Brief research summary

The proposal applies recent effective field theory advances to intensity frontier experiments at Fermilab. Applications include: the implementation of Coulomb-enhanced radiative correc-tions for accelerator neutrino cross sections; analysis of elementary target (hydrogen/deuterium) neutrino data including state of the art radiative corrections; computing radiative corrections to enable a new low-energy search strategy at Mu2e; computing reactor neutrino fluxes using new quantum field theory constraints on the Fermi function for beta decay; computing radiative corrections to semileptonic B decays to enable precision lattice QCD to match experimental precision.

1 Project Overview

This is a Track 1 Intensity Frontier Fellowship proposal, to conduct research at Fermilab during my 2023-2024 sabbatical from U. Kentucky.

Research will be conducted with theoretical and experimental colleagues at Fermilab including Andreas Kronfeld, Michael Wagman and Ruth Van de Water on topics of neutrino interactions and lattice QCD; Steven Gardiner, Pedro Machado and Noemi Rocco on topics of neutrino interactions and generator physics; Minerba Betancourt and Thomas Junk on topics of neutrino experiment; and Robert Bernstein and Pavel Murat on topics relating to Mu2e. Other collaborators are mentioned in the following detailed plans.

2 Detailed plans

Better understanding of neutrino interactions is critical for the next generation of neutrino experiments, demanding e.g. percent-level control over ν_e appearance signals for discoveries at DUNE; robust constraints on radiative and other backgrounds at short-baseline experiments; and accurate calculations to relate increasingly precise lattice QCD calculations to experimental observables. A dominant source of uncertainty on neutrino oscillation signals is the modeling of neutrino interactions with the target nucleus in the near and far detectors. Relating the fundamental quark-level interactions of the neutrino to the complete nuclear response is a difficult multiscale field theory problem. The PI's group is addressing this problem on several fronts. Other topics on intensity frontier physics include muon-electron conversion, nucleon and nuclear beta decay, and quark flavor physics.

2.1 Radiative corrections for accelerator neutrinos

Accelerator based oscillation experiments such as DUNE search for electron flavor neutrinos, ν_e, appearing in a beam of mostly muon flavor neutrinos, ν_μ. A basic premise of this ν_e appearance analysis is that differences between cross sections for ν_e and ν_μ can be controlled with sufficient precision. A near-site detector has access to a large sample of muon flavor neutrinos, and can be used to constrain ν_μ cross sections. However, differences between ν_e and ν_μ cross sections must be controlled theoretically. These differences can be larger than naively expected, e.g. owing to large logarithms in QED perturbation theory. Corrections exceed 10% for the electron energy spectrum in quasielastic neutrino scattering at GeV energies, and large corrections of order 5% remain once real photon events are included, cf. Fig. 3 of Ref. [1]. The neutrino community is lacking a treatment of these radiative corrections in simulations and event generators.

The necessary radiative corrections involve a complicated interplay of detector-dependent real photon effects with multi-photon exchange in the target nucleus. A systematic effective field theory analysis can be used [1, 2] to isolate calculable soft radiation effects that distinguish electron and muon, and parameterize the remaining hadronic structure factors that are independent of lepton flavor. As discussed below, there are a range of compelling projects extending and applying the formalism, and a clear path forward based on the PI's previous work.

In order to systematically incorporate radiative corrections and nucleon-level amplitudes with complete error bars into experimental analyses, the PI's group will also work to develop the necessary event-generator modules.

2.1.1 Coulomb corrections and soft-collinear effective theory

Enhanced radiative corrections occur for large nuclei, where interactions of the final state charged lepton with the nuclear remnant are enhanced in amplitude by a factor of Z, the nuclear electric charge.

For a given nuclear potential, the Coulomb distortion may be computed numerically by integrating the Dirac equation for appropriate initial and final scattering states. However such a procedure is computationally prohibitive for a practical event generator, and would involve issues of delicate cancellations and double counting when comparing ν_e versus ν_μ cross sections and merging with nucleon-level radiative corrections. For typical charged lepton energies in accelerator neutrino experiments, $E_\nu \approx \text{GeV}$, we may expand in powers of Λ/E_ν, where Λ represents a hadronic or nuclear mass scale.

Two effects are observed in this so-called eikonal approximation [3]: first, a shift in phase for scattering waves (effective momentum substitution); and second, an amplitude normalization (focusing). These effects have been argued to largely cancel in certain processes such as the transverse photon component of electron-nucleus scattering. Such cancellations will be different or absent in charged current neutrino interactions, where only the final state lepton suffers Coulomb distortions, and where the long distance photon propagator is replaced by the point-like weak interaction.

The project uses a systematic framework to compute Coulomb radiative corrections using soft-collinear effective field theory, and implements these corrections in modern neutrino experiments. This effort involves former postdocs R. Plestid and O. Tomalak, and current postdoc P. Vander Griend.

