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, Davoudi and Bhattacharya
- CP violation and electric dipole moment of nucleon and nuclei

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- Dark-matter cross sections with nucleon and nuclei

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- 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.

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

IZUBUCHI et al, arXiv:1702.00052 [hep-lat].
CP VIOLATION AND ELECTRIC DIPOLE MOMENT OF NUCLEON AND NUCLEI

MOTIVATION AND TARGET OBSERVABLES

STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

EXTREMELY CHALLENGING CALCULATIONS

$\theta_{QCD}$-INDUCED $p/nEDM$ AT LARGE QUARK MASSES

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

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

$\theta_{QCD}$-INDUCED $p/nEDM$ AT PHYSICAL POINT

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

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

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

$piNN$ AND $NNNN$ CP VIOLATING INTERACTIONS

EDM IN DEUTERON AND LIGHT NUCLEI

Jörg Pretz
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)

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

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

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

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

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.

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 $0\nu BB$ DECAY.

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


\[
\begin{align*}
\left\langle \pi^0 \right| \epsilon_{ijk} (u^T CP_{R,L}d^j) P_L u^k \right| p \rightangle \\
\left\langle \pi^+ \right| \epsilon_{ijk} (u^T CP_{R,L}d^j) P_L d^k \right| p \rightangle
\end{align*}
\]

\[
\begin{align*}
\left\langle 0 \right| \epsilon_{ijk} (u^T CP_{R}d^j) P_L u^k \left| p(\vec{k} = 0) \rightangle \\
\left\langle 0 \right| \epsilon_{ijk} (u^T CP_{L}d^j) P_L u^k \left| p(\vec{k} = 0) \rightangle
\end{align*}
\]

www.hyper-k.org
BARYON-NUMBER NONCONSERVATION AND PROTON DECAY

STRAIGHTFORWARD CALCULATIONS

PHYSICAL-POINT CALCULATIONS

CHALLENGING CALCULATIONS

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

EXTREMELY CHALLENGING CALCULATIONS

PROTON DECAY IN NUCLEAR MEDIUM?

MOTIVATION AND TARGET OBSERVABLES

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**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.

**State of the Art:** Buchof et al., arXiv:1207.3832 [hep-lat]

- 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.

\[
\frac{1}{\tau_{nn}} = \delta m = c_{BSM}(\mu_{BSM}, \mu_W)c_{QCD}(\mu_W, \Lambda_{QCD}) \langle \bar{n} | \Theta | n \rangle
\]
MOTIVATION AND TARGET OBSERVABLES

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

STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

EXTREMELY CHALLENGING CALCULATIONS

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

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

\[ \mathcal{L}_4 \sim \frac{1}{\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \left( u_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L \right) \]
LEPTON-FLAVOR VIOLATION AND MUON TO ELECTRON CONVERSION

MOTIVATION AND TARGET OBSERVABLES

STRAIGHTFORWARD CALCULATIONS

CHALLENGING CALCULATIONS

EXTREMELY CHALLENGING CALCULATIONS

NUCLEON FORM FACTORS (SCALAR, VECTOR, AXIAL, TENSOR, PSEUDOSCALAR) AT $q^2 = m^2_{\mu}$.

MOST RELEVANT IS THE SET OF SCALAR FORM-FACTORS (WITH $u, d, s$ FLAVOR) AND $GG$ OPERATOR.

FEW PERCENT PRECISION ON NUCLEON FORM FACTORS GOING BEYOND IMPULSE APPROX: DIRECTLY EVALUATING MEs IN NUCLEI (2 AND 3 BODY?)

DIRECTLY EVALUATING MEs IN LARGER 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.

MOTIVATION AND TARGET OBSERVABLES

STRAIGHTFORWARD CALCULATIONS
- Few percent precision on nucleon matrix elements.
- Spin-dependent interactions, PDFs in nucleons, etc.?

CHALLENGING CALCULATIONS
- Fully controlled 2 and 3 nucleon matrix elements (disconnected, multiple $a$, $V$, chiral extrapolation). Scalar MEs are the priority.

EXTREMELY CHALLENGING CALCULATIONS
- Direct evaluation in larger nuclei?
RESOURCE REQUIREMENT

ANY NEAR PHYSICAL-POINT CALCULATION INVOLVING MEs 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.

TWO IMPORTANT POINTS TO KEEP IN MIND:
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