NA62

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The NA62 Experiment

The branching ratio (BR) for the decay $K^{+} \rightarrow \pi^{+} \nu\nu$ can be related to the value of the CKM matrix element V_{td} with minimal theoretical uncertainty, providing a sensitive probe of the flavor sector of the Standard Model. The goal of the NA62 experiment at the CERN SPS is to detect ~100 decays decay $K^{+} \rightarrow \pi^{+} \nu\nu$ with a S/B ratio of 10:1.

The experiment makes use of a 75 GeV unseparated positive secondary beam. The total beam rate is 800 MHz, providing ~50 MHz of K^{+}'s. The decay volume begins 102 m downstream of the production target. 5 MHz of kaon decays are observed in the 65-m long fiducial vacuum decay region. Ring-shaped large-angle photon vetoes (LAVs) are placed at 12 stations along the decay region and provide full coverage for decay photons with 8.5 mrad < θ < 50 mrad. The last 35m of the decay region hosts a dipole spectrometer with four straw-tracker stations operated in vacuum. The NA48 liquid-krypton calorimeter (LKr) is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system (e.g.\ for particles traveling in the beam pipe).

LNF group activity: Large Angle Veto detectors

The principal achievements of the photon-veto working group in 2016 were in the assessing the performances of the Large-Angle Veto (LAV) system, which is a responsibility of the LNF group responsibility, as well as providing general support to the experiment, assisting with run planning and coordination, and participating in data taking. Particular progress on the LAV system was made in the following areas:

- Improvement of the level-zero trigger firmware and development of the level-one trigger.

- Implementation and optimization of the reconstruction code.
- Implementation of data quality tools
- Analysis of 2016 data and measurement of system performances.
- Feasibility studies for the experimental program after the end of LHC Run 2.

The LAV system consists of 12 detector stations arranged at intervals of 6 to 10 m along the vacuum tank along its entire length. The first 11 stations are incorporated into the tank itself and are operated in vacuum; the 12th station is placed immediately downstream of the RICH and is operated in air. The diameter of the stations increases with distance from the target, as does the number of blocks in each, from 160 to 256, for a total of 2496 blocks. Each station consists of four or five rings of blocks, with the blocks staggered in azimuth in successive rings. The total depth of a five-layer station is 27 radiation lengths. This structure guarantees high efficiency, hermeticity, and uniformity of response.

The first LAV station, A1, was constructed in 2009 and served as a prototype. By August 2014, all twelve stations were completed, delivered to CERN and installed on the beam line. During the construction of the LAV detectors, more than 2500 lead-glass blocks from the OPAL electromagnetic barrel calorimeter were processed (structurally reinforced, cleaned, fitted with new HV dividers, tested, and characterized).

The particles traversing the LAV detectors mainly consist of photons from kaon decays, as well as muons and pions in the beam halo. For each incoming particle, the veto detectors are expected to provide a time measurement with 1-ns resolution and an energy measurement of moderate precision (of order 10%). To maintain the detection efficiency as high as possible for muons and low energy photons, the system must be operated with thresholds of a few millivolts, i.e., well below the signal amplitude for minimum-ionizing particles (MIP). With an intrinsic time resolution of < 1 ns for the lead-glass blocks and a rise time of 5 ns for the Hamamatsu R2238 PMTs, the requirements on the precision of the time measurement are not difficult to satisfy. On the other hand, the amount of energy deposited in the LAV stations for photons from π^0 decays spans a very wide range, from about 100 MeV up to 30 GeV. Using the measured average photoelectron yield of 0.3 p.e./MeV and a nominal gain of 1×10^6 for the R2238 PMT, one expects a signal charge of 4.5 pC for a MIP, corresponding to a signal amplitude of 20 mV on a 50 load. At the upper end of the photon energy range, signals from 20 GeV showers can reach an amplitude of 10V. The readout chain for the LAV stations consists of two different types of boards, a dedicated front-end board (LAV-FEE) developed for the LAV detector, and a common digital readout board called TEL62, used by many of the NA62 detectors.
This allows the measurement of the time with a resolution of about 1 ns and gives a measurement of the amplitudes using the time-over-threshold (ToT) , moreover FPGAs on board the TEL62 are used to correct raw hit times for slewing and to

produce a level-zero (L0) trigger primitive.

