PEN: a low energy test of lepton universality

Dinko Počanić[*,a] **L.P. Alonzi,**[a] **V.A. Baranov,**[b] **W. Bertl,**[c] **M. Bychkov,**[a]
Yu.M. Bystritsky,[b] **E. Frlež,**[a] **C.J. Glaser,**[a] **V.A. Kalinnikov,**[b] **N.V. Khomutov,**[b]
A.S. Korenchenko,[b] **S.M. Korenchenko,**[b] **M. Korolija,**[d] **T. Kozlowski,**[e] **N.P. Kravchuk,**[b]
N.A. Kuchinsky,[b] **M.C. Lehman,**[a] **D. Mzhavia,**[bf] **A. Palladino,**[ac] **P. Robmann,**[g]
A.M. Rozhdestvensky,[b] **I. Supek,**[d] **P. Truöl,**[g] **A. van der Schaaf,**[g] **E.P. Velicheva,**[b]
M.G. Vitz,[a] **V.P. Volnykh**[b]   **(The PEN Collaboration)**

[a] *University of Virginia, Charlottesville, VA 22904-4714, USA*

[b] *Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia*

[c] *Paul Scherrer Institute, Villigen-Würenlingen AG, Switzerland*

[d] *Rudjer Bošković Institute, Zagreb, Croatia*

[e] *Instytut Problemów Jądrowych im. Andrzeja Sołtana, Świerk, Poland*

[f] *Institute for High Energy Physics, Tbilisi State University, Tbilisi, Georgia*

[g] *Physik-Institut, Universität Zürich, Zürich, Switzerland*

E-mail: pocanic@virginia.edu

Allowed charged π meson decays are characterized by simple dynamics, few available decay channels, mainly into leptons, and extremely well controlled radiative and loop corrections. In that sense, pion decays represent a veritable triumph of the standard model (SM) of elementary particles and interactions. This relative theoretical simplicity makes charged pion decays a sensitive means for testing the underlying symmetries and the universality of weak fermion couplings, as well as for studying pion structure and chiral dynamics. Even after considerable recent improvements, experimental precision is lagging far behind that of the theoretical description for pion decays. We review the current state of experimental study of the pion electronic decay $\pi^+ \to e^+ \nu_e(\gamma)$, or $\pi_{e2(\gamma)}$, where the (γ) indicates inclusion and explicit treatment of radiative decay events. We briefly review the limits on non-SM processes arising from the present level of experimental precision in $\pi_{e2(\gamma)}$ decays. Focusing on the PEN experiment at the Paul Scherrer Institute (PSI), Switzerland, we examine the prospects for further improvement in the near term.

XIII International Conference on Heavy Quarks and Leptons
22-27 May 2016
Blacksburg, Virginia, USA

---

[*]Speaker.

1. Motivation

π mesons (pions), the lightest hadrons, occupy a special place for both the weak and the strong interactions, and remain subjects of study almost 70 years after their discovery [1]. Charged pion decays have provided an important early testing ground for the weak interaction and radiative corrections during the development of modern particle theory. Decays of the charged pion proceed via the weak interaction, strongly reflecting the properties and dynamics of the latter. In particular, the failure of early searches to observe the direct electronic decay of the pion ($\pi \to e\nu$, or π_{e2}) led to an intense examination of the nature of the weak interaction. A low branching fraction of $\sim 1.3 \times 10^{-4}$ was predicted [2] even before the decay's discovery [3]. It is a direct consequence of the $V-A$ nature of the weak interaction, through helicity suppression of the right-handed state of the electron. Furthermore, the predicted radiative corrections for the π_{e2} decay [4, 5] received quick experimental confirmation [6, 7].

Pion decays have more recently been described with extraordinary theoretical precision. Thanks to the underlying symmetries and the associated conservation laws, the more complicated, and thus more uncertain, hadronic processes are suppressed. If the experimental results reach a precision comparable to that of their theoretical description, pion decays offer an outstanding, clean testing ground of universality of lepton and quark couplings. A statistically significant deviation from the standard model expectations would indicate the presence of processes or interactions not included in the standard model, affecting pion decays through loop diagrams.

1.1 The electronic decay, $\pi^+ \to e^+ \nu_e$ (or π_{e2})

The $\pi^- \to \ell \bar{\nu}_\ell$ (or, $\pi^+ \to \bar{\ell} \nu_\ell$) decay connects a pseudoscalar 0^- state (the pion) to the 0^+ vacuum. At the tree level, the ratio of the $\pi \to e\bar{\nu}$ to $\pi \to \mu\bar{\nu}$ decay widths is given by [2, 8]

$$R^\pi_{e/\mu,0} \equiv \frac{\Gamma(\pi \to e\bar{\nu})}{\Gamma(\pi \to \mu\bar{\nu})} = \frac{m_e^2}{m_\mu^2} \cdot \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2} \simeq 1.283 \times 10^{-4}. \tag{1.1}$$

