A new hydrogen-filled Cherenkov detector for Kaon tagging at the NA62 experiment at CERN

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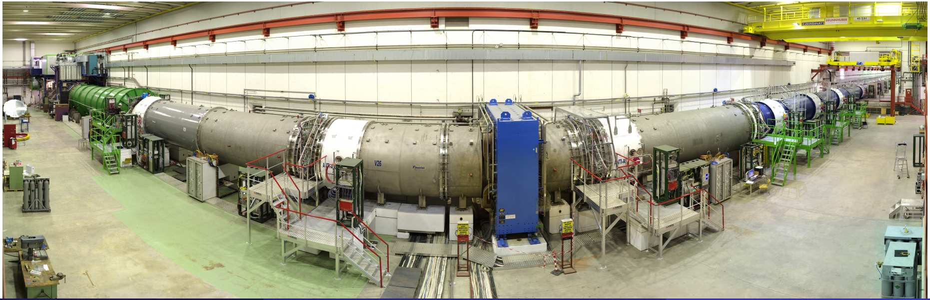
The NA62 experiment at CERN

- Fixed target kaon experiment located in the CERN North Area JINST 12.05 (2017), P05025
- Main goal: measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ to $\mathcal{O}(10\%)$ precision
- SM prediction yields $(8.60 \pm 0.42) \times 10^{-11}$ EPJC 82 (2022) 7, 615
- Ongoing data taking, data collected in 2016-18 and 2021-22 gives signal significance > 5

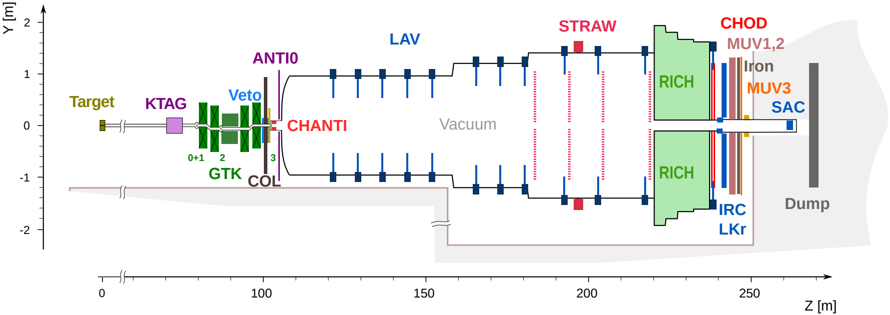
  See Gemma's talk tomorrow
- Broad physics program: exotics searches, rare and forbidden K^+ decays & other

  See Ilarias' talks: yesterday and Friday



The NA62 detector

- Unseparated hadron beam of 75 GeV/c from SPS protons on a Be target
- Decay in-flight technique, with the decay region enclosed in a large vacuum tank
- Upstream: kaon identification by KTAG and momentum measured by GTK (silicon pixel tracker)
- Downstream: STRAW (charged particle spectrometer), PID detectors (RICH, LKr, MUVs), CHOD (timing hodoscope), photon vetoes (SAC, IRC, LAV) and additional vetoes

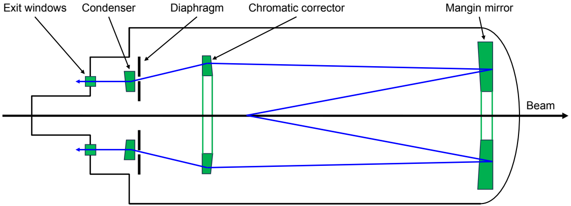


Kaon identification criteria at NA62

- The NA62 beam is a 75 GeV/c unserparated hadron beam with intensity 750 MHz
- Beam composition: 23% p, 6% K^+ and 70% π^+
- The kaons must be unambiguously identified with the following requirements:
  1. Kaon identification efficiency $\eta(K^+) > 95\%$
  2. Pion misidentification probability $< 10^{-4}$
  3. Time resolution of < 100 ps
  4. Rate capability of 45 MHz
- First two conditions are satisfied by a ChErenkov Differential counter with Achromatic Ring focus (CEDAR) detector, which are widely used at CERN since the 1980s CERN Report: CERN-82-13
- A custom photo-detection system was designed to satisfy the latter two, with the whole system referred to as the KTAG NIMA 801 (2015), 86

The CEDAR detector

- Cherenkov light due to passage of beam particles selected by an annular diaphragm slit, centered at r =100 mm and of variable width (∼2 mm default), is read out
- The refractive index of the radiator medium, n is controlled by the choice of gas, pressure and temperature and defines which particle species is "tagged" for a fixed beam momentum
- Correction of chromatic dispersion crucial for achieving target efficiency



