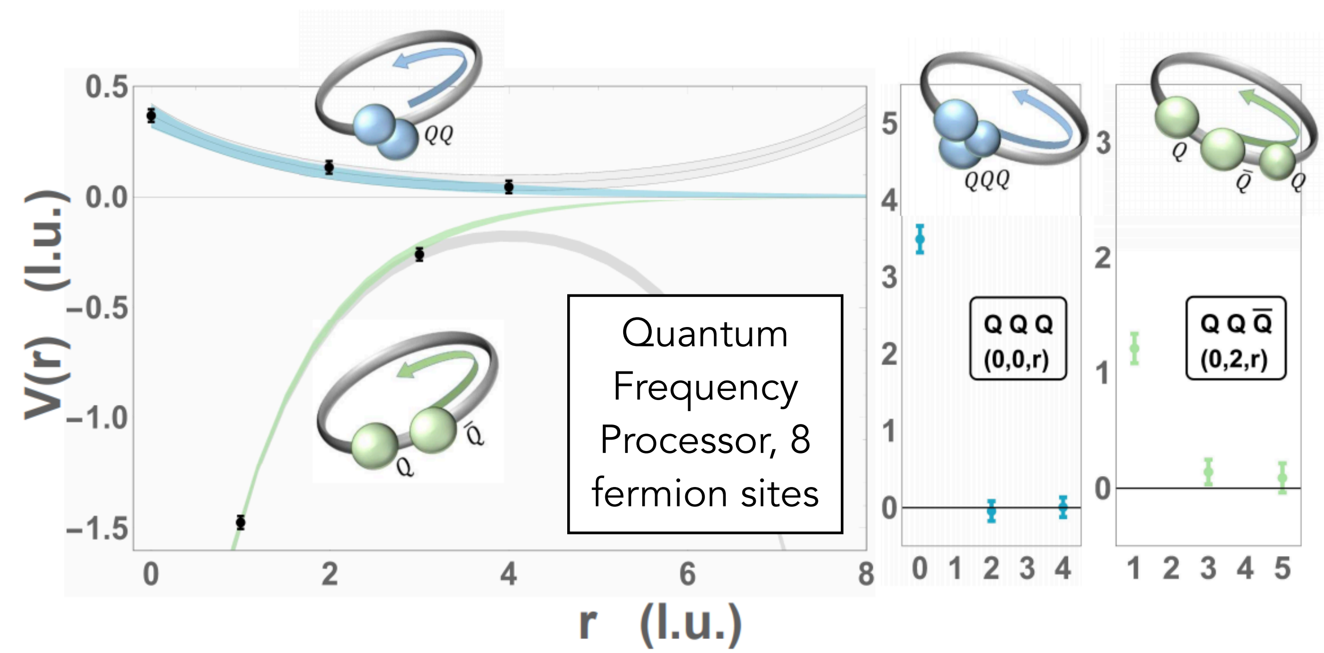
Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



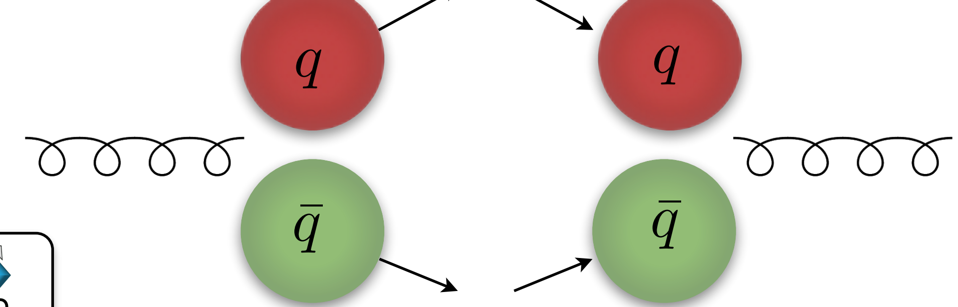
Klco, Dumitrescu, McCaskey, Morris, Pooser, Sanz, Solano, Lougovski, Savage, Phys. Rev. A 98, 032331 (2018)



