Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays

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A. Aguilar-Arevalo[1], D. Bryman[2,3], S. Chen[4], V. Cirigliano[5], A. Crivellin[6,7,8], S. Cuen-Rochin[9], A. Czarnecki[10], L. Doria[11], A. Garcia[12], L. Gibbons[13], C. Glaser[14], M. Gorchtein[11], T. Gorringe[15], D. Hertzog[12], Z. Hodge[12], M. Hoferichter[16], T. Iwamoto[17], P. Kammel[12], J. Kaspar[12], K. Labe[13], J. Labounty[12], S. Ito[18], W. Marciano[19], S. Mihara[20], R. Mischke[3], T. Mori[17], T. Numao[3], W. Ootani[17], C. Ortega Hernandez[1], D. Pocanic[14], D. Salvat[21], T. Sullivan[22]

[1]Universidad Nacional Autonoma de Mexico, [2]University of British Columbia, [3]TRIUMF, [4]Tsinghua University, [5]Los Alamos National Laboratory, [6]Paul Scherrer Institute, [7]University of Zurich, [8]CERN, [9]Universidad Autonoma de Sinaloa, [10]University of Alberta,[11]University of Mainz, [12]University of Washington, [13]Cornell University, [14]University of Virginia, [15]University of Kentucky, [16]University of Bern, [17]University of Tokyo, [18]Okayama University,[19]Brookhaven National Laboratory, [20]KEK, [21]Indiana University, [22]University of Victoria

Abstract

We describe the physics motivation and concept of a next-generation experiment to measure the charged-pion branching ratio to electrons vs. muons, $R_{e/\mu}$, which is extremely sensitive to new physics at high mass scales. The proposed detector system will also measure pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$, and other rare decays to high precision. Order of magnitude improvements in sensitivity to these reactions will probe lepton universality at an unprecedented level, determine V_{ud} in a theoretically pristine manner and test CKM unitarity at the quantum loop level.

The branching ratio $R_{e/\mu}$

The branching ratio $R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu(\gamma)\right)}$ for pion decays to electrons provides the best test of $e-\mu$ universality in charged-current weak interactions. In the standard model (SM), $R_{e/\mu}$ has been calculated with extraordinary precision at the 10^{-4} level as

$$R_{e/\mu}\ (\text{SM}) = (1.2352 \pm 0.0002) \times 10^{-4}\ [1,2],$$

perhaps the most precisely calculated weak interaction observable involving quarks. Because the uncertainty of the SM calculation for $R_{e/\mu}$ is very small and the decay $\pi^+ \to e^+ \nu$ is helicity-suppressed by the V–A structure of charged currents, $R_{e/\mu}$ is extremely sensitive to the presence of pseudo-scalar (and scalar) couplings absent from the SM; a measurement in disagreement with the theoretical expectation would imply the existence of new physics beyond the SM. With measurements of 0.01 % experimental precision, new physics beyond the SM up to the mass scale of 3000 TeV may be accessed by a deviation from the precise SM expectation [2]. Possible sources of deviation include new interactions involving scalar particles like Majorons [3], charged Higgs particles, and leptoquarks [4]. Supersymmetry models with and without R-parity violation [5] or with lepton flavor violating terms [6] could also cause deviations from the SM prediction. Other new physics effects which could modify $R_{e/\mu}$ include massive sterile neutrinos [7] and dark sector processes such as $\pi^+ \to e^+ \nu$ X [8] which are also sought in the PIENU experiments [9].

Contact: David W. Hertzog; hertzog@uw.edu

Currently, the most accurate measurement reported,

$$R_{e/\mu}\ (\mathrm{Expt}) = (1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})) \times 10^{-4}\ [10],$$

is at the 0.2% level of precision. It corresponds to a test of $e-\mu$ universality $g_e/g_\mu = 0.9996 \pm 0.0012$, expressed as the ratio of potentially distinct weak couplings for the electron and muon. The result is in excellent agreement with the SM expectation. The goals of the present TRIUMF PIENU [10,11] and PSI PEN [12] experiments are to improve the measurement precision by another factor of 2 or more to a level of <0.1%. However, even if these goals are realized, this still leaves room for experimental improvement by more than an order of magnitude in uncertainty to confront the SM prediction and to search for BSM effects. The goal of a future experiment discussed below would be a further improvement in precision by an order of magnitude to 0.01%, making the experimental uncertainty comparable to the theoretical uncertainty.

