

PROGRESS REPORT ON USQCD'S WHITEPAPER ON:

# FUNDAMENTAL SYMMETRIES AND SIGNALS FOR NEW PHYSICS

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UNIVERSITY OF MARYLAND AND RIEKN CENTER FOR ACCELERATOR-BASES SCIENCE

THE USQCD EXECUTIVE COMMITTEE TASKED US TO ORGANIZE A GROUP TO RECOGNIZE FUTURE OPPORTUNITIES AND FORMULATE POSSIBLE GOALS FOR LATTICE FIELD THEORY CALCULATIONS RELATED TO THE TOPIC OF FUNDAMENTAL SYMMETRIES AND SIGNALS FOR NEW PHYSICS.

CO-CHAIRS: ZD AND TAKU IZUBUCHI

WE DISCUSSED POSSIBLE TOPICS AND NOMINATED SEVERAL USQCD COLLABORATORS TO CONTRIBUTE TO EACH OF THOSE TOPICS. THESE COLLABORATORS WERE SHORTLY CONTACTED AND KINDLY AGREED TO CONTRIBUTE TO DRAFTING THIS WHITEPAPER.

CO-AUTHORS: YASUICHI AOKI, TANMOY BHATTACHARYA,  
VINCENZO CIRIGLIANO, ETHAN NEIL,  
PHIALA SHANAHAN, SERGEY SYRITSYN AND  
MICHAEL WAGMAN

THE AUTHORS PREPARED A SHORT OUTLINE OF WHAT NEED TO BE DISCUSSED IN THEIR SECTIONS AND TO IDENTIFY STRAIGHTFORWARD, CHALLENGING AND EXTREMELY CHALLENGING LQCD CALCULATIONS RELATED TO EACH TOPIC.

THIS WHITEPAPER IS PECULIAR IN THE SENSE THAT PHYSICS PROBLEMS ARE DIVERSE. SO THE STRUCTURE MAYBE A LITTLE DIFFERENT, BUT WILL STILL BE IN SYNERGY WITH OTHER WHITEPAPERS.

WE HAVE IDENTIFIED SEVERAL PHYSICS SECTIONS, EACH PREPARED BY A SUB-TEAM OF AUTHORS:

AOKI, SYRITSYN AND WAGMAN

BARYON-NUMBER NONCONSERVATION  
AND PROTON DECAY

SYRITSYN AND WAGMAN

BARYON-NUMBER MINUS LEPTON-  
NUMBER NONCONSERVATION AND  
NEUTRON-ANTINEUTRON OSCILLATION

CIRIGLIANO AND SHANAHAN

LEPTON-FLAVOR VIOLATION AND  
MUON TO ELECTRON CONVERSION

CIRIGLIANO, NEIL AND SHANAHAN

DARK-MATTER CROSS SECTIONS  
WITH NUCLEON AND NUCLEI

BHATTACHARYA, CIRIGLIANO, DAVOUDI, IZUBUCHI  
AND SYRITSYN

CP VIOLATION AND ELECTRIC DIPOLE  
MOMENT OF NUCLEON AND NUCLEI

CIRIGLIANO, DAVOUDI AND BHATTACHARYA

LEPTON-NUMBER NONCONSERVATION  
AND NEUTRINOLESS DOUBLE-  $\beta$  DECAY  
OF A NUCLEUS

CIRIGLIANO, DAVOUDI AND BHATTACHARYA

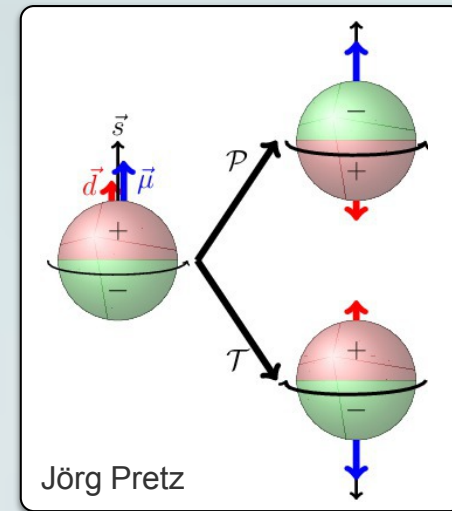
PRECISION  $\beta$  DECAY FOR  
SEARCHES OF NEW PHYSICS