Much progress has been made on the LAV reconstruction code and on the data analysis. The performance of the LAV system has been studied both with data collected under standard conditions, i.e., with a trigger based on the identification of K^+ decay products, and during dedicated muon runs, with the beam dump closed and the muon-sweeping magnets turned of, so that the experiment is traversed only by high-energy muons that penetrate the upstream shielding.

Muon runs were used to establish the threshold settings and to study the efficiency for the reconstruction of hits left by MIPs. Penetrating muon "tracks" in the LAV system were identified by the correlation between hits on blocks at the same azimuthal angle in different stations, as illustrated in Fig. LAV-1. We find that the MIP detection efficiency saturates for values of the low threshold below 6 mV. This led us to adopt a value of 5 mV for the low-threshold working point, as seen in Fig. LAV-2.

Runs in standard conditions are used to measure the time offsets for each channel with respect to the signals from the detectors that provide the experiment's event-time reference (CHOD and KTAG). Hit reconstruction is then performed and slewing corrections are applied. After the application of slewing corrections, time resolutions at the level of 1 ns or better are obtained for all LAV stations, as shown in Fig. LAV-3.

We have attempted to study the detection efficiency for photons using a clean sample of $K^{+} \to \pi^{+}\pi^{0}$ decays in which the π^{+} track is reconstructed, one of the two photons from the π^0 is detected as an LKr calorimeter cluster, and the second photon is expected to be found in one of the LAV detectors on the basis of kinematic closure. At present, the resolution on the extrapolated direction of the photon is not sufficient to allow the efficiency to be determined for individual LAV stations; this may be possible in the future by means of a complete kinematic fit making use of all available information on the K^+ trajectory from the Gigatracker. As a first attempt, we have focused on estimating the global efficiency for the entire LAV system. We thus consider events to be successfully matched if they contain at least one LAV block fired within 5 ns of the $K^{+} \to \pi^{+}\pi^{0}$ event time from the reference detector. MC studies demonstrate that the photon detection inefficiency as determined by this method is dominated by geometrical inefficiencies and upstream photon conversions; the intrinsic inefficiency arising from the LAV detectors itself is less than one-sixth of the observed inefficiency. Relying on the MC estimate for the contribution from the former effects, we find the intrinsic inefficiency to be a few 10^{-3}, with about 5% of the detected photons observed as a signal on an isolated block crossing only the low threshold. These results are preliminary; as noted above, further refinements to the method will be implemented.

The measured efficiency as function of the photon energy is reported in fig: **LAV-4**
We note, however, that obtaining an accurate tag for the determination of the single-photon detection efficiency at the level of 10^{-3} or lower is difficult; determination of the experiment's π^0 overall rejection power is both easier and more relevant for the measurement of BR $K^{+}\to\pi^{+}\nu\nu$

