Journal of Physics: Conference Series **2391** (2022) 012014 doi:10.1088/1742-6596/2391/1/012014

Probing Lepton Flavor Universality with Pion Decays

Douglas Bryman

Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada V6T 1Z1

TRIUMF, Vancouver, BC, Canada V6T 2A3

E-mail: doug@triumf.ca

Abstract. Searches for violation of lepton flavor universality are topical due to hints of discrepancies with Standard Model expectations in studies involving muons, B mesons, and beta decays which may be related by tests of the unitarity of the Cabibbo-Kobayashi-Maskawa quark mixing matrix. The status and prospects of pion decay experiments which offer the most precise tests of $e-\mu$ universality are discussed.

1. Introduction

Since the Standard Model (SM) is clearly not the final word on the fundamental theory, the search for new physics effects proceeds on many fronts. New particles and interactions are being sought directly at high energy colliders and indirectly in searches using numerous techniques (see reviews in Ref. [1]). Indirect searches for violations of symmetries are among the approaches being pursued due to the potential sensitivity to high mass scales. One approximate symmetry built into the SM is lepton flavor universality (LFU). Violation of LFU (LFUV) could occur, for example, if there were interactions with different weak couplings for electrons, muons and tau leptons. LFUV can be probed through a wide range of measurements (see [2] and references therein). Experiments dealing with meson, tau, and beta decays are being pursued vigorously in light of hints of possible new flavor physics effects and the possibly related deviation in first-row unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [3, 4]. In this paper, the sensitivity of current and proposed rare pion decay measurements to LFUV and other non-SM effects will be briefly outlined.

2. Rare Pion Decays and Lepton Universality

As discussed in Ref. [2], the helicity suppressed ratio of pion decay rates

$$R^{\pi}_{e/\mu} = \Gamma[\pi \to e\bar{\nu}_e(\gamma)]/\Gamma[\pi \to \mu\bar{\nu}_\mu(\gamma)]\,, \quad (1)$$

provides the most stringent test of LFU because it can be calculated with extraordinary precision at the 10^{-4} level and can also be measured accurately. $R^{\pi}_{e/\mu}$ is a sensitive probe of non-universal corrections to W-lepton couplings especially if they generate a pseudo-scalar current or an induced scalar current [5]. The exceptionally accurate theoretical calculations of $R^{\pi}_{e/\mu}$ [6, 7, 8, 9] involve the application of chiral perturbation theory (ChPT) and include structure dependent contributions to $\pi \to \ell\bar{\nu}_\ell\gamma$ [10] which are not helicity suppressed. The SM expectation[2] is

$$R(\mathrm{SM})^{\pi}_{e/\mu} = 1.23524(15) \times 10^{-4} \tag{2}$$

where the dominant uncertainty arises from a low-energy constant in ChPT, followed by non-leading logarithmic corrections of $O(\alpha^2)$.

The most precise measurement of $R^{\pi}_{e/\mu}$ was reported by the TRIUMF PIENU experiment [11] which will be discussed below. The result, based on analysis of an initial data set, was

$$R(\mathrm{Exp})^{\pi}_{e/\mu} = (1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})) \times 10^{-4}. \tag{3}$$

The PDG [1] average including previous experiments done at TRIUMF [11, 12, 13] and PSI [14] is

$$R(\overline{\mathrm{Exp}})^{\pi}_{e/\mu} = (1.2327 \pm 0.0023) \times 10^{-4}. \tag{4}$$