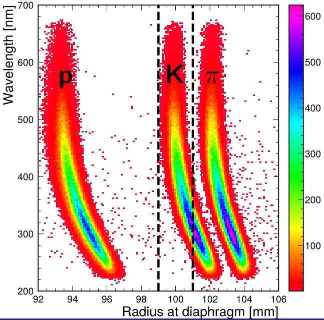
- For a standard CEDAR, the light is collected by 8 PMTs, positioned behind the exit windows
- In the NA62 setup, the light from each window is reflected radially outwards towards a sector (octant) of the KTAG, instrumented with 48 photomultipliers

Motivation for the CEDAR-H

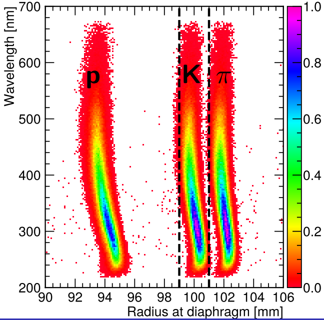
- Beam pions scattered by interaction with the NA62 beamline upstream of the decay region are a significant source of background for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay
- The N_2-filled CEDAR-W (previously used) was the largest contributor to the upstream material budget, with 3.9 % X_0 (3.5 % X_0 due to the radiator gas)
- For a hydrogen-filled CEDAR, the radiator gas contribution reduces to 0.73 % X_0

- New optical system required due to the dispersive properties of hydrogen and required separation of the K^+ and π^+ light rings

H_2-filled CEDAR-W



H_2-filled CEDAR-H



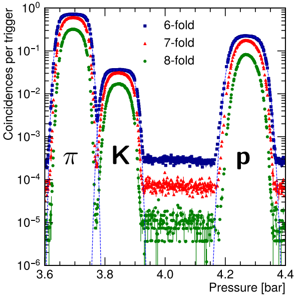
CEDAR-H development and design

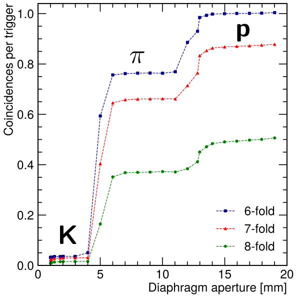
- The position of optical components was fixed to those of a CEDAR-N (*He* at high pressures)
- Iterative optimisation of the optical properties of the components performed numerically at the University of Birmingham, using a full *GEANT4* simulation of the detector
- The study was carried out for various hydrogen pressures aiming at the maximising the photon yield
- A complete description of the CEDAR-H available in JINST 19 (2024) 05, P05005
- Detector was constructed at CERN in 2022, all optical components aligned

CEDAR-H test beam at CERN

- CEDAR-H installed on the H6 beamline at CERN in October 2022, with 8 PMTs as readout
- A pair of scintillator counters positioned on both ends used for triggering
- Coincident signals from at least $N \geq 5$ PMTs used to "tag" target particle species
- Working on a 75 GeV/c unseparated hadron beam derived from SPS proton beam
- The beam composition of 25% p, 4% K^+ and 71% π^+ was verified with a pressure scan and a diaphragm scan at the kaon peak pressure of 3.85 bar

- Pion misidentification probability calculated as $< 10^{-4}$ by extrapolating the edges of the pion peak
- Average of 19.1 detected photons per kaon, calculated from coincidence ratios



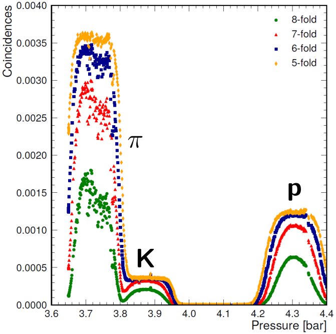


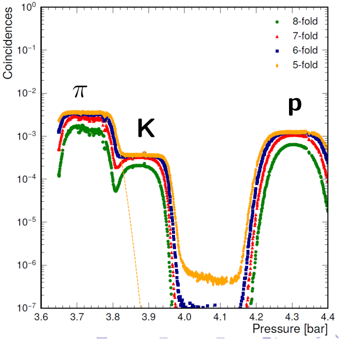
Installation at the NA62 experiment

- The KTAG was installed on the CEDAR-H, with the whole system put into the ECN3 cavern during the 2022-2023 YETS
- Comprehensive safety infrastructure in place to mitigate the risk associated with using hydrogen
  - The KTAG enclosure, housing PMs and readout electronics, flushed with nitrogen
  - Explosive atmosphere (ATEX) zone introduced about $\sim$1 m around the detector
  - Hydrogen concentration sensors installed over both ends of the CEDAR-H vessel