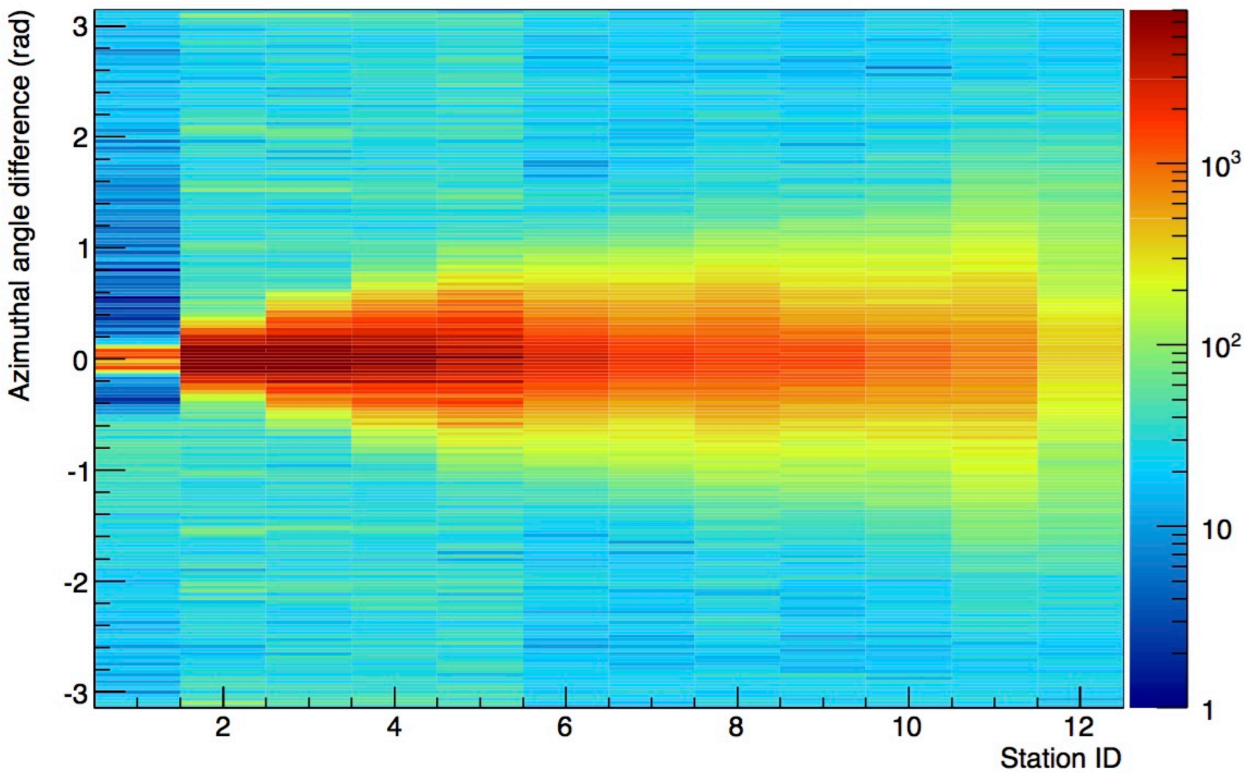


Figure LAV-1. Distribution of difference in azimuth, $\Delta\phi$, between clusters on different stations vs. the number of stations between the most upstream and downstream clusters.

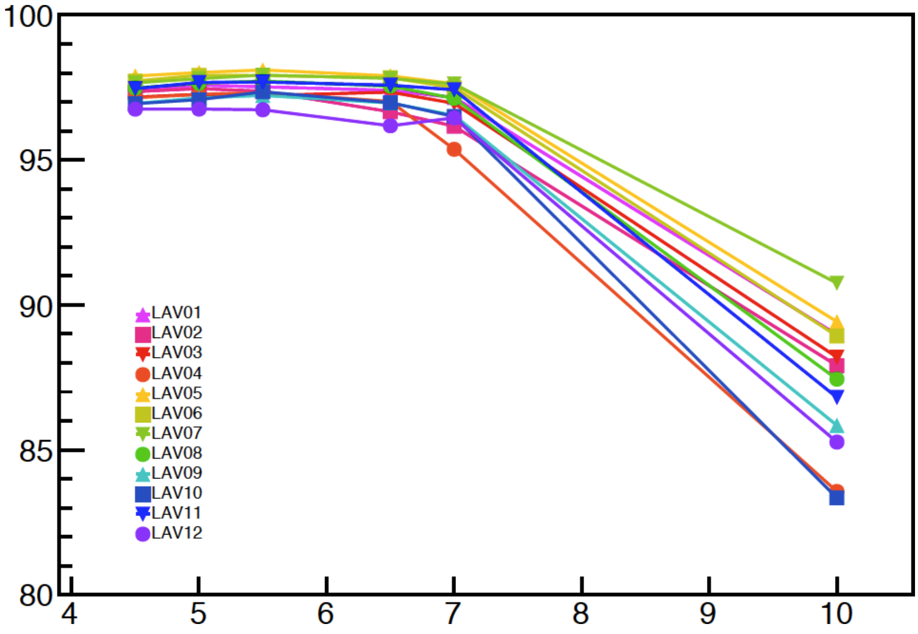


Figure LAV-2. Average MIP detection efficiency for different stations as a function of threshold.