The comparison between theory and experiment given in Eqs. (2) and (4) provides the most precise measure of e–μ universality. The ratio of effective couplings A_ℓ ($\ell = e, \mu$) multiplying the low-energy charged current contact interaction obtained using $R^{\pi}_{e/\mu}$ is

$$\left(\frac{A_\mu}{A_e}\right)_{R^{\pi}_{e/\mu}} = 1.0010 \pm 0.0009\,, \tag{5}$$

in excellent agreement with the SM expectation. Deviation from $A_\ell/A_{\ell'} = 1$ could be due to various mechanisms such as flavor-dependent couplings of the W-boson to the leptonic current. In the context of modified W-boson couplings, LFU tested with $R^{\pi}_{e/\mu}$ probes the couplings of a longitudinally polarized W-boson whereas purely leptonic reactions like $\tau \to \ell\nu_\tau\nu_\ell$ give comparable precision[2] on the couplings of the transversely polarized W-boson. Apparent deviations from $A_\ell/A_{\ell'} = 1$ could also be due the presence of unaccounted-for sterile neutrinos[15].

Charged μ-e universality can also be tested using similar K and W decays[2] and B decays such as $\mathrm{Br}[B \to D^*\mu\nu]/\mathrm{Br}[B \to D^*e\nu]$ [16, 17, 18]; these are interesting in light of possible anomalies in $R(D^{(*)})$=$\mathrm{Br}[B \to D^{(*)}\tau\nu_\tau]/\mathrm{Br}[B \to D^{(*)}\ell\nu_\ell]$ [19, 20, 21] , and $R(K^{(*)})$=$\mathrm{Br}[B \to K^{(*)}\mu^+\mu^-]/\mathrm{Br}[B \to K^{(*)}e^+e^-]$ [22, 23, 24] which reflect the impact of possible four-fermion operators involving leptons and heavy quarks. CKM unitarity tests which rely principally on beta decays and K decays for inputs to the extraction of V_{ud} and V_{us} may be related to LFU since calculation of V_{ud} relies on obtaining G_F from μ decay (see Refs. [4, 2] and references therein). Recently it has been pointed out [25] that V_{us}/V_{ud} can be obtained using the ratio of decay rates $R_V \equiv \Gamma(K \to \pi\ell\nu(\gamma))/\Gamma(\pi^+ \to \pi^0 e^+\nu(\gamma))$ where the uncertainty is dominated by pion beta decay which is discussed below. As illustrated in Fig. 1[2] tensions exist among current determinations of V_{us} and with overall CKM unitarity.

