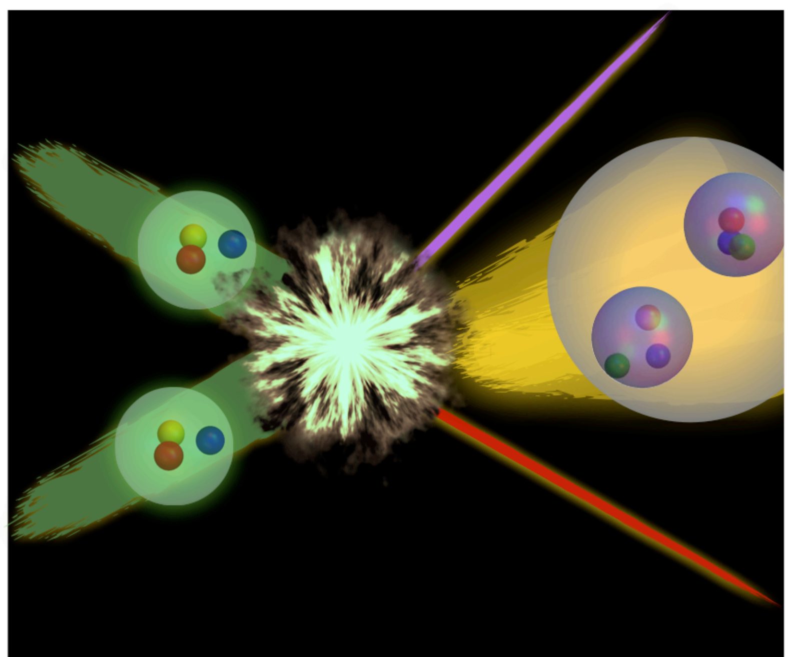
Nuclear Physics from the Standard Model

USQCD All-Hands Meeting

April 21, 2018

Michael Wagman



Nuclear Physics from Lattice QCD

2017 NPLQCD Results:

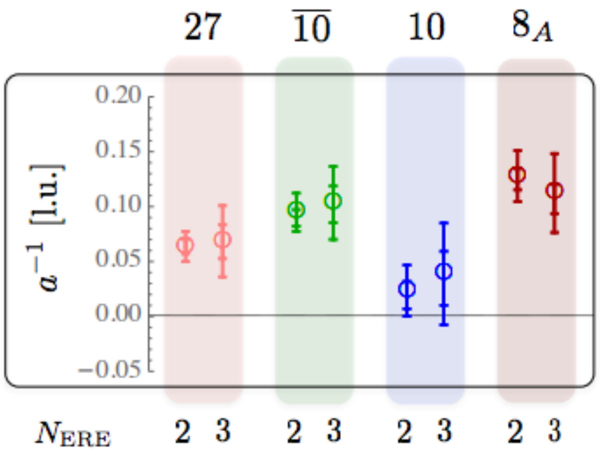
- “Nuclear modification of scalar, axial and tensor charges from lattice QCD,'' Phys. Rev. Lett. 120, no. 15, 152002 (2018)
- “First lattice QCD study of the gluonic structure of light nuclei,” Phys. Rev. D 96, no. 9, 094512 (2017)
- “Baryon-Baryon Interactions and Spin-Flavor Symmetry from Lattice Quantum Chromodynamics,'' Phys. Rev. D 96, no. 11, 114510 (2017)
- “Double-Beta Decay Matrix Elements from Lattice Quantum Chromodynamics,” Phys. Rev. D 96, no. 5, 054505 (2017)
- “Isotensor Axial Polarizability and Lattice QCD Input for Nuclear Double-Beta Decay Phenomenology,” Phys. Rev. Lett. 119 no. 6, 062003 (2017)
- “Proton-Proton Fusion and Tritium Beta-Decay,” Phys. Rev. Lett 119 no. 6, 062002 (2017)

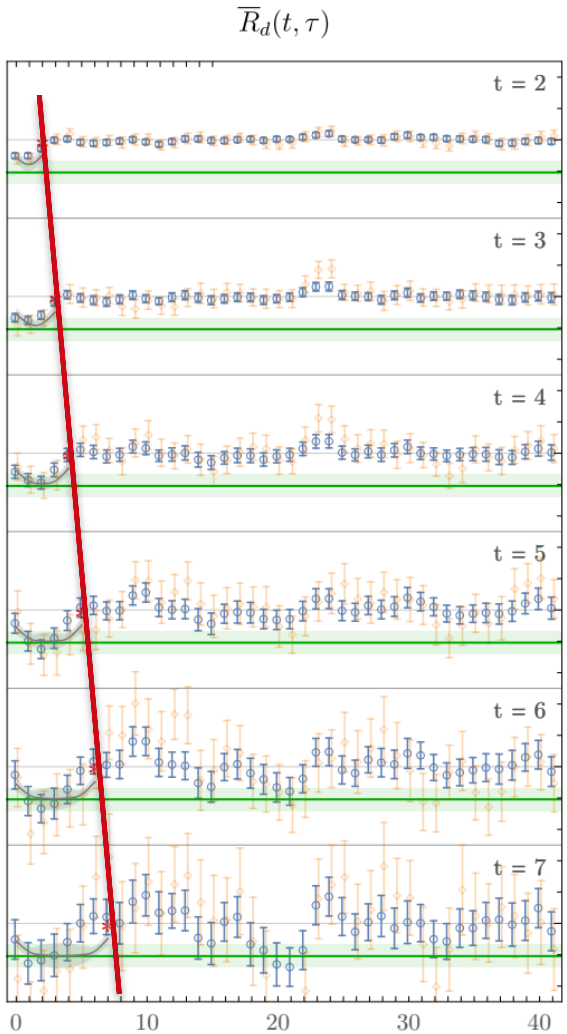
2018 Proposal: Nuclear matrix elements at $m_\pi \sim 450\ \mathrm{MeV}$
Nuclear spectroscopy at $m_\pi \sim 170\ \mathrm{MeV}$

