Accelerator-based Light Particle Searches

at NA62 Experiment

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On behalf of the NA62 Collaboration

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NA62 Collaboration

NA62 COLLABORATION

29 institutes, ≤200 members

Gia Khoriauli - Light Particle Searches at NA62 - PPC2018 Zürich 23.08.2018
NA62 Experiments

- Fixed-target experiments at CERN North Area
  - 400 GeV/c proton beam
  - Secondary $K^+$ decaying in-flight

- Proton beam dump
  - $\sim 10^{18}$ POT / year

- Physics data taking started in 2015
  - $\sim 10^{13}$ recorded $K^+$ decays until 2018
NA62 Primary Task

- Indirect search for NP effects at the multi-TeV scale
  - Precise measurement of very rare FCNC decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$
    - $\text{Br}_{\text{SM}} = (0.84 \pm 0.1) \times 10^3$

- NA62 detector: long decay volume, effective $K^+$ tagging, perfect kinematic reconstruction ($K^+ \rightarrow \pi^+$), particle ID ($\pi, \mu$), photon veto ($\pi^0$ background), timing ($\sim 100$ ps)

- NA62 operation modes: $K^+$ beam and beam dump
  - Quick ($\sim 15$ min), fully reversible switch between the modes
NA62 as a Multipurpose Tool

- High energy & intensity proton beam

- Unique sensitivity (among existing experiments) to New Physics models at MeV-GeV scale → light particles
  - Heavy Neutral Leptons (HNL), Axion-like Particles (ALPs), Dark Photon (A’), Dark Scalar (S)

- Dedicated NA62 studies reviewed in this talk
  - Studies with K$^+$ beam
    - Invisible HNL production from K$^+$ decays in the detector fiducial volume (published)
    - Invisible decays of A’ produced in $\pi^0$ decays in the fiducial volume, (preliminary)
  - Studies with beam dump, only sensitivity estimations
    - Visible decays of HNL, A’, S and ALPs produced at the target in the fiducial volume
NA62 Detector

Detector hall + target hall $\approx 270$ m
NA62 Detector & K\(^+\) Beam

- K\(^+\) secondary beam from the target
  - \( p = 75 \text{ GeV/c} \pm 1\% \) selection with a magnet achromat
  - K\(^+\) only 6\% of the secondary beam (pions, protons, etc.)

- Collect \(4.5 \times 10^{12}\) K\(^+\) decays in decay region / year
  - Nominal intensity of protons on target: \(3 \times 10^{12}/\text{spill}\)
NA62 Detector & Primary Beam Dump

- Primary 400 GeV/c proton beam dump on movable secondary beam collimators, TAXes

- TAXes: copper + iron made collimators of $\sim 22\lambda$, total
  - Located at $\sim 20$ m downstream from target

- $\sim 10^{18}$ protons on target (POT) per year can be collected
  - (Remember SHiP’s plan of $2 \times 10^{20}$ POT (5 years))
Studies with K\(^+\) Beam

HNL SEARCH
Production
Heavy Neutral Leptons

- Neutrino Minimal SM extension, νMSM

- 3 RH neutrinos: N₁, N₂, N₃

- Light N₁, m ~ 10 KeV
  - dark matter candidate

- Heavy N₂, N₃, m ~ 100 MeV – GeV
  - Generation of SM neutrino masses (see-saw)
  - Introduction of extra CPV phases to explain baryon asymmetry through leptogenesis

- HNL can be produced in meson decays → NA62 sensitivity in both K⁺ and beam dump modes
**NA62 Search for Invisible HNL**

- If $m_{\text{HNL}} < m_{K^+}$, then HNL can be produced in $K^+$ decays

\[
\Gamma(K^+ \rightarrow \ell^+N) = \Gamma(K^+ \rightarrow \ell^+\nu) \cdot \rho_{\ell}(m_N) \cdot |U_{\ell4}|^2
\]

- Expected very weak coupling of HNL with SM
  - e.g. $|U_{\ell4}|^2 < 10^{-4}$ → HNL mean free path $>10$ km → invisible
  - $m_{\text{HNL}} < 500$ MeV/c²

- Search for spikes in missing mass spectrum in events with single lepton tracks from $K^+$ decays
NA62 Search for Invisible HNL

- Analysis of $K^+ \rightarrow \mu^+N$ and $K^+ \rightarrow e^+N$ used minimum bias data collected in 2015 at very low primary beam intensity (1% of nominal)
  - $\sim 10^8 K^+$ decays in the NA62 fiducial volume in each positron and muon data samples