Precision frontier experiments require very high statistics as well as extensive evaluation of systematic uncertainties, backgrounds, and biases and distortions in the data selection criteria. The current generation high-precision measurements of $R_{e/\mu}$ at TRIUMF [10,11] and PSI [12] were performed using stopped pions with crystal calorimeters measuring the ratio of positrons from direct $\pi^+ \rightarrow e^+\nu$ decays and the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$. The decay channels are distinguished by their positron energy distributions (monoenergetic for $\pi^+ \rightarrow e^+\nu$ and the Michel spectrum for $\pi^+ \rightarrow \mu^+ \rightarrow e^+$) and by their distinct timing distributions (26 ns pion lifetime and 2.2 μs muon lifetime). By measuring the ratio of positrons detected from the two channels, this technique eliminates first-order acceptance and particle identification uncertainties aiding in reaching high precision. The use of total absorption calorimeters for energy measurements complements the theoretical predictions, which include radiative effects (i.e., $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow e^+\nu\gamma$ decays).

The TRIUMF PIENU experiment used a high resolution (1%) crystal calorimeter (NaI(Tl) and pure CsI) [9,11] and recorded 10^7 $\pi^+ \rightarrow e^+\nu$ events. The PEN experiment at PSI used a large-acceptance highly segmented pure CsI calorimeter. Both experiments are limited by systematic uncertainties related to knowledge of detector response, particularly the line shape for $\pi^+ \rightarrow e^+\nu$ peak events, trigger and other efficiencies, and pulse pile-up effects. To reach 0.01% precision, two orders of magnitude improvement in statistics will be required along with a reduction in overall systematic uncertainties by one order of magnitude.

The new measurement of $R_{e/\mu}$ would build on the techniques refined in the previous experiments with high energy resolution like TRIUMF PIENU and high acceptance for positrons and gammas like PSI PEN. The concept for the new experiment, PIENUXe (Fig. 1), is based on a nearly 4π solid angle liquid xenon (LXe) scintillating calorimeter for detection of positrons and gammas from pion decays. A 25-30 X_0 thick LXe scintillation calorimeter read out with fast-digitized SiPMs has extraordinary properties including high light output (65k photons per MeV deposit), fast timing (~ ns decay time), and near complete containment of EM showers, making it suitable for this application. Based on experience with the MEG LXe photon calorimeter [13] it is reasonable to expect 1-2% energy resolution (comparable to [10]), 50 ps timing resolution, and transverse (depth) position resolution of 5 mm (6 mm). Other features of the setup include Si strip or pixel charged particle tracking, active tracking pion beam and stopping target detection, and pipelined high speed data acquisition.

Due to the fast scintillation response of LXe (orders of magnitude faster than the NaI(Tl) and pure CsI used in [9] and [12]), a low-energy pion beam rate of 10^5 Hz can be used, more than an order of magnitude greater than previous experiments, which were impacted by pulse pile-up effects. Systematic effects would be reduced due to the highly uniform response and depth of the total absorption LXe calorimeter. For example, Fig. 2 shows energy deposited for a 28 X_0 LXe detector compared to a 12 X_0 pure CsI detector (PEN), and the two orders of magnitude potential improvement in determination of the "tail" region-of-interest, a key systematic uncertainty. This calorimeter concept will lead to improved simulations and calibrations, and detailed studies of photo-nuclear and radiative effects.

It is estimated that 2×10^8 $\pi^+ \rightarrow e^+\nu$ events can be collected in one year of operation, satisfying the statistics goal. In addition to improvements in the precision of the PIENU branching ratio, orders of magnitude improvements would be anticipated in sensitivity to sterile neutrinos in decays

$\pi^+ \to e^+ / \mu^+ \nu_H$ and to decays involving dark sector particles like $\pi^+ \to e^+ / \mu^+ \nu$ X.

