ADDENDUM I TO P326
Continuation of the physics programme of the NA62 experiment

The NA62 Collaboration

Abstract

The NA62 experiment took data successfully in 2016-2018, and has proven that the decay-in-flight technique employed for ultra-rare kaon decays works. The NA62 Collaboration proposes to continue the data taking of the experiment during the period after CERN Accelerators Long Shutdown 2 (LS2) and before Long Shutdown 3 (LS3). The continuation will allow NA62 to perform a measurement of the branching ratio of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with significantly improved accuracy, to substantially increase its sensitivity on several rare and forbidden kaon decays, and to reach unprecedented sensitivity in the investigation of several Standard Model (SM) extensions involving faintly interacting long-lived particles.

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1 Introduction

The NA62 experiment took data successfully in 2016–2018, collecting about 2.2×10^{18} protons on target (POT), corresponding to about 6×10^{12} K^+ decays in the sensitive decay volume (before quality cuts). A detailed description of the experimental setup can be found in [1]. The main goal of the experiment is to measure precisely the branching ratio of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$, that is well predicted by the Standard Model and is sensitive to new physics models. The predicted branching ratio is $BR(K^+ \to \pi^+\nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$ [2], which is taken as the Standard Model value throughout this document. A number of new physics models foresee sizeable deviations [3, 4, 5, 6, 7, 8, 9, 10, 11].

The experiment employs a decay-in-flight technique described in detail in the P326 proposal [12]. Such technique has been established and proven to work, and sources of background have been studied in detail and identified [13]. A number of results from 2016 and 2017 data sets were presented to the SPSC Committee [14, 15, 16] and have been published. Recent results on 2017 data were presented at the KAON2019 Conference [17] and at a CERN EP Seminar [18]. The experiment has a wider physics programme, including a range of rare kaon decays studies, precise measurements of kaon decay branching ratios and form factors, searches for forbidden processes like Lepton-Number and Lepton-Flavour-Number Violating processes, and searches for exotic particles such as Dark Photons, Heavy Neutral Leptons, axion-like particles (ALPs), etc. Prospects for taking data dumping the beam of the NA62 sensitive region (dump mode) have been discussed as part of the Physics Beyond Collider initiative [19]. More details of the recent results and prospects can be found in the following sections.

2 $K^+ \to \pi^+\nu\bar{\nu}$ measurement

The analysis of 2016 data, taken at about 40% of the nominal beam intensity, achieved a Single Event Sensitivity (SES) of $(3.15 \pm 0.24) \times 10^{-10}$, with a SM expected signal of $0.267 \pm 0.020_{stat+sys} \pm 0.032_{ext}$ events and a total expected background of $0.15^{+0.092}_{-0.033}|_{stat} \pm 0.013_{sys}$ events. The external uncertainty reflects the uncertainty of the SM branching ratio prediction. A cut-based blind analysis revealed the presence of 1 event in the signal region. A detailed description of the analysis procedure can be found in [13].

The 2017 data set was taken at an average beam intensity of 55% of nominal, collecting $(2.0 \pm 0.2) \times 10^{12}$ K^+ decays in the sensitive decay volume before quality and acceptance cuts. The SES is $(0.389 \pm 0.021) \times 10^{-10}$, with a number of SM expected signal events of $2.16 \pm 0.12_{stat+sys} \pm 0.26_{ext}$. This gives an overall signal efficiency of about 1.3% (defined as the ratio between the number of SM expected signal events and the number of kaon decays times the SM branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$). The expected background of $1.5 \pm 0.2_{stat} \pm 0.2_{sys}$ comes from kaon decays in the sensitive decay volume $(0.59 \pm 0.06_{stat} \pm 0.06_{sys})$, and from K^+ decays originating upstream of the final collimator or from interactions of beam particles in the GTK stations $(0.9 \pm 0.2_{stat} \pm 0.2_{sys})$. A cut-based blind analysis, similar to the 2016 one, resulted in the presence of 2 events in the signal region. The combination of 2016 and 2017 datasets gives a limit on the Branching Ratio of $Br(K^+ \to \pi^+\nu\bar{\nu}) < 1.85 \times 10^{-10}$ at 90%CL [20]. In addition, the $K^+ \to \pi^+\nu\bar{\nu}$ analysis leads to a competitive upper limit on the $\pi^0 \to invisible$ decays [17], and to the search for a dark scalar X in the decay $K^+ \to \pi^+ X$ (in preparation).