The first factor in the above expression, the ratio of squared lepton masses for the two decays, comes from the helicity suppression by the $V-A$ lepton-W boson weak couplings. If, instead, the decay could proceed directly through the pseudoscalar current, the ratio $R^\pi_{e/\mu}$ would reduce to the second, phase-space factor, or approximately 5.5. A more complete treatment of the process includes $\delta R^\pi_{e/\mu}$, the radiative and loop corrections, and the possibility of lepton universality violation, i.e., that g_e and g_μ, the electron and muon couplings to the W, respectively, may not be equal:

$$R^\pi_{e/\mu} \equiv \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2} \frac{m_e^2}{m_\mu^2} \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2} \left(1 + \delta R^\pi_{e/\mu}\right), \tag{1.2}$$

where the "(γ)" indicates that radiative decays are fully included in the branching fractions. Steady improvements over time of the theoretical description of the π_{e2} decay have produced greatly refined calculations of the SM prediction, culminating at the precision level of 8 parts in 10^5:

$$\left(R^\pi_{e/\mu}\right)^{SM} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\bigg|_{calc} = \begin{cases} 1.2352(5) \times 10^{-4} & [9], \\ 1.2354(2) \times 10^{-4} & [10], \\ 1.2352(1) \times 10^{-4} & [11]. \end{cases} \tag{1.3}$$

Comparison with equation (1.1) indicates that the radiative and loop corrections amount to almost 4% of $R^\pi_{e/\mu}$. The current experimental precision lags behind the above theoretical uncertainties by a factor of ~ 23:

$$\left(R^\pi_{e/\mu}\right)^{\text{exp}} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\bigg|_{\text{exp}} = (1.2327 \pm 0.0023) \times 10^{-4}, \tag{1.4}$$

dominated by measurements from TRIUMF and PSI [12–15].

Because of the large helicity suppression of the π_{e2} decay, its branching ratio is highly susceptible to small non-$V-A$ contributions from new physics, making this decay a particularly suitable subject of study, as discussed in, e.g., Refs. [16–21]. This prospect provides the primary motivation for the ongoing PEN [22] and PiENu [23] experiments. Of all the possible "new physics" contributions in the Lagrangian, π_{e2} is directly sensitive to the pseudoscalar one, while other types enter through loop diagrams. At the precision of 10^{-3}, $R^\pi_{e/\mu}$ probes the pseudoscalar and axial vector mass scales up to 1,000 TeV and 20 TeV, respectively [20, 21]. For comparison, unitarity tests of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and precise measurements of several superallowed nuclear beta decays constrain the non-SM vector contributions to > 20 TeV, and scalar ones to > 10 TeV [24]. Although scalar interactions do not directly contribute to $R^\pi_{e/\mu}$, they can do so through loop diagrams, resulting in a sensitivity to new scalar interactions up to 60 TeV [20,21]. The subject was recently reviewed at length in Ref. [25]. In addition, $(R^\pi_{e/\mu})^{\text{exp}}$ provides limits on the masses of certain SUSY partners [19], and on anomalies in the neutrino sector [18].

