Lattice QCD and neutrino-Nucleus Scattering

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Background

• Physics giving rise to neutrino masses identified as focus by 2014 P5 Strategic Plan.

• **US Response** - DUNE (Deep Underground Neutrino Experiment) hosted by FNAL.

• Other efforts in Europe and Japan… …but US leadership…

• For the US Lattice Community:
  – Identify calculations essential to success of program
  – Important questions and impact in both nuclear and particle physics

• *Neutrino Scattering Theory Experiment Collaboration*
  – http://nustec.fnal.gov
  – arXiv:1706.03621v2

• Overlap with *Cold QCD* white paper, (and lepton/quark flavor and fundamental symmetries?).
Introduction
Template

• Introduction
  – Experiment
  – Nuclear Theory Overview
  – Lattice Opportunities
    • Lattice QCD most effective (e.g. form factors)
    • Lattice QCD only way (e.g. two-body currents)
• Straightforward Calculations
• More Challenging
• Most Challenging
• Computational Requirements
Straightforward Calculations

Calculations we know how to do, but need improved control over systematic and statistical uncertainties - pion mass, lattice spacing, disconnected diagrams,…

Nucleon Form Factors

• Calculations of vector form factors well-established: use as validation

• Axial-vector form factors crucial target - charged current and neutral current
  – Determination of axial-current charged radius and $g_A$
  • Key Measures of QCD, cf proton charge radius.
  – Improved disconnected methods for neutral current
  – z-expansion
  – blind analyses
  – analogy with CKM, success of LQCD

Marciano
Nucleon Matrix Elements

• Key precision quantity of lattice calculations
• Neutrino scattering:
  – Additional structure function $F_3$ beyond that of EM interactions
  
  \[
  W_{\alpha\beta} = \left( \frac{q_{\alpha} q_{\beta}}{q^2} - g_{\alpha\beta} \right) W_1 + \frac{1}{M^2} \left( p_{\alpha} - \frac{p \cdot q}{q^2} q_{\alpha} \right) \left( p_{\beta} - \frac{p \cdot q}{q^2} q_{\beta} \right) W_2 \\
  - \frac{i}{2M} \epsilon_{\alpha\beta\rho\sigma} q^\rho q^\sigma W_3
  \]
  
  – different combinations of flavor structure
  – Elucidate role of strangeness in nucleon
  – Low moments of u, d, s and glue in nucleon
  – s vs sbar distribution
More Challenging

Calculation of x-dependence of PDFs
- Refer to Cold QCD white paper for methodology - quasi-PDFs, pseudo-PDFs, hadronic tensor, lattice cross sections
- Extraction of higher-twist effects for lattice cross sections

Resonance production
- Neutrino scattering at low energies (< 3 GeV) excites resonances $N^*$, Delta.
- Formalism developed for infinite-volume momentum-dependent amplitudes from finite-energy shifts at finite volume, and for transition to two-body final states.
- State-of-the-art applications for momentum-dependent scattering amplitudes in meson sector, and in $\rho \rightarrow \gamma^* \pi$; exploratory $\Delta$ phase shift.
- Theoretical and computational needs and expected results for baryon final states in five years.
Axial currents in light nuclei

- Nuclear effects in neutrino nucleus scattering important. Gamow-Teller transitions show transitions in nuclei not simply scaled from \( n \rightarrow p e \nu \).

- Calculations of \( A=2, 3 \) axial transitions in the forward limit have been performed at \( m_\pi = 800 \) MeV. Calculations at the physical quark masses and with rudimentary control of continuum limit will be performed in the 5 years.

- Extension for form factors in nuclei and to moments of PDFs

- Lattice input to EFTs for heavier nuclei
Most Challenging

“Precision” Calculations
• EM and isospin-break effects. Are they relevant?

Axial currents in heavy nuclei
• Direct calculations of matrix elements in argon.
• Direct calculations of matrix elements in carbon and expt. accessible light nuclei; A dependence of EFT effects.
• x-dependence of PDFs in nuclei.
Summary