IL NUOVO CIMENTO **47 C** (2024) 86
DOI 10.1393/ncc/i2024-24086-y

COLLOQUIA: IFAE 2023

High Intensity Kaon Experiments (HIKE) at CERN SPS(*)

R. FIORENZA for the HIKE COLLABORATION(**)
Scuola Superiore Meridionale & INFN, Sezione di Napoli - Napoli, Italy

received 13 February 2024

Summary. — The availability of a kaon beam in the CERN SPS North Area gives a unique possibility of making tests of the Standard Model in the flavour physics sector. The HIKE programme has been presented at CERN to study rare decays of charged and neutral kaons with unprecedented precision. The realization of this programme will allow for tests of lepton flavour universality and lepton number conservation, as well as other precision measurements in the kaon sector and exotic particle searches.

(*) IFAE 2023 - "Intensity Frontier" session

(**) A. T. Akmete, R. Aliberti, F. Ambrosino, R. Ammendola, A. Antonelli, G. Anzivino, R. Arcidiacono, M. U. Ashraf, D. Baigarashev, L. Bandiera, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blake, T. Blazek, B. Bloch-Devaux, P. C. Boboc, V. Bonaiuto, D. Bortoletto, A. M. Bragadireanu, A. Briano Olvera, D. Britton, F. Brizioli, D. Bryman, F. Bucci, V. Büscher, N. Canale, A. Cardini, S. Carsi, A. Ceccucci, P. Cenci, M. Ceoletta, X. Chang, C. Chiarini, P. Cooper, E. Cortina Gil, F. Costantini, A. Cotta Ramusino, P. Cretaro, S. Cutini, G. D'Ambrosio, C. da Via, J. B. Dainton, P. Dalpiaz, H. Danielsson, G. De Bonis, G. De Nardo, D. De Salvador, A. De Santo, F. Dettori, C. Di Donato, L. Di Lella, E. Di Meco, S. Donati, V. Duk, F. Duval, B. Döbrich, J. Engelfried, N. Estrada-Tristan, R. Fantechi, R. Fiorenza, M. Francesconi, O. Frezza, J. R. Fry, A. Fucci, E. Gamberini, R. Gargiulo, A. Gerbershagen, S. Germani, S. A. Ghinescu, A. Gianoli, R. Giordano, M. Giorgi, S. Giudici, F. Gonnella, M. Gorbahn, E. Goudzovski, R. Guida, V. Guidi, H. Heath, Z. Hives, E. B. Holzer, T. Husek, O. E. Hutanu, D. Hutchcroft, D. Hynds, B. Jenninger, J. Jerhot, R. W. L. Jones, Y. Kambar, K. Kampf, C. Kenworthy, D. Kereibay, S. Kholodenko, A. Kleimenova, M. Koval, M. Kreps, Z. Kucerova, A. Lai, G. Lamanna, G. Lanfranchi, C. Lazzeroni, G. Lehmann Miotto, M. Lenti, S. Lezki, G. Lezzani, P. Lichard, F. Lo Cicero, A. Lonardo, P. Lubrano, N. Lurkin, F. Mahmoudi, L. Malagutti, I. Mannelli, F. Marchetto, R. Marchevski, S. Martellotti, V. Martin, D. Martinez Santos, M. Martini, P. Massarotti, K. Massri, A. Mazzolari, E. Menichetti, M. Merola, E. Minucci, M. Mirra, L. Montalto, P. Monti-Guarnieri, M. Moulson, Y. Mukhamejanov, M. Napolitano, M. Needham, R. Negrello, I. Neri, S. Neshatpour, A. Norton, T. Numao, D. Paesani, S. Palestini, I. Panichi, C. Parkinson, E. Pedreschi, M. Pepe, L. Perna, M. Perrin-Terrin, L. Peruzzo, F. Petrucci, R. Piandani, M. Piccini, J. Pinzino, R. Plackett, C. Polivka, L. Pontisso, M. Prest, D. Protopopescu, C. Prouve, M. Raggi, M. A. Reyes Santos, D. Rinaldi, K. A. Rodriguez Rivera, M. Romagnoni, A. Romano, I. Rosa, C. Rossi, P. Rubin, G. Ruggiero, V. Ryjov, S. Sakhiyev, A. Salamon, F. Salvatore, J. Sanders, G. Saracino, F. Sargeni, I. Sarra, M. Schott, J. Schubert, A. Selmi, F. Sgarbossa, A. Shaikhiev, I. Shipsey, F. Simula, M. Soldani, M. Sozzi, T. Spadaro, F. Spinella, J. Swallow, A. Sytov, G. Tinti, A. Tomczak, E. Vallazza, T. Velas, B. Velghe, P. Vicini, R. Volpe, H. Wahl, R. Wanke, V. W. S. Wong and M. Zamkovsky

1. – Scientific context

Rare kaon decays, which proceed at the loop level in the Standard Model (SM), have typical branching ratios (BRs) below 10^{-7}. Figure 1 shows schematically how kaon physics, thanks to such decays, can constrain the unitarity triangle independently of B and D meson physics.