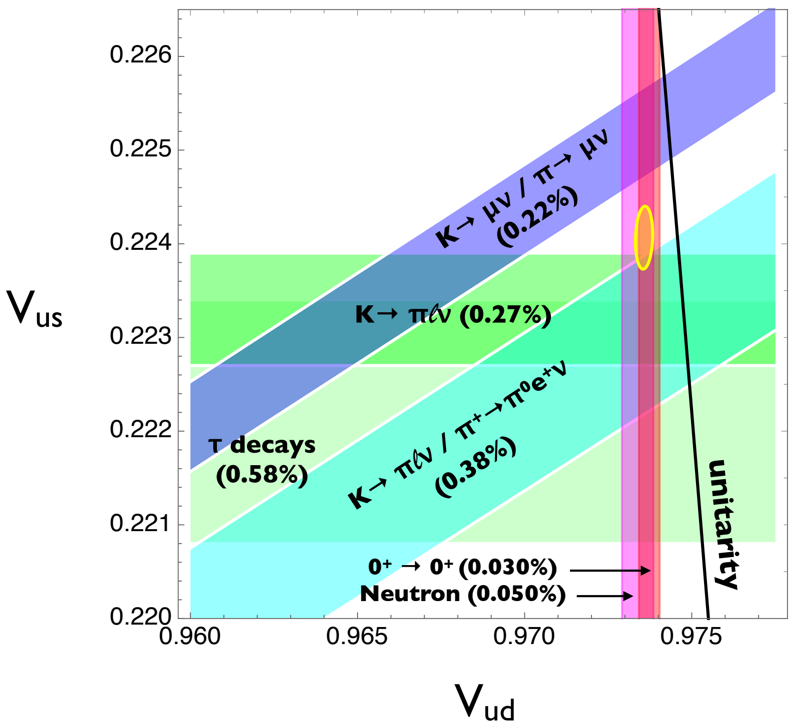

Figure 1. Summary of constraints on V_{ud} and V_{us} (assuming the Standard Model hypothesis) from nuclear, nucleon, meson, and τ lepton decays. For each constraint, the one-sigma uncertainty on V_{us} or V_{ud} is given in parenthesis (see [2] for details). The one-sigma ellipse from a global fit (with χ^2/d.o.f. = 2.8), depicted in yellow, corresponds to $V_{ud} = 0.97357(27)$ and $V_{us} = 0.22406(34)$, implying $\Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1 = (-19.5 \pm 5.3) \times 10^{-4}$. Figure reproduced from [2].

3. Rare Pion Decay Experiments

The TRIUMF PIENU experiment [11, 26] used pions stopped in plastic scintillator and measured decay positrons in a calorimeter consisting of NaI(Tl) and pure CsI crystals. The branching ratio given in Eq. 3 was obtained by separating events into high- and low-energy regions corresponding to the positron energy spectra of $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+ \to e^+$ decays. The time spectra were fit in each region with the $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+ \to e^+$ decay shapes as well as backgrounds originating from sources including pion decays in flight and pile-up contamination from decays of residual muons. The raw branching ratio $R^{raw}_{e/\mu}$ was the ratio of the $\pi^+ \to e^+\nu$ amplitude to the $\pi^+ \to \mu^+ \to e^+$ amplitude. Corrections such as the tail correction for low energy $\pi \to e\nu$ events below the $\mu \to e\bar{\nu}\nu$ spectrum, principally due to electromagnetic shower leakage, were subsequently applied to obtain the final value. PIENU and the PEN [27, 28, 29] experiment (which used a similar technique) aim to further improve the precision of the $\pi \to e\nu$ branching ratio $R^{\pi}_{e/\mu}$ using larger available data sets. However, even when these goals are realized, an experimental improvement by more than an order of magnitude in uncertainty would be valuable to confront the SM prediction (Eq. 2) and to search for non-SM effects.

The recently proposed PIONEER experiment[30] at the Paul Scherrer Institut (PSI) aims for an improvement in precision for $R^{\pi}_{e/\mu}$ by an order of magnitude making the experimental uncertainty comparable to the theoretical uncertainty in Eq. 2. To reach very high precision requires high statistics as well as reduction of systematic uncertainties, backgrounds, biases, and distortions in the data selection criteria. Like PIENU [11] and PEN [27], PIONEER will be done using stopped pions that decay at rest.

The PIONEER detector[30] is illustrated in Fig. 2. An intense pion beam is brought to rest in an instrumented target detector (ATAR) and an electromagnetic calorimeter (CALO) surrounds the stopping target. A cylindrical tracker surrounding the ATAR is used to link the locations of pions stopping in the target to showers in the calorimeter. Features of the PIONEER approach will include improved time and energy resolutions, increased calorimeter depth, high-speed detector and electronic response, large solid angle coverage, and complete event reconstruction. The proposed detector will include a 3π sr, 25 radiation length (X_0) LXe electromagnetic calorimeter, similar in concept to the MEG LXe calorimeter[31]; an alternate crystal-based calorimeter design is also under consideration. The 2×2 cm^2 ATAR is an advanced design fully active LGAD Si-strip detector[32] which will provide fine-grained position and energy-loss measurements for incoming pions, muons from pion decay, and outgoing positrons. The preliminary ATAR geometry has 48 planes, each with 100 $120\mu m$-thick strips on a pitch of $200\mu m$; planes will alternate between horizontal and vertical directions.

PIONEER aims to improve both the statistical and systematic uncertainties in the measurement of $R^{\pi}_{e/\mu}$. In particular, the ATAR particle identification and tracking capabilities will enable improved precision on the tail correction mentioned above, which was the largest source of systematic uncertainty in the PIENU measurement [11]. Figure 3(Left) shows the simulated detector response for $\mu \to e\nu\overline{\nu}$ and $\pi \to e\nu$ decays and the background-suppressed distributions (Right) used to determine the tail correction. The remaining small background is dominated by events with $\pi \to \mu$ decay at rest (DAR) followed by $\mu \to e$ decay decay in flight (DIF) before stopping; it is anticipated that this component can be independently measured. Table 1 gives the estimated uncertainties for the PIONEER measurement of $R^{\pi}_{e/\mu}$ in comparison with [11].

