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

NuSTEC[a] White Paper: Status and Challenges of Neutrino-Nucleus Scattering

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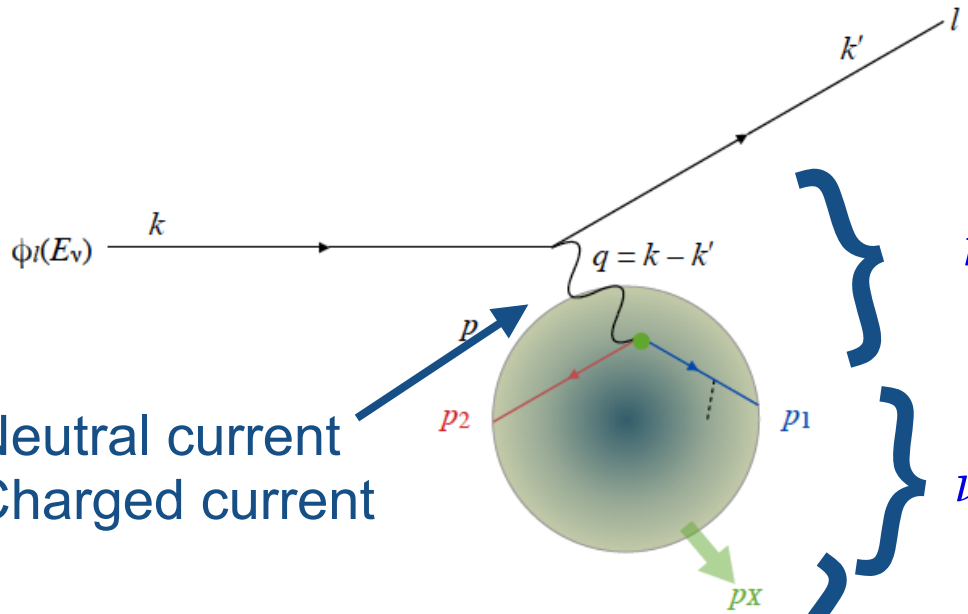
arXiv:1706.03621v2



Neutral current
Charged current

$$\nu N \longrightarrow l N \pi$$

$$l = \mu, e$$

$$\nu_l/\bar{\nu}_l(k) + N(p) \rightarrow l^{\pm}(k') + X(p')$$

Nuclear effects

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 gA

Marciano

    - Key Measures of QCD, cf proton charge radius.
  - Improved disconnected methods for neutral current
  - z-expansion
  - blind analyses
  - analogy with CKM, success of LQCD

Straightforward - II

Nucleon Matrix Elements

- Key precision quantity of lattice calculations
- Neutrino scattering:
  - Additional structure function F_3 beyond that of EM interactions

$$W_{\alpha\beta} = \left(\frac{q_\alpha q_\beta}{q^2} - g_{\alpha\beta}\right) W_1 + \frac{1}{M^2}\left(p_\alpha - \frac{p\cdot q}{q^2} q_\alpha\right)\left(p_\beta - \frac{p\cdot q}{q^2} q_\beta\right) W_2$$
$$- \frac{i}{2M}\epsilon\alpha\beta\rho\sigma p^\rho q^\sigma W_3$$

  - 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 Δ phase shift.
- Theoretical and computational needs and expected results for baryon final states in five years.

Challenging - II

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

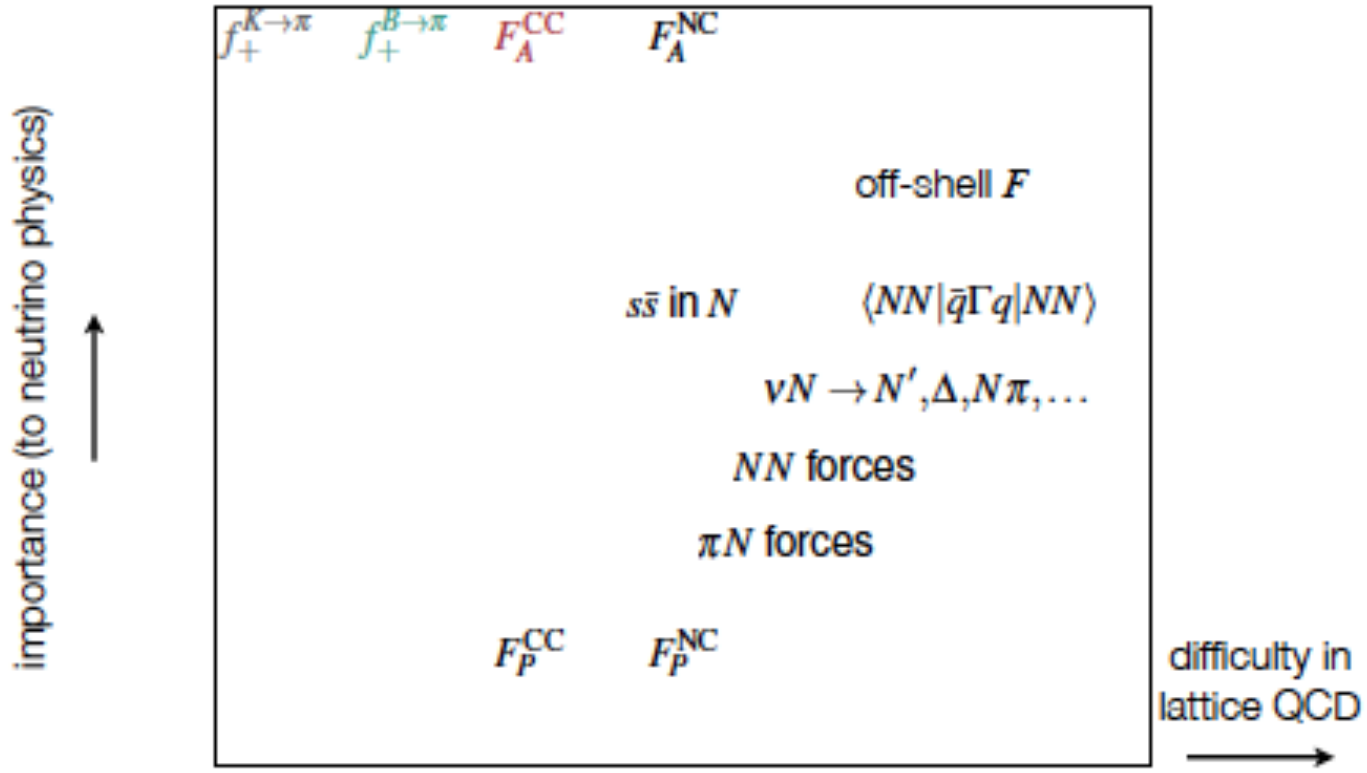
"Precision" Calculations

- 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


$f_+^{K\to\pi}$
$f_+^{B\to\pi}$
F_A^{CC}
F_A^{NC}
off-shell F
$s\bar{s}$ in N
$\langle NN|\bar{q}\Gamma q|NN\rangle$
$\nu N \to N', \Delta, N\pi, \ldots$
NN forces
πN forces
F_P^{CC}
F_P^{NC}
importance (to neutrino physics)
difficulty in lattice QCD