1.2 Radiative electronic decay $\pi \to e\nu\gamma$ (or $\pi_{e2\gamma}$)

It is impossible to discuss the π_{e2} electronic decay without taking into account its radiative variant that becomes indistinguishable in the infrared limit $E_\gamma \to 0$. The decay $\pi^+ \to e^+\nu_e\gamma$ proceeds via a combination of QED (inner bremsstrahlung, *IB*) and direct, structure-dependent (*SD*) amplitudes [8, 26]. Under normal circumstances, as in the $\pi \to \mu\nu\gamma$ decay, the direct amplitudes are hopelessly buried under an overwhelming inner bremsstrahlung background. However, the strong helicity suppression of the primary non-radiative process, $\pi \to e\nu$, also suppresses the bremsstrahlung terms, making the direct structure dependent amplitudes measurable in certain regions of phase space [26, 27]. (The same helicity suppression makes sensitive searches for non-$V-A$ interaction terms possible in precision measurements of the primary $\pi \to e\nu$ decay, as discussed above.) The relative accessibility of hadronic structure amplitudes is of keen interest to effective low-energy theories of the strong interaction, primarily chiral perturbation theory (ChPT), which rely on the *SD* amplitudes to provide important input parameters. Whereas the *IB* amplitude is completely described by QED, the structure-dependent amplitude can be parametrized in terms of the pion form factors. As seen in the tree-level Feynman diagrams in Figure 1, standard $V-A$ electroweak theory requires only two pion form factors, F_A, axial vector, and F_V, vector (or polar-vector), to describe the *SD* amplitude. Thus, a proper experimental description of the $\pi_{e2\gamma}$ decay serves several important goals: (a) improving the accuracy of low energy effective hadronic theories, such as ChPT, (b) enabling a precise determination of the primary π_{e2} decay rate by controlling the systematics of the radiative decay event subset, and (c) providing the opportunity to search for evidence of new particles with of non-SM coupling, such as a putative tensor-interacting
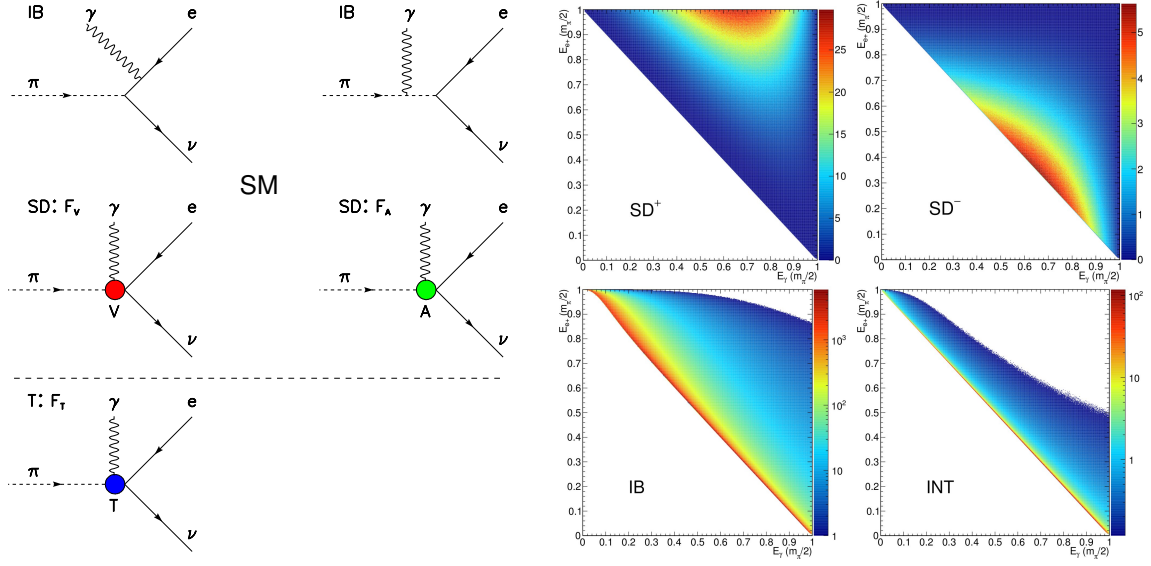
Figure 1: *Left:* tree-level Feynman diagrams of the inner bremsstrahlung (*IB*) and structure-dependent (*SD*) amplitudes determined by the vector and axial-vector form factors, F_V and F_A, respectively. A new interaction type, e.g.,s one mediated by a hypothetical tensor particle discussed in the literature throughout the 1990s and 2000s [28], would add an *SD* amplitude defined by a corresponding form factor, F_T. *Right:* relative strengths of the physics amplitudes in $\pi \to e\nu\gamma$ decay: structure-dependent amplitudes $SD^+ \propto (F_V + F_A)^2$ and $SD^- \propto (F_V - F_A)^2$, inner bremsstrahlung *IB*, and interference $INT \propto (F_V + F_A)S_{int}^+ + (F_V - F_A)S_{int}^-$, plotted as functions of E_γ and E_e.

boson [28] to which the primary, π_{e2} decay process is not sensitive. A recent review of the subject can be found in [29].

The most comprehensive study to date of the $\pi_{e2\gamma}$ decay has been performed by the PIBETA collaboration [30]. This work has provided a narrow constraint on the sum $F_V + F_A$ of the vector and axial vector form factors of the pion, a sub-percent precision measurement of the branching fraction for $E_\gamma > 10\,\text{MeV}$ and $\theta_{e\gamma} > 40°$, as well as a stringent upper bound on F_T, the tensor form factor, previously the subject of considerable controversy [29]. In addition to determining F_V and F_A individually with greatly increased precision compared to previous measurements, the PIBETA collaboration also evaluated, for the first time, the F_V dependence on $q_{e\nu}$, the e^+-ν_e invariant mass. In fact, the PIBETA limit on F_T provides the most stringent constraint on the strength of the tensor weak interaction [31], assumed to be zero in the SM.

The PEN experiment [22], discussed in more detail below, builds on the methods, results and accomplishments of the PIBETA collaboration.

2. The PEN experiment at PSI

In 2006 a new measurement of $R^{\pi}_{e/\mu}$ was proposed at the Paul Scherrer Institute by a collaboration of seven institutions from the US and Europe [22], with the aim to reach