BHATTACHARYA, DAVOUDI AND SHANAHAN

NEW PHYSICS AND PRECISION  
ISOTOPE-SHIFT SPECTROSCOPY

## CP VIOLATION AND ELECTRIC DIPOLE MOMENT OF NUCLEON AND NUCLEI

## MOTIVATION AND TARGET OBSERVABLES

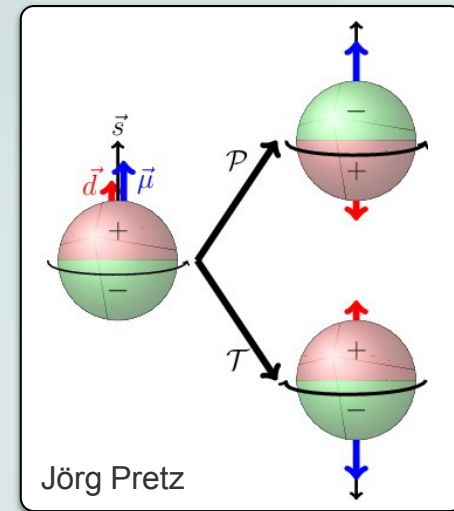


- PERMANENT EDM OF PROTONS, NEUTRONS AND NUCLEI WOULD BE THE BEST EVIDENCE FOR CP VIOLATION BEYOND THE SM.
- SEVERAL NEUTRON EDM EXPERIMENTS ARE PLANNED (SNS AND LANL IN THE US), IMPROVING THE LIMITS BY 2 ORDERS OF MAGNITUDE.
- CONSTRAINING BSM REQUIRES COMBINING DIFFERENT NON-ZERO EDM RESULTS AND MATCHING 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.

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

CP VIOLATION AND ELECTRIC DIPOLE  
MOMENT OF NUCLEON AND NUCLEI

MOTIVATION AND  
TARGET OBSERVABLES



STRAIGHTFORWARD  
CALCULATIONS

CHALLENGING  
CALCULATIONS

EXTREMELY  
CHALLENGING  
CALCULATIONS

$\theta_{\text{QCD}}$ -INDUCED  $p/n$ EDM AT  
LARGE QUARK MASSES

ISOVECTOR  $q$ CHROMO-  
EDM-INDUCED  $n$ EDM AT  
PHYSICAL POINT

WEINBERG 3G-INDUCED  $p/n$ EDM AT LARGE QUARK  
MASSES

$\theta_{\text{QCD}}$ -INDUCED  $p/n$ EDM AT  
PHYSICAL POINT

ISOSCALAR  $q$ CHROMO-EDM-  
INDUCED  $n$ EDM AT PHYSICAL  
POINT, REQUIRES SUBTRACTION  
OF THE FIRST ITEM.

WEINBERG 3G-INDUCED  $p-n$ EDM  
AT PHYSICAL POINT, AGAIN  
MIXING WITH FIRST ITEM

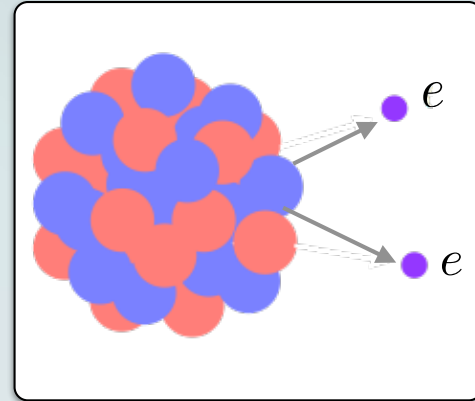
4-QUARK-INDUCED  $p/n$ EDM? REQUIRES 4pt  
FUNCTIONS, AND OFTEN  
DISCONNECTEDS