$K \to \pi\nu\bar{\nu}$ decays are dominated by short distance physics, and, as such, they are calculated very precisely in the SM and they are very sensitive to the physics beyond the SM [1]. The uncertainty on the theoretical prediction of their BRs is dominated by the CKM parameters: the SM expectations without $\left|V_{cb}\right|$ uncertainties are $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$ and $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$ [2]. The latest measurement of $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ is from the NA62 experiment [3], while the current upper limit on $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ has been set by the KOTO experiment [4].

Similarly, $K_L \to \pi^0\ell^+\ell^-$ are theoretically clean decay modes. The sign of the interference of direct and indirect CP violation contributions to their BRs is unknown. The SM predictions are $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) \times 10^{11} = 3.54^{+0.98}_{-0.85}\left(1.56^{+0.62}_{-0.49}\right)$ and $\mathrm{BR}(K_L \to \pi^0\mu^+\mu^-) \times 10^{11} = 1.41^{+0.28}_{-0.26}\left(0.95^{+0.22}_{-0.21}\right)$ in case of constructive (destructive) interference [5]. The most stringent upper limits on these BRs have been given by the KTeV experiment [6, 7].

2. – The NA62 experiment

NA62 is a fixed target experiment at CERN SPS, whose primary goal is to measure $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$. Its experimental layout, schematically shown in fig. 2, is based on the decay-in-flight technique. The primary 400 GeV SPS proton beam impacts on a beryllium target; a secondary 75 GeV unseparated hadron beam is extracted. The secondary beam has an intensity of about 750 MHz, of which 6 % are K^+ mesons. In order to overcome the experimental challenge of measuring such a rare decay, NA62 employs a high-performance detector and TDAQ system [9, 10], which also allow for the study of a broad physics programme, including precision measurements and direct searches for new physics. Recent results were also presented in a dedicated contribution to this conference [11].

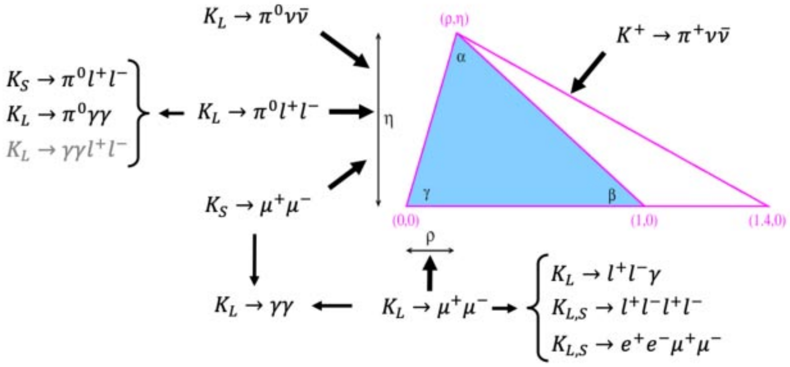

Fig. 1. – Relation between rare kaon decays and the unitarity triangle. [8]

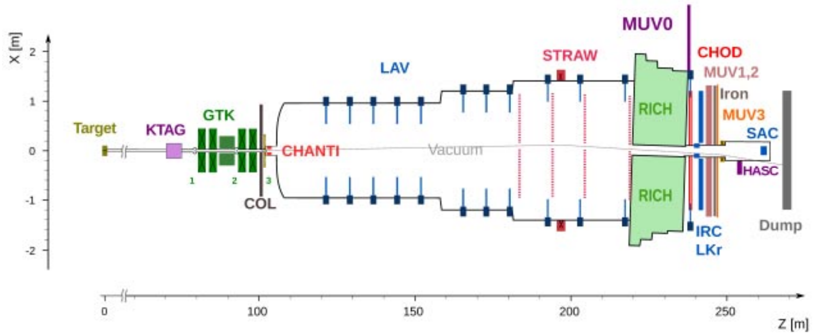

Fig. 2. – Schematic top view of the NA62 experimental layout. [3]