$$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 5 \times 10^{-4}\,. \tag{2.1}$$
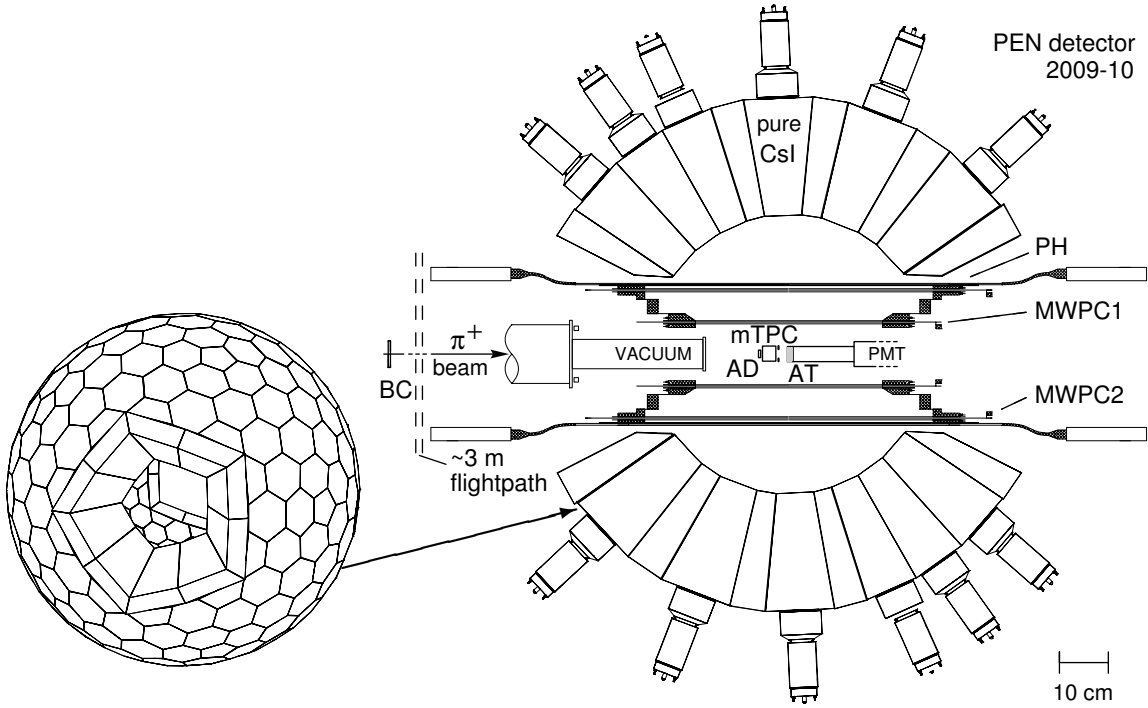
Figure 2: Schematic cross section of the PEN apparatus, shown in the 2009-10 running configuration, with its main components: beam entry with the upstream beam counter (BC), 5 mm thick active degrader (AD), mini time projection chamber (mTPC) followed by a passive Al collimator, and active target (AT), cylindrical multiwire proportional chambers (MWPCs), plastic hodoscope (PH) detectors and photomultiplier tubes (PMTs), 240-element pure CsI electromagnetic shower calorimeter and its PMTs. BC, AD, AT and PH detectors are made of plastic scintillator. For details concerning the detector performance see [32].

The target precision of PEN falls short of matching the theoretical uncertainties given in equation 1.3, by a factor of about 6. Nevertheless, PEN's target uncertainties will considerably expand the mapped area of non-SM parameter space, as discussed in Section 1.1. PEN has acquired data in three runs, in 2008, 2009 and 2010.

2.1 PEN apparatus and measurement method

The PEN experiment uses the key components of the PIBETA apparatus with additions and modifications suitable for a dedicated study of the π_{e2} and $\pi_{e2\gamma}$ decay processes. The PIBETA detector has been described in detail in [32], and used in a series of measurements of rare allowed pion and muon decay channels [29, 30, 33, 34]. The major component of the PEN apparatus, shown in Figure 2, is a spherical large-acceptance ($\sim 3\pi$ sr) electromagnetic shower calorimeter. The calorimeter consists of 240 truncated hexagonal and pentagonal pyramids of pure CsI, 22 cm or 12 radiation lengths deep. The inner and outer diameters of the sphere are 52 cm and 96 cm, respectively. Beam particles entering the apparatus with $p \simeq 75$ MeV/c are first tagged in a thin upstream beam counter (BC) and refocused by a triplet of quadrupole magnets. After a ~ 3 m long flight path they pass through a 5 mm thick active degrader (AD) and a low-mass mini time projection chamber (mTPC), finally to reach a 15 mm thick active target (AT) where the beam pions stop. Decay particles are tracked non-magnetically in a pair of concentric cylindrical multiwire

proportional chambers (MWPC1,2) and an array of twenty 4 mm thick plastic hodoscope detectors (PH), all surrounding the active target. The BC, AD, AT and PH detectors are all made of fast plastic scintillator material and read out by fast photomultiplier tubes (PMTs). Signals from the beam detectors are sent to waveform digitizers, running at 2 GS/s for BC, AD, and AT, and at 250 MS/s for the mTPC.