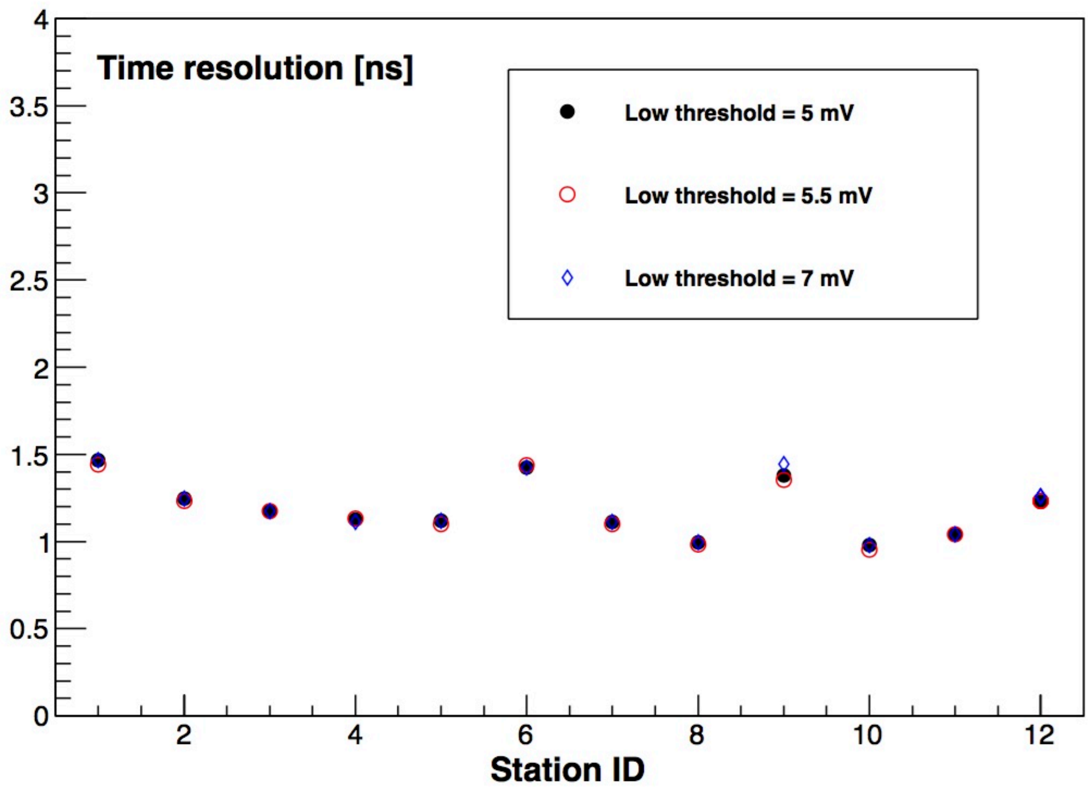
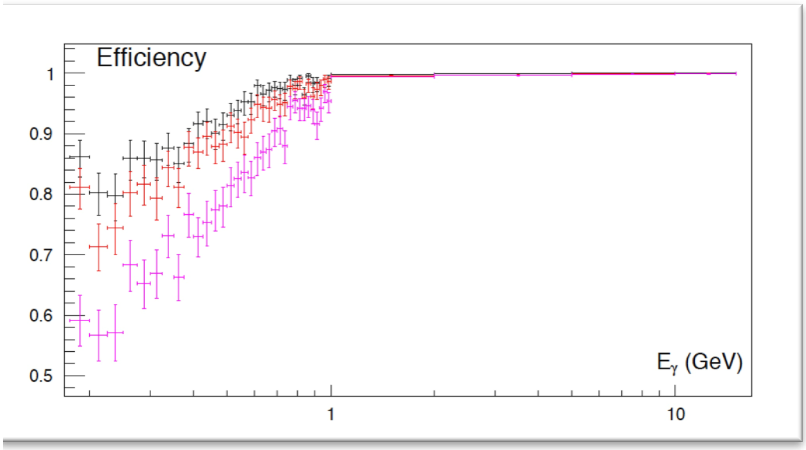


Figure LAV-3. Difference between LAV hit time and event time from KTAG (ns) for different thresholds, for the twelve stations.