A detailed inspection of the $K^+ \to \pi^+\nu\bar{\nu}$ analysis and data taking conditions allows the signal efficiency for K^+ decays in the sensitive volume to be explained in terms of geometrical and kinematic acceptance and reduction factors accounting for the effect of trigger, detector and selection inefficiency. The signal acceptance is 16%, including the definition of the signal regions in terms of squared missing mass and pion momentum. The reduction factors are summarised in Table 1. Here, the box cut refers to a x, y cut at the z-position of the final collimator [13]. The random

Table 1: Break-down of the signal efficiency. For the precise definition of the criteria, see [13, 17].

Kinematic selection and geometrical acceptance	0.16
Cut at final collimator against upstream background (box cut)	0.63
Z vertex cut to tighten the sensitive decay volume definition	0.90
Z vertex versus radius cut at Straw chamber against $K \to 3\pi$ background	0.90
Selection criteria against random veto (RV) in the veto detectors	0.64
Kaon-pion association efficiency	0.75
Particle Identification (PID) efficiency	0.65
Trigger efficiency	0.87
Detector efficiency	0.80
DAQ efficiency	0.75
Overall signal efficiency	0.013

veto inefficiency refers to losses of signal events due to accidental activity in veto detectors, i.e. LKr electromagnetic calorimeter, Large Angle Vetoes, Small Angle Vetoes, and track multiplicity detectors. The 3% signal acceptance quoted elsewhere (see for example [17]) refers to the signal efficiency without including random veto losses, trigger and detector efficiencies.

The value of 10% quoted in the P326 Proposal [12] included estimated reduction factors for random veto (0.8), PID (0.8) and kaon-pion association (0.9).

2.1 Prospect for 2018 data analysis

The data taken in 2018 are being analysed. The beam intensity in 2018 was kept stable at an average of 65% of nominal, optimised for efficient data taking conditions. The number of kaon decays in 2018 data is about 4×10^{12}, about twice those collected in 2017.

Assuming for 2018 the same efficiency, acceptance and intensity as in 2017 as a worst-case-scenario, the expected SM signal events would be 4.4 ± 0.4, for a total of 7.0 ± 0.5 expected SM events in 2016–2018. Conservatively assuming that the background scales like the signal, the expected background in 2018 data would be about 3 events, for a total background in 2016–2018 of 4.7 ± 1.0 events; this corresponds to a background-over-signal ratio of B/S=67%, dominated by the contribution of upstream background. The uncertainty is dominated by the extrapolation from 2017 to 2018, and by the background uncertainty in the 2017 sample.

However, the analysis of 2018 data will benefit from the experience acquired from 2017 data and improvements in the data taking strategy. The following improvements factors are expected:

- The replacement of the final collimator in June 2018 will allow the box cut to be loosened. Nevertheless, this cut cannot be completely removed due to the presence of upstream decays still passing through the hole of the collimator, requiring to keep a safety margin around the hole. Therefore the expected improvement factor will be 1.2.
- The kaon-pion association algorithm can be improved using a Multi-Variate analysis; from preliminary results, the gain factor will be 1.1.
- The PID algorithm can be improved applying looser muon-rejection criteria in the high-missing-mass signal region; the gain factor will be 1.1.

- Considering the present very low level of 3π background, its location in the missing mass versus pion momentum plane and the missing mass resolution, the cut above against 3π can be removed, gaining a factor of 1.1.

Taking into account of the total gain factor above of 1.6, the overall signal efficiency increases from 1.3% to 2.1%. Data from 2018 will be used to study in detail the random veto and how to mitigate its effect after 2021.