2.2 PEN data and their analysis

Measurements of pion decay at rest, such as the one made with the PEN detector, must deal with the challenge of separating the $\pi \to e\nu$ and $\pi \to \mu \to e$ events with great confidence. Hence, as in earlier π_{e2} studies at rest, a key source of systematic uncertainty in PEN is the hard to measure low energy tail of the detector response function. The tail is caused by electromagnetic shower leakage from the calorimeter, mostly in the form of photons. If not properly identified and suppressed, other physical processes contribute events to the low energy part of the spectrum; unlike shower leakage they can also produce high energy events. One process is the ordinary pion decay into a muon in flight, before the pion is stopped, with the resulting muon decaying within the time gate accepted in the measurement. Another is the unavoidable physical process of radiative decay. The latter is well measured and properly accounted for in the PEN apparatus, as in the PIBETA studies of [30, 34]. Shower leakage and pion decays in flight can only be well characterized if the $\pi \to \mu \to e$ chain can be well separated from the direct $\pi \to e$ decay in the target. Therefore much effort has been devoted to digitization, filtering and analysis of the target waveforms [35], as illustrated in Figure 3. The method used to separate the 2-peak (π_{e2}) and 3-peak ($\pi \to \mu \to e$) events is illustrated and explained in Figure 4. The input is provided by the beam and MWPC detectors, used to predict the pion and positron energy depositions in the target, and the times of
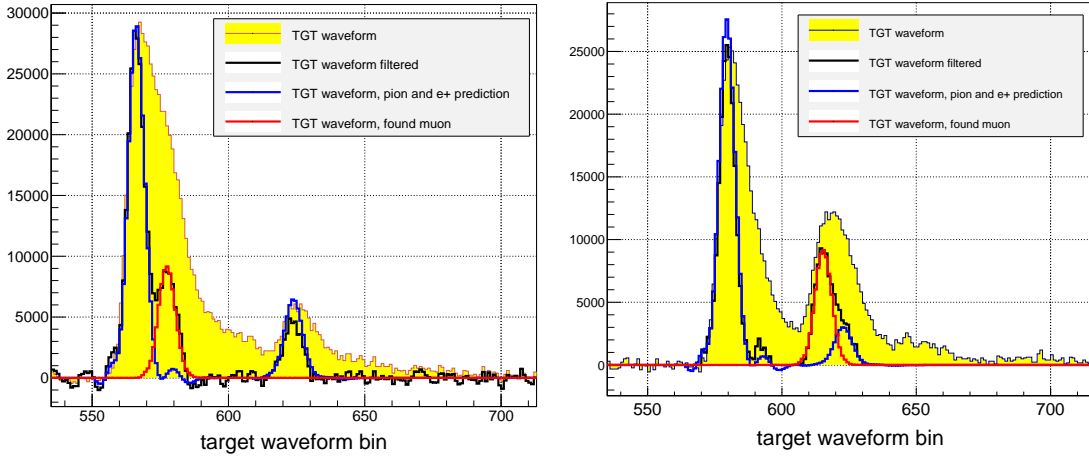
Figure 3: Full and filtered active target (TGT) waveform in the PEN experiment for two challenging $\pi \to \mu \to e$ sequential decay events with an early $\pi \to \mu$ decay (left) and early $\mu \to e$ decay (right). The filtering procedure consists of a simple algebraic manipulation of the signal. To the naked eye both raw waveforms appear to have two peaks only. The separation of events with/without a muon signal depends critically on the accuracy of the predictions for the pion and positron signals. For the pion the prediction is based on the times and energies observed in BC and AD. For the positron the prediction depends on the PH timing and on the pathlength reconstructed with the pion and positron tracking detectors (see Figure 4).
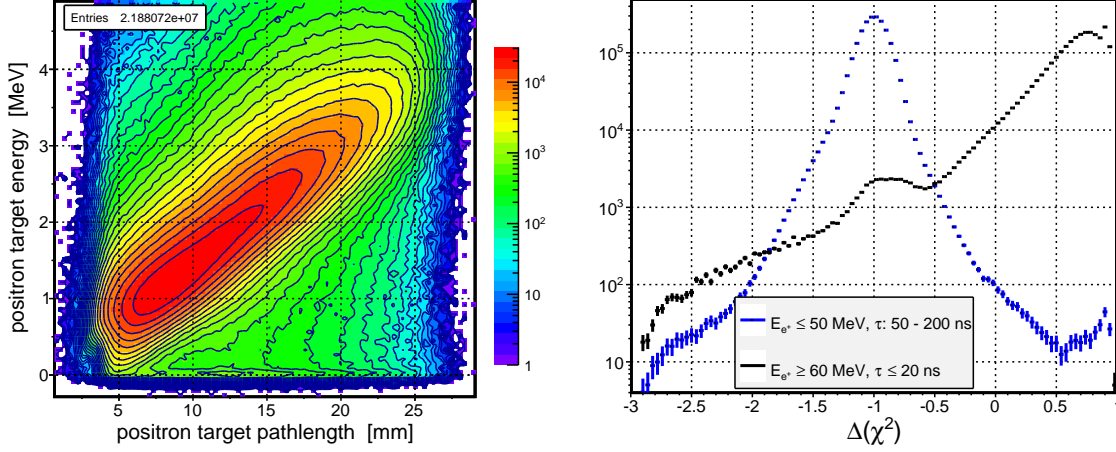
Figure 4: *Left:* correlation between observed positron energy in the target waveform and the e^+ path length in the target, reconstructed from the observed π^+ and e^+ trajectories. Shown are events with proper $\pi \to \mu \to e$ sequences for which the e^+ signal is well separated from other signals. *Right:* difference in χ^2 for the assumptions of a target waveform with/without a muon pulse present. The observable is normalized such that $\pi \to e\nu$ events peak at $+1$, and $\pi \to \mu \to e$ at -1. Shown are events for two different combinations of e^+ energy and decay time resulting in almost pure samples of $\pi \to e\nu$ and $\pi \to \mu \to e$, respectively. Tiny admixtures of the other, suppressed process are readily identified and are of considerable help in reducing the systematic uncertainties.

their respective signals. Once the predicted waveform is subtracted, the remaining net waveform is scanned for the presence of a 4.1 MeV muon peak. The difference between the minimum χ^2 values with and without the muon peak is reported as $\Delta(\chi^2)$, constructed so that clean 2-peak and 3-peak fits return values of $+1$ and -1, respectively. The scan is fast and returns a $\Delta(\chi^2)$ value for every event, as illustrated in the figure.