$piNN$  AND  $NNNN$  CP  
VIOLATING INTERACTIONS

EDM IN DEUTERON AND  
LIGHT NUCLEI

# LEPTON-NUMBER NONCONSERVATION AND NEUTRINOLESS DOUBLE- $\beta$ DECAY OF A NUCLEUS

## MOTIVATION AND TARGET OBSERVABLES



- TON-SCALE EXPERIMENT PLANNED IN THE US, DESIGN AND INTERPRETATION OF THE RESULTS REQUIRES NUCLEAR MEs IN VARIOUS SCENARIOS.
- LNV FROM DIMENSION-5 OPERATOR (LIGHT MAJORANA NEUTRINO EXCHANGE)

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

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

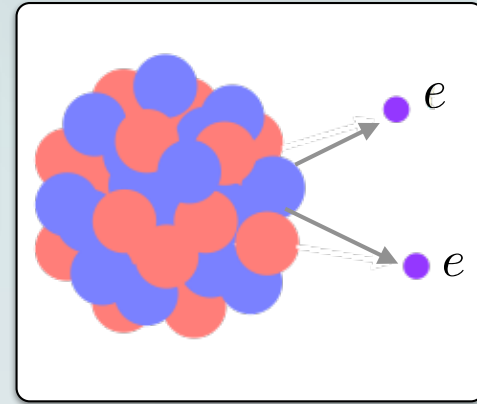
- LNV FROM DIMENSION-9 OPERATORS (“SHORT-DISTANCE” MECHANISMS). REQUIRES MEs OF 4-QUARK CHARGE-CHANGING OPERATORS

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

STATE OF THE ART: CALLATT, arXiv:1608.04793 [hep-lat], NPLQCD, Phys. Rev. Lett. 119, 062003 (2017), Phys. Rev. D 96, 054505 (2017).

LEPTON-NUMBER NONCONSERVATION  
AND NEUTRINOLESS DOUBLE- $\beta$  DECAY  
OF A NUCLEUS

MOTIVATION AND  
TARGET OBSERVABLES



STRAIGHTFORWARD  
CALCULATIONS

CHALLENGING  
CALCULATIONS

EXTREMELY  
CHALLENGING  
CALCULATIONS

PION MATRIX  
ELEMENTS OF  
LOCAL OPERATORS  
(ALMOST DONE).

TWO-NUCLEON AND NUCLEON-  
PION MATRIX ELEMENTS OF  
LOCAL OPERATORS.

PION MATRIX ELEMENT IN  
LIGHT  $\nu$  EXCHANGE SCENARIO

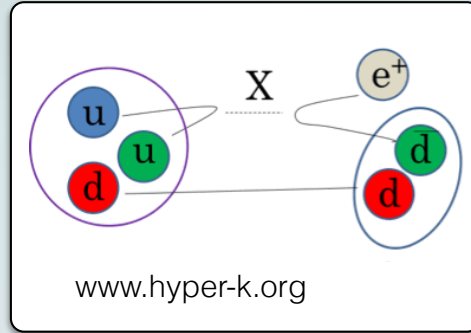
TWO-NUCLEON MATRIX  
ELEMENT IN LIGHT  $\nu$   
EXCHANGE SCENARIO AT  
LARGE QUARK MASSES

FULLY CONTROLLED  
PHYSICAL POINT NN MATRIX  
ELEMENTS IN LIGHT  $\nu$   
EXCHANGE SCENARIO

MORE AMBITIOUS: HIGHER-  
N MATRIX ELEMENTS TO  
DIAGNOSE ANY POTENTIAL  
ISSUES WITH MANY-BODY  
CALCULATIONS OF  $0\nu\beta\beta$   
DECAY.

## BARYON-NUMBER NONCONSERVATION AND PROTON DECAY

## MOTIVATION AND TARGET OBSERVABLES



- GUT AND SUSY-GUT CONSTRAINTS REQUIRE  $p \rightarrow$  MESON MEs. SOME MODELS PREDICT SUPPRESSION OF  $p$  DECAY MEs DUE TO NONPERTURBATIVE DYNAMICS.
- UPCOMING DUNE WILL EXAMINE  $p \rightarrow Klv$  DECAYS WITH BETTER PRECISION, FUTURE hyper-K WILL FURTHER IMPROVE PDECAY CONSTRAINTS.

