Nuclear Theory for New Physics - a DOE Topical Collaboration 2023 Jefferson Lab Users Organization Annual Meeting June 26-29, JLab

André Walker-Loud









NTNP (Nuclear Theory for New Physics)

NTNP

Home

science \sim

people

https://a51.lbl.gov/~ntnp/TC/

Nuclear Theory for New Physics

- About Us
- Commitment to Diversity
- Funding Acknowledgement

Nuclear Theory for New Physics co-chairs: Vincenzo Cirigliano & Saori Pastore

DEI Coordinator: Maria Piarulli

Lattice QCD

Coordinator: Andre' Walker-Loud

EFT / phenomenology Coordinator: Emanuele Mereghetti

 $\searrow u$ EDM 🗢 SPIN EDM BSM TIME FORWARD TIME BACKWARD β decays and new particles T & CP violation and the Origin of Matter

meetings \sim **Code of Conduct**



D We are a new DOE Topical Collaboration

• We are jointly funded by the Offices of Nuclear and High Energy Physics

Nuclear Structure

Coordinator: Heiko Hergert





NTNP: What Science Questions are we Investigating?

* The Standard Model is remarkably successful, but it is at best incomplete





- SM-allowed processes or by observing SM-suppressed processes
- Nuclear physics plays an important role in the search for new physics through a "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model" (2015 NSAC LRP)



• Low-energy experiments can reveal new physics through precision measurements of



NTNP: What Science Questions are we Investigating? * NTNP focuses on selected aspects of the targeted program, with the goal of providing state-of-the-art predictions with quantified uncertainties.

Image credit: Evan Berkowitz



Precision studies of neutron and nuclear beta decays are exquisite probes of the electroweak interactions and can uncover new physics. NTNP: radiative corrections to neutron & nuclear decays and implications for new physics

Time EDM Spin

The discovery of permanent EDMs would point to a microscopic 'arrow of time', with major implications for the origin of the baryon asymmetry. NTNP: ab-initio calculations of Schiff moments of ¹²⁹Xe, ¹⁹⁹Hg, ²²⁵Ra

Image credit: R. Holt, Z. T. Lu, W. Korsch, P. Muller, J. Singh



Image credit: Jefferson Lab



Neutrino-nucleus scattering is a chief tool to learn about neutrino properties in oscillation experiments: connection to DUNE program (HEP). NTNP: ab-initio calculations of neutrino-nucleus scattering in



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This theoretical work is essential to turn experimental measurements into discovery tools

Image credit: R. Holt, Z. T. Lu, W. Korsch, P. Muller, J. Singh



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The three areas share challenges (multi-scale problems!), techniques, and infrastructure Need synergy of EFT / phenomenology, lattice QCD, nuclear structure.

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Image credit: Jefferson Lab



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NTNP: How are we investigating these open questions?



This multi-scale problem requires a coordinated effort with a broad set of expertise including Effective Field Theory & Phenomenology, lattice QCD and many-body nuclear methods

- □ A coordinated, multi-scale theory effort is required
- Effective Field Theory (EFT) and Phenomenology to understand how to couple BSM physics, to a Standard Model EFT (embed high-mass scale BSM physics in short-distance higher-dimensional operators)
- □ Also use EFT to couple this SM-EFT to a hadronic-level EFT of pions and nucleons
- □ Use lattice QCD to compute hadronic-level matrix elements in terms of quark and gluon degrees of freedom
- Could hadronic EFT to many-body nuclear effective theory to perform calculations with nuclei
- Use EFT to couple few-body nuclear EFT to no-core shell model methods in order to compute properties of medium and large nuclei







Two selective topics that we are working on



ainty entirely dominated by experiment [27]. A determination requires a dedicated experimental s planned at the PIONEER experiment [26]. information on V_{us} comes from kaon decays $K_{\ell^2} =$ nd $K_{\ell 3} = K \rightarrow \pi \ell \nu_{\ell}$. The former is typically anarmalizing to $\pi_{\ell 2}$ decays [27], leading to a constraint while $K_{\ell 3}$ decays give direct access to V_{us} when the ng form factor is provided from attice QCD [28]. he global fit to kaon decays, as well as the input onstants, form factors, and radiative corrections, are Sec. 2, leading to

$$= 0.23108(23)_{\exp}(42)_{F_K/F_{\pi}}(16)_{\mathrm{IB}}[\mathbf{0}.\mathbf{222}]$$

$$V_{us}^{K_{\ell 3}} = 0.22330(35)_{\exp}(39)_{f_+}(8)_{\mathrm{IB}}[53]_{\mathrm{total}}, \qquad (7)$$

rors refer to experiment, lattice input for the matrix nd isospin-breaking corrections, respectively. gTothe constraints on V_{ud} , these bands give rise to the picted in Fig. 1: on the one hand, there is a tenn the best fit and CKM unitarity, but another tenentirely from meson decays, is due to the fact that $K_{\ell 3}$ constraints intersect away from the unitarity itional information on V_{us} can be derived from τ 30], but given the larger errors [31, 32] we will focus on the kaon sector.