Davoudi, Detmold, Murphy, Orginos, Parreño, Roche, Shanahan, Tiburzi, Wagman, Winter

Light Nuclei at Heavy Quark Mass

Baryon-baryon interactions are “technically unnatural” with large scattering lengths in all spin-flavor channels



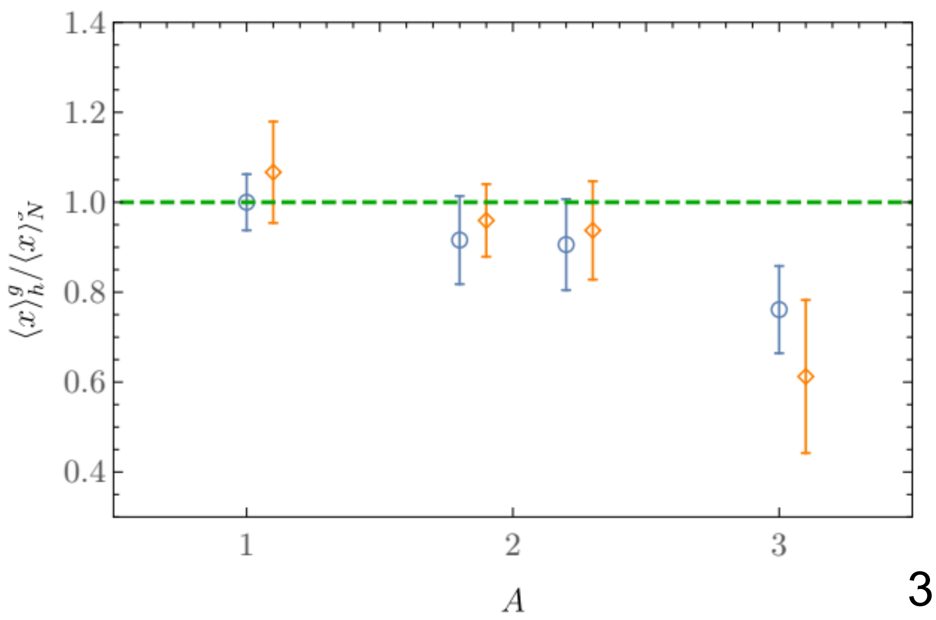


$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

MW, Winter, Chang, Davoudi, Detmold, Orginos, Savage, Shanahan, PRD 96 (2017)

Nuclei have non-trivial gluonic structure, including signals of gluonic transversity not present in isolated nucleons

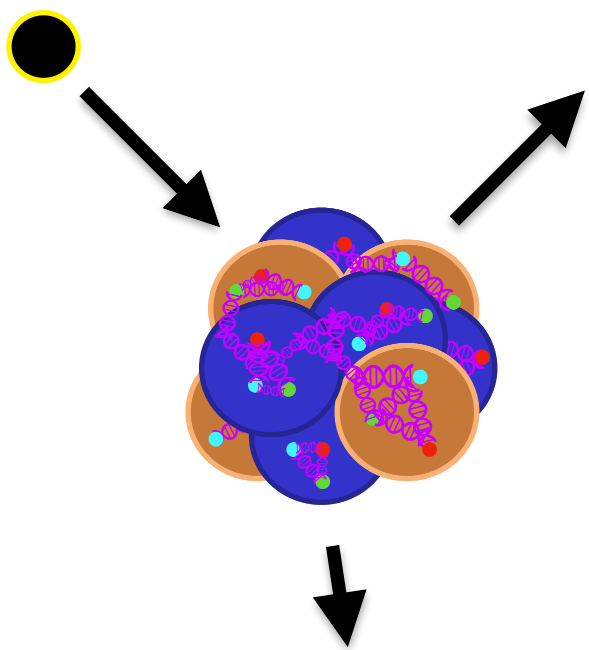
Winter, Detmold, Gambhir, Orginos, Savage, Shanahan, MW, PRD 96 (2017)



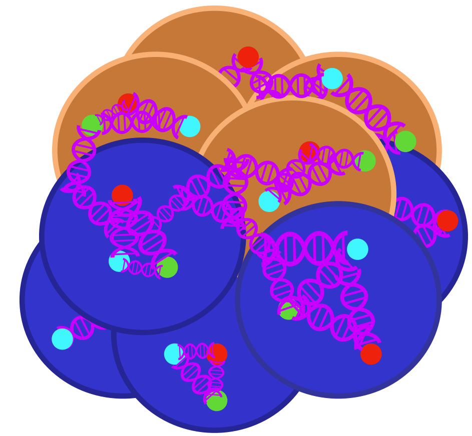
Nuclear Matrix Elements

Matrix elements of one- and two-body currents in nuclei are interesting

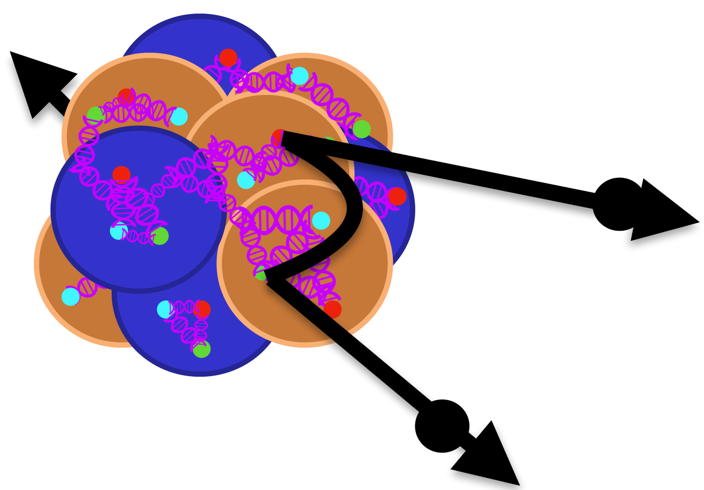
$$g_X(A) = \langle A | J_X | A \rangle$$



