Searches for very weakly-coupled particles beyond the Standard Model with NA62

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The NA62 experiment at CERN is designed to measure precisely the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The intensity and energy of the SPS proton beam used to produce the $K^+$, as well as the hermetic detector coverage and overall geometry, give in addition the opportunity to search for hypothesized weakly-coupled particles at the MeV-GeV mass scale. In these proceedings the focus lies on reviewing these opportunities and sketching the current status of some pertinent searches.

1 Kaon physics with NA62

The NA62 experiment aims to measure to a good accuracy the very small branching ratio (BR) of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, which is $O(10^{-10})$. This BR is rather precisely ($<10\%$ level) predicted from theory and has a recognized sensitivity to new physics \cite{1}. However, the only existing measurement of this BR is based on only seven events \cite{2}, and the experimental precision is thus not sufficient to challenge the theory prediction. NA62 aims to measure this BR at the

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Figure 1: Layout of NA62: The SPS proton beam (from left) hits a beryllium target. A fraction of the secondary beam as well as around $\sim 40\%$ of the primary protons that have not interacted in the target are guided towards an achromat, located approximately 24 m downstream of the target. This achromat, called ‘TAX’, is described in more detail in Figure 2. All beam components (including the remaining 400 GeV component) except for a positive component at $\sim 75$ GeV, are stopped in the TAX. The 75 GeV component eventually is guided along a distance $D$ to the start of a decay volume of length $L$ downstream. Kaons from the secondary hadron beam are eventually identified (CEDAR) and measured (Gigatracker).

10% level by combining a large number of kaon decays $O(10^{13})$ with a hermetic detector system, that can reject other kaon decays in the $\sim 60$ m long fiducial volume (FV) ultimately at the $O(10^{12})$ level. The detector layout is shown in Fig. 1 and a detailed description of the physics case, the experiment and its performance is provided in [3].

To date, NA62 has released a preliminary analysis of 5% of 2016 data, results are described in [4]. In 2017, $\sim 3 \times 10^{12}$ kaon decays have been collected and the experiment will continue data taking in 2018, until the long shutdown of the CERN accelerators.

Besides the main measurement, NA62 has a program to search for lepton number and lepton flavor violating decays. In addition, with existing and near-future data, NA62 has a discovery potential in the search of very weakly-coupled particles beyond the Standard Model. Such particles, if existing at the MeV-GeV scale would have comparably long lifetimes and could have escaped all past detection efforts so far. The need for an increased experimental activity in this area is widely appreciated in the HEP community, since the existence of a ‘Dark Sector’ can be linked to a plethora of open physics questions [5].

2 Beam-line and production modes of novel particles

The kaons of interest for NA62 are produced by interaction of the SPS 400 GeV proton beam in an upstream target, see Fig. 1. The unseparated, positively charged hadron beam is selected in momentum by an achromat, shown and described in Figure 2.

Consequently, in standard data-taking, besides beam halo muons, only these secondary particles (essentially $\pi^+, p, K^+$) at 75 GeV will enter the decay volume of NA62. Interestingly, even during data-taking with the upstream target in place, about 40 % of the primary protons punch through this target and eventually interact in the first collimator C1, cf. Fig 2 with their hadronic shower being absorbed. Another possible mode for data-taking in NA62 is to run as a ‘beam-dump’ such that up to 100% of the 400 GeV protons are stopped in the collimators.

Interactions of 400 GeV protons in the collimator, as well as decays of secondary mesons
before the collimator may be the source of different, so-far undiscovered, weakly-interacting particles, which travel unhindered to the NA62 decay volume and decay into visible final states. Besides the primary beam energy and protons on target (POT), the main variable for the parameter-space-coverage in these searches is geometry: Ideally, the decay volume is close enough to novel particle’s production point to contain the decay products of the most short-lived particles as well as long enough to detect the most long-lived candidates. The comparably small \( D \simeq 80 \text{ m} \), and large \( L \simeq 136 \text{ m} \) (cf. Fig. [1]) of the NA62 setup enable the experiment to extend search parameters beyond past results, e.g. from CHARM and NuCal for axion-like particle searches [6].

In both, nominal and dump data-taking modes, competitive searches for weakly interacting particles beyond the Standard Model are possible. NA62 can make a strong contribution in shedding light on the existence of ‘Dark Sector particles’ using:

1. **Meson decays in the FV:** The large flux of kaons and pions in NA62 suggests to search novel particles in their decays. Examples of recent preliminary results are: Firstly production searches of Heavy Neutral Leptons \( N \) in \( K^+ \rightarrow l^+ N \), with \( l = e, \mu \). Secondly: the search for invisibly decaying Dark Photons \( A' \) from \( K^+ \rightarrow \pi^+ \pi^0 \), where \( \pi^0 \rightarrow \gamma A' \). Preliminary results of both analyses are given in [4].

2. **Parasitic dump production:** The decay of hypothesized new particles in the NA62 decay volume produced upstream can be searched for by dedicated trigger chains (that do not require the presence of a kaon) in parallel to the main trigger. Such decays can be potentially disentangled from hadron beam decays and random track combinations. In 2017 dedicated trigger chains have been set up for multi-track events with at least one or two muons to record decays from (pseudo-)scalars (axion-like particles), Dark Photons and Heavy Neutral Leptons.

3. **Dedicated dump runs:** To achieve the best possible sensitivity in the search for weakly-coupled particles produced upstream, it is mandatory to ‘close’ the collimators (i.e. mis-align bores for the hadron beam). In this setting, background is minimized. The current statistics collected in this mode is of the order of \( \lesssim 10^{16} \text{ POT} \). Specific trigger chains for at least one track or a minimum energy in the Liquid Krypton electromagnetic calorimeter are typically required.

### 3 Outlook and Summary

The NA62 experiment has been designed to sustain a high beam-rate, provide full particle identification, hermetic coverage and very light-material tracking. Besides the main measurement \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \), NA62 has the means and a program to discover weakly-coupled particles beyond the Standard Model.

Consequently, for the 2021-2023 operation of the CERN accelerators, an extended (~ one-year-long) data-taking in dump-mode is being discussed with the aim to collect around \( \sim 10^{18} \text{ POT} \). Reference [7] gives physics examples, projections and results on background rejection. In the meanwhile, data collected in 2016/2017 are used to validate expectations for backgrounds and to perform first analyses possible within the statistics collected so far.

In summary, the NA62 experiment combines the opportunity for precision Standard Model measurements with the discovery potential for wide range of weakly-coupled new physics.
Figure 2: Picture of the ‘TAX’ achromat of the NA62 beamline: It is located \( \sim 80 \) m upstream of the NA62 decay volume. The beam is incident from the left and is dispersed by a magnet before reaching the two collimators, labeled as C1 and C2. For simplicity, only two positive beam components are sketched, whilst in reality a wide momentum spectrum reaches the collimators. C1 (copper/iron) and C2 (full iron) are each \( \sim 1.6 \) m long and each contain small bores (from left to right, not visible in the picture) to allow the passage of the 75 GeV component (sketched in blue) in nominal data taking. The two collimator blocks can be moved along the vertical direction, to either reduce the intensity or completely block the beam (by misaligning the bores) and act as a beam-dump. The upstream beryllium target (not visible in the picture) can be removed for special runs. In this situation the entire 400 GeV primary proton component is dumped into C1.

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