PIONEER also aims to improve the precision for the branching ratio of pion beta decay $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ [33] by a factor of three (ten) in the second (third) phase of the experiment. Pion beta decay, while providing the theoretically cleanest method to obtain $|V_{ud}|$, requires a 10x improvment in the experimental precision to be competitive. However, a 3x improvement in precision of the pion beta decay branching ratio compared to Ref. [33] would allow for a 0.2% accuracy in the determination of the ratio V_{us}/V_{ud}, competitive with the existing determination[25].

Searches for heavy sterile neutrinos ν_H in $\pi^+ \to \ell^+\nu_H$ decays were also performed in the PIENU experiment [34, 35]. PIONEER aims to make improvements in sensitivity by an order of magnitude for processes like $\pi^+ \to e^+\nu_H$ decay as indicated in Figure 4. Similarly, pion decays involving massive or massless weakly interacting neutral bosons X such as axions [36, 37, 38, 39]

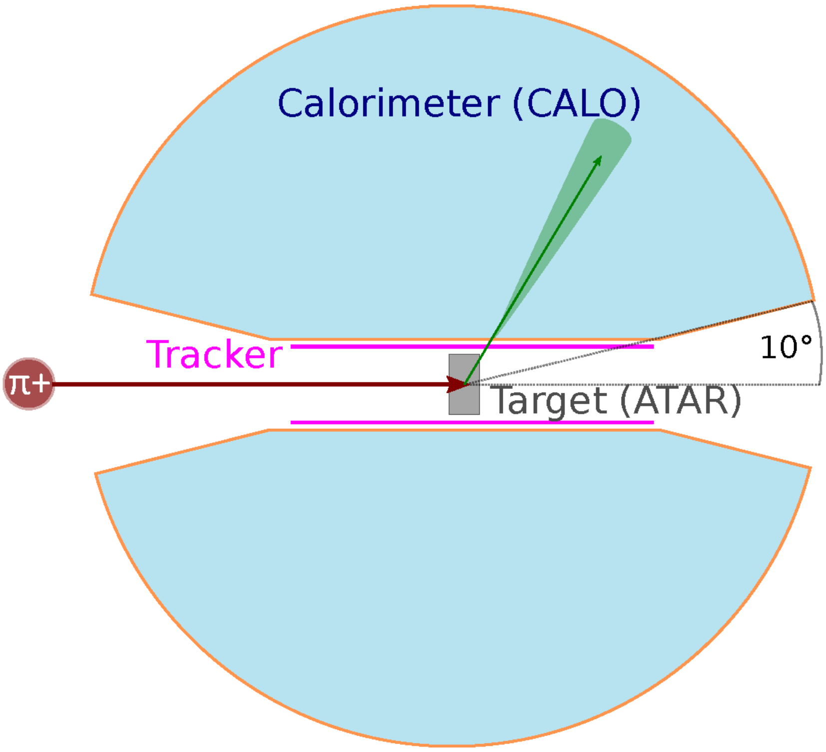

Figure 2. Conceptual layout of the PIONEER rare pion decay experiment[30]. The intense positive pion beam enters from the left and is brought to rest in a highly segmented active target (ATAR). Decay positron trajectories are measured from the ATAR to an outer electromagnetic calorimeter (CALO) through a tracker. The CALO records the energy, time, and location of positron tracks. An example outgoing positron track is shown in green.

Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	$\leq$ **0.01**

Table 1. $R^{\pi}_{e/\mu}$ precision reported by PIENU[11] and estimated precision for PIONEER[30].

and Majorons [40, 41, 42] have been searched for; these may involve dark matter candidates, or impact baryogenesis or the strong CP problems [43]. Other reactions of interest include rare pion decays $\pi^+ \to \ell^+ \nu_\ell \nu \bar{\nu}$ which are highly suppressed; the experimental search for these processes could reveal small non-SM effects such as neutrino-neutrino interactions [44] and six-fermion

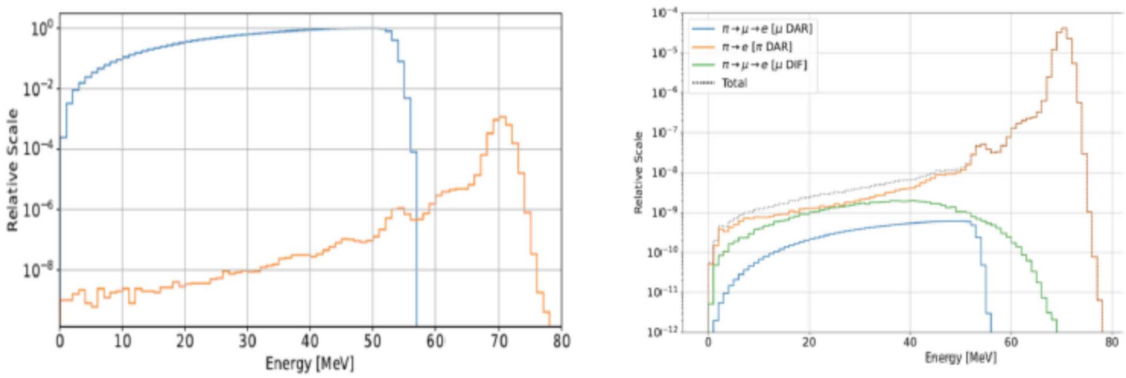

Figure 3. Left: Simulated decay spectra for $\mu \to e\nu\overline{\nu}$ (blue) and $\pi \to e\nu$ (orange) decays. Right: $\mu \to e$ background-suppressed spectra showing the components due to $\pi \to e\nu$ decays (orange) and two remaining backgrounds: $\mu \to e$ DIF after $\pi \to \mu$ DAR (green), and $\mu \to e$ DAR (blue) from $\pi \to \mu$ DIF[30]. See text.

interactions [45, 46], which might compete with the SM processes at first order; considering three models (SM, neutrino-neutrino interaction, and six-fermion) these latter processes were also searched for in PIENU [47] and sensitivity to them will be improved in PIONEER.

4. Conclusions

The status of the searches for violation of lepton flavor universality in the charged current involving pions decays has been discussed. This high precision test of LFU agrees well with the SM expectation at the $O(10^{-3})$ level and is particularly interesting in light of the experimental hints for possible large deviations from LFU in semi-leptonic B decays, the anomalous magnetic moment of the muon[49], and the Cabbibo angle anomaly. The proposed PIONEER experiment aims to improve the test of $e-\mu$ universality in pion decay, the pion beta decay determination of V_{ud}, and searches for exotic decays by an order of magnitude.