After considering the improvements mentioned above, but still conservatively assuming the same B/S, the expected number of SM signal events in 2018 data set is 7.0 ± 0.7 events for about 4.8 ± 1.0 background events. Here the same 20% uncertainty on background estimation as in 2017 is assumed. When summed with the 2016-2017 SM expected events, the total signal events expected in the 2016-2018 sample is 9.5 ± 1.0 SM events for a total background of 6.4 ± 1.3 events.

2.2 Prospect after LS2

Towards the end of the 2018 data taking, tests were performed at 100% nominal beam intensity. The limitations in the TDAQ system identified during such tests are being addressed. To ensure that data can be taken efficiently at 100% nominal intensity when the beam is back after LS2, work is in progress towards further improving the TDAQ efficiency, introducing additional detectors (GTK, HASC, anti-counter), controlling the random veto, reducing the background and optimizing the $K^+ \to \pi^+ \nu \bar{\nu}$ analysis.

The TDAQ will be made more resilient to beam high rate activity this will give a 10% gain in the DAQ efficiency. Studies are on-going and will continue using 2018 data to establish how the effect of random veto can be controlled and maintained at the same level as in 2018 when the beam intensity is increased to 100% of nominal after LS2. The random veto inefficiency effect is mostly due to offline selection cuts designed to remove accidental events firing the veto detectors. The strategy to limit this inefficiency includes the following steps:

- LKr: pileup effect in the LKr gives a sizeable contribution to the random veto since it can drive the calorimeter cluster timing. At present the event reconstruction uses mainly space information and large time windows to address the pileup. Improving the use of the time information in the reconstruction will limit the effect at increasing beam intensity. A recovery of up-to 5% of the random veto efficiency is expected. The improvement can be even larger at higher intensity.

- LAV: at present the veto algorithm does not distinguish between the various LAV stations and does not use the time-over-threshold information. Studies are on–going on how best to use the time–over–threshold information, as well as combining LAV and other kinematic information (for example Z vertex position) to build a refined veto algorithm. A recovery of up-to 5% of the random veto efficiency is expected.

- SAV (IRC and SAC): studies are on–going on how to exploit the angle–energy correlation of photons in SAV with those in LAV and LKr, to perform an event–based optimization of the photon rejection.

- Multiplicity: at present information from tracking and scintillator detectors are used independently. Including also their correlations would allow a reduction of the veto time windows and a general improvement of the quality of the selection.

Eventually the full 2017 and 2018 samples will be needed to combine all the variables contributing to photon rejection and to find the optimal balance between π^0 rejection and π^+ efficiency. For this reason we plan to improve significantly the random veto after 2021 only.

Studies on how to reduce the background are on-going. In particular, these studies suggest that the addition of the following sub-detectors will contribute substantially to background reduction:

- a symmetric HASC station on the opposite side of the beam pipe will help improving the photon rejection; this will lead to a background reduction of $\pi^+\pi^0$ background of a factor 0.8 (consequently $B(\pi^+\pi^0)/S$ will go from 13% to 10%);

- a 4th GTK station, improving the kaon-pion association, and an Anti-Counter, placed before the final collimator, will reduce the upstream background; based on an extensive simulation, this leads to a reduction of the upstream background of a factor 3-4 (consequently $B(upstream)/S$ will go from 40% to about 10%).

Given the upstream background reduction, the signal efficiency will increase by an additional gain factor for the box cut of 1.2 with respect to 2018.

In conclusion the above improvements will result into an increase of the expected signal efficiency to 2.8%, and into a reduction of the background-over-signal ratio to 35-40%. After considering the increase of beam intensity, the expected number of SM signal events in one 2018-equivalent year data set (i.e. 217 days each year assuming the same SPS efficiency as in 2018) is 14.0 ± 1.5 events. Therefore the total SM signal events expected in three 2018-equivalent years of data taking is of the order of 42 ± 5 events. When summed with the 2016-2018 expected events, the total SM signal events expected before LS3 is of the order of 51 ± 5 events.

Finally, after adding the 4th GTK station, the performance of the beam achromat will be improved by the following factors: 14% in time resolution, 25% in momentum resolution, and 3-5% in tracking efficiency. Also the measurement of dy/dz can be decoupled from that of the momentum. The analysis strategy will be re-optimized to improve the signal sensitivity over background ratio and to enhance the number of signal events, moving from being cut-and-count based to employing multi-variate, shape-based techniques. The trigger strategy is being thoroughly revised and improvements are being considered. Hence further improvements in the signal efficiency and background rejection can be expected, albeit not included in the above estimates.