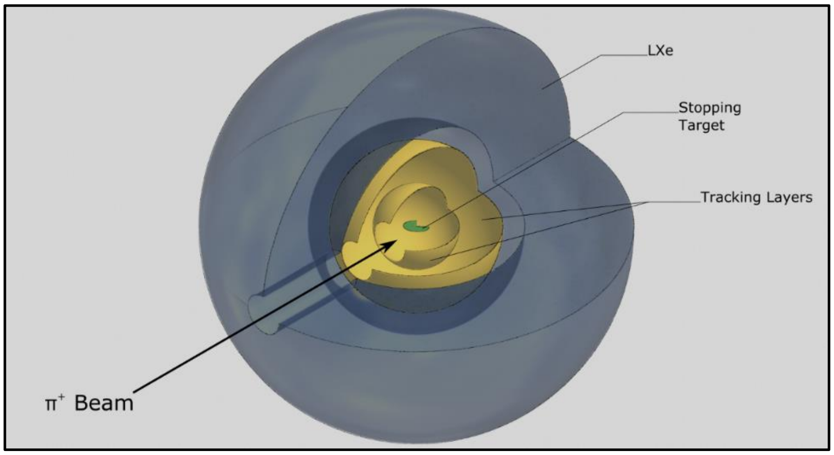

Figure 1. Schematic of a conceptual PIENUXe setup. The beam is stopped in a pixelated, active stopping target surrounded by two thin silicon tracking layers. The entire experiment is enveloped by a liquid xenon electromagnetic calorimeter readout by silicon photo-multipliers.

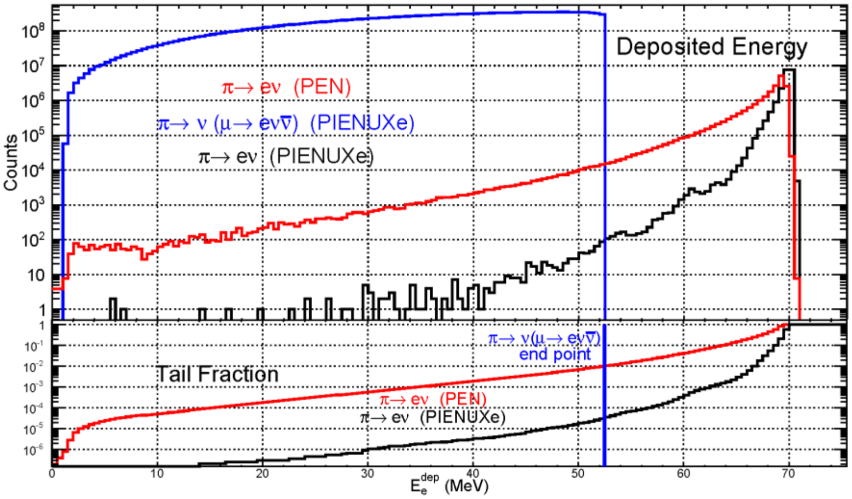

Figure 2. Upper plot: histogram of E_e^{dep}, the π_{e2} positron energy deposited in active components for a proposed 28 X_0 thick spherical LXe concept detector (black), compared with the same for the 12 X_0 pure CsI PEN apparatus (red), along with energy deposition for the background $\pi \to \mu \to e$ decay chain events (blue). Lower plot: comparison of the corresponding "tail" fractions as a function of E_e^{dep}; the LXe concept detector improves on the PEN fraction by two orders of magnitude in the region of interest.

Pion Beta Decay

The detector optimized for a next-gen $R_{e/\mu}$ experiment will also be ideally suited for a high-precision measurement of pion beta decay. Precision measurements of beta decays of neutrons, nuclei, and mesons provide very accurate determinations of the elements $|V_{ud}|$ and $|V_{us}|$ of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [14,15]. Recent theoretical developments on radiative corrections and form factors have led to a 3-5σ tension with CKM unitarity (Fig. 3) which, if confirmed, would point to new physics in the multi-TeV scale (e.g, see Ref. [16] and references therein). Pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ provides the theoretically cleanest determination of the CKM matrix element V_{ud}. With current input one obtains V_{ud} = $0.9739(28)_{\text{exp}}(1)_{\text{th}}$, where the experimental uncertainty comes almost entirely from the BR [17] (pion lifetime contributes δV_{ud} = 0.0001) and the theory uncertainty has been reduced from δV_{ud} = 0.0005