A particularly telling figure regarding the PEN data quality is the decay time comparison of the $\pi \to e\nu$ decay and $\pi \to \mu \to e$ sequence, shown in Figure 5 for a subset of data recorded in 2010. The $\pi \to e\nu$ data follow the exponential decay law over more than three orders of magnitude, and perfectly predict the measured $\pi \to \mu \to e$ sequential decay data once the latter are corrected for random (pile-up) events. Both event ensembles were obtained with minimal requirements (cuts) on detector observables, none of which biases the selection in ways that would affect the branching ratio. The probability of random $\mu \to e$ events originating in the target can be controlled in the data sample by making use of multihit time to digital converter (TDC) data that record past pion stop signals. With this information one can strongly suppress events in which an "old" muon was present ("piled up") in the target by the time of the pion stop that triggered the readout.

The "intrinsic" low energy tail of the PEN response function below ~ 50 MeV, due to shower losses for π_{e2} decay events for pions at rest, amounts to approximately 2% of the full yield. Events with $\pi \to \mu$ decays in flight, with subsequent ordinary Michel decay of the stopped muon in the target, add a comparable contribution to the tail. The two contributions can be simulated accurately, with the respective detector responses independently verified through comparisons with measured data in appropriately selected processes and regions of phase space. Although verified through comparisons with Monte Carlo simulations, the intrinsic tail itself is not directly measurable at the
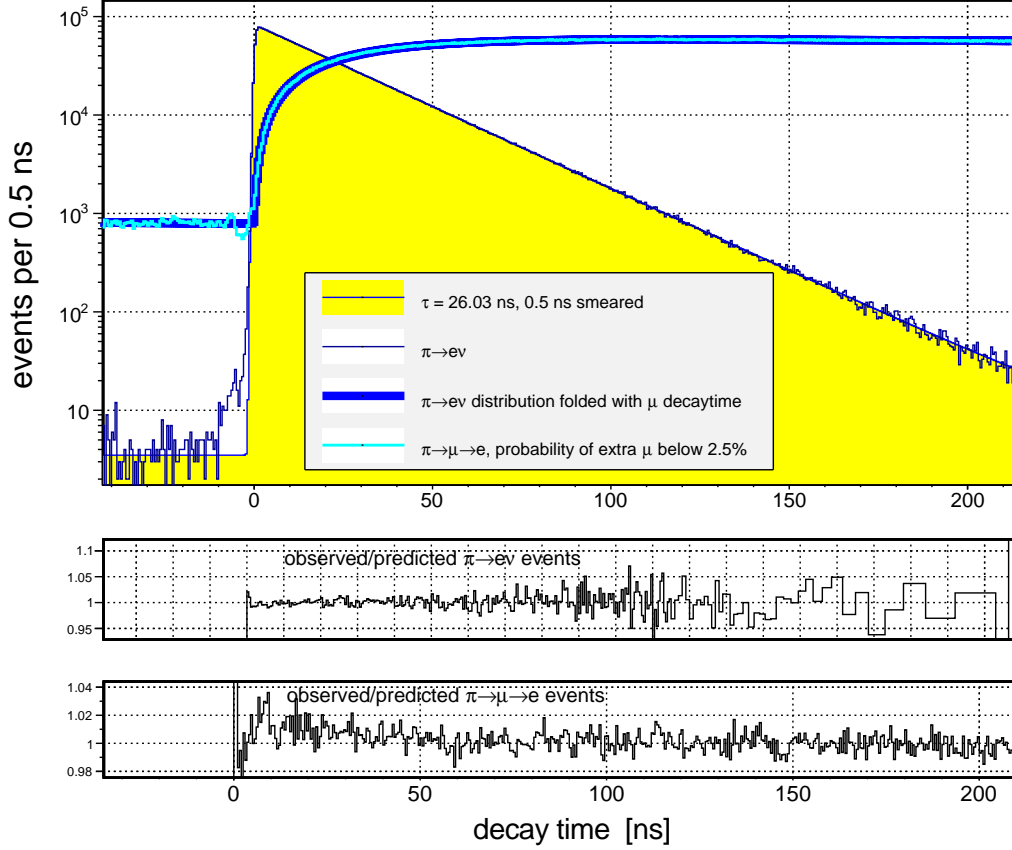
Figure 5: Decay time histograms for a subset of 2010 PEN data: $\pi \to e\nu$ events and $\pi \to \mu \to e$ sequential decay events. The two processes are distinguished primarily by the total e^+ energy and by the absence or presence, respectively, of an extra 4.1 MeV (muon) in the target due to a $\pi \to \mu$ decay. The π_{e2} data are shown with a pion lifetime $\tau_\pi = 26.03$ ns exponential decay function superimposed. The $\pi \to \mu \to e$ data were prescaled by a factor of $\sim 1/64$; they are shown with the cut on the probability of $< 2.5\%$ for a second, pile-up muon to be present in the target at $t = 0$, the time of the nominal pion stop. The turquoise histogram gives the $\pi \to \mu \to e$ yield constructed entirely from the measured $\pi \to e\nu$ data folded with the μ decay rate, and corrected for random muons; it perfectly matches the bold dark blue histogram. The two lower plots show the observed to predicted ratios for π_{e2} and $\pi \to \mu \to e$ events, respectively. The scatter in the ratio plots is statistical in nature.