point of this Letter is that given the various ten- $V_{ud}-V_{us}$ plane, there is urgent need for additional on the compatibility of $K_{\ell 2}$ and $K_{\ell 3}$ data, especially nes to interpreting either of the tensions (CKM uni- $\mathcal{L}_{\ell 2}$ versus $K_{\ell 3}$) in terms of physics beyond the SM particular, the data base for $K_{\ell 2}$ is completely domsingle experiment [33], and at the same time the all kaon data displays a relatively poor fit quality. ints could be scrutinized by a new measurement of branching fraction at the lovel of a fave normil as



Figure 1: Constraints in the $V_{ud}-V_{us}$ plane. The partially overlapping vertical bands correspond to $V_{ud}^{0^+ \to 0^+}$ (leftmost, red) and $V_{ud}^{n, \text{ best}}$ (rightmost, violet). The horizontal band (green) corresponds to $V_{us}^{K_{\ell 3}}$. The diagonal band (blue) corresponds to $(V_{us}/V_{ud})_{K_{\ell 2}/\pi_{\ell 2}}$. The unitarity circle is denoted by the black solid line. The 68% C.L. ellipse from a fit to all four constraints is depicted in yellow ($V_{ud} = 0.97378(26)$, $V_{us} = 0.22422(36)$, $\chi^2/dof = 6.4/2$, p-value 4.1%), it deviates from the unitarity line by 2.8σ . Note that the significance tends to increase in case τ decays are included.

Table 1, where, however, the value for V_{us} from $K_{\ell 3}$ decays includes all charge channels, accounting for correlations among them. The extraction of V_{us} from $K_{\ell 3}$ decays requires further input on the respective form factors, which are taken in the dispersive parameterization from Ref. [71], constrained by data from Pafe [72 78] This larges form factor normalizations decay

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on the compatibility of $K_{\ell 2}$ and $K_{\ell 3}$ data, especially determines to nuclear $0^+ \rightarrow 0^+$ decays (A=10, 14, ...). Use several ab-initio many-body nes to interpreting either of the tensions (CKM uni-(2) versus K_{l3}) in terms of physics beyond methods al QMGereChower MSR GluHOBET by Ko controlled uncertainty cludes all charge channels, accounting for correlations among them. The extraction of V_{us} from $K_{\ell 3}$ decays requires further input on the respective form factors, which are taken in the dispersive parameterization from Ref. [71], constrained by data from Data [72 78] This laguage form factor normalizations doory

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The success of neutrino oscillations experiments • (such as DUNE) requires knowing neutrinonucleus cross sections at few % level over a broad range of energies (flux determination, v energy reconstruction, ...)

- NTNP objectives: First-principles calculations of inclusive and exclusive cross sections
 - Lattice QCD input on single-nucleon • form factors (elastic and not)
 - EFT-based nuclear interactions and currents: retain key many-body correlations
 - Validation: use multiple many-body methods for A=4,12,16,40 & JLAB data on electron scattering

$\nu - A$ scattering



 E_v (GeV)





ν -N cross section

Meyer, Walker-Loud, Wilkinson Ann. Rev. Nucl. Part. Sci. 72 (2022)



 $\label{eq:constraint} \square \ Lattice \ QCD \ determination \ of \ F_A(Q^2) \ is \ inconsistent \ with \ older \ phenomenological \ extraction$

 \Box results in 30% increase in ν -N cross section



v-N cross section



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v-N cross section

- □ Need to solidify lattice QCD result • one final systematic that must be verified with more sophisticated calculational strategy 1-2 years
- Need to incorporate modern lattice QCD information into event generators \Box Significant potential for synergy with e - A scattering program (a) JLab
- \Box Need to compute resonant inelastic structure, $N \rightarrow \Delta$ and $N \rightarrow N\pi, N \rightarrow N\pi\pi, ...$ starting now - this is a 5+ year effort
 - calculations

Q Results from these more complex processes need to be incorporated into the nuclear many-body

a major goal of NTNP is to build the pipeline of lattice QCD results to nuclear many-body calculations



2. State of the Field



 $W^2 = (\Sigma E)^2 - |\Sigma p|^2$

Future directions

Indeed not!

Our pion production model uses a description of resonance production that is "naive and obviously wrong in its simplicity" [F.K.R. PRD3 (1971)]

I trust some bright motivated physicists will fix this soon

Current models are unsatisfactory:

- Simplistic description of neutrino-nucleon interaction
- Unsophisticated description of the nucleus

Heavy reliance on old data (experiments shut down)

~10% uncertainties on effective parameters at best



v-N cross section

- Need to solidify lattice QCD result • one final systematic that must be verified with more sophisticated calculational strategy 1-2 years
- Need to incorporate modern lattice QCD information into event generators \Box Significant potential for synergy with e - A scattering program (a) ILab
- \Box Need to compute resonant inelastic structure, $N \rightarrow \Delta$ and $N \rightarrow N\pi, N \rightarrow N\pi\pi, ...$ starting now - this is a 5+ year effort
 - **Q** Results from these more complex processes need to be incorporated into the nuclear many-body calculations a major goal of NTNP is to build the pipeline of lattice QCD results to nuclear many-body calculations This will also require quantitatively mapping out convergence pattern of baryon chiral perturbation theory In order to fully quantify the theory uncertainty, we must start with convergence of single nucleon



Many more research endeavors NTNP is working on... with many potential connections to JLab Physics Program