2.3 Statistical considerations

Assuming $S = 9.5$ and $B = 6.4 \pm 1.3$, the expected significance of a possible SM signal observation from the 2016+2017+2018 data is 2.5σ using a counting approach. This sensitivity decreases to 2.3σ when considering the 3 events already observed in the 2016+2017 data. Preliminary studies show that a m^2_{miss} and π^+ momentum shape analysis increases the sensitivity by 30-40%, thus potentially allowing to reach 3σ SM signal observation with the full 2016+2017+2018 data set. Using a counting approach and assuming $B/S = 0.40(0.35)$ and B known with 20% accuracy, one year of data taking after LS2 would provide a $3.8(3.9)\sigma$ SM signal evidence when combined with the 2016-2018 data. A shape analysis would raise the significance of the observation to 5σ or above.

Using a pure counting approach and conservatively assuming that the background B fluctuate according to a Poisson distribution, the relative statistical uncertainty, $\delta BR/BR$, on the branching ratio measurement in case of $N = S + B$ observed events is

$$\frac{\delta BR}{BR} \approx \frac{\sqrt{\delta N^2 + \delta B^2}}{S} = \frac{1}{\sqrt{S}}\sqrt{1 + 2\frac{B}{S}}. \qquad (1)$$

If $B/S = 0.40(0.35)$, then $\delta BR/BR \simeq 0.19(0.18)$ for $S = 51$. Therefore three additional 2018-like years of data taking after LS2 will allow NA62 to measure the SM branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ with about 20% statistical precision.

The accuracy of the estimations of the single event sensitivity and background are sources of systematic uncertainty. The 2017 analysis has shown that the single event sensitivity is known with about 5% relative accuracy. On the other hand, the background estimation is subject to 20% uncertainty, corresponding to 8%(7%) relative precision on the branching ratio measurement if $B/S = 0.40(0.35)$. In conclusion the systematic uncertainty is expected to be less than 10%.

3 Rare decays and forbidden processes

The NA62 experiment is equipped with pre-scaled auxiliary trigger chains, allowing for a broad rare and forbidden decay physics programme. Multi-track L0 triggers for collection of K^+ decays to lepton pairs (i.e. di-muons, di-electrons and muon-electron pairs) are based on RICH and CHOD multiplicity requirements, as well as the total LKr energy deposit and MUV3 signal multiplicity conditions. The corresponding L1 trigger performs beam kaon identification by the KTAG and online reconstruction of a negatively charged track in the spectrometer. In 2016–18, about 3×10^{12} kaon decays in the sensitive decay volume have been collected with the di-muon trigger, and about 10^{12} with each of the di-electron and muon-electron triggers. Additionally, over 10^{10} kaon decays have been collected with a minimum bias trigger provided by the CHOD and a non-muon trigger based on RICH and CHOD multiplicity with a MUV3 signal veto condition, both downscaled by factors of $\mathcal{O}(100)$.

The NA62 experiment has already collected the world largest samples for a number of rare decays with three tracks in the final state (including $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\pi^+\pi^-\gamma$ and $K^+ \to \ell_1^+\nu\ell_2^+\ell_2^-$ with $\ell_{1,2} = e, \mu$), as well as a single track in the final state ($K^+ \to e^+\nu$, $K^+ \to e^+\nu\gamma$, $K^+ \to \pi^0 e^+\nu\gamma$, $K^+ \to \pi^+\gamma\gamma$).

In particular, a new measurement of the helicity-suppressed ratio $\Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ [21], which provides a test of lepton flavour universality, would allow to improve on the sub-percent precision of the current best measurement [22], aiming to reduce the existing gap of an order of magnitude between the experimental measurement and the theoretical prediction. In addition, existing data allow for another precision lepton flavour universality test by measuring the ratio $\Gamma(K^+ \to \pi^+e^+e^-)/\Gamma(K^+ \to \pi^+\mu^+\mu^-)$ [23].