- Beam tracker (GTK) was not available by that time → using averaged Kaon momentum
  - Mass resolution studied in MC

- Good mass resolution is very important
  - Amount of background in selected mass window
  - Possible HNL mass splitting
NA62 Search for Invisible HNL

- $m^2_{\text{miss}}$ distribution after final selection of positron sample

- Mass window for each mass hypothesis of HNL:
  $|m - m_{\text{HNL}}| < 1.5\sigma(m_{\text{HNL}})$

- Scan of HNL mass hypothesis in 1 MeV/c$^2$ steps

- Convert observed and expected background events in a mass window into an upper limit on the signal
  - Expected background is calculated from polynomial fit of sidebands of the mass window
NA62 Search for Invisible HNL

- No more than 2.2\(\sigma\) excess of observed upper limit over the expected one for \(|U_{l4}|^2\)

- Reached \(10^{-6} - 10^{-7}\) limits for \(|U_{l4}|^2\) in mass range 170 – 448 MeV/c\(^2\)
  - Best limits above 300 MeV/c\(^2\)

- Pushing \(|U_{l4}|^2\) limits down to \(10^{-8}\) foreseen with data 2016-2018
  - On-going study
Studies with Beam Dump

HNL SEARCH
Visible Decays
NA62 Sensitivity to HNL

- Neutrino portal to dark sector
  \[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H)N_I \]

- \( L_{\text{DS}} \) can include mass terms for one or more HNLs
  - Diagonalising mass matrix \( \rightarrow \) mixing of neutrinos and HNLs
    \[ \nu_\alpha \rightarrow \sum_I U_{\alpha I} N_I \]

- Sensitivity to three different mixing/coupling scenarios, \( U_e^2 : U_\mu^2 : U_\tau^2 \) is studied in the beam dump mode
  - Long lived HNL, decays into 2-track final states

- Available NA62 data sets collected in 2016/2017
  - \( 10^{17} \) POT with \( \pi \mu \) trigger
  - \( 10^{16} \) POT with \( \pi e \) trigger

*Gorbunov, Shaposhnikov, JHEP10 015 (2017)*
NA62 Sensitivity to HNL

- Long-lived HNL decaying into 2 charged particles
  - Assuming $10^{18}$ POT (~1 data taking year of NA62)
  - Reconstruction of all 2-track final states from HNL decays
  - Geometrical acceptance and trigger efficiencies
  - 0 background assumption (proved with $10^{15}$ POT data)
  - Limits @ 90% CL

\[
U^2_e : U^2_\mu : U^2_\tau = 52:1:1
\]
Normal hierarchy of active $\nu$ masses

\[
U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8
\]
Normal hierarchy of active $\nu$ masses

\[
U^2_e : U^2_\mu : U^2_\tau = 0.061:1:4.3
\]
Normal hierarchy of active $\nu$ masses
Studies with K\(^+\) Beam

DARK PHOTON SEARCH
Invisible Decays
Dark Photon

- Extra U(1) gauge symmetry connected with the SM U(1) via kinetic mixing of their gauge fields
  - Extra U(1) gauge boson $A'$ (Dark Photon) with a non-zero mass
  - $\varepsilon$ – mixing and $m_{A'}$ – mass are the theory free parameters

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\varepsilon}{2 \cos \theta_W} F'_{\mu \nu} B_{\mu \nu}.$$  

- Dark photon can couple (QED-like) with the SM fermions and the dark sector particles

- Can be searched at NA62 into visible and invisible decays ($K^+$ beam mode)
  - Production: $K^+ \rightarrow \pi^+ A'$ or $K^+ \rightarrow \pi^+(\pi^0 \rightarrow \gamma A')$
  - Decay: $A' \rightarrow \mu^+ \mu^-$, $e^+ e^-$ or $A' \rightarrow \chi \chi$ (infrared)
NA62 Study of $\pi^0 \to \gamma (A' \to \chi \chi)$

- Large sample of $K^+ \to \pi^+ \pi^0$
  - Control sample for $K^+ \to \pi^+ \nu \bar{\nu}$ analysis
  - Search for decay chain: $\pi^0 \to \gamma A'$ and $A' \to \chi \chi$ (invisible)
  - $m_{A'} < m_{\pi^0}$

- Signal event topology
  - Single $\pi^+$ track and $\gamma$
  - Missing energy, $M_{miss}^2$