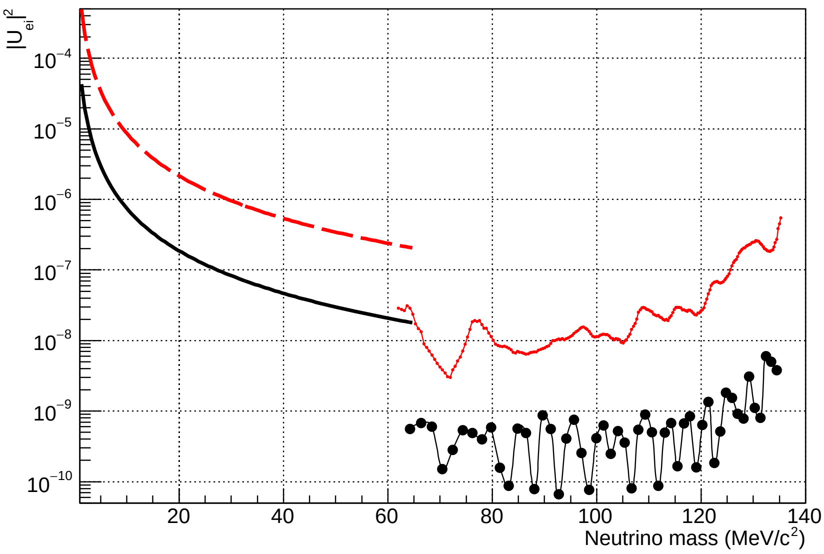

Figure 4. Limits on mixing coefficients for fourth generation neutrinos coupling to electrons $|U_{ei}|^2$ (90% C.L.) from PIENU (red)[11, 34]) and expected sensitivity from PIONEER (black). The lower mass region limits (m_{ν_H} <65 MeV) come from the $R^{\pi}_{e/\mu}$ branching ratio measurement and the higher mass region limits (m_{ν_H} >65 MeV) from a peak search. Figure reproduced from Ref. [48].

Acknowledgments

The author thanks the PIENU and PIONEER collaborations. This work is supported by NSERC grant no. SAPPJ-2018-0017 (Canada).

References

[1] Zyla P A *et al.* (Particle Data Group) 2020 *PTEP* **2020** 083C01
[2] Bryman D, Cirigliano V, Crivellin A and Inguglia G 2021 (*Preprint* `2111.05338`)
[3] Coutinho A M, Crivellin A and Manzari C A 2020 *Phys. Rev. Lett.* **125** 071802 (*Preprint* `1912.08823`)
[4] Crivellin A and Hoferichter M 2020 *Phys. Rev. Lett.* **125** 111801 (*Preprint* `2002.07184`)
[5] Campbell B A and Maybury D W 2005 *Nucl. Phys. B* **709** 419–439 (*Preprint* `hep-ph/0303046`)
[6] Marciano W J and Sirlin A 1993 *Phys. Rev. Lett.* **71** 3629–3632
[7] Finkemeier M 1996 *Phys. Lett. B* **387** 391–394 (*Preprint* `hep-ph/9505434`)
[8] Cirigliano V and Rosell I 2007 *Phys. Rev. Lett.* **99** 231801 (*Preprint* `0707.3439`)
[9] Cirigliano V and Rosell I 2007 *JHEP* **10** 005 (*Preprint* `0707.4464`)
[10] Bijnens J, Ecker G and Gasser J 1993 *Nucl. Phys. B* **396** 81–118 (*Preprint* `hep-ph/9209261`)
[11] Aguilar-Arevalo A *et al.* (PIENU) 2015 *Phys. Rev. Lett.* **115** 071801 (*Preprint* `1506.05845`)
[12] Bryman D A, Dixit M S, Dubois R, Macdonald J A, Numao T, Olaniyi B, Olin A and Poutissou J M 1986 *Phys. Rev. D* **33** 1211
[13] Britton D I *et al.* 1994 *Phys. Rev. D* **49** 28–39
[14] Czapek G *et al.* 1993 *Phys. Rev. Lett.* **70** 17–20
[15] Bryman D A and Shrock R 2019 *Phys. Rev. D* **100** 073011 (*Preprint* `1909.11198`)
[16] Glattauer R *et al.* (Belle) 2016 *Phys. Rev. D* **93** 032006 (*Preprint* `1510.03657`)

