Weak Decays of Strange and Light Quarks

Report of Topical Group RF2 to Snowmass 2021

Rare Processes and Precision Measurements Frontier

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1 Introduction

An essential feature of flavor physics experiments is their ability to probe very high mass scales, beyond the energies accessible directly in collider experiments, due to quantum effects allowing virtual particles to modify the results of precision measurements in ways that reveal the underlying physics. Therefore the ongoing and planned flavor physics experiments will provide essential constraints and complementary information on the structure of models put forward to explain any discoveries at the LHC and future colliders. Furthermore, flavor physics experiments are becoming increasingly important laboratories for high-sensitivity searches for feebly interacting hidden sectors.

This report describes the physics case for the studies of weak decays of strange and light quarks. Ongoing and proposed precision measurements of kaon, hyperon, pion and $\eta^{(\prime)}$ meson decays allow for unique tests of the Standard Model (SM). This includes precision measurements of the elements of the CKM quark-mixing matrix leading to stringent unitarity tests; precision symmetry tests including lepton flavor and lepton number conservation; and precision lepton flavor universality tests. In the context of models beyond the SM description (BSM models), strange and light quark decay experiments provide sensitivity to new physics up to the PeV mass scale, as well as leading sensitivities to scenarios involving feebly interacting hidden sectors below the GeV mass scale.

Experimental studies of weak decays of strange and light quarks currently represent a very active field, and significant progress is expected over the next decade. Two dedicated high-intensity kaon experiments focusing on unique SM tests with ultra-rare decays, NA62 and KOTO, are currently taking data. Moreover, both collaborations are developing ambitious long-term programs. The LHCb experiment at CERN is pursuing a kaon and hyperon decay program, while the BESIII experiment is conducting pioneering searches for direct CP violation in hyperon decays. A new major initiative focused on a precision lepton universality test and a measurement of the mixing matrix element V_{ud} in charged pion decays, PIONEER, has been approved recently at the Paul Scherrer Institute. The Belle II experiment will provide important complementary information from τ decays, including a V_{us} measurement. The JEF η factory under construction at the Jefferson Lab will focus on symmetry tests and searches for hidden sectors in rare $\eta^{(\prime)}$ decays, and a next-generation $\eta^{(\prime)}$ factory proposal, REDTOP, has been put forward. Theory and lattice QCD are making important steps essential for the interpretation of measurements.

The US should take advantage of the above medium-scale initiatives, many of which are centered in Europe and Asia. These experiments lead to powerful physics insights on relatively short time scales, offer opportunities of making leading contributions to potential BSM discoveries, and provide comprehensive experimental training at various stages including experimental design, R&D, detector construction, data collection and analysis.

2 Kaon decays

2.1 Kaon decays in the Standard Model and beyond

Kaon decay studies have played a unique role in the establishment of the Standard Model of particle physics over the past 70 years: CP violation, the suppression of flavor changing neutral currents (FCNC) and the GIM mechanism have been discovered in the kaon system. Because of the relatively small number of decay modes, simple final states, and availability of high-intensity kaon beams leading to large datasets of $\mathcal{O}(10^{13})$ decays, kaon decay experiments continue to be in many ways the quintessential intensity-frontier experiments. At present, kaon physics is focused on precision measurements of highly suppressed loop-induced FCNC processes that may reveal the effects of BSM physics at the 100 TeV scale, above the scale that can be explored directly by the LHC or even a next-generation hadron collider [1, 2]. Kaon decay measurements are complementary to those performed in the B sector, in particular by providing crucial information for the interpretation of the flavor anomalies observed in B decays. Progress in kaon decay physics implies a large amount of experimental work on precision measurements at high-luminosity, using dedicated detectors based on state-of-the-art technologies. On the other hand, significant theoretical work is required to understand the correlations with the other sectors of flavor physics, and to quantify the low-energy effects hindering the interpretation of the measurements.

The well-established rare kaon decays of interest include those for which the short-distance (SD) amplitudes are CP-conserving ($K_L \to \mu^+\mu^-$, $K_S \to \pi^0\ell^+\ell^-$), and those with the SD amplitudes receiving CP-violating contributions in the SM and many BSM scenarios ($K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_S \to \mu^+\mu^-$, $K_L \to \pi^0\ell^+\ell^-$), thereby opening a possibility of searching for new sources of CP violation [1]. The rates of these decays are both extremely suppressed and accurately predicted within the SM. Moreover it has been pointed out recently that $K_S \to \mu^+\mu^-$ is another "golden mode" providing a complementary, theoretically clean observable [3, 4]. While the total $K \to \mu^+\mu^-$ rate is dominated by long-distance (LD) physics, the measurement (in a dedicated high-intensity K_S experiment) of CP violation in the interference of mixing and decay via the time-dependent rate enables the extraction of the purely CP odd short-distance amplitude, which is predicted within the SM with an $\mathcal{O}(1\%)$ uncertainty. Beyond ultra-rare FCNC processes, studies of rare kaon decays provide insight into low-energy QCD, and inputs for the interpretation of the flagship measurements [5].

The current experimental efforts are focused on the $K \to \pi\nu\bar{\nu}$ decays which have a uniquely clean theoretical character due to the small LD contributions. In the standard approach [6], the main theoretical uncertainties in the SM prediction for the $K \to \pi\nu\bar{\nu}$ branching ratios stem from the CKM parameters (V_{cb}, V_{ub} and the γ angle), leading to a 10% accuracy. A novel approach, proposed recently to eliminate the dependence on $|V_{cb}|$ and γ, leads to a 5% precision [7, 8, 9]:

$$\begin{aligned}\mathcal{B}_{\rm SM}(K^+ \to \pi^+\nu\bar{\nu}) &= (8.60 \pm 0.42) \times 10^{-11},\\ \mathcal{B}_{\rm SM}(K_L \to \pi^0\nu\bar{\nu}) &= (2.94 \pm 0.15) \times 10^{-11}.\end{aligned}$$

The non-parametric uncertainties above are 4% (dominated by a LD charm contribution) in the K^+ case, and 1.5% in the K_L case. The accuracy of the SM predictions is expected to improve to about 3% over the next decade, due to lattice QCD progress on the charm contribution [10, 11, 12] and reduction of the external parametric uncertainties. Further advances due to perturbative calculations are unlikely.

The $K \to \pi\nu\bar{\nu}$ decays have been analysed thoroughly in numerous SM extensions [1]. The general scheme for the expected correlation between the K^+ and K_L decays in various scenarios is illustrated in Fig. 1 reproduced from Ref. [13]. Due to the different sensitivity of the two decays to new sources of CP violation, measurements of both $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

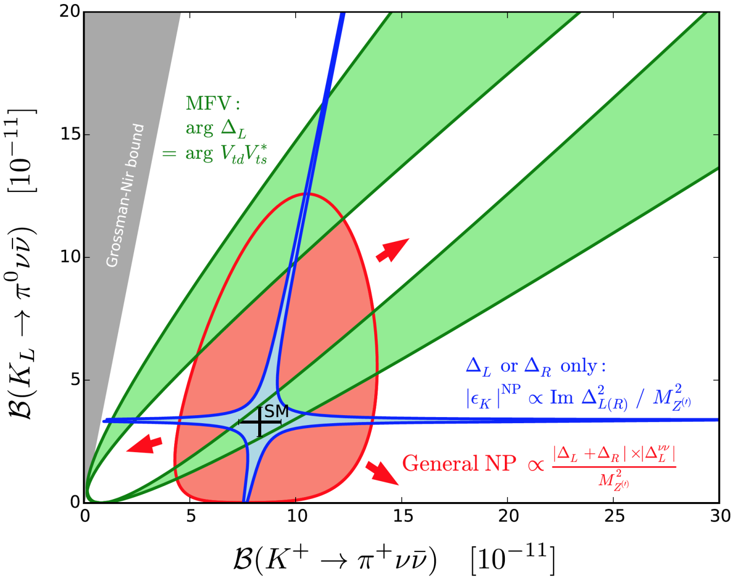

Figure 1: Illustration of the expected modifications of $K \to \pi\nu\bar{\nu}$ branching ratios in several generic BSM scenarios [13]. Note that precision measurement of both decay modes allows determination of the β angle within the SM paradigm [14].

modes are crucial to uncover the possible evidence for new physics in the quark flavor sector, and to distinguish between various classes of new physics models.

More generally, BSM contributions to $K \to \pi\nu\bar{\nu}$ decays are expected to be correlated with BSM effects in other observables. Important correlations have been established with the CP violation parameter ε'/ε and the CP conserving $K_L - K_S$ mass difference ΔM_K in the kaon sector [13, 15, 16], the rates of rare B meson decays $B \to K\nu\bar{\nu}$ and $B \to \mu^+\mu^-$ [17, 18], and the possible lepton flavor universality violating effects in B decays [19]. Furthermore, experimental study of the $K^+ \to \pi^+\nu\bar{\nu}$ kinematic distribution allows testing the Dirac vs Majorana nature of the neutrino, probing $\mathcal{O}(10\ \mathrm{TeV})$ operator scales in different quark and neutrino flavors compared to neutrinoless double beta decay [20].

In spite of their significant sensitivity to new physics, no new experiments are currently planned to measure with increased precision direct or indirect CP violation in $K^0 \to \pi\pi$ decays, or the mass difference ΔM_K, since the current experimental precision on these quantities exceeds the theoretical uncertainties in their SM prediction. Nevertheless the quantities ε, ε' and ΔM_K offer opportunities for the discovery of new physics as the improving capabilities of lattice QCD provide increasingly accurate SM predictions [21, 22, 23]. Over the next decade, the accuracy of the SM predictions for ΔM_K, ε and ε' is expected to improve by a factor of five in each case. If this is achieved for the calculation of ε', the theoretical precision would match that of the experiment, $\mathrm{Re}(\varepsilon'/\varepsilon) = 16.6(2.3) \times 10^{-4}$ [24, 25], potentially motivating a new measurement.

