PROPERTIES OF LIGHT NUCLEI FROM LATTICE QCD
The errors are obtained from statistical and systematic errors added in quadrature. Shown together are the linear extrapolation in $1_{\text{NN}}$ as a function of $1_{\text{NN}}$, together with the fit (statistical only) in the $S_{0}$ channel. (Middle left) Effective energy shift $E_{\text{NN}}$ and $E_{\text{NN}}$, from the smeared source with both non-relativistic (open square) and relativistic (solid square) operators. Shown together are the linear extrapolation in $1_{\text{NN}}$ channel. (Lower left) Energy shift $E_{\text{NN}}$, from statistical and systematic errors added in quadrature. (Lower right) Same in the operators (solid square). Shown together are the linear extrapolation in $1_{\text{NN}}$ function of $1_{\text{NN}}$, together with the fit (statistical only) in the $S_{0}$ channel. (Upper left) $E_{\text{NN}}$ channel as a function of $1_{\text{NN}}$), together with the fit (statistical only) in the $S_{0}$ channel. (Upper right) Same in the $e_{01}^{+0}$ channel. (Right) The results from relativistic operators. The plateaux of Ref. [HALQCD], JHEP1610(2016)101 are also shown by black lines (central value and 1 statistical errors) for comparison. (Right) The results from relativistic operators.
HAL2016

from Iritani et al [HALQCD], JHEP1610(2016)101

\[ R(t) = \frac{C_{NN}(t)}{(C_{N}(t))^2} \]

When single hadrons are in ground state there is consistency between extracted energy or energy shifts.
Wall and Exp sources give different $\Delta E$

**Figure 15**. The reconstructed effective energy shifts $\Delta E_{\text{eff}}(t)$ for the wall source (red bands) and the smeared source (blue bands) at $L = 40, 48$ and $64$. The effective energy shifts in the direct method are also shown for the wall (red circles) and smeared (blue squares) sources. The black dashed lines are the energy shifts for the ground state of the HAL QCD Hamiltonian in the finite volume evaluated at $t_0/a = 13$. (Left) $0 \leq t/a \leq 24$. (Right) $0 \leq t/a \leq 175$.

Based on HALQCD potential $\Delta E_{\text{exp}}^{NN}$ has large contamination from excited states $\Delta E_{\text{wall}}^{NN}$ is almost flat.

**Important:** check using variational analysis $\rightarrow$ large computational cost

This work: check with high precision calculation

NB: this fig now for $\Xi\Xi$ rather than $\text{NN}$, but same behaviour seen
Wall and Exp sources give different $\Delta E$

For more details, see extensive high statistics study by PACS-CS
T. Yamazaki et al [PACS collaboration], LATTICE 2017
arXiv:1710.08066
updates in YITP workshop in 2019
http://www2.yukawa.kyoto-u.ac.jp/~flqcd2019/slides/Yamazaki.pdf

NB: this fig now for $\Xi\Xi$ rather than NN, but same behaviour seen
PACS 2017 HIGH STATISTICS

Effective $2m_N$ and $E_{NN}$

![Graph showing effective $2m_N$ and $E_{NN}$ for different sources and times.]

$\sim t_{NN} \sim 12$

- **exp source**
- **wall source**

$t_{NN} \sim 16$, $t_N \sim 17$

- **exp source**
- **wall source**

Completely consistent in plateau regions

**Table:**

<table>
<thead>
<tr>
<th>$L$</th>
<th>$T$</th>
<th>source</th>
<th>$N_{meas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>64</td>
<td>Exp</td>
<td>15,544,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall</td>
<td>8,307,200</td>
</tr>
<tr>
<td>20</td>
<td>64</td>
<td>Exp</td>
<td>5,504,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall</td>
<td>4,480,000</td>
</tr>
<tr>
<td>32</td>
<td>64</td>
<td>Exp</td>
<td>10,496,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall</td>
<td>8,307,200</td>
</tr>
</tbody>
</table>

Amazing statistics!