- Pressure scan performed with reduced beam intensity, confirming the beam composition and defining the operational kaon peak pressure as 3.88 bar
- Fine alignment to the beam direction (within $\pm 7\,\mu$rad) achieved by maximising the observed number of photons per kaon candidate
- Kaon candidate - constructed from hits in at least 5 octants of the KTAG within a 4 ns window

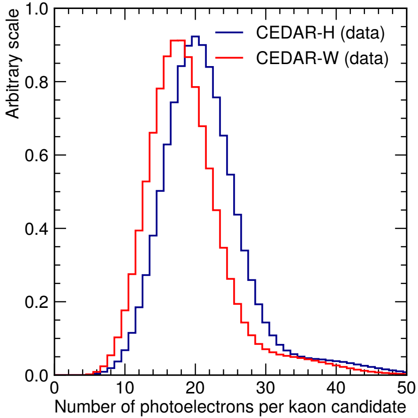
- The mean number of detected photons per kaon candidate was 21.7
- Pion misidentification probability $< 10^{-4}$, as computed from the fitted tail of the pion peak





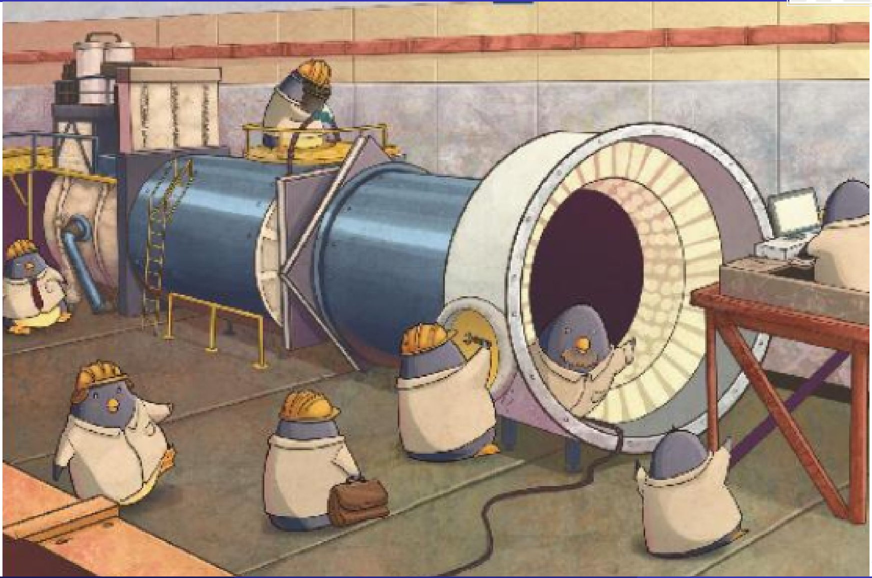
CEDAR-H performance in 2023 and 2024

- The upgraded KTAG detector successfully collected data throughout 2023 and 2024 campaigns
- The long-term performance with the CEDAR-H surpassed that of the previously used N_2-filled CEDAR-W
- Number of photons per kaon candidate (2 ns window), $N_\gamma = 20.6$
- Efficiency of kaon detection, as evaluated from $K^+ \to \pi^+\pi^+\pi^-$ events, $\eta(K^+) = 99.7\%$
- Resolution of the kaon crossing time, $\sigma_t(K^+) = 300\text{ps}/\sqrt{N_\gamma} \simeq 65\text{ps}$
- Pion misidentification probability $< 10^{-4}$



Conclusion

- A new CEDAR detector was proposed for the NA62 experiment to minimise the material in the path of the beam by changing the radiator gas to hydrogen
- The optical system of the new CEDAR-H was optimised using a full simulation of the detector
- The CEDAR-H was constructed and validated during a test beam at CERN in 2022
- The detector was commissioned at the NA62 experiment for the 2023 data-taking campaign and operated in 2023 and 2024 with an efficiency of 99.7% and a timing resolution of $\sim$65 ps
- The performance of the KTAG with the CEDAR-H surpasses both the kaon tagging requirements of NA62 and the performance of with the N_2-filled CEDAR-W
- The total amount of upstream material in the path of the beam was reduced by $> 50\%$, significantly decreasing the fraction of the $K^+ \to \pi^+ \nu \bar{\nu}$ trigger bandwidth occupied by events with scattered beam particles
- The reduction of material in the path of the beam benefits
  - the $K^+ \to \pi^+ \nu \bar{\nu}$ analysis (less potential background)
  - the concurrently collected data for other K^+ channels (lower trigger downscalings allowed)



Test beam

KTAG