required precision because of the statistical uncertainties arising in the tail data selection procedure. Radiative decay processes are directly measurable and accounted for in the branching fraction data analysis. More information about the PEN/PIBETA detector response functions is given in [32].

We next turn our attention to the strongly radiative decay events, i.e., those with energetic photons that lead to clearly separated e^+ and γ initiated showers in the PEN CsI calorimeter. The PEN collaboration has recorded a substantial new data set of such events, to be added to the previously recorded PIBETA $\pi_{e2\gamma}$ data set. Since the PEN beam stopping rate is lower than that used in the cleanest, 2004 PIBETA run, the impact on the statistical uncertainties, while significant, will not be profound. However, the cleaner running conditions of PEN allow for easier access to the kinematic region $E_\gamma, E_e < 50$ MeV, previously strongly contaminated by the muon decay background. These

are the regions needed to probe the SD^- amplitude critically, as seen in Figure 1. Accessing SD^- opens the prospects for a new determination of the quantity $F_V - F_A$, poorly constrained in the main PIBETA result [30], and, hence, for an improved model-independent experimental determination of F_V. These results will be forthcoming in the near future.

3. Conclusions

During the three production runs, from 2008 to 2010, the PEN experiment accumulated some 2.3×10^7 $\pi \to e\nu$, and more than 1.5×10^8 $\pi \to \mu \to e$ events, as well as significant numbers of pion and muon radiative decays. A comprehensive blinded analysis is under way to extract a new experimental value of $R^\pi_{e/\mu}$. As of this writing, there appear to be no obstacles that would prevent the PEN collaboration from reaching a precision of $\Delta R/R < 10^{-3}$. The competing PiENu experiment at TRIUMF [23] has a similar precision goal. The near to medium future will thus bring about a substantial improvement in the limits on e-μ lepton universality, and in the related limits on non-SM, non-$V-A$ processes and couplings.

It is important to note that even subsequent to the completion of the PEN and PiENu data analyses, there will remain considerable room for improvement of experimental precision with high payoff in terms of limits on physics not included in the present Standard Model. If fully successful, the current experiments will bridge the current gap between the experimental and theoretical uncertainty levels only half-way, leaving room for new experiments. Furthermore, this work remains relevant and complementary to the direct searches on the energy frontier currently underway at particle colliders, providing valuable theoretical cross checks.

Acknowledgments

References

[1] C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini and C.F. Powell, *Processes involving charged mesons*, *Nature* **159** (1947) 694.

[2] R.P. Feynman and M. Gell-Mann, *Theory of Fermi interaction*, *Phys. Rev.* **109** (1958) 193.

[3] T. Fazzini, G. Fidecaro, A.W. Merrison, H. Paul and A.V. Tollestrup, *Electron decay of the pion*, *Phys. Rev. Lett.* **1** (1959) 247.

[4] S.M. Berman, *Radiative corrections to pion beta decay*, *Phys. Rev. Lett.* **1** (1958) 468.

[5] T. Kinoshita, *Radiative corrections to pi-e decay*, *Phys. Rev. Lett.* **2** (1959) 477.

[6] H.L. Anderson, T. Fujii, R.H. Miller and L. Tau, *Branching ratio of the electronic mode of positive pion decay*, *Phys. Rev.* **119** (1960) 2050.

[7] E. Di Capua, R. Garland, L. Pondrom and A. Strelzoff, *Study of the decay $\pi \to e + \nu$*, *Phys. Rev.* **133** (1964) B1333.

[8] For a detailed discussion of the $\pi_{e2(\gamma)}$ decays see, e.g., D.A. Bryman, P. Depommier and C. Leroy, *$\pi \to e\nu$, $\pi \to e\nu\gamma$ decays and related processes*, *Phys. Rep.* **88** (1982) 151.

[9] W.J. Marciano and A. Sirlin, *Radiative corrections to π_{l2} decays*, *Phys. Rev. Lett.* **71** (1993) 3629.

[10] M. Finkemeier, *Radiative corrections to π_{l2} and K_{l2} decays*, *Phys. Lett. B* **387** (1996) 391 [hep-ph/9505434].