- Data driven background ($\pi^0 \to \gamma\gamma$ with one photon lost in acceptance) estimation

$$M_{miss}^2 = (P_K - P_\pi - P_\gamma)^2$$

Minimum bias data: 2 $\gamma$ on LKr, simulate 1$\gamma$ loss

MC:
- $m_{A'} = 30$ MeV
- $m_{A'} = 60$ MeV
- $m_{A'} = 90$ MeV

$M_{miss}^2$ (GeV$^2$)
NA62 Study of $\pi^0 \to \gamma (A' \to \chi \chi)$

- No significant excess of events observed $\rightarrow$ improved limits at 90% CL (preliminary)
  - $A'$ mass range: $\sim 50 \text{ MeV}/c^2 < m_{A'} < 90 \text{ MeV}/c^2$
  - Only small fraction of data 2016 is used, $1.5 \times 10^{10} K^+$ decays

- Analysis with full 2016 data set is on-going
Studies with Beam Dump

DARK PHOTON SEARCH
Visible Decays
NA62 Sensitivity to $A'\rightarrow \mu^+\mu^-, e^+e^-$

- Production of $A'$ directly at the Beryllium target
  - Secondary meson decays: e.g. $pN \rightarrow X(\pi^0 \rightarrow \gamma A')$
  - Bremsstrahlung off primary beam: $pN \rightarrow XA'$
  - $A'$ production in QCD processes is not included in MC

- Reconstruction of displaced decay vertices of $A'\rightarrow e^+e^-$, $A'\rightarrow \mu^+\mu^-$ in the fiducial volume pointing back to target

- Sensitivity estimated assuming $10^{18}$ protons on target and 0 background

- Data sets from 2016/2017 runs for dedicated analysis
  - $3 \times 10^{17}$ POT with di-muon trigger
  - $5 \times 10^{16}$ POT with di-electron trigger
NA62 Sensitivity to $A' \rightarrow \mu^+\mu^-, e^+e^-$

- Model of $A'$ coupling with only the SM is considered

- Higher sensitivity expected with beam dump on TAXes
  - Enhanced meson production, less background, etc
Studies with Beam Dump

DARK SCALAR SEARCH
Dark Scalar

- Scalar portal to Dark Sector
  \[ L_{\text{scalar}} = L_{\text{SM}} + L_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H, \quad L_{\text{DS}} = S\bar{\chi}\chi + \ldots. \]

- Sensitivity to simplified model with \( \lambda = 0 \) studied by NA62 in the beam dump mode
  - The model implies single S production from meson decays: \( B,D \rightarrow KS, K \rightarrow \pi S \)
  - Parameters to be explored are \( m_S \) and mixing angle with Higgs \( \theta = \frac{\mu v}{m_h^2 - m_S^2} \)

- Data sets collected in 2016/2017
  - \( 3 \times 10^{17} \) POT with di-muon trigger
  - \( 5 \times 10^{16} \) POT with di-electron trigger
NA62 Sensitivity to Dark Scalar

- MC simulation of single S production in meson decays
- Sensitivity estimate assuming $10^{18}$ POT (~1 year of data taking at NA62 with beam dump mode)
- Reconstruction of all 2-track final states of S decay
  - ee, $\mu \mu$, $\pi \pi$, KK
  - Reconstructed vertex pointing back to TAXes
  - Acceptance included
  - 0 background assumed
- Estimate limits @ 90% CL
Studies with Beam Dump

ALPs SEARCH
Axion-Like Particles

- Light ALPs can serve as dark matter candidates and mediators between SM and dark sectors

\[ L_{\text{axion}} = L_{\text{SM}} + L_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta \]

- Sensitivity to long-lived ALPs produced in beam dump mode is studied
  - Assuming dominant interaction of ALPs with SM photons

- ALPs produced only in photon fusion (Primakoff production) are simulated
  - Copper TAXes → coherent \( Z^2 \) enhancement of production rate
  - Low \( p_T \) ALPs → good acceptance in detector
NA62 Sensitivity to ALPs

- Sensitivity is estimated assuming $10^{18}$ POT at TAXes
  - 1 day data ($\sim 10^{16}$ POT) is already enough to obtain significant results

- ALPs decaying into two photons in the fiducial volume are simulated
  - Both photons are in the acceptance of LKr (el.mag. calorimeter)
  - 0 background assumed

- Estimate limits @ 90% CL

- Analysis with $5 \times 10^{15}$ POT data (2017) is on-going

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NA62 Present & Future: Run 2 & 3

- Run 2: $K^+$ beam for $K^+ \rightarrow \pi^+\nu\bar{\nu}$, dark photon, HNL, LNV/LFV decays, etc.