[18-20] to δV_{ud} = 0.0001 via a lattice QCD calculation of the radiative corrections [21]. The current precision of 0.3% on V_{ud} makes $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ irrelevant for the CKM unitarity tests, because super-allowed nuclear beta decays provide a nominal precision of 0.015%. In order to make $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ relevant to CKM unitarity tests, two precision targets can be identified:

(i) As advocated in Ref. [16], a three-fold improvement in BR precision compared to [17] would allow for a 0.2% determination of V_{us}/V_{ud} via the ratio

$$R_V = \Gamma\big(K \to \pi l \nu(\gamma)\big)/\Gamma\big(\pi^+ \to \pi^0 e^+ \nu(\gamma)\big),$$

independent of the Fermi constant, short-distance and structure-dependent radiative corrections. This would match the precision of the current extraction of V_{us}/V_{ud} from the axial channels [22] via $R_A = \Gamma(K \to \mu\nu(\gamma))/\Gamma\big(\pi \to \mu\nu(\gamma)\big)$ (see Fig. 3), thus providing a new competitive constraint on the $V_{us} - V_{ud}$ plane and probing new physics that might affect vector and axial channels in different ways.

(ii) A more ambitious target is an order of magnitude improvement (factor of 10 to 20) in the BR precision. This would provide the theoretically cleanest extraction of V_{ud} at the 0.02% level.

The tension in the first row CKM unitarity test in Fig. 3 can also be interpreted as a sign of lepton flavor universality violation (LFUV) [24]. In particular, assuming that this originates from modified W-ℓ-ν couplings, mainly the determination from β decays is affected, due to a CKM enhancement by, $(V_{ud}/V_{us})^2 \sim 20$. If this effect is real, and corrected for, the red bar would move to the left. Such a modification of the W-μ–ν couplings would also affect $R_{e/\mu}$. This connection provides further motivation for the current proposal, especially because the sensitivity to LFUV would be comparable to future improved constraints from β decays. Moreover, recent global fits to EW observables and tests of LFU show a preference for $R_{e/\mu}$ bigger than its SM expectation [25, 26].

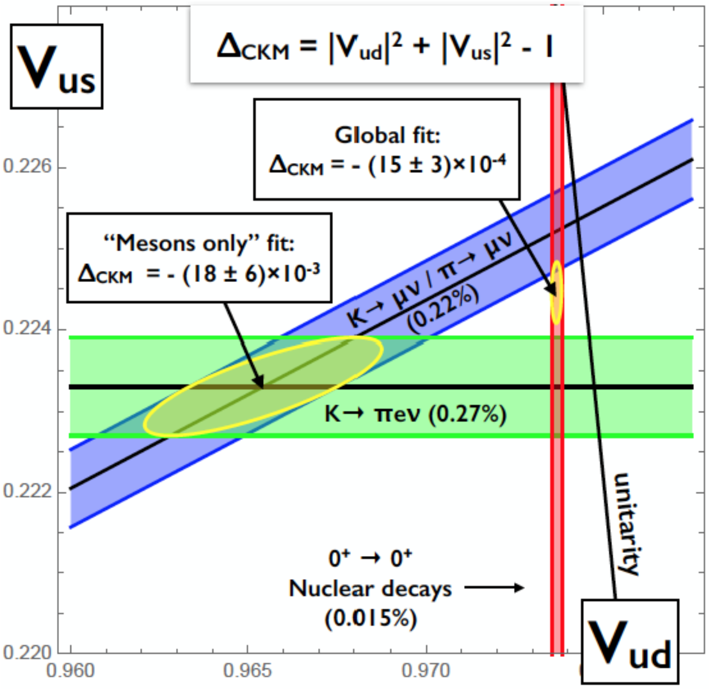

Figure 3: Existing tensions in the 1st-row CKM unitarity test [23].

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