Measurements of semileptonic kaon decays $K \to \pi\ell\nu$ provide the principal input for the extraction of the CKM parameter V_{us} while the ratios of (semi)leptonic K^+ and π^+ decay rates are used to extract the ratio V_{us}/V_{ud}, with inputs provided from lattice QCD [26]. Determination of V_{us} from kaon, pion and τ decays, combined with V_{ud} measurement from super-allowed beta decays [27] and neutron decays [28, 29], gives rise to a 3σ deficit in first-row CKM unitarity relation; a tension of similar significance is observed between $K \to \ell\nu$ and $K \to \pi\ell\nu$ rates [30, 31]. The resulting Cabibbo angle anomaly is illustrated, and quantified, in Fig. 2.[1] The uncertainty in

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[1] Note that $N_f = 2+1+1$ FLAG average for $f_+(0)$ [26] is used. A recent result for $N_f = 2+1$ leads to a smaller $f_+(0)$ value [32] while compatible within 1σ with the $N_f = 2+1$ FLAG average, and within 1.5σ with the $N_f = 2+1+1$ value.

V_{us} comes in equal parts from the experimental errors and theoretical uncertainties in the ratio of decay constants, f_K/f_π, and the $K \to \pi\ell\nu$ form factor, $f_+(0)$. Substantial improvements in the lattice QCD calculations of these hadronic factors are expected in the next five years, thanks to decreased lattice spacing and accurate evaluation of electromagnetic effects [33, 34, 35, 36]. Note that significant progress on the calculation of radiative corrections has been achieved recently, reducing the electromagnetic correction uncertainties to a negligible level [37, 38, 39, 40]. It is important that improvements in the accuracy of kaon decay measurements are achieved; in particular a precision measurement of the ratio of $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu$ rates is well-motivated [30].

It should be noted that the Belle II experiment is planning to extract V_{us} at an improved precision, with respect to the τ-decay band shown in Fig. 2, from a dedicated suite of inclusive and exclusive $[\mathcal{B}(\tau^- \to K^-\nu)/\mathcal{B}(\tau^- \to \pi^-\nu)]$ measurements of τ decays, combined with theory improvements [41]. Measurements of inclusive hadronic decays of the τ lepton provide a unique opportunity to extract $|V_{us}|$ which does not involve theoretically estimated hadronic form factors or decay constants, therefore providing a possibility to cross-check the kaon results. The theory inputs in this case are based on operator product expansion and finite energy sum rules.

The kaon sector offers opportunities for precision lepton flavor universality tests by measuring the ratios $\mathcal{B}(K^+ \to \pi^+e^+e^-)/\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)$, $\mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$ and $\mathcal{B}(K \to \pi e\nu)/\mathcal{B}(K \to \pi\mu\nu)$, exploiting the cancellation of hadronic effects [31, 46]. Searches for lepton flavor and lepton number violating $K^+ \to \pi^-(\pi^0)\ell^+\ell^+$, $K^+ \to \pi(\pi^0)\mu e$, $K_L \to (\pi^0)(\pi^0)\mu^\pm e^\mp$ and $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$ decays, with sensitivities to branching ratios at the $\mathcal{O}(10^{-12})$ level, represent interest in the context of BSM models involving flavor-violating ALPs [47] or massive Majorana neutrinos. The constraints on active-sterile mixing angles between Majorana neutrinos obtained from the experimental limits on the $K^+ \to \pi^-\ell^+\ell^+$ decays are stronger than those obtained from neutrinoless double beta decay searches below the kaon mass [48].

Kaon decays represent uniquely sensitive probes of light hidden sectors due to the availability of large datasets and the suppression of the kaon decay width. The possible search strategies have been reviewed recently [49], and the following have been identified as the most promising. Searches for the $K \to \pi X_{\rm inv}$ decay, where $X_{\rm inv}$ represents an invisible particle, by extension of the $K \to \pi\nu\bar{\nu}$ measurements represent a unique probe into the Higgs mixed dark scalar and ALP phase space. Searches for resonances in the $K \to \pi\ell^+\ell^-$ and $K \to \pi\gamma\gamma$ decay spectra are complementary to searches at beam-dump experiments for a significant ALP mass range. Searches for heavy neutral lepton (N) production in $K^+ \to \ell^+N$ decays are approaching the seesaw neutrino mass models with $\mathcal{O}(100\text{ MeV})$ sterile neutrinos [42], as illustrated for the electron coupling in Fig. 3. Finally, searches for a leptonic force mediator (X) in $K^+ \to \mu^+\nu X$ decays can probe a region of parameter space providing an explanation for the muon $g-2$ anomaly [50].

2.2 Current and planned kaon experiments

The availability of high-intensity kaon beams at the CERN SPS North Area and the J-PARC Hadron Experimental Facility opens unique possibilities for precision SM tests in the quark flavor sector. Significant experimental progress in kaon decay measurements is expected in the coming decade through the exploitation of dedicated operating experiments (NA62 at CERN and KOTO at J-PARC). In the long term, building on the success of the current generation of experiments, ambitious initiatives are taking shape both at CERN and J-PARC to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio to 5% and the $K_L \to \pi^0\nu\bar{\nu}$ branching ratio to 20% precision [51]. These planned experiments would also pursue a comprehensive physics program including lepton flavor universality tests, lepton flavor and number conservation tests, precision rare decay measurements, and searches for hidden sectors.

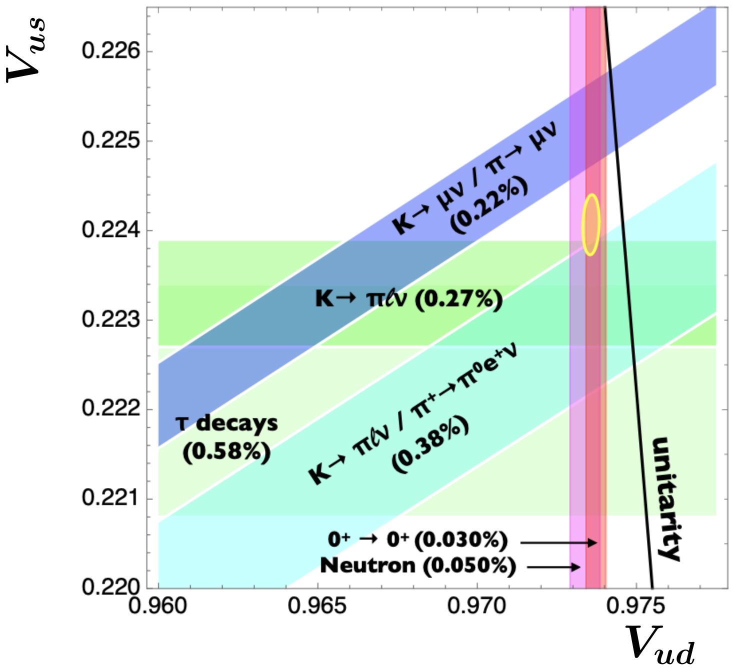

Figure 2: Constraints on V_{ud} and V_{us} obtained from measurements of kaon, pion, τ lepton, nuclear and neutron decays [31], leading to the Cabibbo angle anomaly.

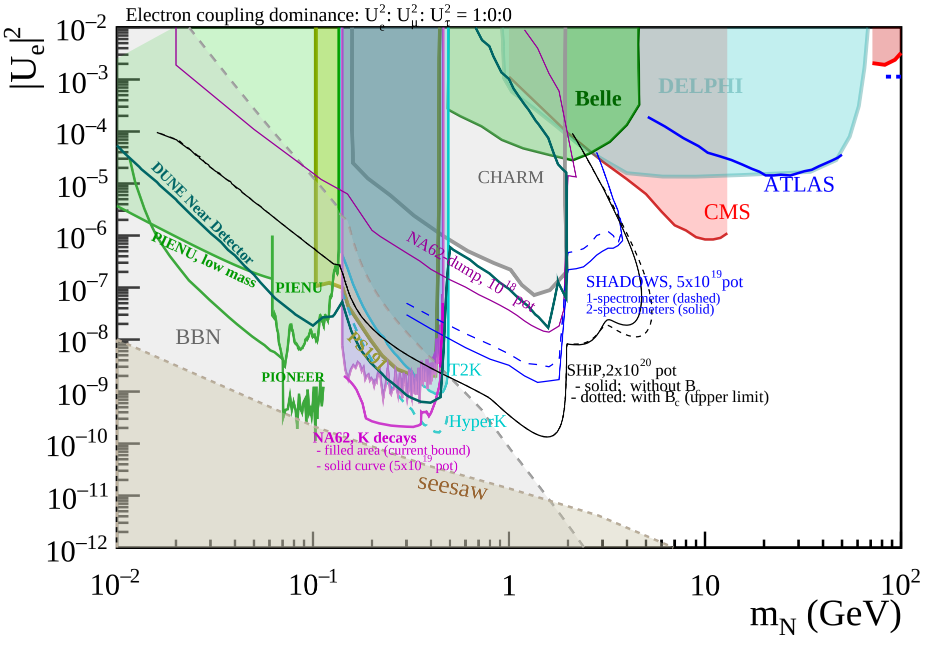

Figure 3: Existing (solid areas) and projected upper limits on electron couplings of heavy neutral leptons [42]. World-leading limits below 400 MeV/c^2 come from $K^+ \to e^+N$ searches at NA62 [43], $\pi^+ \to e^+N$ searches at PIENU [44], and lepton flavor universality tests at PIENU [45]. Present (NA62 Run 2) and future K^+ experiments at CERN, and Phase I of the PIONEER experiment approved at PSI, are expected to bring further improvements towards the seesaw bound.