- Run 3: many interesting fields to be studied with minimal (or no upgrades at all) of the existing setup
  - In $K^+$ beam mode:
    - If needed improve $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $A' \rightarrow$ invisible, invisible HNL
      - All benefit from the same trigger signature
  - In proton beam dump mode:
    - ALPs, Dark scalar, $A'$, HNL: all in visible decays

- 1 year of data taking in beam dump mode during Run 3 is under consideration
Summary

- NA62 experiment at CERN to measure $K^+$ rare (BR $\sim 10^{-10}$) decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$: very promising first result

- High energy & intensity proton beam + long decay volume & advanced detector system $\rightarrow$ NA62 as a very powerful tool to search for hidden sector light particles
  - Dark Photon, Dark Scalar, ALPs, HNL
  - MeV to GeV mass range, weak coupling with the SM
  - Visible and invisible decays

- Operation in $K^+$ beam or proton beam dump mode
  - Easy switch between the modes
  - Both considered after the long shutdown 2 (2021)

- Results (published, preliminary, MC) of various analysis of searches for particles in MeV-GeV mass scale at NA62 were presented
Kaon Identification – KTAG (CEDAR)

- **ChErenkov Differential counter with Achromatic Ring focus**
  - Filled with Nitrogen
  - Time resolution \( \approx 70 \) ps
  - 45 MHz of total rate

- **Gas pressure adjusted for \( K^+ \) selection with** \( p_K = 75 \) GeV/c

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Table 3

<table>
<thead>
<tr>
<th>Detector performance parameter</th>
<th>1 sector</th>
<th>2 sectors</th>
<th>3 sectors</th>
<th>4 sectors</th>
<th>5 sectors</th>
<th>6 sectors</th>
<th>7 sectors</th>
<th>8 sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>100%</td>
<td>99%</td>
<td>99%</td>
<td>98%</td>
<td>96%</td>
<td>88%</td>
<td>57%</td>
</tr>
</tbody>
</table>
GigaTracker (GTK) consists of three stations of silicon pixel detectors and the achromat of dipole magnets.
The GigaTracker detector

- Three stations of hybrid silicon pixel detectors
  - sensor+ASICs assembly
  - O-ring
  - steel vessel (in vacuum)

- 3 equal stations
  - 18000 channels per station
  - 0.005 $X_0$ per station
  - Momentum resolution: 0.2%
  - Angular resolution (in x-z and y-z planes): 16 $\mu$rad
  - Track time resolution: 74 ps

- 750 MHz total rate of incident particles

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STRAW Spectrometers

- 4 equal stations
  - 4 straw chambers per station
    - X-Y and U-Y views

- First time straw chambers operating in vacuum
  - 0.018 $X_0$ in total
Resolution of Spectrometers

- 1-track event selection
  - Good track originated from a Kaon decay in the fiducial volume
    - Pion track hypothesis

![](image)

Figure 7: Distribution of $m^2_{miss}$ as a function of pion momentum for kaon events selected on control data. The signal regions (red box) in the $(m^2_{miss}, p_\pi^+$) plane are drawn for reference.

7.5 Kinematic Reconstruction Performances

The fraction of $K^+ \rightarrow \pi^+\pi^0\pi^0$ and $K^+ \rightarrow \pi^+\pi^+$ events entering in the signal regions is measured using corresponding samples of $K^+ \rightarrow \pi^+\pi^+\pi^0$ and $K^+ \rightarrow \pi^+\pi^0$ decays collected by the control trigger concurrently with the PNN trigger. Both selections start from kaon events. Two electromagnetic-like clusters in LKr are looked for to select $K^+ \rightarrow \pi^+\pi^0$; the $K^+$ decay vertex is computed assuming that the clusters originated from $\pi^0$ decay and is required to be within $115 < Z_{vertex} < 165$ m. The $\pi^0$ selection is kept fully independent of $K^+$ and $\pi^+\pi^+$ kinematic variables to avoid any bias in the reconstructed $m^2_{miss}$. The same criteria for particle identification ("particle ID") and photon rejection in LAV, IRC and SAC used to select $K^+ \rightarrow \pi^+\pi^+\pi^0$; a cut on the extra activity in LKr cleans the sample further. $K^+ \rightarrow \pi^+\pi^+$ are selected requiring a hit in MUV3 associated to the track within $\pm 5$ ns from the pion time and MIP clusters in LKr, MUV1 and MUV2. No RICH particle ID requirement is applied to the muon to avoid biasing in the kinematics. The range $115 < Z_{vertex} < 165$ m is considered in the selection of this sample. Photon rejection is applied like in $K^+ \rightarrow \pi^+\pi^+\pi^0\pi^0$ selection (Section 7.8).