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

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

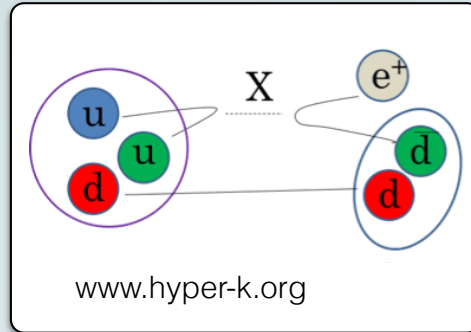
$$\langle 0 | \epsilon_{ijk} (u^{iT} C P_R d^j) P_L u^k | p(\vec{k} = \vec{0}) \rangle$$

$$\langle 0 | \epsilon_{ijk} (u^{iT} C P_L d^j) P_L u^k | p(\vec{k} = \vec{0}) \rangle$$

STATE OF THE ART 10%-15% UNCERTAINTY: Y. Aoki et al., Phys. Rev. D 96, 014506 (2017).

BARYON-NUMBER NONCONSERVATION  
AND PROTON DECAY

MOTIVATION AND  
TARGET OBSERVABLES



STRAIGHTFORWARD  
CALCULATIONS

CHALLENGING  
CALCULATIONS

EXTREMELY  
CHALLENGING  
CALCULATIONS

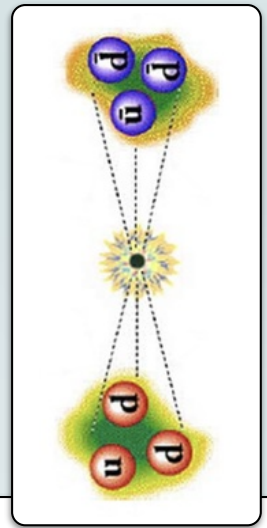
PHYSICAL-POINT  
CALCULATIONS

PHYSICAL-POINT  
CALCULATIONS WITH  
CONTROLLED SYSTEMATIC  
(MULTIPLE VOLUMES,  
LATTICE SPACING, ETC.)

PROTON DECAY IN  
NUCLEAR MEDIUM?

BARYON-NUMBER MINUS LEPTON-NUMBER NONCONSERVATION AND NEUTRON-ANTINEUTRON OSCILLATION

MOTIVATION AND TARGET OBSERVABLES



- IMPACT OF BARYON VIOLATION ON BARYOGENESIS DEPENDING ON ITS SCALE RELATIVE TO THE SCALE AND ORDER OF THE PHASE TRANSITION.
- TWO TYPES OF EXPERIMENTS: SLOW NEUTRON BEAMS AND OSCILLATION IN NUCLEAR MEDIUM WITH A DISTINCT 5-PION FINAL STATE.

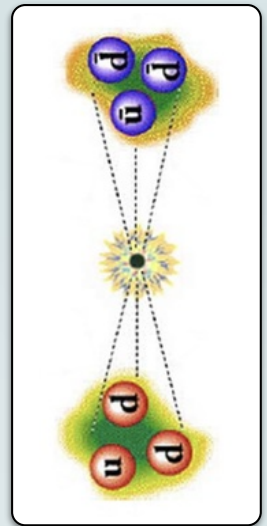
- THEORETICAL UNCERTAINTIES IN NEUTRON BEAM EXPTS EASIER TO CONTROL. BOUNDS COULD BE IMPROVED BY A FACTOR OF 1000 IN NEXT EXPERIMENTS.
- LQCD EVALUATES MATRIX ELEMENTS OF 6-QUARK OPERATORS THAT CONVERT NEUTRON TO ANTINEUTRON.

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

STATE OF THE ART: BUCHOF et al., arXiv:1207.3832 [hep-lat]

BARYON-NUMBER MINUS LEPTON-  
NUMBER NONCONSERVATION AND  
NEUTRON-ANTINEUTRON OSCILLATION

MOTIVATION AND  
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STRAIGHTFORWARD  
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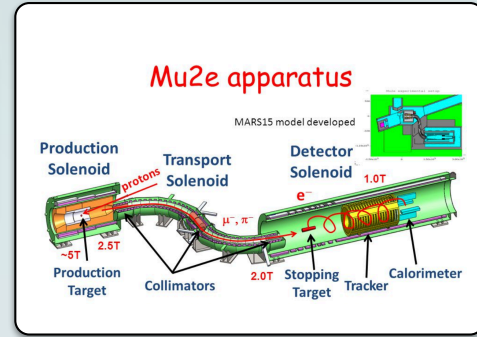
SINGLE-NEUTRON  
MATRIX ELEMENTS  
(SENSITIVE TO  
DISCRETIZATION,  
CHIRAL SYMMETRY  
IS IMPORTANT).