Axial currents relevant for single- and double-beta decay, polarized quark structure



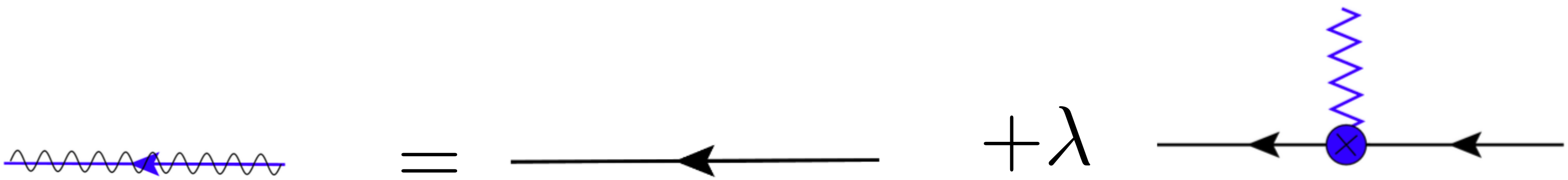
Scalar currents relevant for dark matter direct detection and isotope shift measurements



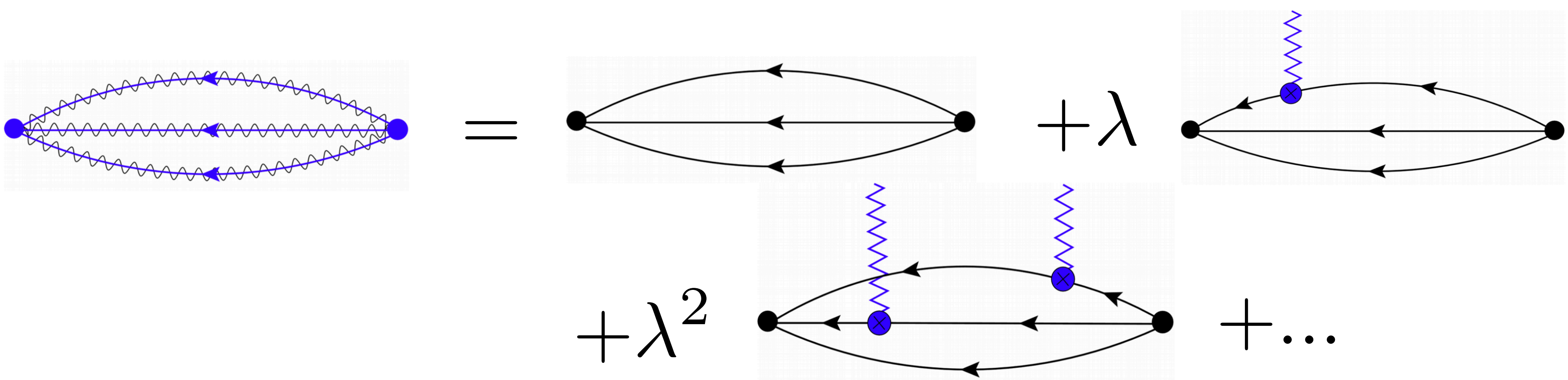
Tensor currents relevant for nuclear Electric Dipole Moments and quark transversity

Compound Propagators

Current operator insertions describing linear response to a background field can be added to quark propagators with sequential source techniques



Linear response and matrix elements of composite particles obtained from linear combinations of “background fields” where nonlinear terms cancel



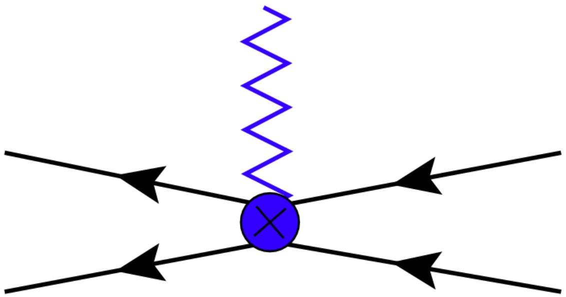
Multi-baryon contractions of compound propagators can be performed straightforwardly

Savage, Shanahan, Tiburzi, MW, Winter, Beane, Chang, Davoudi, Detmold, Orginos, PRL 119 (2017)

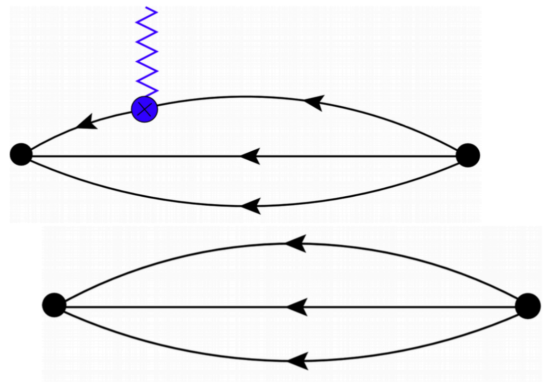
Bouchard, Chang, Kurth, Orginos, Walker-Loud, PRD 96 (2017)