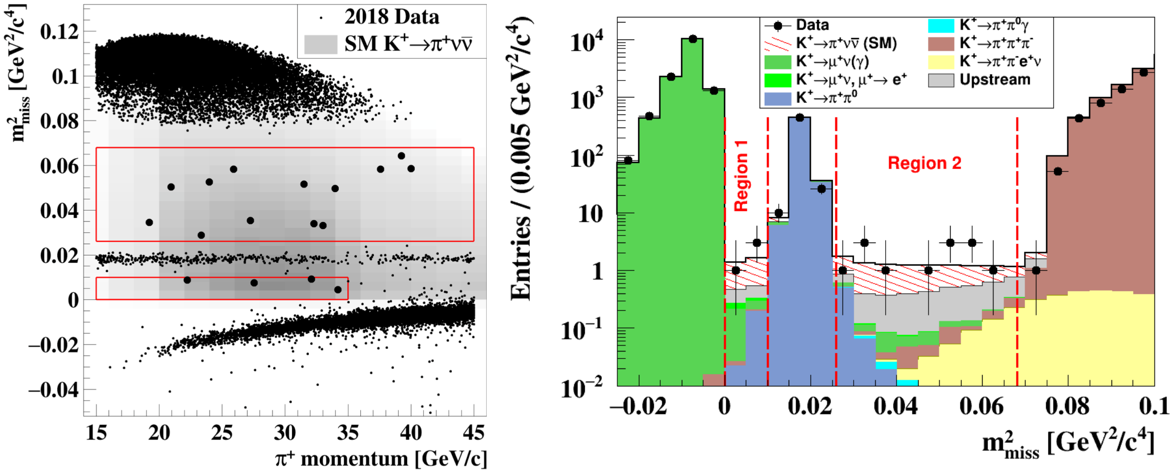

Figure 4: Distribution of the seventeen $K^+ \to \pi^+\nu\bar{\nu}$ candidates observed by the NA62 experiment in the 2018 dataset [53] in terms of reconstructed π^+ momentum in the laboratory frame and squared missing mass $m^2_{\rm miss}$ (left), and its $m^2_{\rm miss}$ projection (right). The two signal regions free from the main backgrounds are shown with rectangles in the left panel, and the backgrounds (estimated mainly with data-driven methods) are shown in the right panel.

The main goal of the NA62 experiment at CERN is the measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ decay. The experiment operates a high-intensity unseparated K^+ beam with a momentum of 75 GeV/c derived from primary 400 GeV/c protons extracted from the SPS accelerator in spills of 4.8 s duration, and measures kaon decays in a 60 m long fiducial region located in a vacuum tank [52]. The setup includes trackers and Cherenkov detectors for the incoming kaons and for the final-state particles, as well as calorimeters and a hermetic photon veto system. The key detectors deliver a sub-100 ps time precision, thereby providing clean event reconstruction and manageable random veto effects at the nominal 45 MHz beam kaon rate. The signal signature consists of an incoming K^+ in time with a final-state π^+, not kinematically compatible with $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^0$ and $K^+ \to 3\pi$ decays (which defines two signal regions in terms of the missing mass), and no extra in-time activity. Background suppression relies on $\mathcal{O}(10^{-8})$ muon rejection by particle identification, and $\mathcal{O}(10^{-8})$ rejection of $\pi^0 \to \gamma\gamma$ decays by the photon veto system.

The NA62 Run 1 dataset, collected in 2016–2018 at a typical beam intensity of 2.2×10^{12} protons on target (POT) per spill, amounts in total to 2.2×10^{18} POT and about 6×10^{12} useful K^+ decays. Analysis of this sample has led to an evidence for the $K^+ \to \pi^+\nu\bar{\nu}$ decay with 3.4σ significance, based on 20 signal candidates with an estimated background of $7.03^{+1.05}_{-0.82}$ events dominated by K^+ decays upstream of the decay region [53]. The branching ratio is measured to be

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6\,^{+4.0}_{-3.4}\,|_{\rm stat} \pm 0.9_{\rm syst}\right) \times 10^{-11},$$

and the kinematic distribution of the candidates observed in the 2018 dataset is shown in Fig. 4. This represents an improvement in sensitivity with respect to an earlier result from the BNL E787/E949 experiments, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [54].

The experience of NA62 Run 1 has firmly established the decay-in-flight technique. The setup has subsequently been upgraded, including installation of an additional beam tracker station, installation of new veto detectors both upstream and downstream of the decay region, and improvements to the trigger and data acquisition (TDAQ) system [55]. These upgrades have brought the $K^+ \to \pi^+\nu\bar{\nu}$ measurement in a low-background, high-acceptance regime, primarily due to the reduction of background from upstream decays. NA62 Run 2 started in 2021 (reaching the nominal proton beam intensity of 3.3×10^{12} POT/spill), and is approved until LHC Long Shutdown 3 (LS3), i.e. until the end of 2025, aiming at a 10% precision on the $K^+ \to \pi^+\nu\bar{\nu}$ rate measurement.

A comprehensive program (HIKE – "High-Intensity Kaon Experiments") for the study of the rare decays of K^+ and K_L mesons with high-intensity beams after LS3 is envisioned at CERN, to be carried out in multiple phases using shared detectors and infrastructure [51]. The program includes an experiment to measure $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ at the 5% level, an experiment to measure $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ at the 20% level, and an experiment with a K_L beam and a final-state particle tracker focused measurements of the $K_L \to \pi^0\ell^+\ell^-$ decays [56] while also allowing the characterization of the K_L beam. Collection of up to 10^{19} POT in beam-dump mode is also foreseen, providing unique sensitivity to forward production of feebly-interacting particles; beam-dump operation in conjunction with an off-axis detector has been proposed [57]. These experiments rely on the delivery of a high-intensity proton beam from the SPS to the present NA62 experimental hall (2.1×10^{13} POT/spill, 1.3×10^{19} POT/year). With duty cycle optimization, the required proton flux can be delivered, allowing high-intensity kaon experiments to run as part of a robust fixed-target program in the CERN North Area [58]. It should be noted that SPS operation is foreseen until at least 2038.

The planned $K^+ \to \pi^+\nu\bar{\nu}$ experiment at CERN aiming at 400 SM candidates with a signal-to-background ratio $S/B \gg 1$ is based on similar principles to NA62, and is expected to employ a similar experimental layout. The experiment would operate at up to six times the nominal NA62 beam intensity, necessitating a substantial upgrade to bring the time resolutions to the 20 ps level. Design studies for the principal detectors (including a silicon pixel beam tracker, a straw downstream tracker, Cherenkov detectors for particle identification, and the photon veto system) are in progress, and a Letter of Interest is in preparation. The baseline design for the $K_L \to \pi^0\nu\bar{\nu}$ experiment at CERN is the KLEVER project aiming to collect 60 SM events with $S/B = 1$ [59]. A high-energy K_L beam, with a mean momentum of 40 GeV/c, facilitates the rejection of $K_L \to \pi^0\pi^0$ and other backgrounds by detection of the additional photons in the final state. Extensive design studies performed include the options for the upgrade of proton beam transport [60, 61] and secondary neutral beam production and transport [62] required to reach the design beam intensity, as well as layout optimization and physics performance studies [63]. Suppression of the Λ decay background is likely to require an extension of the experimental hall. Baseline designs of the main electromagnetic calorimeter, small and large-angle photon vetoes and charged-particle rejection detectors have been proposed, and beam tests of the prototypes have been performed.

The main goal of the KOTO experiment at J-PARC is the measurement of the $K_L \to \pi^0\nu\bar{\nu}$ decay. The experiment derives its K_L beam with a peak momentum of 1.4 GeV/c from the primary 30 GeV protons extracted from the J-PARC main ring. Kaon decays in a 2 m long fiducial region are studied using a detector consisting of a CsI electromagnetic calorimeter and a hermetic system of veto counters surrounding the decay volume. The signal signature consists of two in-time photons from the $\pi^0 \to \gamma\gamma$ decay detected in the CsI calorimeter, consistent with emission in the decay volume under the π^0 mass hypothesis, with a large transverse momentum. Using the 2015 dataset corresponding to 2.2×10^{19} POT, a single event sensitivity of 1.3×10^{-9} has been achieved, and an upper limit has been obtained for the decay branching ratio by observing no signal candidates [64]:

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9} \quad \text{at 90\% CL.}$$

In the 2016–2018 dataset corresponding to 3.05×10^{19} POT, three signal candidates are observed, which is statistically consistent with the expected background of 1.22 ± 0.26 events dominated by $K^\pm \to \pi^0 e^\pm \nu$ decays of charged kaons produced in charge-exchange reactions of the K_L beam halo in the collimators [65]. The above background estimate is based on the measured beam halo and $K^{\pm}$ fluxes. While the single event sensitivity of 7.2×10^{-10} (corresponding to 0.04 SM signal events) improves on the 2015 data, the upper limit obtained on the decay branching ratio is weaker due to the apparent background fluctuation.

The KOTO dataset collected in 2019–2021 is twice the size of the 2016–2018 dataset. An upstream veto detector was installed in 2021 to reduce the charged-kaon background. A further dataset is expected to be collected in 2022–2025, with a gradual increase of the beam intensity (up to 100 kW beam power) and an upgraded TDAQ system. The foreseen improvements to the setup include installation of a second upstream veto detector and an upstream sweeping magnet, which is expected to suppress the charged-kaon flux to a negligible level and bring the measurement into a low-background regime. It is expected to reach the SM single event sensitivity of $O(10^{-11})$ by 2025.

The experience gained by KOTO has allowed planning for a next-generation experiment, KOTO step-2 [51]. The proposal relies on the foreseen extension of the J-PARC Hadron Hall, and involves a complete rebuild of the detector. A redesigned beamline would provide a higher K_L momentum (peaking at 3 GeV/c, and improved K_L flux, and a reduced halo and neutron flux. The proposed detector involves a 12 m long decay region and a calorimeter with a 3 m diameter, leading to a factor of 5 larger acceptance with respect to KOTO. A sensitivity estimate is reported in Ref. [51]: the expected SM signal yield is 35 events while the estimated background is 56 ± 3 events (with the largest contribution from $K_L \to \pi^0\pi^0$ decay with two undetected photons), assuming a running time of 3×10^7 s with a 100 kW beam. This is sufficient for a 5σ discovery of the $K_L \to \pi^0\nu\bar{\nu}$ decay, assuming the SM branching ratio.