The data collected also provide record sensitivities to the rates of most lepton number and flavour violating K^+ decays, as well as production of long-lived and short-lived resonances in multi-body K^+ decays which can be interpreted in terms of dark vector, dark scalar or axion emission [24, 25, 26]). The background contamination for most processes is lower than in the previous experiments.

Recent NA62 results include new upper limits on the branching fractions of lepton number violating decays (at 90% CL) obtained with a partial data set [27]:

$$\begin{aligned} \mathcal{B}(K^+ \to \pi^-e^+e^+) &< 2.2 \times 10^{-10}, \\ \mathcal{B}(K^+ \to \pi^-\mu^+\mu^+) &< 4.2 \times 10^{-11}. \end{aligned}$$

In addition, new upper limits on the production of heavy neutral leptons (N) in $K^+ \to e^+N$ and $K^+ \to \mu^+N$ decays have been presented recently at the Kaon 2019 conference [17] and improving over the previous limits in the 140–460 MeV/c^2 heavy neutral lepton mass range by 1–2 orders of magnitude.

A number of on-going analyses based on the 2016–18 data set are expected to produce results by 2021. These include measurements of $K^+ \to \pi^+\mu^+\mu^-$ form factor parameters, $K^+ \to e^+\nu\gamma$ and $K^+ \to \pi^0e^+\nu\gamma$ decay rates, that provide important tests of Chiral Perturbation Theory describing low energy weak processes [28, 29, 30, 31]. Significant efforts go into the validation and improvement of the simulation of the detector response, aiming to understand and reduce the systematic uncertainties on these measurements.

Improvements to the rare decay trigger chains made during LS2 will allow the reduction of the pre-scaling factors and collection of even larger rare decay data sets between LS2 and LS3, entering a high precision era for all rare K^+ decays. The advances expected with the future data set include measurements of the $K^+ \to \pi^+e^+e^-$ and $\pi^0 \to e^+e^-$ processes with the world's largest samples of these decays; measurement of the $K^+ \to \pi^+\gamma e^+e^-$ decay and the first observation of the $K^+ \to \pi^+\gamma\mu^+\mu^-$ decay; improvement of the sensitivities to all forbidden K^+ decays to the range of 10^{-12} to 10^{-11}, and the sensitivity to $\pi^0 \to \mu^\pm e^\mp$ decays to the level below 10^{-10}. A new precision measurement of the $\pi^0 \to e^+e^-$ decay rate will resolve the existing 2σ tension between the SM theoretical prediction [32] and the latest experimental result [33], and thus contribute to understanding of the role of the hadronic light-by-light scattering in muon g-2 [34].

Considering the data volume, the control of systematic effects is crucial for the precision measurements. Data collection between LS2 and LS3 will provide an opportunity of recording special data samples as required to address specific systematic effects and background sources with data-driven methods, using insights from detailed physics analysis. Therefore data collected after LS2 will help reducing both the statistical and systematic uncertainties on rare decay measurements.

Data taking after LS2 could include additional trigger conditions for exploratory studies of the neutrino sector. The very large sample of $K^+ \to \mu^+\nu$ decays can be exploited to select events in which the neutrino interacts in the LKr. Neutrinos of the typical 10 GeV energy interact through deep inelastic charged current processes, producing a detectable hadronic shower in the LKr calorimeter, while the muon could be detected in the MUV. With 10^{13} kaon decays, a few hundred neutrino interaction events are expected. Reconstructing for the first time all the three particles in the $K^+ \to \mu^+\nu$ process would constitute the first tagged neutrino study with precise neutrino energy reconstruction exploiting the two-body decay kinematics.