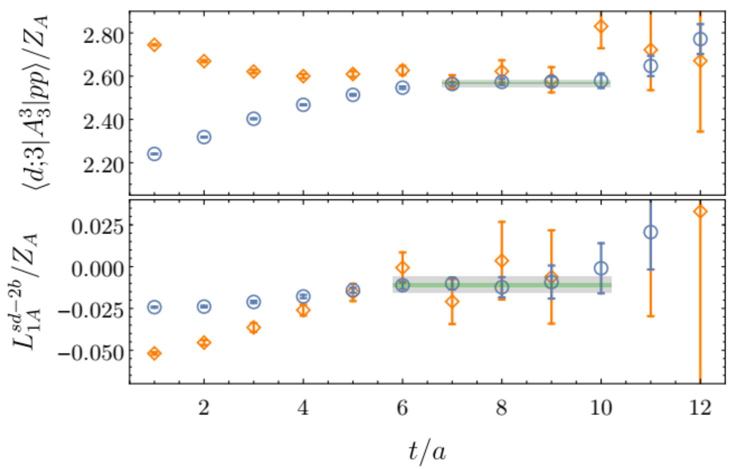
Matching to Pionless EFT

Bound dineuteron state mixes with bound deuteron state through axial current, transition matrix element related to proton-proton fusion in EFT



$$L_{1A} = 3.9(0.2)(1.0)(0.4)(0.9)$$

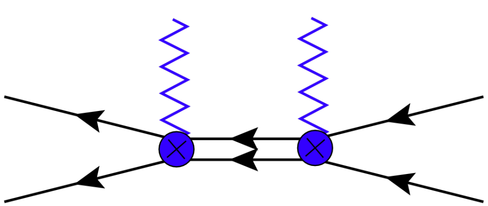


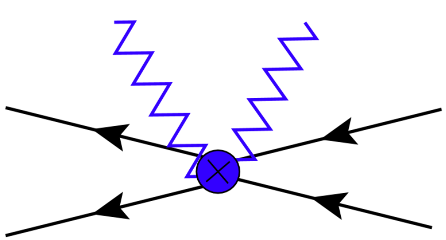


Pionless EFT interactions can be fit to LQCD data (e.g. by matching background field correlators), future EFT calculations can then predict properties of larger nuclei

See e.g. INT Program INT-17-2a

Two axial current insertions can mix pp and nn states, allowing LQCD simulations to constrain polarizabilities contributing to double but not single beta decay

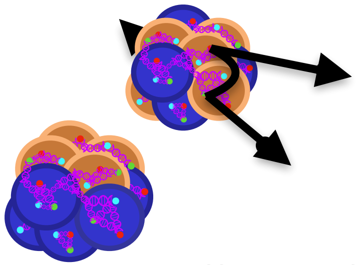




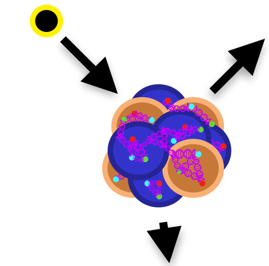
Savage, Shanahan, Tiburzi, MW, Winter, Beane, Chang, Davoudi, Detmold, Orginos, PRL 119 (2017)

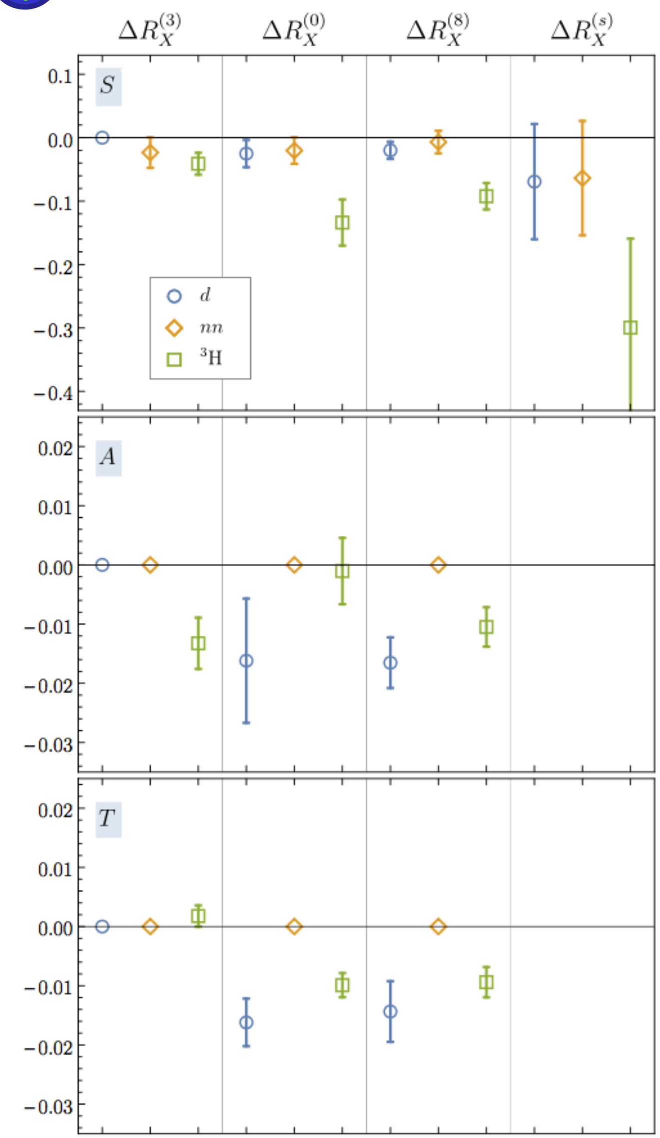
Shanahan, Tiburzi, MW, Winter, Chang, Davoudi, Detmold, Orginos, Savage, PRL 119 (2017)

Tiburzi, MW, Winter, Chang, Davoudi, Detmold, Orginos, Savage, Shanahan, PRD 96 (2017)