NEUTRON-ANTINEUTRON  
ANNIHILATION MATRIX  
ELEMENT

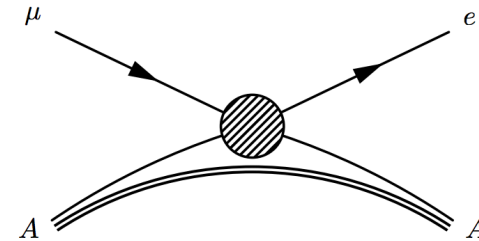
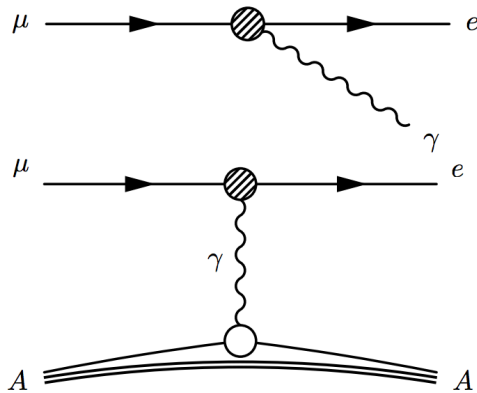
NEUTRON-ANTINEUTRON  
ANNIHILATION MATRIX  
ELEMENT IN NUCLEI  
(DEUTERON?) FOR super-K/  
SNO/SUDAN

# LEPTON-FLAVOR VIOLATION AND MUON TO ELECTRON CONVERSION

## MOTIVATION AND TARGET OBSERVABLES



RELIABLE MATRIX ELEMENTS WILL HELP ESTABLISH PATTERN OF LFV SIGNATURES IN VARIOUS DECAY CHANNELS DEPENDING ON THE UNDERLYING MECHANISM.

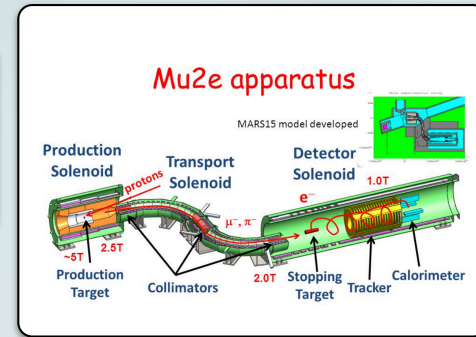


$$\mathcal{L}_d \sim \frac{1}{\Lambda^2} m_\mu \bar{\mu}_L \sigma_{\mu\nu} e_R F^{\mu\nu}$$

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

# LEPTON-FLAVOR VIOLATION AND MUON TO ELECTRON CONVERSION

## MOTIVATION AND TARGET OBSERVABLES



### STRAIGHTFORWARD 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**  
**OPERATOR**.

### CHALLENGING CALCULATIONS

FEW PERCENT PRECISION  
ON NUCLEON FORM FACTORS

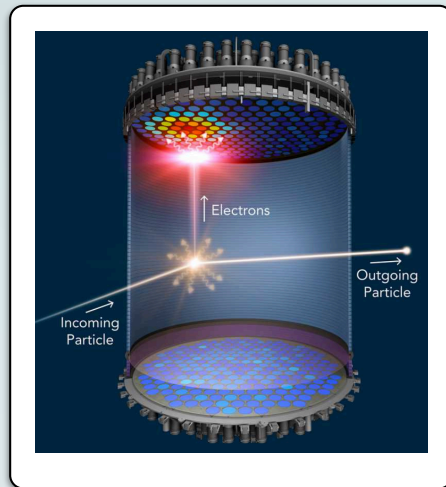
GOING BEYOND IMPULSE  
APPROX: DIRECTLY  
EVALUATING MEs IN NUCLEI  
(2 AND 3 BODY?)