4 NA62 in dump mode

The NA62's long decay volume and detector characteristics - highly efficient photon vetoes, low material budget, PID capability and excellent tracking performance - make NA62 a suitable experiment for the search of feebly-interacting long-lived particles. The default Be target can be moved away from the beam and the 400-GeV protons allowed to impinge on the two 1.6 m long, beam defining, Fe/Cu collimators (TAX, about 21 nuclear interaction lengths when closed) located about 22 m downstream of the target. The muon halo emerging from the dump is partially swept away by the existing muon clearing system. Switching from the standard beam operation to the beam-dump operation takes of the order of minutes. Details of this operation mode can be found in the Physics Beyond Collider beam documentation [35]. A sample of 10^{18} POT correspond to 10^{18} mesons with the ratios per species $\pi^0/\eta/\eta'/\Phi/\rho/\omega = 6.4/0.68/0.07/0.03/0.94/0.95$, and to $10^{15}(10^{12})$ charmed (beauty) mesons. The mesons might decay to exotic particles (dark photons, heavy neutral leptons, etc.) that are expected to have feeble interactions with SM fields and therefore to be extremely long lived; an exotic particle produced in the target might reach the NA62 sensitive volume, decaying therein. An additional source of exotic particles involves the Primakoff production from virtual or real photons copiously produced in the dump [36].

Detailed studies of the possible background sources have started. During 2016–2018, a sample of about 3×10^{16} POT was collected in about 50 hours of operation, using minimum bias triggers on charged particle tracks. No residual background is found when searching for two-track, zero-net-charge vertices in the current dataset. Concurrently, a sample of 2×10^{16} POT was collected for the search of ALP decays to two photons with a trigger based on signal from the electromagnetic calorimeter. The analysis of this neutral sample shows that with present data NA62 can be sensitive to previously unexplored regions of the ALP parameter space.

The preliminary analysis of these data concluded that, with the present apparatus, a large fraction of the possible background events might enter the decay volume off-axis, outside the sensitive volumes of upstream vetoes (in particular, the CHANTI and LAV sub-detectors). Additional veto instrumentation at the entrance of the decay volume at large angle would be beneficial to control the background in exotic searches, guaranteeing high-efficiency veto capability for charged particles. Given the rates expected when running in beam dump, the requested time resolution for minimum-ionizing particles (MIPs) is of the order of a (few) ns. Preliminary studies suggest that a design based on scintillator tiles can veto MIPs at a level better than 10^3. A hodoscope (Anti0) is being built, to be installed at the start of the decay volume during LS2.

In order to identify the various background sources, a Geant4-based simulation of the beam line has been developed by the Conventional Beam working group within the Physics Beyond Colliders [35]. The simulation has been successfully validated against the data recorded. When running in beam-dump mode, the background is dominated by the effects of muons produced by kaon and pion decays. This can happen in flight, if the mesons are produced in the residual material still present after the target has been lifted, or within the hadronic shower developing in the TAX itself. The second component is softer and distributed with larger spread than the first. The rate for positive muons is dominated by the TAX-produced component. The origin of negative tracks has contributions of the same order from both the TAX and the target. Detailed studies of background sources are still in progress, using all the data collected so far, as well as the simulation.

NA62 plans to collect 10^{18} POT operating in dump mode before LS3; this corresponds to about 90 days at nominal intensity. The beam intensity can however surpass the nominal one and reduce the data taking time, since there are no limitations on the detector or trigger and data acquisition performances, provided the radiation and safety constraints are satisfied; The NA62 projected sensitivity for 10^{18} POT and zero expected background has been studied extensively as part of the Physics Beyond Colliders initiative, and has been found to surpass that of competitive experiments in the same time range. Details on the various new-physics models and the quantitative assumptions behind these limits are given in the BSM PBC Working group report [37].

5 Beam request

The NA62 experiment requests beam time during the entire period between LS2 and LS3, and the continuous support for the improvements foreseen and the operation of the experiment.

This will allow NA62 to achieve a measurement of the branching ratio of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with better than 20% statistical precision for a SM signal. The beam time will also allow a substantial improvement in the sensitivity for several rare and forbidden kaon decays, and to collect enough data in dump mode to reach a record sensitivity in the investigation of the SM extensions involving faintly interacting long-lived particles in a short timescale.

References

[1] E. Cortina Gil et.al. (NA62 collab.), Journal of Instrumentation 12 (2017) P05025

[2] A.J. Buras, D. Buttazzo, J. Girrbach-Noe and R. Knegjens, J. High Energy Phys. 1511 (2015) 33

[3] M. Blanke, A.J. Buras and S. Recksiegel, Eur. Phys. J. C 76 (2016) 182.