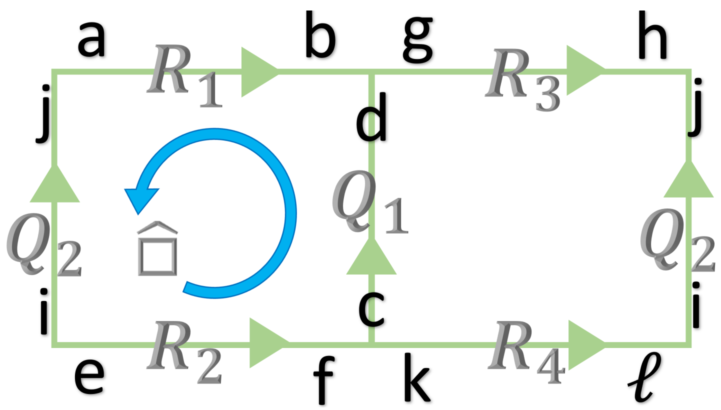
Nguyen, Tran, Zhu, Green, Huerta Alderete, ZD, Linke, *PRX Quantum* 3 (2022) 2, 020324.

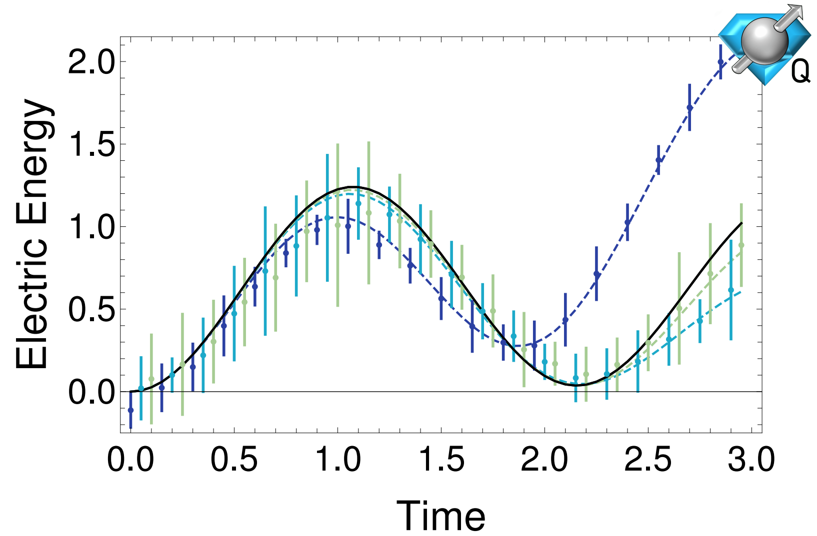


Lu, Klco, Lukens, Morris, Bansal, Ekström, Hagen, Papenbrock, Weiner, Savage, Lougovski, Phys. Rev. A 100, 012320 (2019)