Nuclear Responses

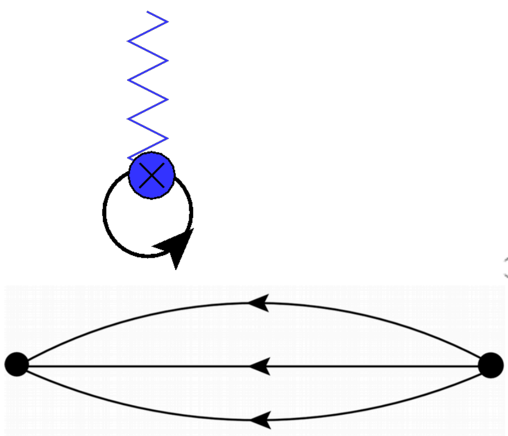


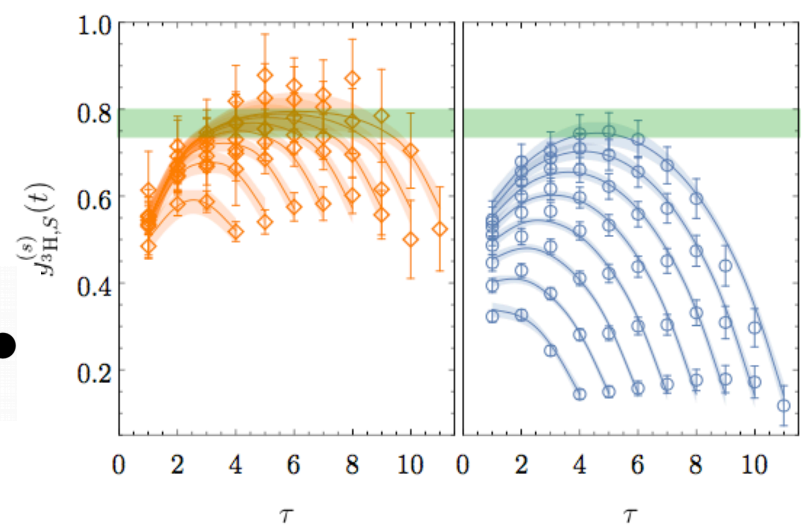


Full spin-flavor decomposition computed of static responses of A=1-3 nuclei to external probe

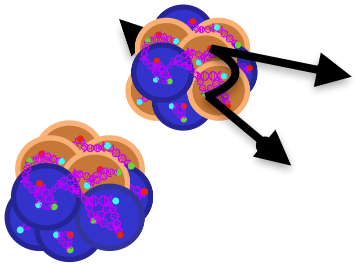
Disconnected diagrams efficiently computed with hierarchical probing, contribute significantly to scalar isoscalar matrix elements

Gambhir, Stathopulos, Orginos, J. Sci. Comput. 39 (2017)

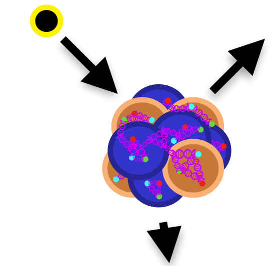




Chang, Davoudi, Detmold, Gambhir, Orginos, Savage, Shanahan, Tibuzri, MW, Winter, PRL 120 (2018)



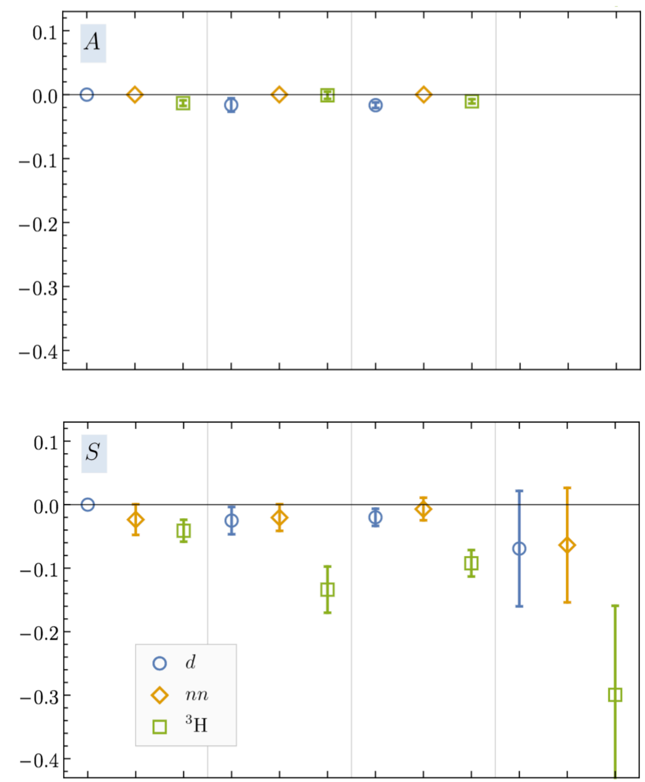
Nuclear Medium Effects



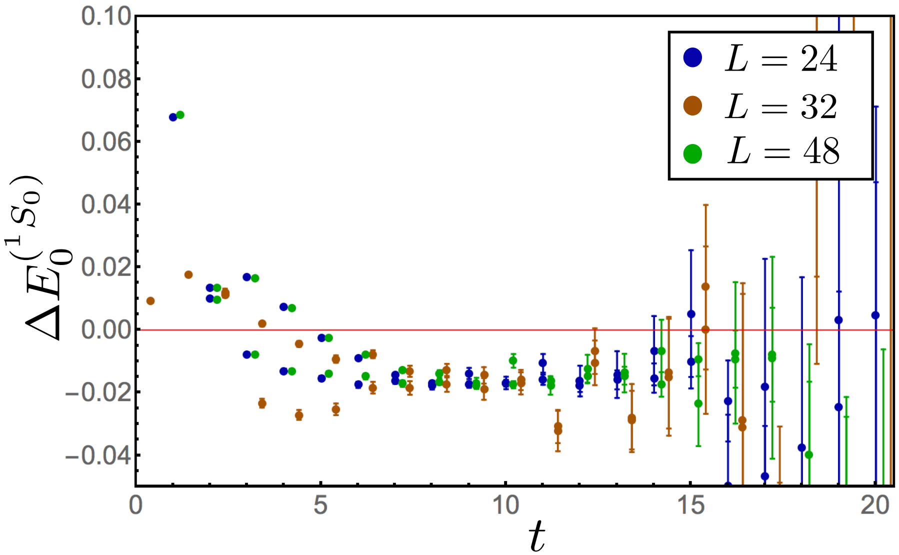
Isovector axial charge shows 1-2% nuclear effects in ^3H beta-decay rate with heavier quark masses (5% in nature)