[4] M. Blanke, A.J. Buras, B. Duling, K. Gemmler and S. Gori, J. High Energy Phys. 0903 (2009) 108.

[5] A.J. Buras, D. Buttazzo and R, Knegjens, J. High Energy Phys. 1511 (2015) 166.

[6] G. Isidori, F. Mescia, P. Paradisi, C. Smith and S. Trine, J. High Energy Phys. 0608 (2006) 064.

[7] T. Blazek and P. Matak, Nucl. Phys. Proc. Suppl. 198 (2010) 216.

[8] M. Tanimoto and K. Yamamoto, Prog. Theor. Exp. Phys. 2016 (2016) 123B02.

[9] M. Bordone, D. Buttazzo, G. Isidori and J. Monnard, Eur. Phys. J. C 77 (2017) 618.

[10] C. Bobeth and A. J. Buras, J. High Energy Phys. 1802 (2018) 101.

[11] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98 (2018) 030001.

[12] P326 Proposal, CERN-SPSC-2005-013, https://cds.cern.ch/record/832885
NA62 Technical Design, https://cds.cern.ch/record/1404985?ln=en

[13] E. Cortina Gil et.al. (NA62 collab.), Phys. Lett. B791 (2019) 156.

[14] CERN-SPSC-2017-013, https://cds.cern.ch/record/2256924?ln=en

[15] CERN-SPSC-2018-010, https://cds.cern.ch/record/2312430?ln=en

[16] CERN-SPSC-2019-012, https://cds.cern.ch/record/2668548?ln=en

[17] The International Conference on Kaon Physics 2019, Perugia, Italy, https://indico.cern.ch/event/769729/sessions/318725/20190910

[18] NA62 CERN EP Seminar, https://indico.cern.ch/event/846814/

[19] Physics Beyond Colliders, http://pbc.web.cern.ch

[20] Giuseppe Ruggiero's talk at KAON2019 and NA62 paper in preparation

[21] V. Cirigliano and I. Rosell, Phys. Rev. Lett. 99 (2007) 231801.

[22] C. Lazzeroni *et al.* (NA62 collab.), Phys. Lett. B719 (2013) 326-336.

[23] A. Crivellin, G. D'Ambrosio, M. Hoferichter and L.C. Tunstall, Phys. Rev. D93 (2016) 074038.

[24] F. Bezrukov and D. Gorbunov, J. High Energy Phys. 05 (2010) 010.

[25] D. Alves and N. Weiner, J. High Eenergy Phys. 07 (2018) 092.

[26] G. Krnjaic, G. Marques-Tavares, D. Redigolo and K. Tobioka, arXiv:1902.07715.

[27] E. Cortina Gil *et al.*, Phys. Lett. B797 (2019) 134794.

[28] V. Cirigliano, G. Ecker, H. Neufeld, A. Pich and J. Portoles, Rev. Mod. Phys. 84 (2012) 399.

[29] G. Ecker, A. Pich and E. de Rafael, Nucl. Phys. B291 (1987) 692.

[30] J. Bijnens, G. Ecker, and J. Gasser, Nucl. Phys. B396 (1993) 81.

[31] G. Ecker, A. Pich, and E. de Rafael, Nucl. Phys. B303 (1988) 665.

[32] T. Husek, K. Kampf, and J. Novotný, Eur. Phys. J. C74 (2014) 3010.

[33] E. Abouzaid *et al.*, Phys. Rev. D75 (2007) 012004.

[34] Muon g-2 Experiment, https://muon-g-2.fnal.gov/

[35] Report from the Conventional Beams Working Group to the Physics beyond Colliders Study and to the European Strategy for Particle Physics, CERN-PBC-REPORT-2018-002

[36] B. Dbrich, J. Jaeckel and T. Spadaro, J. High Energy Phys. 1905 (2019) 213

[37] J. Beacham *et al.*, Physics Beyond Colliders at CERN: Beyond the Stadard Model Working Group Report, arXiv:1901.09966