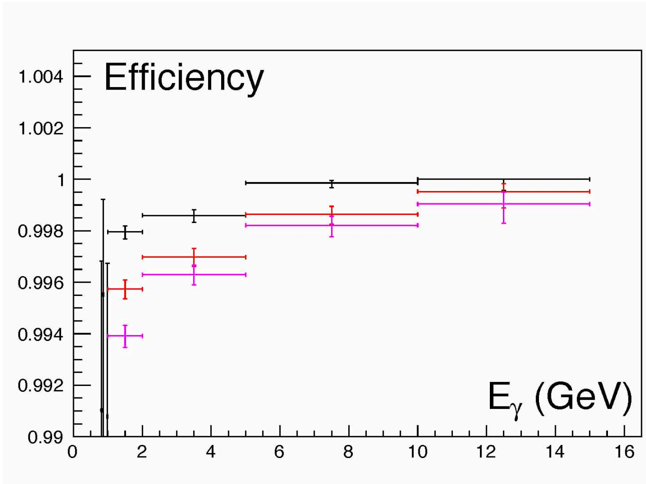


Figure LAV-4. LAV efficiency as function of the photon energy.

As far as the hardware concern, during 2015 we experienced a problem of discharges on the LAV high voltage feed- through. The LNF team in collaboration with an Italian industry ha developed a new multi-pin feed-through capable to keep 2 KVolt voltages, all the LAV HV flanges have been replaced. Moreover the board that will be used to pulse via LED's the lead-glass has been produced and tested by LNF electronic service.

LNF group activity: SAC and IRC

The small-angle veto detectors, SAC and IRC, are shashlyk type electromagnetic calorimeters that provide veto coverage for photons with polar angles down to zero degrees. They are exposed to a very high rate of photons from kaon decays and, for the IRC, muons from pion and kaon decays. After a comprehensive design review in early 2014, the IRC was assembled at Frascati and shipped to CERN for installation before the first NA62 run.

During this year the following tasks were accomplished:

- Analysis of 2016 data and evaluation of the SAC and IRC performance.

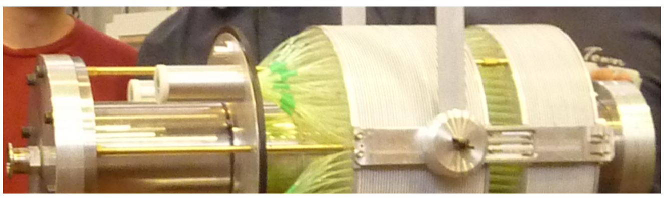


Figure SAV-1. The IRC assembly before shipping to CERN.

Both detectors were operated from the beginning of the run. The signals were read out with the standard NA62 readout system, based on the LAV-FEE and TEL62 boards, as described above. As for LAV12, L0 primitives were generated for the IRC and SAC. Copies of the IRC and SAC signals were also provided to the LKr calorimeter readout modules, so that the SAC and IRC were also available for use in the L0 trigger from the calorimeter readout chain.

A simple online monitor was implemented for the SAC and IRC, based only on the total normalized rate, defined as the total number of hits in each detector normalized to the total number of recorded events for each burst, as shown in Figure SAV-2. This allowed monitoring of changes in the trigger definition and beam alignment, in addition to the proper operational status of the detectors.

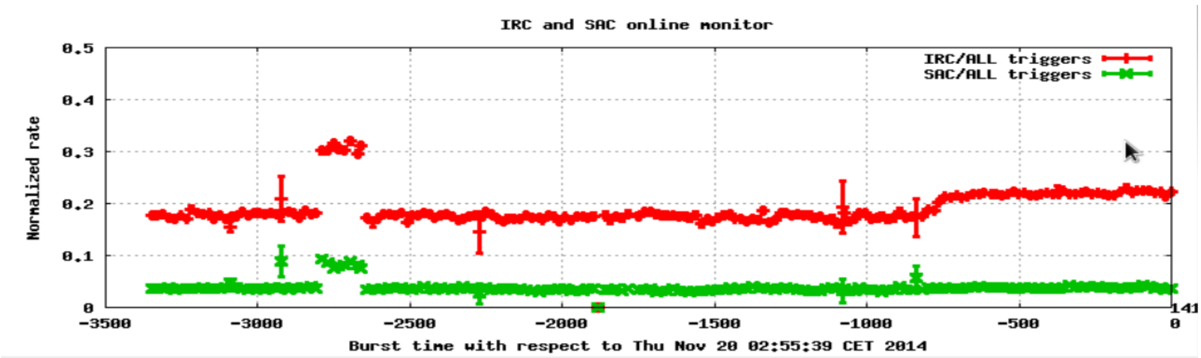


Figure SAV-2. The online monitor for the SAC and IRC.