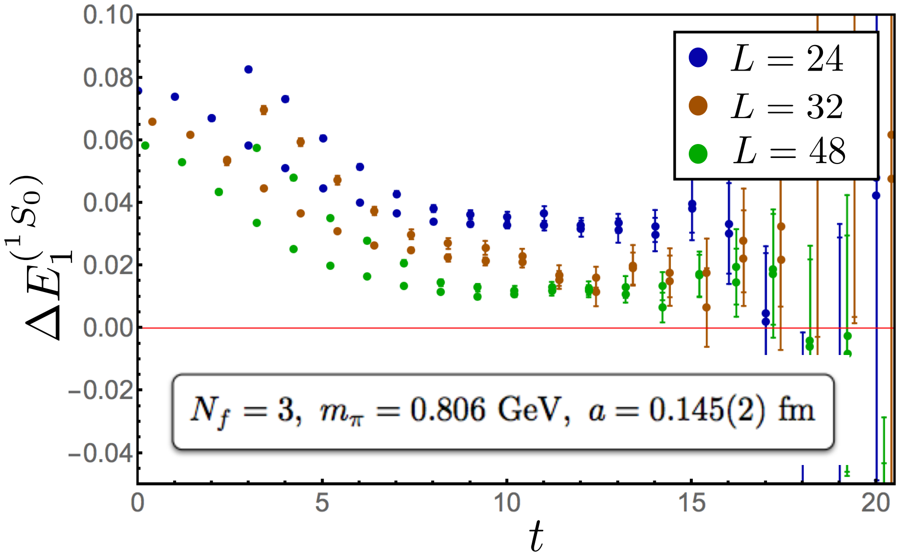
Tensor charges shows similar or smaller nuclear effects, scalar charges unexpectedly shows much larger nuclear effects

	d	pp	^{3}H	Expect.
$R_A^{(0)}$	1.98(1)	–	0.999(6)	$2S_3$
$R_A^{(3)}$	–	–	0.987(4)	$4T_3S_3$
$R_A^{(8)}$	1.983(4)	–	0.990(3)	$2S_3$
$R_A^{(s)}$	–	–	–	BS_3
$R_S^{(0)}$	1.97(2)	1.98(2)	2.87(4)	B
$R_S^{(3)}$	–	1.98(2)	0.96(2)	$2T_3$
$R_S^{(8)}$	1.98(1)	1.99(2)	2.90(2)	$2T_8$
$R_S^{(s)}$	1.93(9)	1.94(9)	2.70(14)	B
$R_T^{(0)}$	1.984(4)	–	0.990(2)	$2S_3$
$R_T^{(3)}$	–	–	1.002(2)	$4T_3S_3$
$R_T^{(8)}$	1.986(5)	–	0.991(3)	$2S_3$
$R_T^{(s)}$	–	–	–	BS_3