The experimental signature of the $K^+ \to \pi^+\nu\bar{\nu}$ decay is extremely weak: the signal must be discriminated against all the other kaon decays (most importantly $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^0$, $K^+ \to 3\pi$, $K^+ \to \pi^+\pi^- e^+\nu$), and decays and beam interactions that happen upstream of the fiducial volume. To this aim, a signal region is defined in terms of $m^2_{\text{miss}} = (P_K - P_\pi)^2$, which is kept blinded until completion of the analysis and gives a factor $O(10^4)$ rejection of the background from kaon decays. This is complemented by an $O(10^7)$ muon rejection and $O(10^7)$ π^0 rejection, which rely on timing between subdetectors of $O(100\,\text{ps})$. The estimation of the backgrounds is data-driven. Data collected from 2016 to 2018 has led to a single event sensitivity of $\left(0.839 \pm 0.053_{\text{syst}}\right) \times 10^{-11}$: having observed 20 events, and expecting $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$ SM signal events with $7.03^{+1.05}_{-0.82}$ background events, NA62 produced the measurement $\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\big|_{\text{stat}} \pm 0.9_{\text{syst}}\right) \times 10^{-11}$ [3], the most precise so far for this BR.

NA62 has started its second physics run in 2021, and has been approved for data taking until the Long Shutdown 3. Improvements in the beamline and detector, as well as in the reconstruction and analysis, are being made, in order to reach the goal of measuring $\text{BR}(K^+ \to \pi^+\nu\bar{\nu})$ at 15 % precision by the end of the data taking.

3. – The HIKE programme

The HIKE (High Intensity Kaon Experiments) programme is an important opportunity to study rare kaon decays, both charged and neutral, at the SPS North Area, where fixed-target runs are foreseen after LS3 through the FCC era. It includes multiple phases; a proposal for Phases 1 and 2 has been submitted to the CERN SPSC [8]. The phases will have similar experimental setup, which will make it possible to reuse any detector that is upgraded at any point for later stages.

Phase 1: a multi-purpose K^+ decay experiment. – The primary goal for the first phase is to measure $\text{BR}(K^+ \to \pi^+\nu\bar{\nu})$ at $O(5\,\%)$. The K^+ beam, with mean momentum of $75\,\text{GeV}/c$, will be produced by the primary SPS beam of 13×10^{12} protons per pulse (ppp) at $400\,\text{GeV}/c$ (to be compared to the nominal intensity of NA62, 3.3×10^{12} ppp), impinging at zero angle on the target. The experimental layout for Phase 1, shown schematically in fig. 3, follows the same structure as the NA62 layout, as its success has proven that its technique is suitable for a precision measurement of $\text{BR}(K^+ \to \pi^+\nu\bar{\nu})$.

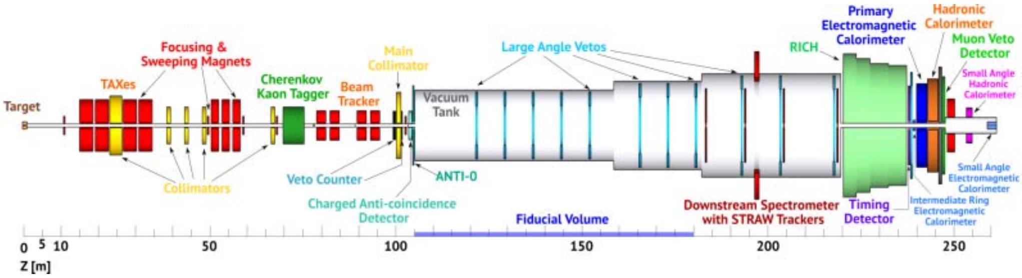

Fig. 3. – Experimental layout for HIKE Phase 1, with an aspect ratio of 1:10. [8]

The vast NA62 experience [12-21] shows that it will be well within the possibilities of such a detector to use kaon decays to also test lepton universality, lepton number and flavour conservation, and low-energy QCD, and to search for hidden-sector mediators in K^+ decays. Also, by collecting data in a short data-taking period with low intensity and a minimum-bias trigger, HIKE Phase 1 could give an important contribution to the debate around the CKM first row unitarity and to the knowledge of the main K^+ decay modes.