NB: have exp & wall rather than smeared & wall, quenched cfgs


Comparison of different source calculations in two-nucleon channel at large quark mass
WILL DETMOLD
MIT

PROPERTIES OF LIGHT NUCLEI FROM LATTICE QCD

Santa Fe Lattice Meeting 2019, Santa Fe, August 30th 2019
THE INTENSITY FRONTIER

- Seek new physics through quantum effects
- Precise experiments
  - Sensitivity to probe the rarest interactions of the SM
  - Look for effects where there is no SM contribution
- Major component is nuclear targets
- Important focus of HEP/NP experimental program
  - Neutrino physics
  - Dark matter direct detection
  - Charged lepton flavour violation, EDMs, $\beta\beta$-decay,
INTENSITY FRONTIER

LONG BASELINE NEUTRINO EXPERIMENTS

- Deep Underground Neutrino Experiment
  - Flagship facility for US HEP for next decades
  - Determine neutrino mass hierarchy and extract mixing parameters
- Neutrino scattering on argon target
  - Need fluxes/energies to high accuracy
  - Need to know interactions with argon over a wide range of energies

INTENSITY FRONTIER

NUCLEI IN NEW PHYSICS

- Scalar currents
  - Dark matter direct detection
  - Lepton flavour violation: $\mu 2e$
  - Precision spectroscopy
- Tensor currents
  - Electric dipole moments of neutrons and nuclei
- Neutrinoless double beta decay
How well do we know nuclear matrix elements?

Gamow-Teller transitions in nuclei
- Well measured for large range of nuclei (30<A<60)
- Many nuclear structure calculations (shell-model,...) describe spectrum well
- Matrix elements systematically off by 20-30%
- Correct using 2 body currents

Fundamental understanding from QCD

---

INTENSITY FRONTIER

PRECISION NUCLEAR PHYSICS

- Very challenging to explore all of NP from QCD
- Exploit effective degrees of freedom
- Establish quantitative control through linkages between different methods
  - QCD forms a foundation determines few body interactions & matrix elements
  - Match existing EFT and many body techniques onto QCD
- Exact many body: GFMC, NCSM, lattice EFT
- Density Functional, Mean field
- Shell model, coupled cluster, configuration interaction
HADRONS AND NUCLEI

QCD FOR NUCLEAR PHYSICS

- Nuclear physics is Standard Model physics
  - Can compute the mass of lead nucleus ... in principle
- Complex physics
  - Wide range of scales
  - Closely spaced excitations
- Numerical challenges:
  - Statistical sampling
  - Contraction complexity
Nuclear physics is Standard Model physics

Can compute the mass of lead nucleus ... in principle

Complex physics

Wide range of scales

Closely spaced excitations

Numerical challenges:

Statistical sampling

Contraction complexity
QCD FOR NUCLEAR PHYSICS

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Complex physics
  - Wide range of scales
  - Closely spaced excitations

Numerical challenges:
  - Statistical sampling
  - Contraction complexity

- $195 \text{ M}_{\text{Pb}}$
- $172 \text{ m}_{\text{t}}$
- $68 \text{ M}_{\text{Ge}}$
- $4.18 \text{ m}_{\text{b}}$
- $1.875 \text{ M}_{\text{D}}$
- $1.275 \text{ m}_{\text{c}}$
- $0.938 \text{ M}_{\text{p}}$
- $0.250 \Lambda_{\text{QCD}}$
- $0.095 \text{ m}_{\text{s}}$
- $0.005 \text{ m}_{\text{d}}$
- $0.002 \text{ m}_{\text{u}}$
HADRONS AND NUCLEI

QCD FOR NUCLEAR PHYSICS

- Nuclear physics is Standard Model physics
  - Can compute the mass of lead nucleus ... in principle
- Complex physics
  - Wide range of scales
  - Closely spaced excitations
- Numerical challenges:
  - Statistical sampling
  - Contraction complexity

![Graph showing mass scales and energy levels for 73Ge]
**NUCLEI**

- New algorithms enabling study of nuclei
- Efficient contractions
- Graph theory & recursions [WD & Savage 2011; WD & Orginos 2012, Doi&Endres 2012; Gunther&Varnhorst 2013; WD & Vachaspati 2014]
- ... and lots of computing!