Current and proposed $K \to \pi\nu\bar{\nu}$ experiments at CERN and J-PARC pursue a broad physics program beyond the flagship measurements (see Section 2.1). As an example, the availability of auxiliary trigger lines during NA62 Run 1 has already allowed lepton flavor and number conservation tests [66, 67, 68], and searches for hidden-sector particle production in kaon decays [43, 69, 70, 71, 72]. Similarly, KOTO has published several searches for forbidden decays and hidden-sector mediators [64, 73]. The sensitivities of the future experiments to the branching fractions of the forbidden kaon decays are expected reach $\mathcal{O}(10^{-12})$. It should also be noted that kaon experiments serve as "π^0 factories" allowing for precision measurements of rare decays of tagged, Lorentz-boosted π^0 mesons.

Considering the recent hints for lepton flavor universality violation [74], lepton universality tests in kaon decays at the present and future $K^+ \to \pi^+\nu\bar{\nu}$ experiments at CERN deserve a specific discussion. The ratio $\mathcal{B}(K^+ \to \pi^+e^+e^-)/\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)$ is expected to be measured to a 1% accuracy from the first dedicated analysis with reduced intrinsic and external uncertainties, improving by a factor of about five on the present status [75]. A measurement of the ratio $R^K_{\mu e} = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$ at the per mil level is feasible, improving on the present precision of $R^{K\mathrm{exp}}_{\mu e} = 2.488(9) \times 10^{-5}$ [75] dominated by a result from an early phase of the NA62 experiment carried out with the NA48/2 detector [76]. However a dedicated, optimised experiment is probably required to match accuracy of the SM prediction $R^{K\mathrm{SM}}_{\mu e} = 2.477(1) \times 10^{-5}$ [77], in terms of both statistical and systematic uncertainties.

The LHCb experiment at the LHC, optimized for short-lived beauty hadrons in terms of the decay length and the transverse momenta of the decay products, carries out a complementary program of K_S decay measurements exploiting the $\mathcal{O}(1\ \mathrm{barn})$ cross-section for production of kaons in the experiment's acceptance. With a total reconstruction and trigger efficiency for K_S and hyperon decays of $\mathcal{O}(10^{-4})$ for Run 1 and Run 2 data, LHCb has provided several world-leading results, including an upper limit $\mathcal{B}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 90% CL obtained with the full dataset collected to date [78]. An upgraded trigger to be operated during Run 3 is expected to bring significant improvements in sensitivity [79].

In summary, kaon decays are highly sensitive probes of the flavor and CP violating sector of any SM extension. The ambitious initiatives for next-generation kaon experiments at CERN and

J-PARC represent a significant increase in scope relative to existing experiments. While the US community is exploring possible expansions to the physics program that could be achieved with future upgrades to the Fermilab proton accelerator complex, participation in kaon experiments at CERN and/or J-PARC is currently the only opportunity for US physicists to contribute to this vital area of research.

3 Hyperon decays

Studies of hyperon decays are complementary to kaon physics, as their baryon number and spin properties provide different sensitivity to BSM interactions. While CP violation in kaon decays was discovered back in 1964, it is yet to be established in hyperon decays. Important efforts in this direction were made in the first decade of the century by the HyperCP experiment at Fermilab which studied decays of hyperons produced by a 800 GeV/c proton beam incident on a target [80, 81].

A novel approach is employed by the BESIII experiment, where the copious production of spin-entangled hyperon-antihyperon pairs at the J/ψ resonance is exploited to make direct comparison of the baryon and antibaryon decay properties. A recent proof-of-concept measurement of the direct CP violating asymmetry of the Λ and $\bar{\Lambda}$ decay parameters to a 0.5% accuracy, based on a sample of 10^{10} J/ψ events collected in 2017–2019, represents the most precise CP symmetry test in the hyperon sector to date [82]. Further measurements of weak phases and CP violating asymmetries performed by BESIII include those in the $J/\psi \to \Sigma^+\bar{\Sigma}^-$ [83] and $J/\psi \to \Xi^-\bar{\Xi}^+$ [84] decays; no asymmetry is observed in either case. A next-generation J/ψ factory is expected to collect a dataset of $\mathcal{O}(10^{12})$ J/ψ events, and the statistical precision of the CP tests can be improved using longitudinally-polarized electron beams [85]. This would allow observation of statistically significant asymmetries at the $\mathcal{O}(10^{-4})$ level of the SM prediction [86], providing further insight into the mechanism of CP violation in the baryon sector.

The BESIII experiment is also pursuing a program of rare hyperon decay measurements [87, 88]. In particular, upper limits have recently been established on the rates of lepton number violating hyperon decays: $\mathcal{B}(\Sigma^- \to pe^-e^-) < 6.7 \times 10^{-5}$ and $\mathcal{B}(\Sigma^- \to \Sigma^+ X) < 1.2 \times 10^{-4}$ at 90% CL, where X denotes any possible particle combination [89]. Considering that these and other searches are almost background-free, one expects significant improvement in sensitivity at next-generation J/ψ factories. Rare hyperon decay measurements are also carried out by the LHCb collaboration. The first evidence for the for the $\Sigma^+ \to p\mu^+\mu^-$ decay has been reported with the Run 1 dataset, leading to $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+1.8}_{-1.3}\right) \times 10^{-8}$ [90] consistent with the SM expectation and inconsistent with the HyperCP anomaly [91]. Future LHCb datasets promise a broad hyperon decay program, including measurements of semileptonic decays, as well as lepton universality, baryon and lepton number conservation tests [79].

In summary, hyperons provide complementary information to kaons in terms of probing BSM physics. The two current experiments, BESIII and LHCb, are exploiting different methodologies for CP asymmetry and rare decay measurements, and offer future prospects.

4 Charged pion decays

Relatively simple dynamics, the small number of available decay channels, and the well controlled radiative and loop corrections make charged pion decays a sensitive means for testing the underlying symmetries and the universality of weak fermion couplings, as well as for improving the understanding of chiral dynamics. Charged pion decays have provided important early insight into the $V - A$ nature of the weak interaction following the discovery of the suppression of the $\pi^+ \to e^+\nu$ decay. The ratio of leptonic decay rates of the charged pion,

$R_{e\mu} = \mathcal{B}(\pi^+ \to e^+\nu)/\mathcal{B}(\pi^+ \to \mu^+\nu)$, is computed within the SM to an exceptional accuracy due to the cancellation of hadronic effects, $R_{e\mu}^{\rm SM} = 1.23524(15) \times 10^{-4}$ [31]. Precision measurements of this quantity are of high interest, leading to sensitive lepton universality tests. The current world average of $R_{e\mu}^{\rm exp} = 1.2327(23) \times 10^{-4}$ [75], dominated by a measurement from the PIENU experiment at TRIUMF [92], has a remarkable 0.2% precision.

Phase I of the PIONEER experiment approved at the Paul Scherrer Institute (PSI) [93, 94], motivated in part by the recent hints for lepton flavor universality violation [74], aims to measure the quantity $R_{e\mu}$ to a 10^{-4} precision based on a sample of 2×10^8 $\pi^+ \to e^+\nu$ decays to be collected in three years of operation, thereby improving the current world average by a factor of about 15 [75]. This would match the accuracy of the SM calculation [31], thereby probing effects of new particles up to the PeV mass scale [95]. The schedule includes extensive detector R&D efforts, and full-scale physics operation can be expected to start in 2029.

The design of the PIONEER experiment is based on the experience from its predecessors PIENU at TRIUMF [92] and PEN/PIBETA at PSI [96, 97], and is optimized for handling of high beam rates and for reduction of the systematic uncertainties. The layout involves a high-intensity π^+ beam brought to rest in a highly segmented active target, a LXe electromagnetic calorimeter surrounding the target and providing a 3π sr solid-angle coverage, as well as beam and positron trackers.

Phase I of the experiment will operate with a continuous high-intensity (300 kHz), low-momentum (55 MeV/c) pion beam focused to a small spot size within the target dimensions. The low beam momentum allows for a separator to be used to reduce the contamination of muons and positrons in the beam to a level below 10%. The segmented active target based on Low Gain Avalanche Detector (LGAD) technology [98] represents a key new feature of the experiment. The target design involves 50 layers (of 2×2 cm^2 dimensions) of silicon strip sensors positioned transverse to the beam, at two perpendicular strip orientations, with a 200 μm pitch and a 120 μm thickness along the beam. The target will provide excellent resolutions on both position and time (100 ps), thus allowing for reduction of backgrounds from beam pion and muon decays in flight based on the energy deposit pattern, and minimization of acceptance-related systematic effects.

The monoenergetic positron from $\pi^+ \to e^+\nu$ decays of the stopped pions has an energy of 69.3 MeV. On the other hand, positrons from the decay chain $\pi^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu\bar{\nu}$ form the Michel spectrum with the endpoint of 52.3 MeV. Therefore the majority of positrons from $\pi^+ \to e^+\nu$ decays are well isolated from the Michel spectrum and can be identified using a high-resolution calorimeter. The principal challenge lies in determining the low-energy tail of the electromagnetic shower, located under the Michel spectrum. A liquid xenon (LXe) calorimeter read out by UV-sensitive phototubes and vacuum ultraviolet silicon photomultipliers has been proposed, drawing on the experience from the MEG and MEG-II experiments [99, 100, 101]. This option provides fast timing, high light yield, uniform response and excellent energy resolution (1.5% at 70 MeV). A LXe calorimeter of $25X_0$ thickness is expected to provide an intrinsic positron energy tail fraction below 52 MeV at the 0.5% level for signal events (to be compared to 3% achieved by PIENU with a $19X_0$ thick calorimeter). The tail fraction can be measured to a 10^{-2} precision in relative terms, using control datasets. Therefore the systematic uncertainty in the $R_{e\mu}$ measurement due to the energy tail correction, which amounted to 0.12% and represented a fundamental limitation of the PIENU experiment [92], will be reduced to a level below 10^{-4}.