[17] Abdesselam A *et al.* (Belle) 2017 (*Preprint* 1702.01521)
[18] Waheed E *et al.* (Belle) 2019 *Phys. Rev. D* **100** 052007 [Erratum: Phys.Rev.D 103, 079901 (2021)] (*Preprint* 1809.03290)
[19] Lees J P *et al.* (BaBar) 2012 *Phys. Rev. Lett.* **109** 101802 (*Preprint* 1205.5442)
[20] Aaij R *et al.* (LHCb) 2018 *Phys. Rev. D* **97** 072013 (*Preprint* 1711.02505)
[21] Abdesselam A *et al.* (Belle) 2019 (*Preprint* 1904.08794)
[22] Aaij R *et al.* (LHCb) 2017 *JHEP* **08** 055 (*Preprint* 1705.05802)
[23] Aaij R *et al.* (LHCb) 2019 *Phys. Rev. Lett.* **122** 191801 (*Preprint* 1903.09252)
[24] Aaij R *et al.* (LHCb) 2021 (*Preprint* 2103.11769)
[25] Czarnecki A, Marciano W J and Sirlin A 2020 *Phys. Rev. D* **101** 091301 (*Preprint* 1911.04685)
[26] Aguilar-Arevalo A *et al.* 2010 *Nucl. Instrum. Meth. A* **621** 188–191 (*Preprint* 1003.2235)
[27] PEN Collaboration http://pen.phys.virginia.edu/
[28] Glaser C J *et al.* (PEN) 2018 PEN experiment: a precise test of lepton universality *13th Conference on the Intersections of Particle and Nuclear Physics* (*Preprint* 1812.00782)
[29] Pocanic D, Frlez E and van der Schaaf A 2014 *J. Phys. G* **41** 114002 (*Preprint* 1407.2865)
[30] Altmannshofer W *et al.* (PIONEER) 2022 (*Preprint* 2203.01981)
[31] Mihara S 2011 *J. Phys. Conf. Ser.* **308** 012009
[32] Mazza S M (PIONEER) 2021 *Instruments* **5** 40 (*Preprint* 2111.05375)
[33] Pocanic D *et al.* 2004 *Phys. Rev. Lett.* **93** 181803 (*Preprint* hep-ex/0312030)
[34] Aguilar-Arevalo A *et al.* (PIENU) 2018 *Phys. Rev. D* **97** 072012 (*Preprint* 1712.03275)
[35] Aguilar-Arevalo A *et al.* (PIENU) 2019 *Phys. Lett. B* **798** 134980 (*Preprint* 1904.03269)
[36] Jaeckel J and Ringwald A 2010 *Ann. Rev. Nucl. Part. Sci.* **60** 405–437 (*Preprint* 1002.0329)
[37] Jeong K S, Jung T H and Shin C S 2020 *Phys. Rev. D* **101** 035009 (*Preprint* 1811.03294)
[38] Agrawal P and Howe K 2018 *JHEP* **12** 029 (*Preprint* 1710.04213)
[39] Alves D S M and Weiner N 2018 *JHEP* **07** 092 (*Preprint* 1710.03764)
[40] Gelmini G B and Roncadelli M 1981 *Phys. Lett. B* **99** 411–415
[41] Chikashige Y, Mohapatra R N and Peccei R D 1981 *Phys. Lett. B* **98** 265–268
[42] Aulakh C S and Mohapatra R N 1982 *Phys. Lett. B* **119** 136–140
[43] Wilczek F 1982 *Phys. Rev. Lett.* **49** 1549–1552
[44] Bardin D Y, Bilenky S M and Pontecorvo B 1970 *Phys. Lett. B* **32** 121–124
[45] Ericson T E O and Glashow S L 1964 *Phys. Rev.* **133** B130–B131
[46] Vanzha A, Isaev A and Lapidus L 1971 *Sov. J. Nucl. Phys.* **12** 325 [Yad. Fiz. **12**, 595 (1970)]
[47] Aguilar-Arevalo A *et al.* (PIENU) 2020 *Phys. Rev. D* **102** 012001 (*Preprint* 2006.00389)
[48] Altmannshofer W *et al.* (PIONEER) 2022 Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment *2022 Snowmass Summer Study* (*Preprint* 2203.05505)
[49] Abi B *et al.* (Muon g-2) 2021 *Phys. Rev. Lett.* **126** 141801 (*Preprint* 2104.03281)