[11] V. Cirigliano and I. Rosell, *Two-loop effective theory analysis of $\pi(K) \to e\bar{\nu}_e[\gamma]$ branching ratios*, *Phys. Rev. Lett.* **99** (2007) 231801 [hep-ph/0707.3439].

[12] D.I. Britton *et al.*, *Measurement of the $\pi^+ \to e^+\nu$ branching ratio*, *Phys. Rev. Lett.* **68** (1992) 3000.

[13] D.I. Britton *et al.*, *Improved search for massive neutrinos in $\pi^+ \to e^+\nu$ decay*, *Phys. Rev. D* **46** (1992) R885.

[14] G. Czapek *et al.*, *Branching ratio for the rare pion decay into e^+ and ν_e*, *Phys. Rev. Lett.* **70** (a993) 17.

[15] A. Aguilar-Arevalo *et al.*, *Improved measurement of the $\pi \to e\nu$ branching ratio*, *Phys. Rev. Lett.* **115** (2015) 071801 [hep-ex/1506.05845].

[16] R.E. Shrock, *General theory of weak processes involving neutrinos*, *Phys. Rev. D* **24** (1981) 1232.

[17] O.U. Shanker, *$\pi_{\ell2}$, $K_{\ell3}$ and K^0–$\bar{K}^0$ constraints on leptoquarks and supersymmetric particles*, *Nucl. Phys.* **B204** (1982) 375.

[18] W. Loinaz *et al.*, *NuTeV anomaly, lepton universality, and nonuniversal neutrino-gauge couplings*, *Phys. Rev. D* **70** (2004) 113004 [hep-ph/0403306].

[19] M.J. Ramsey-Musolf, S. Su and S. Tulin, *Pion leptonic decays and supersymmetry*, *Phys. Rev. D* **76** (2007) 095017 [hep-ph/0705.0028].

[20] B.A. Campbell and D.W. Maybury, *Constraints on scalar couplings from $\pi^\pm \to \ell^\pm\nu_\ell$*, *Nucl. Phys.* **B709** (2005) 419 [hep-ph/0303046].

[21] B.A. Campbell and A. Ismail, *Leptonic pion decay and physics beyond the electroweak standard model*, hep-ph/0810.4918.

[22] http://pibeta.phys.virginia.edu, and links therein.

[23] http://pienu.triumf.ca, and links therein.

[24] K.A. Olive *et al.* (Particle Data Group), *Review of Particle Physics*, *Chin. Phys. C* **40** (2016) 100001.

[25] D.A. Bryman, W.J. Marciano, R. Tschirhart and T. Yamanaka, *Rare kaon and pion decays: Incisive probes for new physics beyond the standard model*, *Annu. Rev. Nucl. Part. Sci.* **61** (2011) 331.

[26] For a detailed discussion see, e.g., J.F. Donoghue, E. Golowich and B.R. Holstein, *Dynamics of the Standard Model*, Cambridge University Press, Cambridge 1992.

[27] A.M. Bernstein and B.R. Holstein, *Neutral pion lifetime measurements and the QCD chiral anomaly*, *Rev. Mod. Phys.* **85** (2013) 49 [hep-ph/1112.4809].

[28] M.V. Chizhov, *Discovery of new physics in radiative pion decays?*, *Pisma Fiz. Elem. Chast. Atom. Yadra* **2** (2005) no. 4, 7-16, [hep-ph/0402105], and references therein.

[29] D. Počanić, E. Frlež and A. van der Schaaf, *Experimental study of rare charged pion decays*, *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 114002 [hep-ex/1407.2865].

[30] M. Bychkov, D. Počanić, B.A. VanDevender, *et al.*, *New precise measurement of the pion weak form factors in $\pi^+ \to e^+\nu\gamma$ decay*, *Phys. Rev. Lett.* **103** (2009) 051802 [hep-ex/0804.1815].

[31] T. Bhattacharya, V. Cirigliano, S.D. Cohen, A. Filipuzzi, M. Gonzalez-Alonso, M.L. Graesser, Rajan Gupta, and Huey-Wen Lin, *Probing novel scalar and tensor interactions from (ultra)cold neutrons to the LHC*, *Phys. Rev.D* **85** (2012) 054512 [hep-ph/1110.6448].

[32] E. Frlež, D. Počanić, K. Assamagan, *et al.*, *Design, commissioning and performance of the PIBETA detector at PSI*, *Nucl. Instrum. Meth. A* **526** (2004) 300 [hep-ex/0312017].

[33] D. Počanić, E. Frlež, V.A. Baranov, *et al.*, *Precise measurement of the* $\pi^+ \to \pi^0 e^+ \nu$ *branching ratio*, *Phys. Rev. Lett.* **93** (2004) 181803 [hep-ex/0312030].

[34] E. Frlež E, D. Počanić, V.A. Baranov *et al.*, *Precise measurement of the pion axial form-factor in the* $\pi^+ \to e^+ \nu \gamma$ *decay*, *Phys. Rev. Lett.* **93** (2004) 181804.

[35] A. Palladino, *Investigating lepton universality via a measurement of the positrionic pion decay branching ratio*, PhD thesis, University of Virginia (2012), and to be published.