The broader physics program of PIONEER Phase-I includes searches for ultra-rare π^+ decay modes, searches for heavy neutral lepton production in $\pi^+ \to \ell^+ N$ decays improving by an order-of-magnitude on the PIENU experiment [44, 45, 102] in terms of sensitivity to the coupling parameters $|U_{\ell 4}|^2$ as illustrated for the electron coupling in Fig. 3, a search for $\pi^+ \to e^+\nu X$ decay involving axions or hidden sectors, and a search for production of a feebly interacting neutral boson produced in $\mu^+ \to e^+ X$ decay.

In the longer term, Phase II of the PIONEER experiment will focus on the measurement of pion beta decay ($\pi^+ \to \pi^0 e^+ \nu$) rate to 0.2% precision, improving by a factor of three over the measurement performed by the dedicated PIBETA experiment, $\mathcal{B} = 1.036(6) \times 10^{-8}$ [103], which currently dominates the world average. This process offers the theoretically cleanest determination of the CKM element V_{ud}: thanks to the recent progress in lattice QCD calculations of the radiative corrections [104], the intrinsic theory uncertainty in the V_{ud} extraction is now reduced to the 0.01% level. The excellent theory precision allows for a CKM unitarity test [31, 105], which is of high interest in the context of the Cabibbo angle anomaly (Fig. 2). The challenge of the $\pi^+ \to \pi^0 e^+ \nu$ measurement is determined by the low branching ratio of $\mathcal{O}(10^{-8})$. To collect a sample of 7×10^5 signal events in 4–5 years of operation during Phase II, an increase in the beam rate to above 10 MHz is required, which can be achieved with larger beam momentum and emittance than in Phase I. The $\pi^+ \to \pi^0 e^+ \nu$ decay will be detected by observing the characteristic nearly back-to-back photons from $\pi^0 \to \gamma\gamma$ decay, normalizing to the $\pi^+ \to e^+ \nu$ decay.

Phase III of the experiment aims for another factor of three improvement in the $\pi^+ \to \pi^0 e^+ \nu$ rate measurement. The ultimate precision on $|V_{ud}|$ is expected to reach the 0.02% level, which is comparable to the currently most precise determination from superallowed beta decays. Collection of 7×10^6 signal events would be required for this measurement.

In summary, an ambitious π^+ decay research program spanning more than a decade has been approved at PSI, addressing the key issues in the quark flavor sector (lepton universality and CKM unitarity) at a new level of precision. The US groups are leading proponents of the project, with a strong expertise in the key detector systems. Support of the US effort at both universities and national labs is crucial.

5 Decays of $\eta^{(\prime)}$ mesons

5.1 Theory overview

The $\eta^{(\prime)}$ mesons have the quantum numbers of the vacuum and the Higgs boson, except for parity. This is a rare occurrence in nature, which not only constrains the decay dynamics of these mesons, but also provides a pure initial state free of any SM charge. Strong and electromagnetic $\eta^{(\prime)}$ decays are either anomalous or forbidden at the lowest order due to symmetries and angular momentum conservation, which enhances the relative importance of higher-order contributions and new weakly-coupled interactions. Therefore $\eta^{(\prime)}$ decays provide a unique, flavor-conserving laboratory for investigation of fundamental physics under a broad theme of symmetry and symmetry-breaking, both within the SM and beyond. The highest-priority decay channels [106], allowing for precision SM tests, searches for BSM physics, discrete symmetry violation or potential new light particles, are listed in Table 1. It should be noted that, with a sufficiently large sample of $\eta^{(\prime)}$ meson decays, all the four portals connecting the SM with possible dark sectors could be explored, including the vector [107, 108, 109], (pseudo)scalar [110, 111] and heavy neutral lepton portals.

Standard Model decays

- The $\eta \to 3\pi$ decay provides the only experimental determination of the light quark mass difference, $m_d - m_u$. This decay is forbidden by isospin symmetry: three pions cannot combine into a system with vanishing angular momentum, zero isospin, and even C-parity. Isospin-breaking contributions can arise in the SM from either electromagnetic or strong interactions. The $\eta \to 3\pi$ decay is unique because the electromagnetic contributions vanish at leading order in Chiral Perturbation Theory (χPT) [112, 113], and higher order contribu-

Decay channel	Standard Model	Discrete symmetries	Light BSM particles
$\eta \to \pi^+\pi^-\pi^0$	Light quark masses	C/CP violation	Scalar bosons
$\eta^{(\prime)} \to \gamma\gamma$	η–η' mixing, partial widths		
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$	LFU	Z' bosons, dark photon
$\eta \to \pi^0\gamma\gamma$	Higher-order χPT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	
$\eta \to \pi^0\ell^+\ell^-$		C violation	Scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$	LFU	ALPs, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$		C violation, LFU	ALPs

Table 1: High-priority $\eta^{(\prime)}$ decays, with emphasis on synergies of SM and BSM investigations [106].

tions are also suppressed [114, 115], providing direct access to $m_d - m_u$ via the quark mass double ratio $Q = (m_s^2 - \hat{m}^2)/(m_d^2 - m_u^2)$, with $\hat{m} = (m_u + m_d)/2$. Theoretical issues to be addressed concern a more precise matching to the χPT representation, which currently constitutes the dominating theoretical uncertainty [116], and an improved implementation of radiative corrections and other higher-order isospin-breaking effects [115, 117]. In principle, $\eta' \to 3\pi$ can also give access to the light quark mass difference. However the interpretation of $\eta' \to 3\pi$ measurements requires significant theoretical advances: while a dispersive representation to describe the Dalitz plot distributions is within reach, its matching to a systematic effective field theory comparable to the program for $\eta \to 3\pi$ (χPT, even if supplemented with large-N_c arguments) requires further development.

- Precision measurements of the $\eta^{(\prime)} \to \gamma\gamma$ decay widths are of importance for several reasons: they serve as reference channels for other decays; they provide the normalization of the corresponding transition form factors and thus contribute to our understanding of hadronic light-by-light scattering in $(g-2)_\mu$ [118]; and their pattern allows the extraction of η–η' mixing parameters, improving the understanding of the $U(1)_A$ anomaly and its interplay with chiral symmetry.

- The $\eta^{(\prime)}$ transition form factors both have an impact on hadronic contributions to $(g-2)_\mu$, and provide insight into the hadronic structure. Data in different kinematic regimes, from all possible decay and production processes, should be analyzed simultaneously, with theoretical representations apt for such analytic continuation. Besides direct measurements, the statistical leverage of using hadronic decay channels to reconstruct the transition form factors dispersively should be taken advantage of, in particular via data on decays such as $\eta' \to 2(\pi^+\pi^-)$, $\eta' \to \pi^+\pi^-e^+e^-$, $\eta' \to \omega e^+e^-$ (or, in a production reaction, $e^+e^- \to \eta\pi^+\pi^-$). Detailed differential information represents the primary goal.

- The $\eta \to \pi^0\gamma\gamma$ decay: while decay amplitude suppression in the chiral expansion and the interplay between vector exchange and scalar S-wave rescattering dynamics make for a highly interesting theoretical challenge to predict its properties accurately, the interpretation in terms of fundamental insights needs to be improved. This includes a simultaneous analysis of $\eta \to \pi^0\gamma\gamma$, $\eta' \to \eta\gamma\gamma$ and $\eta' \to \pi^0\gamma\gamma$ decays, and the relation to hadronic light-by-light scattering. In addition to high-precision investigation of QCD dynamics, these processes also allow a search for new light particles.

Symmetry tests and lepton flavor/universality violation

- P and CP violation. From the theory point of view, a large number of P and CP-violating $\eta^{(\prime)}$ decays are excluded indirectly through the stringent neutron EDM bounds. An exception is the muon polarization asymmetry in the $\eta \to \mu^+\mu^-$ decay probing flavor-conserving CP violation in the second generation [119]. Improved experimental bounds on classic channels such as $\eta^{(\prime)} \to \pi\pi$ are welcome but unlikely to find evidence of BSM physics in the foreseeable future.

- C and CP violation. On the theory side, much of the literature on C and CP violation in $\eta^{(\prime)}$ decays, particularly in regards to the appearance of mirror symmetry breaking in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot, predates the SM, and little has been done within a modern context. The C and CP-violating charge asymmetry in the Dalitz plot appears through the interference of a new-physics amplitude with the SM, making it linear, rather than quadratic, in C and CP-violating parameters [120]. The manner in which this effect can be generated has been studied in SM effective field theory (SMEFT), and it can be related to operators not participating in the generation of a permanent EDM [121, 122]. In contrast, given EDM constraints, the traditional C-violating channel $\eta^{(\prime)} \to 3\gamma$ probes BSM physics that is C and P-violating but CP-conserving. It should be investigated further how large the $\eta^{(\prime)} \to 3\gamma$ rate could be in such a scenario. On the experimental side, the study of C and CP-violating asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot offers synergies with the QCD/SM motivation for high-precision investigations of this channel [120, 123]. Channels originally proposed to test C and CP-violation can also be used to search for new light particles. These include $\eta^{(\prime)} \to \pi^0(\pi^0)\ell^+\ell^-$ which are C and CP-violating as single-γ processes in QED, but can arise from new light (pseudo)scalar bosons.

- Second class currents in τ decays, such as $\tau^- \to \pi^-\eta^{(\prime)}\nu$, are suppressed in the SM by isospin-violating effects to a few parts in 10^{-5}. This offers an interesting case to search for BSM physics, as the rates of $\tau^- \to \pi^-\eta^{(\prime)}\nu$ decays are enhanced by the contribution of scalar currents from a putative extended Higgs sector [124] or leptoquark bosons [125]. A precision measurement of the $\tau^- \to \pi^-\eta^{(\prime)}\nu$ branching fraction expected at Belle II [41] would put stringent constraints on non-SM scalar interactions, stronger than those from other low-energy observables [126], provided theoretical progress in the determination of the scalar form factor is made.