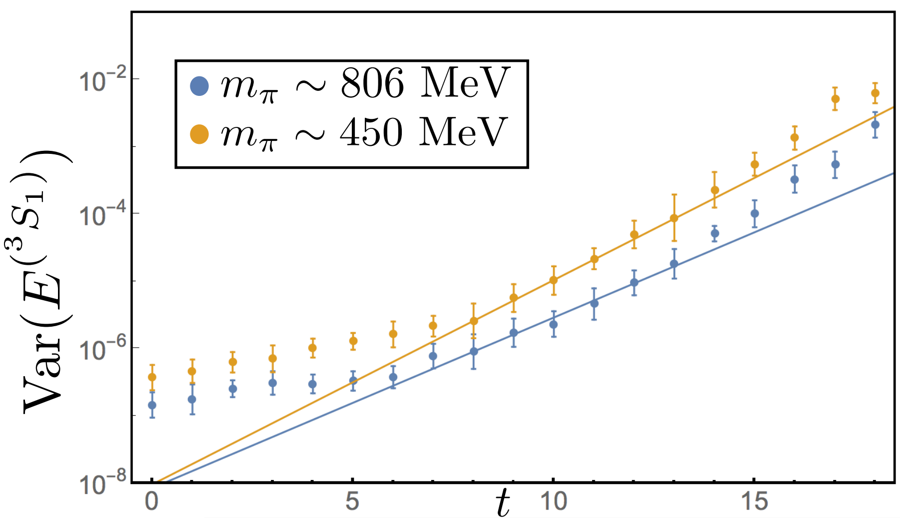
Plateaus, Noise, and Quark Mass



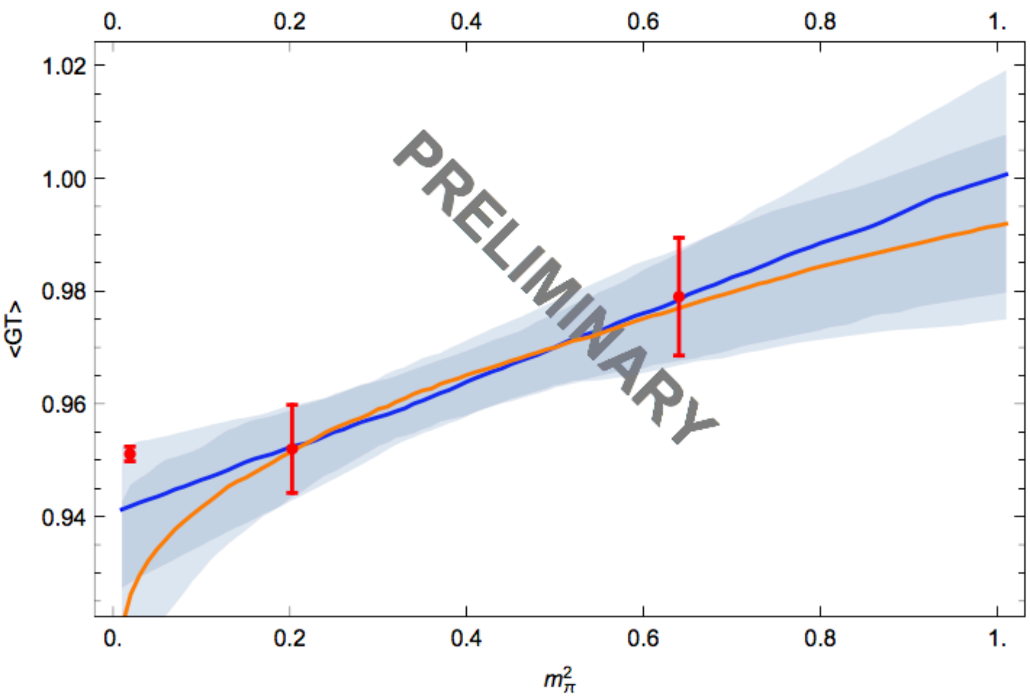


$m_\pi \sim 806$ MeV two-baryon correlators show clear ground-state plateaus independent of sink and weakly-dependent on volume (vs power law scaling in excited states), pass checks suggested by HALQCD collaboration

At lighter pion masses, the Golden Window shrinks and subsequent Parisi-Lepage variance growth becomes more rapid



Nuclei at Lighter Quark Masses



Explorations at $m_\pi \sim 450$ MeV and scaling $m_\pi \sim 806$ MeV resources suggests

$$N_{sources} \sim 10^5$$

sufficient for 3σ determination of nuclear charge modifications and $L_{1,A}$ at $m_\pi \sim 450$ MeV

4x more sources disconnected diagram sources planned as at $m_\pi \sim 806$ MeV

Reliable (3σ) evidence of nuclear modifications has phenomenological impact:

— dark matter direct detection searches would be forced to model “scalar quenching” effects analogous to axial quenching in double-beta decay searches

— the sensitivity of new physics searches examining isotope shifts in light nuclei such as helium will be directly determined from QCD

— tensor modifications will inform possible nuclear EDM experiments

Nearly Physical Nuclei

Compound propagator inversion and correlator calculations run efficiently on KNLs with QPhiX inverter at $m_\pi \sim 450$ MeV

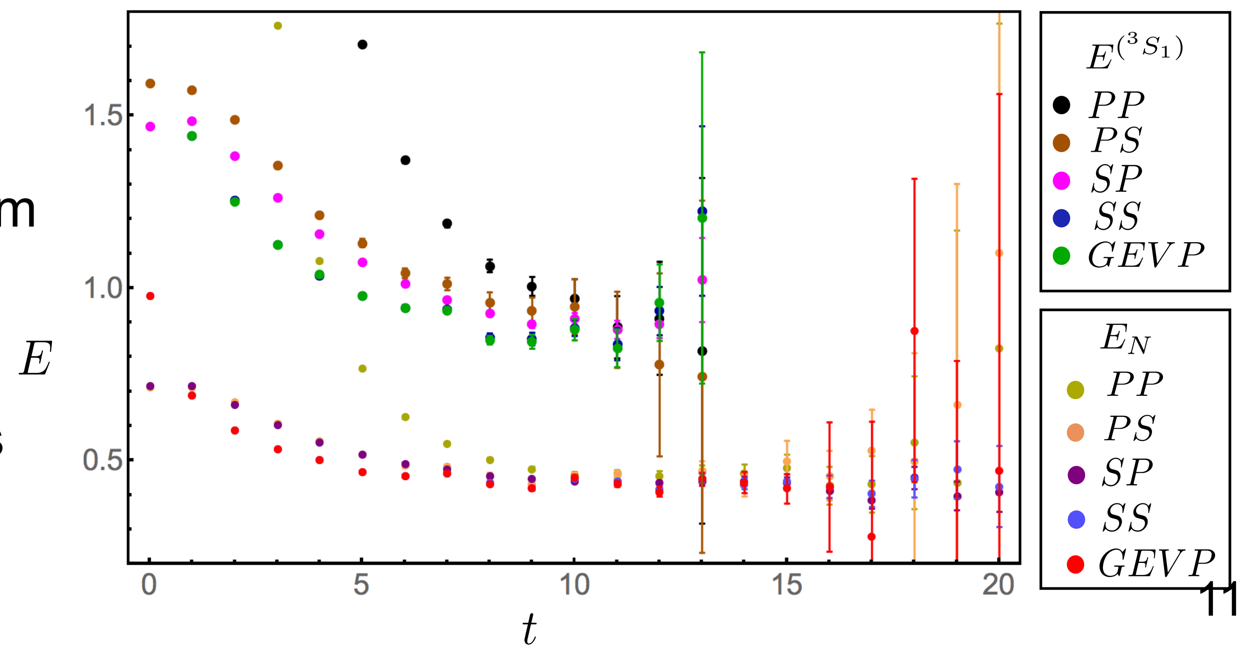
Multigrid is necessary for efficient calculations at lighter quark masses

We've benchmarked QUDA mutligrid inverters and QDP-JIT/LLVM contraction codes on K20s and find order of magnitude speedups at $m_\pi \sim 170$ MeV