The response of both detectors to MIPs was studied with data from the muon runs discussed in the previous section. The SAC and IRC event rates for different thresholds were fit with a cumulative Landau distribution function. The most probable value for the MIP signal amplitude was found to be around 4 mV, which is consistent with expectation, and stable in both data sets. The time resolution for muons was better than 2 ns for the SAC and better than 1.6 ns for the IRC, while the time resolution measured with tagged photons from $K^{\pm} \to \pi^{\pm}\pi^{0}$ decays was better than 1 ns. The IRC inefficiency has been measured using a sample of $K^{\pm} \to \pi^{\pm}\pi^{0}$, inefficiency of the order of few 10^{-4} has been obtained.

LNF group activity: Data analysis and future activities

The 2016 data taking was the first Physics run for NA62 , data taking mostly performed at 40% of the nominal intensity, was limited by the quality of the SPS slow extraction. A sample of $5x10^{11}$ kaon decays in the 60m long fiducial volume has been collected. From this data set the attempt to measure the $K^{+} \to \pi^{+}\nu\nu$ will be performed. As previously stated the π^0 rejection is an important ingredient for this analysis and LNF team has given a crucial contribution to this item.

The 2016 data as been analyzed to assess π^0 rejection factor using $K^{+} \to \pi^{+}\pi^0$ decay, the result is about 10^{-7} and can be improved.

A big effort has been done also on the exotic physics search, that is LNF group responsibility.

High-intensity setup, trigger system flexibility, and detector performance high-frequency tracking of beam particles, redundant PID, ultra-high-efficiency photon vetoes make NA62 particularly suited for searching new-physics effect from different scenarios. In particular the search for the dark photon A' in the decay chain $K^{+} \to \pi^{+}\pi^0$, $\pi^0 \to A'\gamma$, A' to invisible has been performed using part of 2016 data set.

Upper limits at the 90% CL in the plane of the coupling (e) versus the A' mass (MA) are shown in Fig. **ana-**1: the limit obtained (black curve) is compared with that obtained when assuming equal counts for data and background (red curve).

Results indicate that the statistical capability of NA62 allows improving on previous recent results. A more refined background evaluation might be needed: this point will be clarifed after analysis of further statistics.

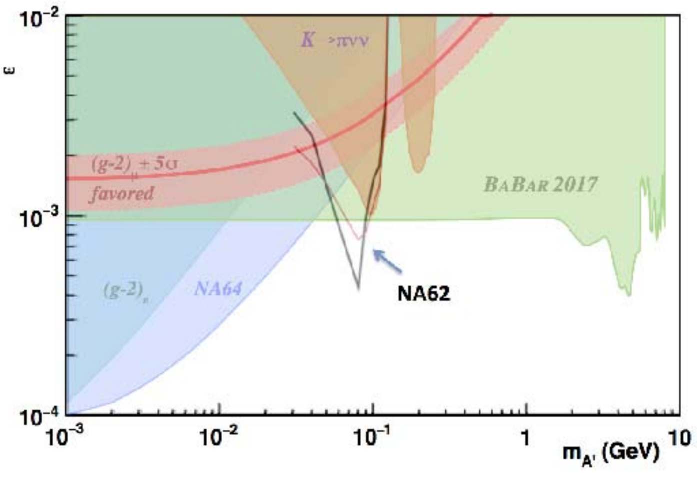


Fig **ana-1**: 90%-CL upper limit in the e2 vs M_A plane.In black, the upper limit obtained is compared to that with equal data and background counts. Upper limits from NA62 are compared to main other results from search of A invisible decays.

For the past few years, have been leading the effort in the NA62 Collaboration to develop a vision for the evolution of the experimental program after the end of LHC Run 2.