\[
\frac{\text{cost}(N A Z)}{\text{cost}(\text{proton})} \sim (2Z + N)(2N + Z)!/2
\]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Naive</th>
<th>Optimised</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>250,000</td>
<td>~100</td>
</tr>
<tr>
<td>$^8\text{Be}$</td>
<td>$10^{31}$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>$10^{1300}$</td>
<td>?</td>
</tr>
</tbody>
</table>
**CASE STUDY: NUCLEI IN LQCD**

**NPLQCD**

- Case study QCD with unphysical quark masses ($m_n \sim 800$ MeV, 450 MeV)

1. Spectrum and scattering of light nuclei ($A < 5$) [PRD 87 (2013), 034506]


3. Nuclear reactions: $np \rightarrow d\gamma$ [PRL 115, 132001 (2015)]

4. Gamow-Teller transitions: $pp \rightarrow de\nu$, $g_A(^3H)$ [PRL 119 062002 (2017)]

5. Double $\beta$ decay: $pp \rightarrow nn$ [PRL 119, 062003 (2017)]

6. Parton structure ($A < 4$) [PRD 96 094512 (2017)]

7. Scalar/tensor currents ($A < 4$) [PRL 2018]

---

**Past Collaborators**

- Saul Cohen
- Pari Junnarkar
- Huey-Wen Lin
- Aaron Torok
- Tom Luu
- Andre Walker-Loud
- Mike Wagman
- Saul Cohen
- Phiala Shanahan

---

**Current Collaborators**

- Brian Tiburzi
- Frank Winter
- Silas Beane
- David Murphy
- Zohreh Davoudi
- Emmanuel Chang
- William Detmold
- Assumpta Parreno
- Martin Savage
- Frank Winter
- Michael Wagman
- Jonas Wilhelm

---

Case study QCD with unphysical quark masses ($m_{\pi} \sim 800$ MeV, 450 MeV)

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7. Scalar/tensor currents ($A<4$) [PRL 2018]

new since 2017
NUCLEI (IN A HEAVY QUARK UNIVERSE, $M_\pi \sim 800$ MEV)

- 2013: first QCD calculation of nuclei (heavy masses as numerically cheaper)
HADRONs AND NUCLEI

NUCLEI (IN A HEAVY QUARK UNIVERSE, $M_\pi \sim 800$ MEV)

- Combine LQCD and nucleon based many-body effective field theory (EFT) methods
- Matching to LQCD determines NN, NNN interactions: allows predictions for larger nuclei

Further studies extend to complex nuclei such as $^{16}$O [Contessi et al, Bansal et al.]

MORE EFFECTIVE: DIRECTLY MATCH FV ENERGIES IN LQCD AND EFT

[Barnea et al, PRL 2015]
Hadron/nuclear energies are modified by presence of fixed external fields

Eg: fixed B field

\[ E_{h;jz}(B) = \sqrt{M_h^2 + (2n + 1)|QheB| - \mu_h \cdot B} - 2\pi \beta_h^{(M0)}|B|^2 + \ldots \]

QCD calculations with multiple fields enable extraction of coefficients of response

- Magnetic moments, polarisabilities, …

Similar techniques to study EW interactions, DM interactions, twist-2 matrix elements
MAGNETIC STRUCTURE

- LQCD calculation of nuclear magnetic moments ($\mu$) and magnetic polarisabilities ($\beta$, deformation in B field)
- Simple shell model expectations
- Lattice results suggest heavy quark mass nuclei are shell-model like!