Phase 2: a multi-purpose K_L decay experiment. – The second phase will employ a neutral beam, with a production angle of 2.4 mrad and a 0.4 mrad opening angle [22]. With an intensity of 20×10^{12} ppp (6 times the NA62 intensity), 3.8×10^{13} K_L decays per year are expected, with a mean momentum of 45 GeV/c. A sketch of the beamline and detector is shown in fig. 4. The adjustments to the detector with respect to Phase 1 include removal of KTAG, beam tracker and RICH, and shortening of the spectrometer, with a reduction of the spectrometer magnetic field of about 20 %.

The main goal of Phase 2 will be the first observation and measurement of $K_L \to \pi^0 \ell^+ \ell^-$ decays, improving on the current KTeV single event sentivities by two orders of magnitude [6, 7]. The main backgrounds are the Greenlee decays $K_L \to \gamma\gamma\ell^+\ell^-$ [23], which are irreducible, and are suppressed exploiting the different kinematics. This will require an excellent energy resolution of the electromagnetic calorimeter to reconstruct the π^0 mass peak in the signal decay.

Precision measurements and searches for rare and forbidden K_L decays will also be possible, such as the measurement of BR($K_L \to \mu^+\mu^-$), the potential first measurement of BR($K_L \to e^+e^-$), the search for $K_L \to \mu^\pm e^\mp$, the measurement of BR($K_L \to \gamma\gamma$).

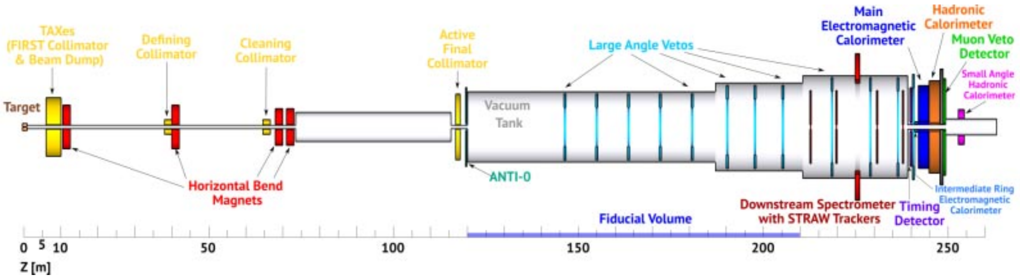

Fig. 4. – Experimental layout for HIKE Phase 2, with an aspect ratio of 1:10. [8]

HIKE-dump. – During Phases 1 and 2, there will be the possibility to periodically run in a special beam-dump mode. This allows to perform direct searches for long-lived, feebly-interacting particles (FIPs), similarly to what is already currently possible to do at NA62 [25], but at a substantially higher intensity, which is foreseen to increase the statistics by a factor 50 compared to the NA62 beam-dump dataset. The switch between the kaon mode and the beam-dump modes can be done with ease, allowing for specific online calibration procedures and flexibility in data taking scheduling. HIKE-dump will complement the SHADOWS experiment, which will searching for FIPs off-beam-axis by running concurrently with HIKE [26].

Phase 3: KLEVER. – A later third phase, also known as KLEVER, is being considered for the long term future, with the specific aim of measuring $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$ [24]. Such an experiment is designed to be complementary to KOTO, in that the beam energy would be significantly larger. As a consequence, boosted photons from K_L decays are easier to veto, but on the other hand a 150 m beamline extension is needed in order to suppress backgrounds from K_S and Λ decays.

4. – HIKE detectors

The increase of intensity with respect to NA62 implies the challenge of maintaining the same detector performance, and in particular the loss of signal events from accidental coincidence (around 35 % at NA62), at acceptable levels: this will require the time resolution of all the detectors to improve accordingly. Most of the detectors will need therefore need rebuilding, or, if the detector technology is intrinsically sufficiently fast, an upgrade of the readout will be required.

Beam tracker. – The NA62 beam tracker (GigaTracker, GTK) will need to be upgraded for the usage in Phase 1, as the time resolution for a single hit will have to scale according to the intensity, from less than 200 ps to below 50 ps; the radiation hardness should also improve by a factor 4 or more and the pixel efficiency should be kept larger than 99 %. A strong option is the TimeSPOT project [27], which is developing hybrid 3D-trenched pixels, in which the pixel electrode geometry is optimized for timing performance.