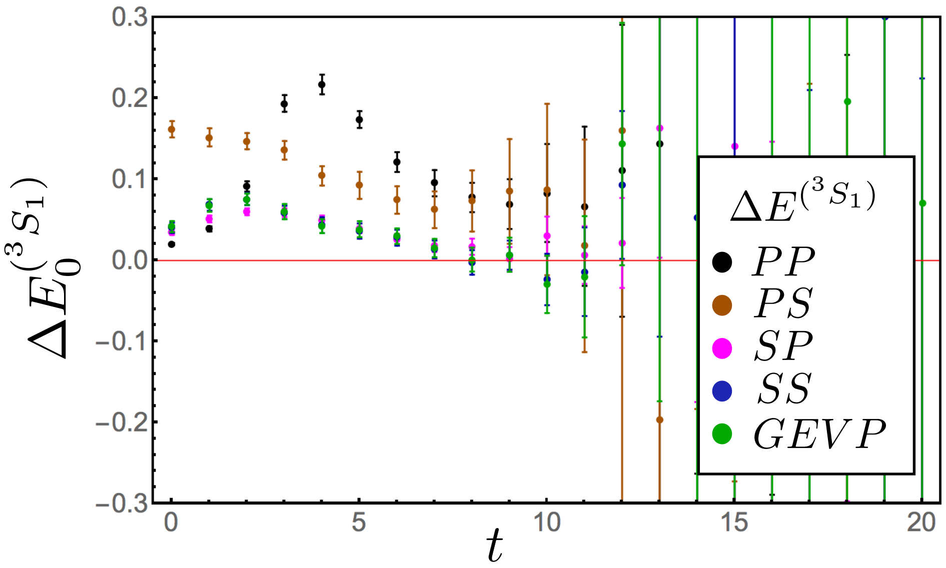
Actively exploring various source constructions methods:

- Generalized eigenvalue problem with multiple smearing
- Matrix-Prony
- Generalized pencil-of-functions
- Phase reweighting

$N_f = 2+1,\ m_\pi \sim 170\ \text{MeV},\ a \sim 0.09\ \text{fm}$



Statistical Scaling



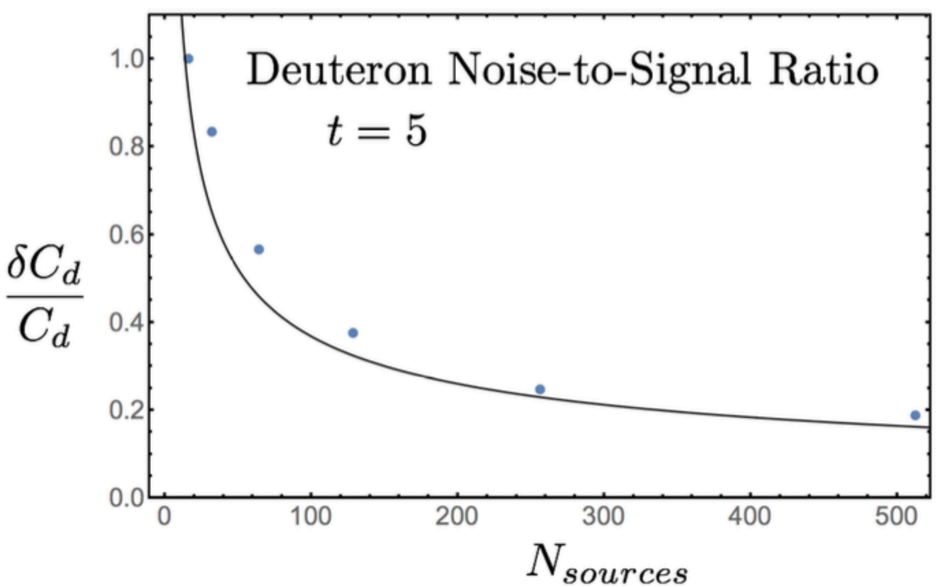
$t = 10$ smallest separation consistent with a negative finite-volume energy shift

Extrapolating (far!) from present exploratory statistics, 2 MeV precision requires

$$N_{sources} \sim 1.7 \times 10^6$$

Resource needs also estimated by scaling precision from

$$e^{2\times 2(M_N - \frac{3}{2} m_\pi)(0.5 \text{ fm})}$$



$$N_{sources} \sim 1.7 \times 10^6$$

Consistent with 2009 expectations

$$N_{sources} \sim 1.6 \times 10^6$$

2018 Allocation Request

Requesting first stage of spectroscopy resources for one volume with $m_\pi \sim 170\ \mathrm{MeV}$

— Results can be matched to finite-volume EFT to fit low-energy constants and constrain the nuclear force at near physical point masses.

— Results will also allow more precise estimates of the computational cost of future calculations of nuclei in larger volumes with $m_\pi \sim 170\ \mathrm{MeV}$ that we intend to pursue with future USQCD and non-USQCD resources

Nuclear matrix elements at $m_\pi \sim 450\ \mathrm{MeV}$ have clear goals and resource needs, USQCD resources target 3σ signals of $L_{1,A}$ and nuclear charge modifications

Task	Volume	m_π [MeV]	N_{cfg}	N_{src}	GPU Time [C2050-hrs]	KNL Time [`jpsi` core-hrs]
A: Spectroscopy	$48^3 \times 96$	170	800	256	2.12×10^6	–
B: Scalar	$32^3 \times 96$	450	800	128	–	9.4×10^6
B: Axial	$32^3 \times 96$	450	800	128	–	9.4×10^6
B: Tensor	$32^3 \times 96$	450	800	128	–	9.4×10^6
B: Disconnected	$32^3 \times 96$	450	800	512	–	17.1×10^6
Total Request					2.12×10^6	45.3×10^6