- Lepton flavor violation. In light of strong constraints on $\mu \to e$ conversion on nuclei, further theoretical studies are required to motivate the searches for the lepton flavor violating $\eta^{(\prime)} \to e^\pm\mu^\mp$ decays. On the other hand, decays that violate charged lepton flavor by two units, such as $\eta^{(\prime)} \to e^\pm e^\pm \mu^\mp \mu^\mp$, are not similarly constrained.

- Lepton flavor universality (LFU). Leptonic and semileptonic decays of the $\eta^{(\prime)}$ mesons have clear experimental signatures, and represent a good opportunity for LFU tests. The most relevant groups of processes are $\eta^{(\prime)} \to \ell_1\bar{\ell}_1\ell_2\bar{\ell}_2$ and $\eta^{(\prime)} \to \gamma\ell\bar{\ell}$. The decay amplitude is dominated by the $\eta^{(\prime)} \to \gamma\gamma$ vertex in both cases. This contribution may be affected by BSM physics, for example t-channel exchange of a leptoquark.

5.2 Planned $\eta^{(\prime)}$ decay experiments

The JEF experiment [127, 128] under construction at Jefferson Laboratory aims for precision measurements of a wide range of $\eta^{(\prime)}$ decays, with emphasis on rare decay modes. The experiment was approved in 2017, and the data collection is expected to start in 2024. The JEF physics program includes improved measurements of SM $\eta^{(\prime)}$ decays and tests of discrete symmetries, as discussed in Section 5.1. Highly boosted $\eta^{(\prime)}$ mesons will be produced at the JEF experiment by a 8–12 GeV tagged photon beam via the $\gamma + p \to \eta^{(\prime)} + p$ reaction, at a rate of 5×10^7 of both η and η' species in 100 days of operation. The experiment will use an upgraded GlueX setup [129]. In particular, the new forward electromagnetic calorimeter (FCAL-II) will involve a new high-granularity array of 1600 $PbWO_4$ scintillating crystals of 2×2 cm^2 cross-section in the central region. A prototype array of 140 crystals was tested successfully at Jefferson Laboratory in 2019 [130], and FCAL-II construction is currently in progress. Photons and leptons from $\eta^{(\prime)}$ decays will be measured by the FCAL-II calorimeter, while charged $\eta^{(\prime)}$ decay products will be measured by the GlueX solenoid magnetic spectrometer and time-of-flight detectors. Backgrounds will be suppressed thanks to $\eta^{(\prime)}$ tagging via recoil proton detection. The highly-boosted $\eta^{(\prime)}$ mesons and the tagging capability offers two orders of magnitude improvement in background suppression and improved control of systematic effects with respect to earlier experiments [131, 132, 133, 134, 135].

In the longer term, the proposed next-generation REDTOP $\eta^{(\prime)}$ factory aims to produce $\mathcal{O}(10^{14})$ η mesons and $\mathcal{O}(10^{12})$ η' mesons in a few years of operation [122], addressing at a new level of precision rare $\eta^{(\prime)}$ decays, BSM physics, and searches for the violation of fundamental symmetries or lepton flavor universality. From the experimental point of view, REDTOP is complementary to JEF: it is designed to final states with at least two charged particles, as opposed to neutral particles. Recent studies indicate that the experiment could reach sensitivity to the branching ratios of certain BSM processes of the order 10^{-11}. The REDTOP proposal involves production of $\eta^{(\prime)}$ mesons via decays of baryonic resonances by nuclear scattering of a continuous-wave proton beam in a Lithium target composed of multiple thin foils. Proton kinetic energy of 1.8 (3.6) GeV is proposed for η (η') production. In the η mode, the required proton rate of 10^{11} POT/second (corresponding to 30 W beam power) would generate an inelastic interaction rate of 1 GHz and produce 5.1×10^6 η mesons per second. The proposed REDTOP setup employs a 4π geometry surrounding the target, and includes a vertex detector capable of identifying secondary vertices, a central tracker, a threshold Cherenkov detector used for particle identification and time-of-flight measurements, and a dual-readout sampling electromagnetic calorimeter. The $\eta^{(\prime)}$ mesons will be produced almost at rest, therefore minimization of the material budget in the detector is a primary consideration (in particular, the expected total beam pipe and tracker material budget is below $1\% X_0$). The high inelastic interaction rate poses significant challenges for timing, trigger and data processing. Although the choice of technologies for the trackers and the facility hosting the experiment are still to be finalized (FNAL, CERN, BNL, GSI, ESS and HIAF have been considered), the experiment aims to start taking data within the next decade.

In summary, η and η' mesons provide a unique, flavor-conserving laboratory for tests of low-energy quantum chromodynamics and searches for BSM physics, and there is a strong physics case for η factories. The JEF experiment is expected to improve significantly the precision on $\eta^{(\prime)}$ decay measurements in the next decade. Design and sensitivity studies are in progress for a next-generation $\eta^{(\prime)}$ factory, REDTOP.

6 Summary

Precision measurements of strange and light quark decays represent an essential element in the international particle physics program. Present and next-generation experiments, performed at high-intensity facilities, have a unique potential to observe signatures of new physics beyond the SM description at mass scales well beyond those directly accessible by current or foreseeable accelerators (up to the PeV scale), or to discover hidden sectors (with mediator masses below 1 GeV). Major progress in kaon, hyperon, pion, and $\eta^{(\prime)}$ decay measurements is foreseen in the next decade, and progress in theory and lattice QCD will be crucial for the interpretation of the experimental results.

It is recommended that the US particle physics community maintains and extends the involvement with this vital area of research, taking advantage of the medium-scale initiatives, many of which are centered in Europe and Asia. These experiments lead to powerful physics insights on relatively short time scales, offer opportunities of making leading contributions to potential BSM discoveries, and provide comprehensive experimental training at various stages including experimental design, R&D, detector construction, data collection and analysis.

References

[1] J. Aebischer, A.J. Buras and J. Kumar, *On the Importance of Rare Kaon Decays: A Snowmass 2021 White Paper*, in *2022 Snowmass Summer Study*, 3, 2022 [2203.09524].

[2] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *Can we reach the Zeptouniverse with rare K and $B_{s,d}$ decays?*, *JHEP* **11** (2014) 121 [1408.0728].

[3] G. D'Ambrosio and T. Kitahara, *Direct CP Violation in $K \to \mu^+\mu^-$*, *Phys. Rev. Lett.* **119** (2017) 201802 [1707.06999].

[4] A. Dery, M. Ghosh, Y. Grossman and S. Schacht, *$K \to \mu^+\mu^-$ as a clean probe of short-distance physics*, *JHEP* **07** (2021) 103 [2104.06427].

[5] V. Cirigliano, G. Ecker, H. Neufeld, A. Pich and J. Portoles, *Kaon Decays in the Standard Model*, *Rev. Mod. Phys.* **84** (2012) 399 [1107.6001].

[6] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, *$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ in the Standard Model: status and perspectives*, *JHEP* **11** (2015) 033 [1503.02693].

[7] A.J. Buras and E. Venturini, *Searching for New Physics in Rare K and B Decays without $|V_{cb}|$ and $|V_{ub}|$ Uncertainties*, 2109.11032.

[8] A.J. Buras and E. Venturini, *The Exclusive Vision of Rare K and B Decays and of the Quark Mixing in the Standard Model*, 2203.11960.

[9] A.J. Buras, *Standard Model Predictions for Rare K and B Decays without New Physics Infection*, 2209.03968.

[10] Z. Bai, N.H. Christ, X. Feng, A. Lawson, A. Portelli and C.T. Sachrajda, *$K^+ \to \pi^+\nu\bar{\nu}$ decay amplitude from lattice QCD*, *Phys. Rev. D* **98** (2018) 074509 [1806.11520].

[11] RBC, UKQCD collaboration, *Lattice QCD study of the rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ at a near-physical pion mass*, *Phys. Rev. D* **100** (2019) 114506 [1910.10644].

[12] T. Blum et al., *Discovering new physics in rare kaon decays*, in *2022 Snowmass Summer Study*, 3, 2022 [2203.10998].

[13] A.J. Buras, D. Buttazzo and R. Knegjens, *$K \to \pi\nu\bar{\nu}$ and ε'/ε in simplified new physics models*, *JHEP* **11** (2015) 166 [1507.08672].

[14] G. Buchalla and A.J. Buras, $\sin 2\beta$ *from $K \to \pi\nu\bar{\nu}$*, *Phys. Lett. B* **333** (1994) 221 [hep-ph/9405259].

[15] A.J. Buras, *New physics patterns in ε'/ε and ε_K with implications for rare kaon decays and ΔM_K*, *JHEP* **04** (2016) 071 [1601.00005].

[16] J. Aebischer, A.J. Buras and J. Kumar, *Another SMEFT story: Z' facing new results on ϵ'/ϵ, ΔM_K and $K \to \pi\nu\bar{\nu}$*, *JHEP* **12** (2020) 097 [2006.01138].

[17] W. Altmannshofer, A.J. Buras, D.M. Straub and M. Wick, *New strategies for New Physics search in $B \to K^*\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$ and $B \to X_s\nu\bar{\nu}$ decays*, *JHEP* **04** (2009) 022 [0902.0160].

[18] A.J. Buras, J. Girrbach-Noe, C. Niehoff and D.M. Straub, *$B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond*, *JHEP* **02** (2015) 184 [1409.4557].

[19] M. Bordone, D. Buttazzo, G. Isidori and J. Monnard, *Probing Lepton Flavour Universality with $K \to \pi\nu\bar{\nu}$ decays*, *Eur. Phys. J. C* **77** (2017) 618 [`1705.10729`].

[20] F.F. Deppisch, K. Fridell and J. Harz, *Constraining lepton number violating interactions in rare kaon decays*, *JHEP* **12** (2020) 186 [`2009.04494`].

[21] N.H. Christ and Z. Bai, *Computing the long-distance contributions to ε_K*, *PoS* **LATTICE2015** (2016) 342.

[22] RBC, UKQCD collaboration, *Direct CP violation and the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay from the standard model*, *Phys. Rev. D* **102** (2020) 054509 [`2004.09440`].

