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Progress in Physics (107)

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In search for a complete theory of nature

Attempts over many decades to understand elementary particles and their interactions have culminated in the most successful theory of nature thus far: the Standard Model of particle physics. The validity of the Standard Model has been established by numerous measurements obtained with a wide variety of experimental techniques over more than half a century. However, despite the success of the Standard Model, we are still confronted with many unresolved puzzles and open problems. The open questions in particle physics are a result of the shortcomings of the Standard Model, which fails to accommodate several experimentally established phenomena: the presence of gravitating dark matter that is five times more abundant than ordinary baryonic matter; the observed predominance of matter over antimatter in the universe (CP violation); explanation of the pattern of quark and lepton masses and their mixings (flavour puzzle). Flavour refers to the type of elementary particle, i.e. quarks and leptons. The latter problem is directly related to the couplings of the Higgs boson to fermions. These couplings result in the observed hierarchical structure of the flavour sector, which requires an extension of SM for its explanation. The consensus within the particle physics community is that the Standard Model is not the complete picture but an effective theory with a finite number of parameters fixed experimentally. Therefore, the Standard Model is a low-energy approximation of a theory with more degrees of freedom, which, if detected, could provide a solution to the above problems.

The search for a complete theory of nature and the energy scale associated with it can be addressed in two different but complementary ways: searching for direct production of new particles at high energies; study of rare decays and precision measurements of Standard Model parameters. The lack of discoveries from direct searches at the Large Hadron Collider at CERN suggests that the next relevant physics scale is beyond the direct reach of the present state-of-the-art colliders. Flavour physics offers indirect sensitivity to new physics at much higher energies than those accessible directly. The presence of new physics can be detected by the study of rare decays, where even small effects can compete with the heavily suppressed Standard Model contribution. These effects can be produced by heavy particles not part of the Standard Model, which can be virtually exchanged between the particles involved in the decay, thus modifying the probabilities to observe these rare processes in our detectors.

To probe these high mass scales, particles involving a strange (*s*) quark, called *K*-mesons or kaons, come to the rescue. Kaons are made up of a strange and an up or down quark, depending on their charge. Many of the ideas that established the Standard Model were first inferred by studying the kaon system, with notable examples being the *c*, *b*, and *t* quarks, as well as the discovery of CP violation. A particular type of rare kaon decays, where a kaon decays to pion and a neutrino-antineutrino pair $(\nu\bar{\nu})$ are considered the stars of flavour physics. Their rates, also called branching fractions, can be calculated with high precision and are often referred to as golden channels of flavour physics due to their high discovery potential. Experimental information of these decays is highly anticipated by the community and can be essential for uncovering new physics. The charged kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ decay is currently being studied by the NA62 experiment at CERN [1], while it's neutral counterpart, the $K_L \to \pi^0\nu\bar{\nu}$ is being searched for by the KOTO experiment in Japan [2].

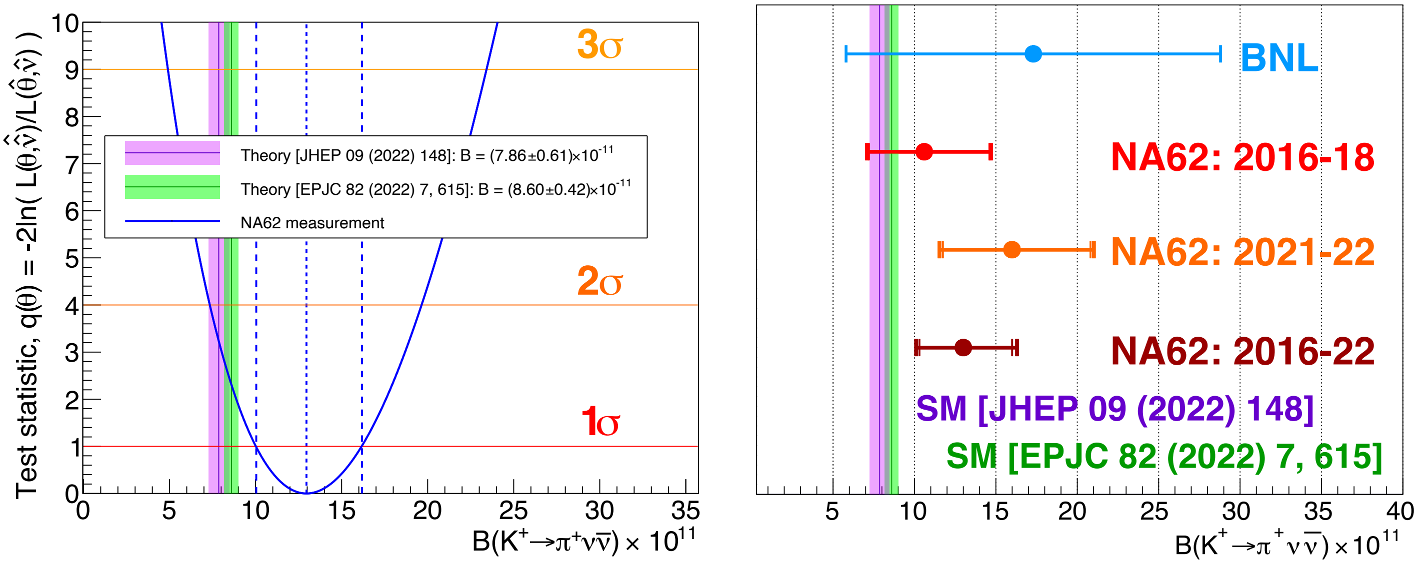

Fig. 1: Left: profile likelihood test statistic q as a function of the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction for 2016–2022 data. Right: summary of measurements of the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction from the BNL E787 and E949 experiments [9], and the NA62 experiment using the 2016 – 2018 [7], 2021 – 2022 and 2016 – 2022 data. Statistical and total uncertainties are shown by thinner and thicker vertical bars, respectively. These are compared to the two recent SM predictions [3, 4].