NA62 LNF group members are representative in the CERN working group Physics beyond Collider for different physics item: exotic physics search in NA62 and in a possible NA62 run in dump mode, feasibility studies for the measurement of the BR($K_L \rightarrow \pi^0 \nu\nu$).

Exotic physics :

One year long run in “beam-dump” mode using the NA62 detector will allow to access a new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP’s, etc.

If we assume 2×10^{18} 400-GeV POT and we search for displaced, leptonic, two-body decays originating from the T10 target and we assume zero-background we can evaluate expected 90%-CL exclusion plot on dark photon and heavy neutral lepton, as it is shown in fig. **ana-2-3**.

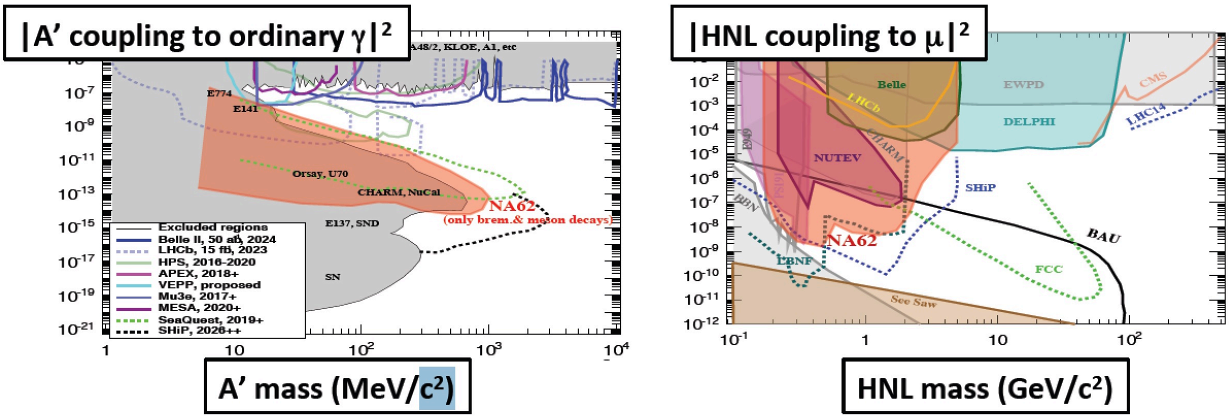


Fig **ana-2-3**: 90%-CL upper limit in the e2 vs M plane for dark-photon (left) and heavy neutral lepton (right)

The search for axion-like particles produced by Primakov process in the TAX collimator has been also studied**.** ALP-decay to γγ in NA62 fiducial volume and if we assume zero-background we can evaluate expected 90%-CL exclusion plot.