The top-row plots in Figure 8 show the distribution of $K^+ \rightarrow \pi^+\pi^0\pi^0$ control events with $15 < p_\pi^+ < 35$ GeV/c in the $(m^2_{miss}(\text{No GTK}), m^2_{miss}(\text{RICH}))$ and $(m^2_{miss}(\text{GTK}), m^2_{miss}(\text{RICH}))$.
The hadron beam enters from the left and travels throughout the length of the detector in an evacuated beam pipe. A zoom on one of the two disks accommodating the light sensors (PMs) is shown on the left; the mirror mosaic is made visible through the neon container (vessel) on the right.

The radiator vessel is evacuated before being filled with neon gas. During operation, the neon pressure is then kept constant at about 990 mbar with the vessel sealed. Small gas losses due to leaks are compensated by occasional top-ups. This concept has the advantage that temperature variations do not influence the gas density.

The photon detection sensitivity range starts at wavelength above 190 nm, which makes the detector performance practically insensitive to impurities like oxygen and H₂O in the gas. Other impurities, like for example CO₂, are not present naturally and can be kept sufficiently low.

The neon density influences the refractive index following the relation:

\[ n = 1 + \left( \frac{n_0 - 1}{\rho_0} \right) \rho \]

where \( n_0 \) is the refractive index (1.000067) and \( \rho_0 \) is the density (0.9001 kg/m³) of neon gas at NTP; \( \rho \) is the density at operating conditions (\( \rho = 0.814 \) kg/m³ for T= 25°C and P=1 bar).

**Mirror layout**

A mosaic of 20 spherical mirrors is used to reflect the Cherenkov light cone into a ring on the PM array in the mirror focal plane (Figure 42). To avoid absorption of reflected light by the beam pipe the mirrors are divided into two spherical surfaces: one with the centre of curvature to the left and one to the right of the beam pipe. The total reflective surface exceeds 6 m².

The mirrors have a nominal radius of curvature of 34 m and hence a focal length of 17 m. The mosaic includes 18 mirrors of regular hexagonal shape (350 mm side) and two half mirrors.

- **Neon at 1 bar**
- **70 ps track time resolution**
  - Reference detector for L0 trigger

**Vessel:** ~17 m long, filled with Neon

Mirror Mosaic (17m focal length)
Particle Identification - RICH

~10^2 muon suppression factor in a work region

- 15 GeV/c < p_{track} < 35 GeV/c
Particle Identification – LKr & MUVs

7.2 Liquid Krypton Calorimeter (LKr)

7.2.1 LKR Detector

NA62 is re-using the former NA48 Liquid Krypton calorimeter, which is described in Figure 21. The LKR is a quasi-homogeneous calorimeter filled with about 9,000 liters of liquid Krypton at 120 K, housed inside a cryostat. The calorimeter extends from the beam pipe ($R = 8\text{cm}$) to a radius of 128 cm and the depth is 127 cm (27 radiation length). The sensitive area is divided in 13,248 longitudinal cells of about 2x2cm cross-section. The cells are formed by Cu-Be electrodes aligned along the experiment axis (Z), they have a zig-zag shape to avoid inclusions when a particle shower is very close to the anode (see Figure 22). The signal produced by a particle crossing the LKr is collected by preamplifiers mounted inside the cryostat, directly attached to the calorimeter strips, and is then sent out using 50 kΩ coaxial cables and feedthroughs on the top of the cryostat. The signals are then sent to the transceiver boards, plugged directly on the feedthroughs and sharing the Faraday cage made by the cryostat.

The external components of the cryogenics and the auxiliary parts of the readout system (power supplies, transceivers, HV , calibration system) have been consolidated in order to prepare the detector for a new decade of data taking. The former NA48 LKR readout system, based on gain-switching, 10-bit FADCs was phased out to satisfy the demanding rate requirements of NA62.