2.1.2 Radiative corrections for elementary target data

Even with a near detector, neutrino oscillation experiments are not immune to hadronic uncertainties in ν_μ cross sections. This situation is due to flux differences between near and far detectors (owing to beam divergence and oscillation); degeneracies between interaction uncertainty and detector response calibration; and neutrino energy reconstruction biases due to invisible particles. Regardless of whether nuclear corrections are derived ab initio, or obtained from data driven models, the elementary neutrino-nucleon scattering amplitudes are a limiting uncertainty in the cross section program: no nuclear model can give results more precise than its inputs. The PI will continue a program of determining the elementary amplitudes, their uncertainties, and the impact of these uncertainties on oscillation observables. There is potential for improvements from a range of approaches, including lattice QCD [4] and new elementary target experiments [5]. Future high-statistics (anti)neutrino scattering experiments, such as DUNE have the potential to access nucleon structure with unprecedented precision from antineutrino scattering on the hydrogen as a part of the hydrocarbon molecule. As a benchmark, the project will study the projected uncertainty for extractions of the nucleon axial radius at DUNE and compare them to other sources.

The nucleon axial radius is a fundamental parameter impacting the electroweak processes of leptons and nucleons. Important examples are elastic neutrino-nucleon scattering and muon capture by the proton. The sparsity of existing experimental data implies a large uncertainty on this important parameter, and has motivated the consideration of new experimental probes and first principles lattice QCD evaluations. The comparison of new and precise predictions for r_A^2 requires a rigorous evaluation of radiative corrections. The project will evaluate these corrections, apply them to the extraction of r_A^2 from elementary target neutrino scattering data, and discuss the comparison of lattice QCD evaluations of r_A^2 to experimental extractions. These efforts involve former current graduate student K. Borah, former postdoc O. Tomalak, and experimentalists K. McFarland (U. Rochester) and R. Petti (U. South Carolina).

2.2 Radiative corrections for beta decay and reactor antineutrino spectra using heavy particle effective theory

Measurements of the neutron lifetime and of superallowed beta decay transition rates provide our most precise determination of fundamental constants such as the CKM matrix element V_{ud} [6] and the nucleon axial coupling g_A [7]. Besides probing fundamental electroweak and strong interactions physics, discrepancies between these measurements and derived Standard Model predictions could indicate the presence of new physics.

It is known that QED radiative corrections can have a dramatic impact on these measurements, owing to enhancements of large nuclear electric charge Z and of small electron velocity β. Such corrections are historically summed in a so-called Fermi function for the process $F(Z, E)$, depending on the electron or positron energy E. Although the Fermi function captures leading corrections, it is not phrased in a quantum field theory language that allows other subleading but important corrections to be included systematically. The project develops the quantum field theory description of the Fermi function and applies the formalism to the phenomenology of nucleon and nuclear beta decay and reactor antineutrino spectra. The former applications impact the determination of fundamental constants and constraints on new physics. The latter application impacts searches for new physics with reactor neutrinos [8].

In contrast to beta decay, the application to reactor antineutrino data involves [9, 10]: very large nuclear charge ($Z = 92$ for ^{238}U); the uncharged antineutrino spectrum versus the charged electron/positron spectrum [11]; the differential spectrum versus the total integrated rate; and nuclear transitions beyond just the superallowed $0^+ \to 0^+$ transitions which are a focus of V_{ud} determinations.

The project implements high-order radiative corrections in combination with a properly defined Fermi function, and phrases nuclear size and structure corrections as systematic power corrections in quantum field theory. These efforts involve former postdoc R. Plestid and current postdoc P. Vander Griend.

2.2.1 Quantum field theory of the Fermi function

The Fermi function [12] describes electron propagation in a nuclear Coulomb field, and accounts for QED radiative corrections that are enhanced at either small electron velocity β or large nuclear charge Z. For precision applications, the Fermi function must be combined with other sources of radiative corrections and with scale- and scheme-dependent hadronic and nuclear matrix elements. We present the field theory factorization formula for the Fermi function, and use the formalism to systematically sum logarithmically enhanced radiative corrections using renormalization group methods. Our analysis provides an all-orders demonstration of factorization, and explicit results for a class of Feynman diagram integrals at arbitrary loop order. We establish constraints on logarithmically enhanced radiative corrections involving subleading powers of Z at a given order in the fine structure constant α, and compute corrections to nuclear beta decay at order $\alpha(Z\alpha)^2\log(\Lambda_{\rm nuc.}/m_e)$, where $\Lambda_{\rm nuc.}$ denotes a nuclear scale and m_e is the electron mass.

2.2.2 Neutron beta decay

The Fermi function for beta decay [12] describes a class of enhanced radiative corrections arising from electron or positron propagation in a nuclear Coulomb field. The corrections are parametrically enhanced at small β and/or at large Z. However, neither limit holds for neutron beta decay. For example, the electron velocity spectrum (for simplicity in this illustration, computed at tree level and in the heavy nucleon limit), is given by

$$\frac{d\Gamma(n\to pe\nu)}{d\beta} \propto \frac{\beta^2}{(1-\beta^2)^{\frac{5}{2}}}\left[\frac{\Delta}{m_e} - \frac{1}{\sqrt{1-\beta^2}}\right]^2 , \tag{1}$$

where $\Delta = m_n - m_p$ is the difference in nucleon masses and the allowed range is $0 \le \beta \le \sqrt{1-m_e^2/\Delta^2}$. The spectrum is strongly suppressed at small velocity: the mean velocity is $\langle\beta\rangle \approx 0.7$, and less than 0.1% of the total decay rate involves electron velocity $\beta < 0.1$ (less than 10% involves $\beta < 0.5$).