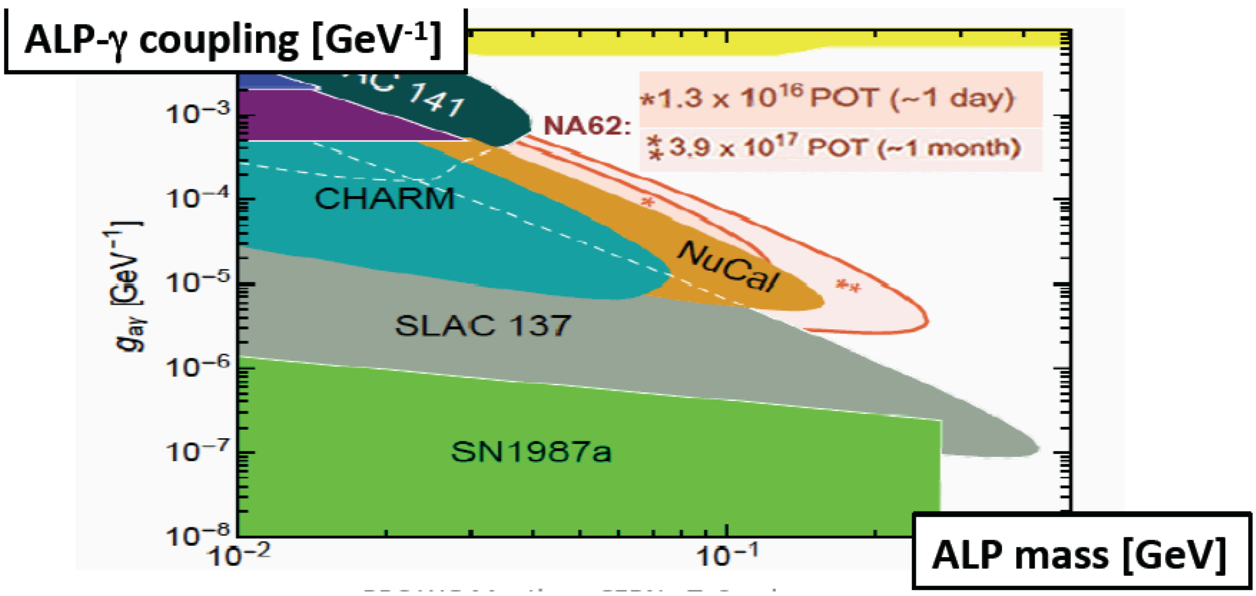


Fig **ana-4**: 90%-CL upper limit in the coupling vs M plane for ALP

For this search, two few-hour, dedicated runs have been taken in November 2016. In these runs the T10 target was removed and the proton beam was dumped entirely into the TAX collimators. If backgrounds can be sufficiently rejected, the data taken so far could be enough to slightly improve the sensitivity for these particles beyond existing limits in the region of a few tens of MeV in a so-far untested region of two-photon coupling. For the analysis of these runs, the data reconstruction has recently been adapted to facilitate background rejection.

In order to make full use of the power of the $K \rightarrow \pi\nu\nu$ decays in the search for new physics, it is important to measure both decay modes, $K^+ \rightarrow \pi^+\nu\nu$ and $K_L \rightarrow \pi^0\nu\nu$, since different new physics
models affect the rates for each channel differently. The LNF group is leading the effort to perform detailed design studies for an experiment (KLEVER) to measure $BR(K_L \rightarrow \pi^0\nu\nu)$ at the CERN SPS to succeed NA62, reusing as much of the existing apparatus as possible, including possibly the NA48 liquid-krypton calorimeter. The mean momentum of K_L mesons decaying in the fiducial volume is 70 GeV; the decay products are boosted forward, so that less demanding performance is required from the large-angle photon veto detectors. On the other hand, the layout poses particular challenges for the design of the small-angle vetoes, which must reject photons from K_L decays escaping through the beam pipe amidst an intense background from soft photons and neutrons in the beam.
Under LNF leadership, the basic layout for the KLEVER experiment was developed and the essential feasibility of the experiment was demonstrated by simulation in the context of a PRIN grant concluding in early 2016. The project was selected for inclusion in the Physics Beyond Colliders study to identify priorities in non-collider physics at CERN through 2040, to serve as input to the next update of the European Strategy for Particle Physics. In this context, the LNF group is continuing to lead the effort to progress from basic feasibility studies to an experimental proposal.

Published paper

1)C. Lazzeroni et al., Measurement of the _0 electromagnetic transition form factor slope", Physics Letters B768 (2017) 38, CERN-EP-2016-323, arXiv:162.08162 [hep-ex].
2)The NA62 Collaboration, The beam and detector of the NA62 experiment at CERN", submitted to JINST.

CONFERENCE TALKS

M. Raggi: Search for dark photon at NA48/2, and measurement of p0 form factor

KAON 2016 conference 14-17 September 2016
School of Physics and Astronomy,
University of Birmingham

S. Martellotti: Recent results and prospects for NA62 experiment
June 11th-13th, 2016, Anacapri, Italy: 6th international workshop on
Theory, Phenomenology and Experiments in Flavour Physics

M. Muolson:

- Prospects for an experiment to measure BR(KL -> pi0 nu nu-bar) at the CERN SPS (KAON 2016, Birmingham, UK, 17-Sep-16)
- Prospects for an experiment to measure BR(KL -> pi0 nu nu-bar) at the CERN SPS (Physics Beyond Colliders Kickoff Workshop, CERN, 07-Sep-16)
- Search for K+ -> pi+ nu nu-bar at NA62 (ICHEP 2016, Chicago, 6-Aug-16)