Spectrometer. – A downstream spectrometer analogous to the NA62 straw tracker will have to be built: straws with diameter smaller than 5 mm will be used. A new optimization of the geometric placement of the straws in a single view, consequent to the smaller diameter, has been performed, resulting in a choice of 8 straws per view: in order to reduce the detector material budget, the straw thickness will be reduced from 36 µm to less than 20 µm.

Main Electromagnetic Calorimeter. – Multiple options are being considered. The LKr calorimeter, built for the NA48 experiment and currently used at NA62, meets the HIKE requirements for the efficiency and energy resolution, but not for the time resolution: studies are being performed in order to understand whether it is possible to upgrade its readout electronics to reach the required time resolution, which, for Phase 1, is 4 times better than the current one.

Meanwhile, more studies are ongoing about building a new electromagnetic calorimeter: the baseline option is a shashlyk calorimeter based on the PANDA calorimeter [28], in turn based on the KOPIO calorimeter [29], which consists in alternating layers of lead absorber and injection-moulded polystyrene scintillator with a resulting radiation length of 3.80 cm and a sampling fraction of 39 %; scintillation light would be read by either SiPMs or new generation metal-package PMTs. "Spy tiles", optically-isolated scintillator bricks located at key points in the longitudinal shower development, can be used to provide additional information for PID purposes, especially to be used in Phase 2 for γ/n separation. Less conventional choices for the light emitter or for the matrix material are also being taken into account in synergy with the AIDAinnova project NanoCal, which could provide fast and bright signals, or good radiation hardness.

5. – Conclusion

HIKE proposes a broad and long-term programme of high energy physics at the intensity frontier. It will allow for measurement of important flavour physics observables at an unprecedented level of precision, by using cutting-edge detector technologies. Innovative R&D is already ongoing to build the HIKE detectors. The CERN North Area is the only place worldwide where such a comprehensive programme of kaon physics may be addressed experimentally, which gives a unique and timely opportunity to address a strongly motivated physics case.

REFERENCES

[1] Buras A. J., Buttazzo D. and Knegjens R., *JHEP*, **11** (2015) 166.
[2] Buras A. J. and Venturini E., *Acta Phys. Pol. B*, **53** (2021) 6-A1.
[3] NA62 Collaboration, *JHEP*, **06** (2021) 093.
[4] KOTO Collaboration, *Phys. Rev. Lett.*, **122** (2019) 021802.
[5] Mescia F., Smith C. and Trine S., *JHEP*, **08** (2006) 088.
[6] KTeV Collaboration, *Phys. Rev. Lett.*, **93** (2004) 021805.
[7] KTeV Collaboration, *Phys. Rev. Lett.*, **84** (2000) 5279.
[8] HIKE Collaboration, CERN-SPSC-2023-031, SPSC-P-368.
[9] NA62 Collaboration, *JINST*, **12** (2017) P05025.
[10] NA62 Collaboration, *JHEP*, **03** (2023) 122.
[11] NA62 Collaboration (Rosa I.), these proceedings.
[12] NA62 Collaboration, arXiv:2311.01837.
[13] NA62 Collaboration, *JHEP*, **09** (2023) 040.
[14] NA62 Collaboration, *JHEP*, **11** (2022) 011.
[15] NA62 Collaboration, *Phys. Lett. B*, **830** (2022) 137172.
[16] NA62 Collaboration, *Phys. Lett. B*, **838** (2022) 137679.
[17] NA62 Collaboration, *Phys. Rev. Lett.*, **127** (2021) 131802.
[18] NA62 Collaboration, *Phys. Lett. B*, **797** (2019) 134794.
[19] NA62 Collaboration, *Phys. Lett. B*, **816** (2021) 136259.
[20] NA62 Collaboration, *Phys. Lett. B*, **807** (2020) 135599.
[21] NA62 Collaboration, *JHEP*, **03** (2021) 058.
[22] Gatignon L., Bernhard J. *et al.*, CERN-PBC-REPORT-2022-002.
[23] Greenlee H. B., *Phys. Rev. D*, **42** (1990) 3724.
[24] HIKE Collaboration, arXiv:2211.16586.
[25] NA62 Collaboration, *JHEP*, **09** (2023) 035.
[26] SHADOWS Collaboration, CERN-SPSC-2023-029, SPSC-P-367.
[27] Lai A., `https://doi.org/10.1109/NSSMIC.2018.882431`.
[28] PANDA Collaboration, arXiv:1704.02713.
[29] Atoian G. S. *et al.*, *Nucl. Instrum. Methods A*, **584** (2008) 291.