[23] B. Wang, *Lattice calculation of the mass difference between the long- and short-lived K mesons for physical quark masses*, Ph.D. thesis, Columbia U. (main), 2021. 10.7916/d8-fmzr-ys91.

[24] NA48 collaboration, *A Precision measurement of direct CP violation in the decay of neutral kaons into two pions*, *Phys. Lett. B* **544** (2002) 97 [`hep-ex/0208009`].

[25] KTeV collaboration, *Precise Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System*, *Phys. Rev. D* **83** (2011) 092001 [`1011.0127`].

[26] Y. Aoki et al., *FLAG Review 2021*, `2111.09849`.

[27] J.C. Hardy and I.S. Towner, *Superallowed $0^+ \to 0^+$ nuclear β decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity*, *Phys. Rev. C* **102** (2020) 045501.

[28] A. Czarnecki, W.J. Marciano and A. Sirlin, *Neutron Lifetime and Axial Coupling Connection*, *Phys. Rev. Lett.* **120** (2018) 202002 [`1802.01804`].

[29] C.-Y. Seng, X. Feng, M. Gorchtein and L.-C. Jin, *Joint lattice QCD–dispersion theory analysis confirms the quark-mixing top-row unitarity deficit*, *Phys. Rev. D* **101** (2020) 111301 [`2003.11264`].

[30] V. Cirigliano, A. Crivellin, M. Hoferichter and M. Moulson, *Scrutinizing CKM unitarity with a new measurement of the $K_{\mu 3}/K_{\mu 2}$ branching fraction*, `2208.11707`.

[31] D. Bryman, V. Cirigliano, A. Crivellin and G. Inguglia, *Testing Lepton Flavor Universality with Pion, Kaon, Tau, and Beta Decays*, `2111.05338`.

[32] PACS collaboration, *$K_{\ell 3}$ form factors at the physical point towards the continuum limit*, `2206.08654`.

[33] N. Carrasco, V. Lubicz, G. Martinelli, C.T. Sachrajda, N. Tantalo, C. Tarantino et al., *QED Corrections to Hadronic Processes in Lattice QCD*, *Phys. Rev. D* **91** (2015) 074506 [`1502.00257`].

[34] P.A. Boyle, V. Guelpers, A. Juettner, C. Lehner, F.O. hOgain, A. Portelli et al., *QED corrections to leptonic decay rates*, *PoS* **LATTICE2018** (2019) 267 [`1902.00295`].

[35] X. Feng, L. Jin and M.J. Riberdy, *Lattice QCD Calculation of the Pion Mass Splitting*, *Phys. Rev. Lett.* **128** (2022) 052003 [`2108.05311`].

[36] C.-Y. Seng, X. Feng, M. Gorchtein, L.-C. Jin and U.-G. Meißner, *New method for calculating electromagnetic effects in semileptonic beta-decays of mesons*, *JHEP* **10** (2020) 179 [`2009.00459`].

[37] C.-Y. Seng, D. Galviz and U.-G. Meißner, *A New Theory Framework for the Electroweak Radiative Corrections in K_{l3} Decays*, *JHEP* **02** (2020) 069 [1910.13208].

[38] C.-Y. Seng, D. Galviz, M. Gorchtein and U.G. Meißner, *High-precision determination of the Ke3 radiative corrections*, *Phys. Lett. B* **820** (2021) 136522 [2103.00975].

[39] C.-Y. Seng, D. Galviz, M. Gorchtein and U.-G. Meißner, *Improved K_{e3} radiative corrections sharpen the $K_{\mu 2}$–$K_{\ell 3}$ discrepancy*, *JHEP* **11** (2021) 172 [2103.04843].

[40] C.-Y. Seng, D. Galviz, M. Gorchtein and U.-G. Meißner, *Complete theory of radiative corrections to $K_{\ell 3}$ decays and the V_{us} update*, *JHEP* **07** (2022) 071 [2203.05217].

[41] Belle-II collaboration, *Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond*, 2207.06307.

[42] A.M. Abdullahi et al., *The Present and Future Status of Heavy Neutral Leptons*, in *2022 Snowmass Summer Study*, 3, 2022 [2203.08039].

[43] NA62 collaboration, *Search for heavy neutral lepton production in K^+ decays to positrons*, *Phys. Lett. B* **807** (2020) 135599 [2005.09575].

[44] PIENU collaboration, *Improved search for heavy neutrinos in the decay $\pi \to e\nu$*, *Phys. Rev. D* **97** (2018) 072012 [1712.03275].

[45] D.A. Bryman and R. Shrock, *Constraints on Sterile Neutrinos in the MeV to GeV Mass Range*, *Phys. Rev. D* **100** (2019) 073011 [1909.11198].

[46] A. Crivellin, G. D'Ambrosio, M. Hoferichter and L.C. Tunstall, *Violation of lepton flavor and lepton flavor universality in rare kaon decays*, *Phys. Rev. D* **93** (2016) 074038 [1601.00970].

[47] C. Cornella, P. Paradisi and O. Sumensari, *Hunting for ALPs with Lepton Flavor Violation*, *JHEP* **01** (2020) 158 [1911.06279].

[48] A. Abada, V. De Romeri, M. Lucente, A.M. Teixeira and T. Toma, *Effective Majorana mass matrix from tau and pseudoscalar meson lepton number violating decays*, *JHEP* **02** (2018) 169 [1712.03984].

[49] E. Goudzovski et al., *New Physics Searches at Kaon and Hyperon Factories*, 2201.07805.

[50] G. Krnjaic, G. Marques-Tavares, D. Redigolo and K. Tobioka, *Probing Muonphilic Force Carriers and Dark Matter at Kaon Factories*, *Phys. Rev. Lett.* **124** (2020) 041802 [1902.07715].

[51] KOTO, LHCb, NA62/KLEVER, US Kaon Interest Group collaboration, *Searches for new physics with high-intensity kaon beams*, 4, 2022 [2204.13394].

[52] NA62 collaboration, *The Beam and detector of the NA62 experiment at CERN*, *JINST* **12** (2017) P05025 [1703.08501].

[53] NA62 collaboration, *Measurement of the very rare $K^+ \to \pi^+ \nu \overline{\nu}$ decay*, *JHEP* **06** (2021) 093 [2103.15389].

[54] BNL-E949 collaboration, *Study of the decay $K^+ \to \pi^+ \nu \bar{\nu}$ in the momentum region $140 < P_\pi < 199$ MeV/c*, *Phys. Rev. D* **79** (2009) 092004 [0903.0030].

[55] NA62 Collaboration, "2021 NA62 status report to the CERN SPSC." 2021.

[56] F. Mescia, C. Smith and S. Trine, *$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$: A Binary star on the stage of flavor physics*, *JHEP* **08** (2006) 088 [hep-ph/0606081].

[57] W. Baldini et al., *SHADOWS (Search for Hidden And Dark Objects With the SPS)*, 2110.08025.

[58] H. Bartosik et al., *SPS operation and future proton sharing scenarios for the SHiP experiment at the BDF facility*, Tech. Rep. CERN-ACC-NOTE-2018-002, CERN (2018).

[59] KLEVER Project collaboration, *KLEVER: An experiment to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at the CERN SPS*, 1901.03099.

[60] D. Banerjee et al., *The report of the Conventional Beams Working Group to the Physics Beyond Colliders study and to the European Strategy for Particle Physics*, Tech. Rep. CERN-PBC-NOTES-2018-005, CERN (2018).

[61] L. Gatignon et al., *Report from the Conventional Beams Working Group to the Physics Beyond Colliders study and to the European Strategy for Particle Physics*, Tech. Rep. CERN-PBC-REPORT-2018-002, CERN (2018).

[62] M. Van Dijk et al., *The K12 beamline for the KLEVER experiment*, .

[63] J. Beacham et al., *Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report*, *J. Phys. G* **47** (2020) 010501 [1901.09966].

[64] KOTO collaboration, *Search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ decays at the J-PARC KOTO experiment*, *Phys. Rev. Lett.* **122** (2019) 021802 [1810.09655].

[65] KOTO collaboration, *Study of the $K_L \to \pi^0 \nu\bar{\nu}$ Decay at the J-PARC KOTO Experiment*, *Phys. Rev. Lett.* **126** (2021) 121801 [2012.07571].

[66] NA62 collaboration, *Searches for lepton number violating K^+ decays*, *Phys. Lett. B* **797** (2019) 134794 [1905.07770].

[67] NA62 collaboration, *Search for Lepton Number and Flavor Violation in K^+ and π^0 Decays*, *Phys. Rev. Lett.* **127** (2021) 131802 [2105.06759].

[68] NA62 collaboration, *Searches for lepton number violating $K^+ \to \pi^-(\pi^0)e^+e^+$ decays*, 2202.00331.

[69] NA62 collaboration, *Search for production of an invisible dark photon in π^0 decays*, *JHEP* **05** (2019) 182 [1903.08767].

[70] NA62 collaboration, *Search for a feebly interacting particle X in the decay $K^+ \to \pi^+ X$*, *JHEP* **03** (2021) 058 [2011.11329].

[71] NA62 collaboration, *Search for π^0 decays to invisible particles*, *JHEP* **02** (2021) 201 [2010.07644].

[72] NA62 collaboration, *Search for K^+ decays to a muon and invisible particles*, *Phys. Lett. B* **816** (2021) 136259 [2101.12304].

[73] KOTO collaboration, *First search for $K_L \to \pi^0 \gamma$*, *Phys. Rev. D* **102** (2020) 051103 [2006.14918].

[74] O. Fischer et al., *Unveiling Hidden Physics at the LHC*, 2109.06065.

[75] Particle Data Group collaboration, *Review of Particle Physics*, *PTEP* **2020** (2020) 083C01.

[76] NA62 collaboration, *Precision Measurement of the Ratio of the Charged Kaon Leptonic Decay Rates*, *Phys. Lett. B* **719** (2013) 326 [1212.4012].