DIGITAL EXAMPLES FOR NON-ABELIAN LGTs

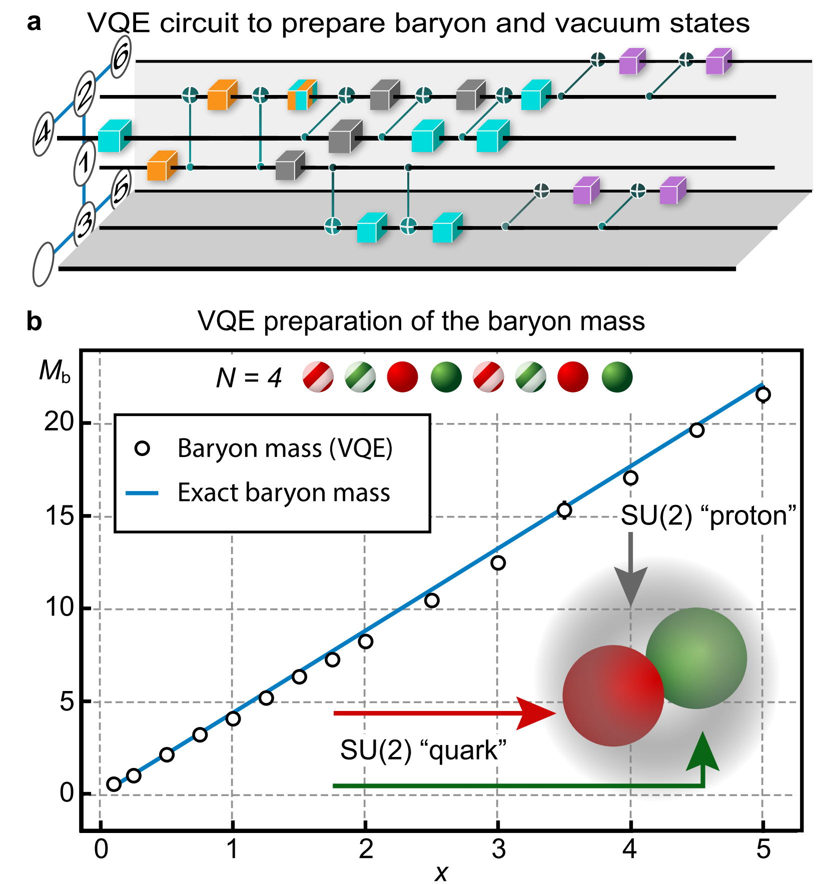




Real-time dynamic of pure SU(3) with global irrupts on IBM

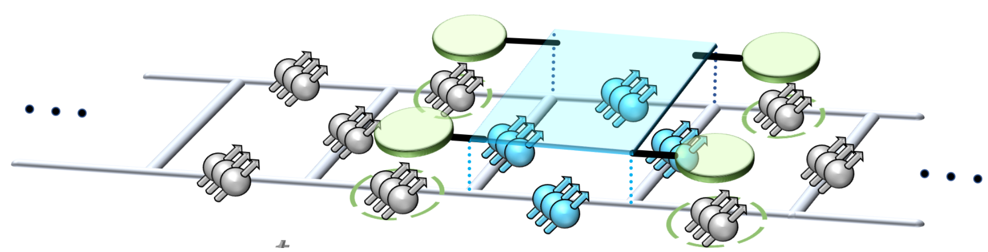
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

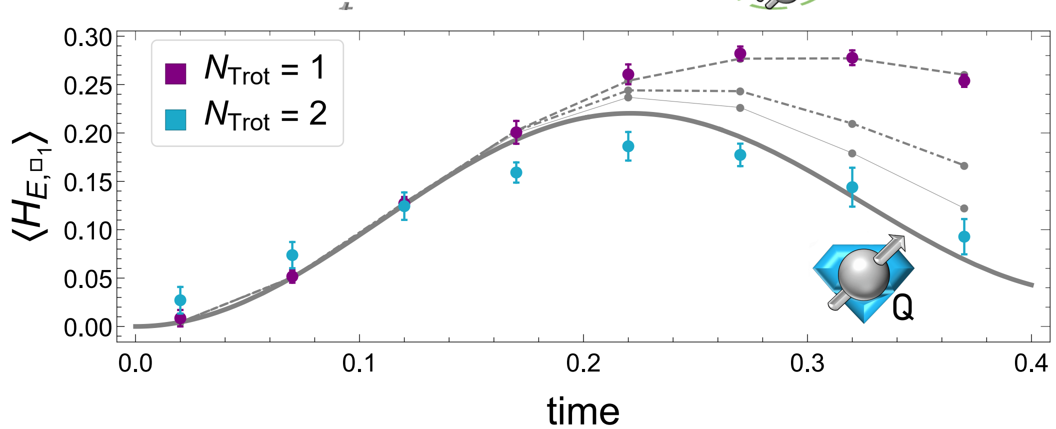
Low-lying spectrum of SU(2) with matter in 1+1 D on IBM



Atas et al, Nature Communications 12, 6499 (2021). SU(3) example: Atas et al: arXiv:2207.03473 [quant-ph].

Real-time dynamic of pure SU(2) with global irreps on IBM





Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

See also studies on D-wave annealers: Rahman et al, Phys. Rev. D 104, 034501 (2021), Illa and Savage, arXiv:2202.12340 [quant-ph], Farrel et al, arXiv:2207.01731 [quant-ph].

Physics
CP Violation and Neutrino Phenomenology
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:

Theorists supporting the research program in searches for new physics in rare processes in nucleon and nuclei include 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.

Lattice field theorists have long identified the impactful calculations in this area and are pushing the frontiers of exploratory as well as mature full-scale computations of quantities of relevance to this 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 over the next decade.

To expedite the computations and combat signal-to-noise and sign problems associated with finite-density systems and/or dynamical quantities, lattice field theorists are exploring new computational paradigms such as machine learning and quantum computing.

MANY THANKS TO A VIBRANT COMMUNITY AND TO THE AUTHORS OF MANY INSIGHTFUL LOIs AND WHITEPAPERS…

QUESTIONS?