![Diagram showing magnetic moments and polarisabilities for different nuclei.]
Big Bang Nucleosynthesis

- Light nuclei are formed during the initial few minutes after the Big Bang.
- First nuclear reaction: slow neutron capture $\text{np} \rightarrow \text{d}\gamma$
  - 2015: First QCD calculation of a nuclear reaction
  - Reproduced measured rate
  - Ready to make predictions
ELECTROWEAK PROCESSES

- Single $\beta$-decay
  LQCD calculation of decay of tritium

- Double $\beta$-decay
  - Neutrinoful case is rarest process observed
  - Neutrinoless case
    - Majorana particles? Lepton number violation? Baryon asymmetry?
  - Rates depend on nuclear matrix elements
    - Currently quite uncertain but important for design of future DBD search experiments
  - Proton-Proton fusion powering the Sun
TRITIUM BETA DECAY

- Tritium decay half life
  \[ \frac{(1 + \delta_R) f_V}{K/G_V^2} t_{1/2} \]
  known from theory or expt.

- Biggest uncertainty in
  \[ g_A \langle GT \rangle = \langle ^3\text{He} | \overline{q} \gamma_5 \gamma_k | ^3\text{H} \rangle \]

- Form ratios of correlators in axial background fields to extract QCD matrix element
  \[ \frac{R_{^3\text{H}}(t)}{R_p(t)} \xrightarrow{t \to \infty} \frac{g_A(^3\text{H})}{g_A} = \langle GT \rangle \]
AXIAL MATRIX ELEMENTS

MASS DEPENDENCE OF TRITON AXIAL CHARGE

PRELIMINARY
First step in chain of reactions powering stars like the sun

Intricate process involve all three SM forces

Difficult to measure (Coulomb barrier)

2017: LQCD calculation of $pp$ fusion rate
  - Uncertainties competitive with phenomenological extractions
  - Next generation calculations will improve precision
    - Improve solar modelling
**PROTON–PROTON FUSION**

- First step in chain of reactions powering stars like the sun
- Intricate process involve all three SM forces
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- 2017: LQCD calculation of \( pp \) fusion rate
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**PROTON-PROTON FUSION**

- First step in chain of reactions powering stars like the sun
- Intricate process involve all three SM forces
- Difficult to measure (Coulomb barrier)
- 2017: LQCD calculation of $pp$ fusion rate
  - Uncertainties competitive with phenomenological extractions
  - Next generation calculations will improve precision
    - Improve solar modelling
**DOUBLE BETA DECAY**

- **QCD calculation of subprocess**
  \[ n n \rightarrow p p \bar{e} e \bar{\nu} \bar{\nu} \]
  [NPLQCD, PRL 2017b]
  - Revealed significant nuclear effects (even beyond \( g_A \) quenching)

- **Beginning calculations of neutrinoless processes**
  [WD, Murphy 1811.0554]
  - Disallowed pion transition as a test
  \[ \pi^- \rightarrow \pi^+ e^- e^- \]
  - Light nuclei are next
DM direct detection experiments search for recoil of nucleus from DM scattering

One popular class of DM interactions is through scalar exchange

\[ \mathcal{L} = \frac{G_F}{2} \sum_q \kappa_q (\bar{\chi}\chi)(\bar{q}q) \]

Direct detection depends on nuclear matrix element

\[ \overline{m}\langle Z, N|\bar{u}u + \bar{d}d| Z, N\rangle \]

At hadronic/nuclear level
**NUCLEON SCALAR COUPLING**

- Single nucleon contribution
- Calculated in LQCD
- Results from many groups

Summary from Shanahan 2016

- Fukugita et al. (95)
- Dong et al. (96)
- SESAM Collaboration (98)
- Leinweber et al. (04)
- Procura et al. (06)
- JLQCD Collaboration (08)
- Young & Thomas (10)
- BMW Collaboration (12)
- QCDSF Collaboration (12)
- QCDSF Collaboration (12)
- Semke et al. (12)
- Alvarez–Ruso et al. (13)
- Shanahan et al. (13)
- Lutz et al. (14)
- Ren et al. (15)
- χQCD Collaboration (15)
- χQCD Collaboration (15)
- BMW Collaboration (16)
- RQCD Collaboration (16)
- ETM Collaboration (16)
NUCLEAR EFFECTS CAN BE LARGE!