An ambitious measurement

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay has an experimental signature that is both very simple and extremely challenging. The only particles that can be measured are the K^+ and the π^+ produced in the decay, while the neutrino-antineutrino $\nu\bar{\nu}$ pair is not detected. Not only that, but the decay has a probability of less than one in ten billion in the Standard Model [3, 4]. The ambitious goal to measure this extremely rare process was undertaken by the NA62 collaboration and an experiment was designed to address these challenges.

NA62 uses a flux of highly boosted K^+ particles produced when a high-intensity proton beam, provided by the Super Proton Synchrotron at CERN, collides into a stationary target. The K^+ particles are then guided to a vacuum tank where they decay in flight. Both the K^+ and its decay products are precisely detected and identified except for the neutrinos, which show up as missing energy. Highly-efficient veto detectors are used to remove events with extra activity not associated to the K^+ and the π^+ particles to ensure the necessary background suppression. Using the data collected in 2016 - 2018, NA62 proved the feasibility of the decay-in-flight technique to study $K^+ \to \pi^+ \nu\bar{\nu}$ decays. In a series of papers NA62 demonstrated the necessary background control and provided the first hint for the existence of the rare kaon decay [5–7].

Profiting from the careful studies of the collected data, a set of upgrades to the experimental setup were implemented after 2018. New and upgraded detectors were installed, which allowed operation at 30 % higher beam intensities. These hardware upgrades combined with improvements to data analysis techniques allowed the collection of signal candidates 50 % faster than before, while adding new tools to suppress background. With all of this improvements in place, NA62 restarted its data-collection campaign in 2021 and has been collecting data since.

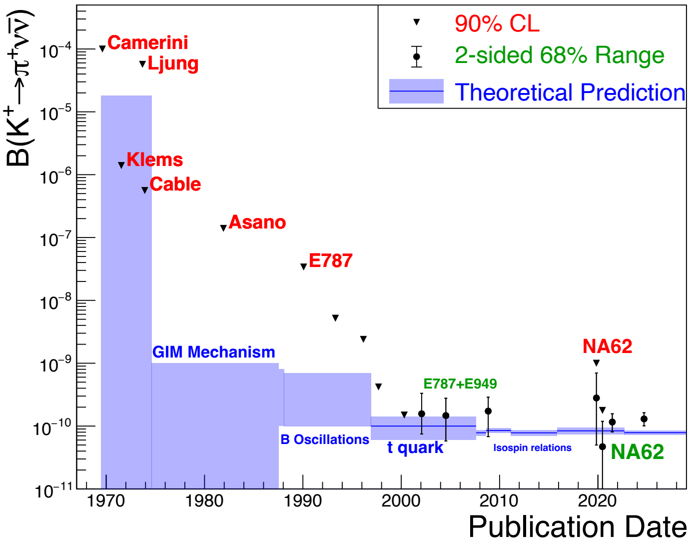

Fig. 2: Historical plot showing the development the progress in our understanding of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay since the 1970s. The blue shaded area represents the theoretical prediction for the decay and the impact of key developments in our understanding of the Standard Model. Experimental upper limits are shown with triangles and red labels. Measurements are depicted with points with error bars and green labels.

A long awaited observation

On 24 September 2024 at a seminar at CERN [8], the NA62 collaboration released the latest result from their flagship measurement obtained with the data collected between 2016 and 2022. The analysis team observed 51 events in the signal region to be compared with 18^{+3}_{-2} expected background events. A signal with a statistical significance of 5σ was found, which corresponds to a value for the branching fraction of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 13.0^{+3.3}_{-2.9} \times 10^{-11}$. An article detailing the measurement was uploaded on arXiv [10] and submitted to a peer-reviewed journal for publication.

This monumental result marks the first observation of the golden kaon mode and makes the $K^+ \to \pi^+ \nu\bar{\nu}$ process the rarest particle decay ever observed. The measured value is 50 % larger than the value predicted by SM but still compatible within 1.7σ. One reason for the discrepancy could be the presence of new particles which through quantum fluctuations enhance the probability of the process, but more data is needed to confirm that hypothesis. The NA62 collaboration which now counts about 200 people, has already collected a dataset double in size in 2023 and 2024 and is expected to triple it by the end of the data-taking campaign in late 2026. The larger dataset paired with an improved analysis procedure would allow NA62 to confirm or exclude the possibility of NP in this decay within the next few years. Switzerland is strongly involved in the NA62 experiment through École Polytechnique Fédérale de Lausanne (EPFL) and its LPHE Unit. Members of the group have leading roles in the silicon pixel tracker of NA62, as well as in the flagship $K^+ \to \pi^+ \nu\bar{\nu}$ analysis.

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