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

[78] LHCb collaboration, *Constraints on the $K^0_S \to \mu^+\mu^-$ Branching Fraction*, *Phys. Rev. Lett.* **125** (2020) 231801 [2001.10354].

[79] A.A. Alves Junior et al., *Prospects for Measurements with Strange Hadrons at LHCb*, *JHEP* **05** (2019) 048 [1808.03477].

[80] HyperCP collaboration, *HyperCP: A High-rate spectrometer for the study of charged hyperon and kaon decays*, *Nucl. Instrum. Meth. A* **541** (2005) 516 [hep-ex/0405034].

[81] HyperCP collaboration, *Search for CP violation in charged-Xi and Lambda hyperon decays*, *Phys. Rev. Lett.* **93** (2004) 262001 [hep-ex/0412038].

[82] BESIII collaboration, *Precision measurements of decay parameters and CP asymmetry in Λ decays*, 2204.11058.

[83] BESIII collaboration, *Σ^+ and $\bar{\Sigma}^-$ polarization in the J/ψ and $\psi(3686)$ decays*, *Phys. Rev. Lett.* **125** (2020) 052004 [2004.07701].

[84] BESIII collaboration, *Probing CP symmetry and weak phases with entangled double-strange baryons*, *Nature* **606** (2022) 64 [2105.11155].

[85] N. Salone, P. Adlarson, V. Batozskaya, A. Kupsc, S. Leupold and J. Tandean, *Study of CP violation in hyperon decays at Super Charm-Tau Factories with a polarized electron beam*, in *2022 Snowmass Summer Study*, 3, 2022 [2203.03035].

[86] J. Tandean and G. Valencia, *CP violation in hyperon nonleptonic decays within the standard model*, *Phys. Rev. D* **67** (2003) 056001 [hep-ph/0211165].

[87] BESIII collaboration, *First Measurement of the Absolute Branching Fraction of $\Lambda \to p\mu^-\bar{\nu}_\mu$*, *Phys. Rev. Lett.* **127** (2021) 121802 [2107.06704].

[88] BESIII collaboration, *Search for the hyperon semileptonic decay $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$*, *Phys. Rev. D* **104** (2021) 072007 [2108.09948].

[89] BESIII collaboration, *Search for the lepton number violating decay $\Sigma^- \to pe^-e^-$ and the rare inclusive decay $\Sigma^- \to \Sigma^+ X$*, *Phys. Rev. D* **103** (2021) 052011 [2012.03592].

[90] LHCb collaboration, *Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$*, *Phys. Rev. Lett.* **120** (2018) 221803 [1712.08606].

[91] HyperCP collaboration, *Evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$*, *Phys. Rev. Lett.* **94** (2005) 021801 [hep-ex/0501014].

[92] PiENu collaboration, *Improved Measurement of the $\pi \to e\nu$ Branching Ratio*, *Phys. Rev. Lett.* **115** (2015) 071801 [1506.05845].

[93] PIONEER collaboration, *PIONEER: Studies of Rare Pion Decays*, 2203.01981.

[94] PIONEER collaboration, *Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment*, in *2022 Snowmass Summer Study*, 3, 2022 [2203.05505].

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

[96] D. Pocanic, E. Frlez and A. van der Schaaf, *Experimental study of rare charged pion decays*, *J. Phys. G* **41** (2014) 114002 [1407.2865].

[97] PEN collaboration, *PEN experiment: a precise test of lepton universality*, in *13th Conference on the Intersections of Particle and Nuclear Physics*, 11, 2018 [1812.00782].

[98] PIONEER collaboration, *An LGAD-Based Full Active Target for the PIONEER Experiment*, *Instruments* **5** (2021) 40 [2111.05375].

[99] S. Mihara, *MEG liquid xenon detector*, *J. Phys. Conf. Ser.* **308** (2011) 012009.

[100] MEG collaboration, *Search for the lepton flavour violating decay $\mu^+ \to \mathrm{e}^+\gamma$ with the full dataset of the MEG experiment*, *Eur. Phys. J. C* **76** (2016) 434 [1605.05081].

[101] MEG II collaboration, *The design of the MEG II experiment*, *Eur. Phys. J. C* **78** (2018) 380 [1801.04688].

[102] PIENU collaboration, *Search for heavy neutrinos in $\pi \to \mu\nu$ decay*, *Phys. Lett. B* **798** (2019) 134980 [1904.03269].

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

[104] X. Feng, M. Gorchtein, L.-C. Jin, P.-X. Ma and C.-Y. Seng, *First-principles calculation of electroweak box diagrams from lattice QCD*, *Phys. Rev. Lett.* **124** (2020) 192002 [2003.09798].

[105] A. Czarnecki, W.J. Marciano and A. Sirlin, *Pion beta decay and Cabibbo-Kobayashi-Maskawa unitarity*, *Phys. Rev. D* **101** (2020) 091301 [1911.04685].

[106] L. Gan, B. Kubis, E. Passemar and S. Tulin, *Precision tests of fundamental physics with η and η' mesons*, *Phys. Rept.* **945** (2022) 2191 [2007.00664].

[107] J.L. Feng, B. Fornal, I. Galon, S. Gardner, J. Smolinsky, T.M.P. Tait et al., *Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions*, *Phys. Rev. Lett.* **117** (2016) 071803 [1604.07411].

[108] A.E. Nelson and N. Tetradis, *CONSTRAINTS ON A NEW VECTOR BOSON COUPLED TO BARYONS*, *Phys. Lett. B* **221** (1989) 80.

[109] S. Tulin, *New weakly-coupled forces hidden in low-energy QCD*, *Phys. Rev. D* **89** (2014) 114008 [1404.4370].

[110] A.I. B. Batell, A. Freitas and D. McKeen, *Probing light dark matter with a hadrophilic scalar mediator*, *Phys. Rev. D* **100** (2019) 095020.

[111] Y.-S. Liu, I.C. Cloët and G.A. Miller, *Eta Decay and Muonic Puzzles*, *Nucl. Phys.* **B** (2019) 114638 [1805.01028].

[112] J.S. Bell and D.G. Sutherland, *Current algebra and $\eta \to 3\pi$*, Nucl. Phys. B **4** (1968) 315.

[113] D.G. Sutherland, *Current algebra and the decay $\eta \to 3\pi$*, Phys. Lett. **23** (1966) 384.

[114] R. Baur, J. Kambor and D. Wyler, *Electromagnetic corrections to the decays $\eta \to 3\pi$*, Nucl. Phys. B **460** (1996) 127 [`hep-ph/9510396`].

[115] C. Ditsche, B. Kubis and U.-G. Meissner, *Electromagnetic corrections in $\eta \to 3\pi$ decays*, Eur. Phys. J. C **60** (2009) 83 [`0812.0344`].

[116] G. Colangelo, S. Lanz, H. Leutwyler and E. Passemar, *Dispersive analysis of $\eta \to 3\pi$*, Eur. Phys. J. C **78** (2018) 947 [`1807.11937`].

[117] S.P. Schneider, B. Kubis and C. Ditsche, *Rescattering effects in $\eta \to 3\pi$ decays*, JHEP **02** (2011) 028 [`1010.3946`].

[118] G. Colangelo et al., *Prospects for precise predictions of a_μ in the Standard Model*, `2203.15810`.

[119] P. Sanchez-Puertas, *CP violation in η muonic decays*, JHEP **01** (2019) 031 [`1810.13228`].

[120] S. Gardner and J. Shi, *Patterns of CP violation from mirror symmetry breaking in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot*, Phys. Rev. D **101** (2020) 115038 [`1903.11617`].

[121] J. Shi, *Theoretical Studies of C and CP Violation in $\eta \to \pi^+\pi^-\pi^0$ Decay*, Ph.D. thesis, Kentucky U., 2020. 10.13023/etd.2020.388.

[122] REDTOP collaboration, *The REDTOP experiment: Rare η/η' Decays To Probe New Physics*, `2203.07651`.

[123] H. Akdag, T. Isken and B. Kubis, *Patterns of C- and CP-violation in hadronic η and η' three-body decays*, JHEP **02** (2022) 137 [`2111.02417`].

[124] M. Jung, A. Pich and P. Tuzon, *Charged-Higgs phenomenology in the Aligned two-Higgs-doublet model*, JHEP **11** (2010) 003 [`1006.0470`].

[125] D. Bečirević, S. Fajfer, N. Košnik and O. Sumensari, *Leptoquark model to explain the B-physics anomalies, R_K and R_D*, Phys. Rev. D **94** (2016) 115021 [`1608.08501`].

[126] E.A. Garcés, M. Hernández Villanueva, G. López Castro and P. Roig, *Effective-field theory analysis of the $\tau^- \to \eta^{(\prime)}\pi^-\nu_\tau$ decays*, JHEP **12** (2017) 027 [`1708.07802`].

[127] M. Dugger et al., "Eta Decays with Emphasis on Rare Neutral Modes: The JLab Eta Factory (JEF) Experiment." 2014.

[128] H. Al Ghoul et al., "Update to the JEF proposal (PR12-14-004)." 2017.

[129] GlueX collaboration, *The GlueX Beamline and Detector*, Nucl. Instrum. Meth. A **987** (2021) 164807 [`2005.14272`].

[130] A. Asaturyan et al., *Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab*, Nucl. Instrum. Meth. A **1013** (2021) 165683.

[131] A2 collaboration, *Recent Results on Meson Decays from A2*, EPJ Web Conf. **218** (2019) 03002.

[132] A2 collaboration, *Study of η and η' Photoproduction at MAMI*, *Phys. Rev. Lett.* **118** (2017) 212001 [`1701.04809`].

[133] WASA-AT-COSY collaboration, *η meson physics with WASA-at-COSY*, *EPJ Web Conf.* **199** (2019) 01006.

[134] KLOE-2 collaboration, *η and η' physics in KLOE*, *EPJ Web Conf.* **218** (2019) 08003.

[135] BESIII collaboration, *η and η' physics at BESIII*, *PoS* **CD15** (2016) 032.