- LQCD study of scalar couplings for $A=1,2,3$
- Unexpectedly large (~10%) deviation from sum of nucleon matrix elements for $A=3$
- Naive extrapolation to $^{136}\text{Xe}$ implies significant consequences for dark matter detection sensitivity
EMC-type effects from Lattice QCD

Understanding the quark and gluon structure of matter

How is the partonic structure of nucleons modified in nuclei?

Encoded in EMC-type effects

ENCODING IN EMC-TYPE EFFECTS

(EMC: Aubert et al., 1983)

Thanks to Phiala for slides!
EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD: Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- **BUT** EMC effects in moments are very small

Classic EMC effect is defined in $F_2$:

$$ F_2(x, Q^2) = \sum_{q=u,d,s,...} x e_q^2 [q(x, Q^2) + \bar{q}(x, Q^2)] $$

- Number density of partons of flavour $q$
- $x$-integrals of numerator and denominator $\int_0^1 dx x^n q(x, Q^2)$
EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- **BUT** EMC effects in moments are very small


- **F**igure showing the ratio of Mellin moments for light nuclei.
- **g**luon, **u** quark, and **d** quark contributions.
- 1% level EMC effects in PDF moments for light nuclei.
Momentum fraction of nuclei

First investigation of EMC-type effects from LQCD: Nuclear effects in Mellin moments of PDFs

- Lowest Mellin moment of spin-independent PDF defines fraction of momentum of nucleus A carried by parton of type f
  \[
  \langle x \rangle^f_A = \int_0^1 dx \, x f^A(x) \quad \sum_{f=q,g} \langle x \rangle^f_h = 1
  \]

- Momentum sum rule implies nucleus-independent ratio of quark and gluon EMC effects in the first moment
  \[
  \left( \frac{\langle x \rangle_q^f}{\langle x \rangle_p^f} - 1 \right) = E^f_A
  \]

\[
\frac{E^g_A}{E^q_A} = -\frac{\langle x \rangle_q^g}{\langle x \rangle^g_p} \approx -1.4
\]

\(\overline{\text{MS}} (\mu = 2\text{GeV})\)
Matrix elements of the Energy-Momentum Tensor in light nuclei

First QCD determination of momentum fraction of nuclei

- Few-percent determination of quark momentum fraction
  ~10% determination of strange quark contributions

Isoscalar (BARE)

\[ m_\pi \sim 800 \text{ MeV} \]
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

\textbf{first QCD determination of momentum fraction of nuclei}

\begin{itemize}
    \item Few-percent determination of quark momentum fraction
    \item \( \sim 10\% \) determination of strange quark contributions
\end{itemize}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    title={Strange (BARE)},
    xlabel=$m_\pi \sim 800$ MeV,
    ylabel=$<x^s>_h$,
    legend style={at={(0.99,0.45)},anchor=north east},
    legend entries={Proton, Diproton, Deuteron, $^3$He},
    ymin=0.0000, ymax=0.012,
    xmin=0.002, xmax=0.012,
]
\addplot[scatter, only marks, mark options={solid}, error bars/.cd, y dir=both, y explicit]
coordinates {
    (0.004, 0.008) +- (0.0005, 0.0005),
    (0.006, 0.010) +- (0.0005, 0.0005),
    (0.008, 0.012) +- (0.0005, 0.0005),
    (0.010, 0.012) +- (0.0005, 0.0005),
};
\end{axis}
\end{tikzpicture}
\end{center}
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

- first QCD determination of momentum fraction of nuclei

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology

Ratio of quark momentum fraction in nucleus to nucleon

Isoscalar

- Small mixing with gluon EMT operators (neglected)
- Sum rule constraint

Normalised to proton result

\( m_\pi \sim 800 \text{ MeV} \)
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

First QCD determination of momentum fraction of nuclei

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology

Ratio of quark momentum fraction in nucleus to nucleon

- No mixing
- No sum rule constraint

Normalised to proton result

$\langle X_{u-d}\rangle_{\text{proton/NSN}}$

$Isovector$

$m_\pi \sim 800$ MeV
Matrix elements of the spin-independent gluon operator in nucleon + light nuclei

first determination of gluon momentum fraction of nuclei

Doubly challenging:

- Nuclear matrix element
- Gluon observable (suffer from poor signal-to-noise)
- BUT: clean signals at ~5% precision

Deuteron gluon momentum fraction

$R_a(t, \tau)$

Ratio of three-point to two-point

operator insertion time $\tau$

[NPLQCD PRD96 094512 (2017)]
Gluon momentum fraction of nuclei

Matrix elements of the spin-independent gluon operator in nucleon + light nuclei [NPLQCD PRD96 094512 (2017)]

- First determination of gluon momentum fraction of nuclei
- Constraints at ~10% level on EMC-effect in gluon momentum fraction
- Small mixing with quark EMT operators (neglected)
- Sum rule constraint

Ratio of gluon momentum fraction in nucleus to nucleon

![Graph showing the ratio of gluon momentum fraction in nucleus to nucleon for different masses of π. The x-axis represents the mass of π, with values around 450 MeV and 800 MeV. The y-axis represents the ratio, normalized to the proton result. The graph includes error bars for each data point.](image)
Momentum fractions of nuclei

- First determination of all components of momentum decomposition of light nuclei
- Small mixing between quark and gluon EMT operators neglected
- Constraint on either quark or gluon EMC in this quantity implies constraint on the other from sum rules:

\[ m_\pi \sim 800 \text{ MeV} \]
Exotic glue in the deuteron

a "pure" EMC-type effect

Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

Exotic glue operator:

- nucleon $\langle p | O | p \rangle = 0$
- nucleus $\langle N, Z | O | N, Z \rangle \neq 0$

Jaffe and Manohar, "Nuclear Gluonometry"
Exotic glue in the deuteron

a “pure” EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$:
changes both photon and target helicity by 2 units

- **Unambiguously gluonic:** no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin $\geq 1$
- **Experimentally measurable** in unpolarised electron DIS on polarised target
  - Nitrogen target: JLab LoI 2015
  - Polarised nuclei at EIC
- Moments calculable in LQCD
Exotic glue in the deuteron

a “pure” EMC-type effect

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Measure azimuthal variation

$$\lim_{Q^2 \to \infty} \frac{d\sigma}{dx \, dy \, d\phi} = \frac{e^4 M E}{4\pi^2 Q^4} \left[ x y^2 F_1(x, Q^2) + (1 - y) F_2(x, Q^2) - \frac{x(1 - y)}{2} \Delta(x, Q^2) \cos 2\phi \right]$$
Exotic glue in the deuteron

a “pure” EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$: changes both photon and target helicity by 2 units

Parton model interpretation: gluonic transversity

$$\Delta(x,Q^2) = -\frac{\alpha_s(Q^2)}{2\pi} \text{Tr} Q^2 x^2 \int_x^1 \frac{dy}{y^3} [g_{\hat{x}}(y,Q^2) - g_{\hat{y}}(x,Q^2)]$$

$g_{\hat{x},\hat{y}}(y,Q^2)$: probability of finding a gluon with momentum fraction $y$ linearly polarised in $\hat{x}, \hat{y}$ direction
Non-nucleonic glue in deuteron

Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

- First moment of gluon transversity distribution in the deuteron
  [Jaffe, Manohar PLB223 (1989) 218]

- First evidence for non-nucleonic gluon contributions to nuclear structure: LQCD with $m_\pi \sim 800$ MeV [NPLQCD PRD96 (2017)]

- Magnitude relative to momentum fraction as expected from large-$N_c$

nucleon: $\langle p|\mathcal{O}|p \rangle = 0$
nucleus: $\langle N, Z|\mathcal{O}|N, Z \rangle \neq 0$
FROM QCD TO NUCLEI

OUTLOOK

- Nuclei are under study directly from QCD
  - Spectroscopy of light nuclei and exotic nuclei
  - Structure: magnetic moments, parton structure
  - Interactions: $np \rightarrow dy$, $pp \rightarrow de+\nu$, $nn \rightarrow pp$, DM
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics
  - Critical role in current and upcoming intensity frontier experimental program
- Exponential improvements needed for larger nuclei: machine learning & quantum computing