Despite the absence of large Z or small β, it is well known that the neutron decay rate suffers a large, $\sim 9\%$, first order QED radiative correction [13], 100 times larger than the naive expectation of $\alpha/(2\pi) \approx 10^{-3}$. While a portion of this correction arises from electroweak logarithms and can be resummed by standard means, the largest contributions arise from the low-energy matrix element and are "resummed" in a standard treatment [14] using a classical Fermi function. After integrating over phase space the estimated corrections to the rate behave as [14]

$$1 + 4.6\,\alpha + 16\,\alpha^2 + 34\,\alpha^3 + \dots . \tag{2}$$

Here we address two questions related to this phenomenological treatment. First, the Fermi function ansatz predicts, cf. Eq. (2), a permille-level contribution from second-order corrections, larger than the precision goals for V_{ud} determinations from neutron beta decay. Since the Fermi function does not give a controlled approximation to the complete decay amplitude beyond first order, what should replace the Fermi function ansatz and the associated second-order correction? Second, the coefficients of α^n in Eq. (2) are large, and increasing. More provocatively, in units of the natural prefactor $(\alpha/4\pi)^n$, the coefficients are 58, 2500, 69000, ... What is the source of these large coefficients in the perturbative expansion for the low energy matrix element? Even if the second order and higher-order terms in Eq. (2) are spurious, what is the source of the large first-order correction, and can it be resummed?

The project establishes that the large first-order correction appearing in Eq. (2) is absent for a process where the momentum transfer in the electron-proton system is spacelike, versus timelike. The enhancement is associated with the continuation from spacelike to timelike momentum transfers. In the effective theory description, this continuation is systematically described by a renormalization group analysis relating negative values of μ^2, (where the perturbative series is free of π^2 enhancements) to positive values of μ^2, (where the low energy matrix element is combined with hadronic coupling constants to obtain physical predictions).

2.2.3 Semileptonic heavy meson decay

Experimental partial rates for the semileptonic decay $B \to \pi \ell \bar{\nu}_\ell$ can be combined with lattice QCD results to obtain the CKM matrix element $|V_{ub}|$ to a precision of a few percent [15], in tension with extractions from the inclusive $B \to X_u \ell \bar{\nu}_\ell$ process. It is important to ensure that QED radiative corrections are implemented consistently between theory and experiment, accounting for theory scheme dependence and experimental detector effects. The effective theory framework for Coulomb radiative corrections can be applied to the semileptonic heavy meson decay process. The project will reformulate historical treatments of radiative corrections for this process into modern effective theory language and provide a rigorous error bar arising from QED corrections for current and future $|V_{ub}|$ extractions.

2.3 Enabling new physics searches at Mu2e

Charged lepton flavor violation (CLFV) is a long sought-after target of searches for physics Beyond the Standard Model (BSM) [16]. Two upcoming facilities, Mu2e [17–19], and COMET [20–22] will search for $\mu \to e$ with unprecedented sensitivity. These experiments leverage the extreme kinematics in $\mu \to e$, where almost all of the muon's rest mass is converted into the electron's kinetic energy. The experiments therefore focus on the near endpoint region of maximal electron energy where Standard Model (SM) backgrounds are highly suppressed. Unfortunately, the same kinematic suppression applies to almost *any* process other than $\mu \to e$, making searches for additional BSM decays using the high energy region datasets at Mu2e and COMET extremely challenging [23, 24].

Signal yields improve dramatically for many BSM scenarios in the regime of electron energy that is kinematically allowed for a free muon decay at rest. In this regime any particle lighter than the muon's mass can be produced and discovered with indirect search techniques. The simplest scenario to test is the two-body decay $\mu^+ \to e^+ X$. The positively charged muon will decay at rest resulting in a mono-energetic positron signal. Fortuitously, both Mu2e and COMET plan to collect substantial μ^+ datasets, prior to data taking in the high energy window relevant for $\mu \to e$, in order to test the detector responses. These datasets can also be used to search for light new physics.

The project will provide theoretical support to estimate the ability of $\mu \to e$ facilities to probe, or discover, new physics with their detector validation datasets [25]. In particular, a dedicated run with μ^+, collecting data below the Michel edge $E_e \lesssim 52$ MeV, allows a bump hunt in the observed e^+ spectrum searching for two-body decays $\mu^+ \to e^+ X$ or $\pi^+ \to e^+ X$, with X a light new physics particle. Mu2e can potentially explore new parameter space beyond present astrophysical and laboratory constraints for a set of well motivated models including: axion like particles with flavor violating couplings ($\mu^+ \to e^+ a$), massive Z' bosons ($\mu^+ \to Z' e^+$), and heavy neutral leptons ($\pi^+ \to e^+ N$). This effort involves theory collaborators R. Plestid and J. Zupan, and experimentalists S. Huang, D. Koltick and P. Murat.