7.2.2 Performances of the LKR

The excellent energy, space and time resolutions of the LKr calorimeter have been demonstrated by NA48. In NA62 the LKR detector is a key element for vetoing photons (in the region from...
Particle Identification - LKr

- 9000 litres of liquid krypton
  - $T = 120$ K

As a middle angle photon veto
- Angular coverage: 1 - 8.5 mrad
- Time resolution: 300 ps
- Detection inefficiency $10^{-3} - 10^{-5}$
  - $E\gamma = 1 - 10$ GeV

- <1% Resolution @ 20 GeV
  - $27X_0$
Particle Identification - Muon Vetos

- **MUV1 & MUV2**
  - “Sandwich”-type calorimeters
    - Iron + scintillator
  - 7.4λ

- **MUV3**: fast muon L0 trigger
  - 2 orthogonal planes of scintillator slabs

- $10^5$ muon suppression factor from MUVs
# Particle Identification Performance

**RICH**
- Likelihood discriminator

<table>
<thead>
<tr>
<th>PID</th>
<th>$\pi^+$ efficiency</th>
<th>$\mu^+$ efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeters</td>
<td>77%</td>
<td>$0.6 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>RICH</td>
<td>80%</td>
<td>$2.5 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

**Calorimeters**
- Boosted Decision Trees
7.1.2 Construction details

The OPAL modules (lead-glass block plus PMT) were manufactured by Hamamatsu during the mid-1980s. Their recycling required substantial care throughout the assembly procedure. The interface between the stainless-steel flange and lead glass block is fragile, and was found to be critically damaged in a few percent of the modules upon first examination. This was attributed to thermally-induced stress from the differing expansion coefficients of the steel and glass.

The first step in the processing of the modules at Frascati was therefore to reinforce the interface. Using epoxy resin, 27 cm$^2$×0.3-mm thick stainless-steel plates were attached across the glass-steel interface on all four sides of the block. Calculations indicated and static tests confirmed that the reinforced bond is several times stronger than the original bond. In any case, to prevent breakage, a concerted effort was made to avoid exposing the modules, even in those in fully assembled detectors, to temperatures outside the range of 15–30°C. This led to special considerations during storage, installation, and above all, transport of the completed detectors to CERN during the summer and winter months.

7.2 Liquid Krypton Calorimeter (LKr)

7.2.1 LKR Detector

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7.2.2 Performances of the LKr

The excellent energy, space and time resolutions of the LKr calorimeter have been demonstrated by NA48 [21]. In NA62 the LKr detector is a key element for vetoing photons (in the region from $10^{-3}$ to $10^{-4}$). Photon detection inefficiency: $\sim 10^{-4}$

Photon detection inefficiency: $\sim 10^{-3}$ – $10^{-5}$

Photon detection inefficiency: $\sim 10^{-3}$ – $10^{-4}$
Large Angle Photon Veto

- 12 ring-shaped stations
  - 11 stations operating in vacuum
  - Angular coverage: 8.5 – 50 mrad
  - Detection inefficiency: $10^{-4}$
    - $E_\gamma > 200$ MeV

- Sensitive material: lead-glass blocks from the OPAL calorimeter

- At least 21$X_0$ depth for incident particles
- **Intermediate Ring Calorimeter**

- **Small Angle Calorimeter**

- $10^8$ total $\pi^0$ rejection together with large and middle angle photon vetos
Regions of $K^+ \to \pi^+\nu\bar{\nu}$ Selection

Under pion hypothesis

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \to \mu^+\nu\mu$</td>
<td>63%</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^0$</td>
<td>21%</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi\pi$</td>
<td>7%</td>
</tr>
</tbody>
</table>
First result of $\text{Br}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ measurement with 2016 data

- 1 signal candidate observed (expected 0.27 SM signal events against 0.15 background events)

$$m_{\text{miss}}^2 = \left( P_{K^+} - P_{\pi^+} \right)^2$$

SM expectation

- $\text{Br}_{\text{SM}} = (0.84 \pm 0.1) \cdot 10$

Results (published soon)

Current best result from E787/949 at BNL (@ 68% CL)

$$\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} @ 95\% \text{ CL}$$

$$\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} @ 68\% \text{ CL}$$

$$\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$
NA62 Search for Invisible HNL

Number of observed events, expected background events with uncertainties and stemmed observed and expected upper limits on the signal @ 90% CL as functions of HNL mass.

![Graphs showing data for K^+ -> e^+N and K^+ -> μ^+N events.](image-url)

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