### EXTREMELY CHALLENGING CALCULATIONS

DIRECTLY EVALUATING  
MEs IN LARGER NUCLEI

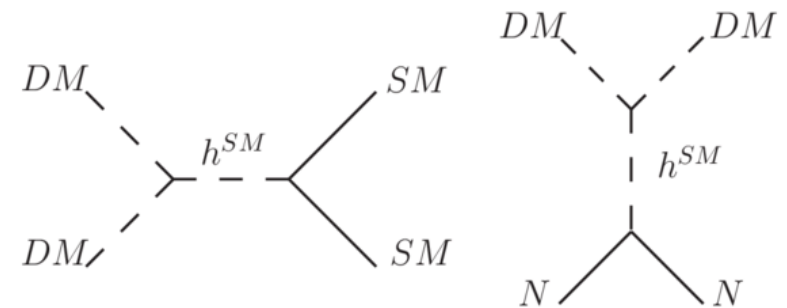
## DARK-MATTER CROSS SECTIONS WITH NUCLEON AND NUCLEI

## MOTIVATION AND TARGET OBSERVABLES



- AXION DARK MATTER (BSM, THERMO WHITEPAPERS?).
- STRONGLY-INTERACTING DARK SECTOR (BSM WHITEPAPERS).
- WEAKLY-INTERACTING MASSIVE PARTICLES (THIS WHITEPAPER).
- STANDARD MODEL INPUT 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? OTHER INTERACTIONS? REQUIRES KNOWLEDGE OF PARTON STRUCTURE OF NUCLEI.

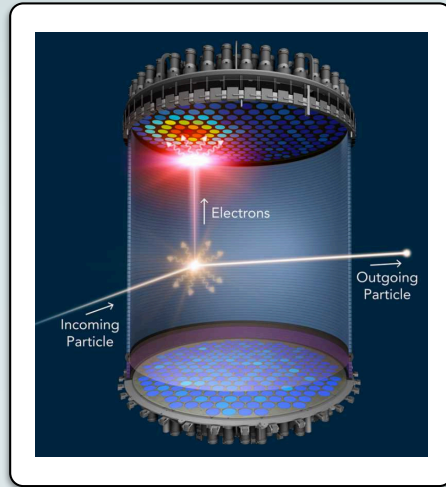


**STATE OF THE ART: 10%–15% UNCERTAINTY ON SCALAR MES IN NUCLEON, e.g., YANG et al., Phys. Rev. D 94, 054503 (2016).**

**THE FIRST CALCULATION OF SCALAR MES IN LIGHT NUCLEI AT 800MeV PION MASS, NPLQCD, Phys. Rev. Lett. 120, 152002 (2018).**

DARK-MATTER CROSS SECTIONS  
WITH NUCLEON AND NUCLEI

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TARGET OBSERVABLES



STRAIGHTFORWARD  
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CHALLENGING  
CALCULATIONS

EXTREMELY  
CHALLENGING  
CALCULATIONS

FEW PERCENT PRECISION  
ON NUCLEON MATRIX  
ELEMENTS.

SPIN-DEPENDENT  
INTERACTIONS, PDFS  
IN NUCLEONS, ETC.?

FULLY CONTROLLED 2 AND 3  
NUCLEON MATRIX  
ELEMENTS (DISCONNECTED,  
MULTIPLE  $a$ ,  $V$ , CHIRAL  
EXTRAPOLATION). SCALAR  
MEs ARE THE PRIORITY.

DIRECT EVALUATION IN  
LARGER NUCLEI?

## RESOURCE REQUIREMENT



### TWO IMPORTANT POINTS TO KEEP IN MIND:

ANY NEAR PHYSICAL-POINT CALCULATION INVOLVING ME<sub>s</sub> BETWEEN MULTIPLE NUCLEONS REQUIRES **MULTIPLE LARGE** VOLUMES, BOOSTS, ETC. TO EXTRACT PHYSICAL QUANTITIES.

CHIRALITY PLAYS AN IMPORTANT ROLE IN CLASSIFICATION OF MANY NEW PHYSICS RELATED MATRIX ELEMENTS.

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