SEARCH FOR NEW PHYSICS WITH KAONS AT NA62

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Flavor 2019
MIAPP, MPI for Astrophysics, Garching
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NA62 — A General-purpose Experiment

**Flavour Physics**

- Search for **New Physics** in rare decays via indirect effect in loops.
- \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)
- **LNV**: \( K^+ \rightarrow \pi^- l^+ l^+ \)
- **LFV**: \( K^+ \rightarrow \pi^+ e^\pm \mu^\mp, ... \)

**Hidden Sector**

- Search for **feeblly interacting, long-lived, light and neutral particles**
- **Heavy Neutral Leptons (HNL)**, **Dark Photons**, **ALPs**
NA62 — A General-purpose Experiment

Flavour Physics
Search for New Physics in rare decays via indirect effect in loops.

Search for Lepton Flavour and Number Violation and other forbidden decays

Hidden Sector
Search for feebly interacting, long-lived, light and neutral particles

Heavy Neutral Leptons (HNL), Dark Photons, ALPs

\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

LNV: \( K^+ \rightarrow \pi^- l^+ l^+ \)

LFV: \( K^+ \rightarrow \pi^\pm e^\mp \mu^\pm \),...
The NA62 Apparatus
The NA62 Apparatus

[Diagram showing the NA62 apparatus with various components labeled]
The NA62 Apparatus

SPS protons
400 GeV/c
$10^{12}$ p/s
The NA62 Apparatus

Detectors for Secondary Beam
- Kaon ID (KTAG)
- Beam Tracker
- Beam guard ring (CHANTI)

SPS protons
400 GeV/c
$10^{12}$ p/s

Secondary beam
75 GeV/c, 750 MHz
$K^+$ (6%), $\pi^+$ (70%), $p$ (23%)

TARGET
Beam Tracker
Beam guard ring (CHANTI)
E.M. calorimeters
E.M. calorimeter (forward)
Hadron calorimeter

Momentum selection & collimation
1 m

Vacuum
100 m
150 m

Charged particle tracking
Charged particle time stamping
Photon detection
Particle ID

The NA62 Apparatus

Rainer Wanke, BSM Physics with Kaons, Flavor 2019, May 21st, 2019
The NA62 Apparatus

Detectors for Secondary Beam
- Kaon ID (KTAG)
- Beam Tracker
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SPS protons
400 GeV/c
$10^{12}$ p/s

Secondary beam
75 GeV/c, 750 MHz
$K^+$ (6%), $\pi^+$ (70%), $p$ (23%)

$K^+$ decay
60 m long
$\sim$ 5 MHz

Detectors for Decay Products
- Charged Particle Tracking
- Photon Detection
- Particle ID
NA62 Past, Present & Future

▶ 2016: 40% of nominal intensity, $13 \times 10^{11}$ protons on target

➔ $\sim 5 \times 10^{11} K^+$ decays recorded

▶ 2017/18: 60% of nominal intensity

➔ $> 8 \times 10^{12} K^+$ decays on tape

» Better data quality assessment

» Higher data taking efficiency

▶ Measurement of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ presented here 2016 data only (4 weeks of data taking).
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Golden channels in Kaon Physics

- Only penguin & box diagrams
  - high sensitivity for new physics beyond the SM!

- All diagrams proportional to $V^*_{ts} V_{td}$. 

$K \rightarrow \pi \nu \bar{\nu}$
\( K \to \pi \nu \bar{\nu} \) Branching Fractions (SM)

- \( B(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \left( \frac{\text{Im} \lambda_t}{\lambda^5} X \left( \frac{m_t^2}{m_W^2} \right) \right)^2 \) with \( \lambda_t = V_{ts}^* V_{td} \), \( \lambda = |V_{us}| = 0.225. \)

(No charm, since \( V_{cs}^* V_{cd} \) practically real.)

- \( B(K^+ \to \pi^+ \nu \bar{\nu}) = \kappa_+ \left( \left( \frac{\text{Im} \lambda_t}{\lambda^5} X \left( \frac{m_t^2}{m_W^2} \right) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X \left( \frac{m_t^2}{m_W^2} \right) + \frac{\text{Re} \lambda_c}{\lambda} P_0 \left( \frac{m_c^2}{m_W^2} \right) \right)^2 \right) \approx \kappa_+ \lambda_t^2 \left( X \left( \frac{m_t^2}{m_W^2} \right) / \lambda^5 \right)^2 + \text{charm contributions} \)

- Hadronic contributions by isospin rotation of \( K \to \pi e \nu \):
  \[ \kappa_L = (2.23 \pm 0.01) \times 10^{-10} \]
  \[ \propto \lambda^8 \cdot B(K_L \to \pi^\pm e^\mp \nu) \]
  \[ \kappa_+ = (5.17 \pm 0.03) \times 10^{-11} \]
  \[ \propto \lambda^8 \cdot B(K^+ \to \pi^0 e^+ \nu) \]

- Unitarity triangle:
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Theoretical Prediction

Theoretical prediction within the Standard Model:  
(Buras, Buttazzo, Girrbach-Noe, Knegjens, JHEP11 (2015) 033)

\[
\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}
\]
\[
\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}
\]

- Largest uncertainties: Knowledge on $|V_{ub}|$, $|V_{cb}|$ and $\gamma$!
$K \rightarrow \pi \nu \bar{\nu}$ beyond the SM

- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - $Z/Z'$ models with pure LH/RH couplings
  - Littlest Higgs with $T$ parity
- Models without above constraints
  - Randall-Sundrum

(BR($K_L \rightarrow \pi^0 \nu \bar{\nu}$) × 10$^{11}$, BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) × 10$^{11}$)

(M.Moulson, KAON 2016)
How to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$?

NA62 employs new technique for the measurement:

- Kaons with high momentum $\rightarrow$ Kaon decay in flight.
- Signal signature: $K^+$ track + $\pi^+$ track + nothing else.
- Trigger: 1 track + $\mu/\gamma$ veto (+ control trigger for backgr. estimation)

- Signal reconstruction by measurement of missing mass:

$$m^2_{\text{miss}} \approx m_K^2 (1 - \frac{p_\pi}{p_K}) + m_\pi^2 (1 - \frac{p_K}{p_\pi}) - p_K p_\pi \theta^2_{\pi K}$$
How to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$?

Two regions without background from other $K^+$ decays:

- **Region 1:** $0 < m_{\text{miss}}^2 < 0.01 \text{ GeV}^2/c^4 \quad \Rightarrow \quad \text{Acc} \approx 4.5\%$
- **Region 2:** $0.026 < m_{\text{miss}}^2 < 0.068 \text{ GeV}^2/c^4 \quad \Rightarrow \quad \text{Acc} \approx 14.5\%$

(only geometrical acceptance)

$\Rightarrow$ **Main background suppression by kinematics!**
How to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$?

Main backgrounds:

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR</th>
<th>Suppression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$ ($K_{\mu2}$)</td>
<td>0.63</td>
<td>Kinematics, $\mu$-ID</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$ ($K_{2\pi}$)</td>
<td>0.20</td>
<td>Kinematics, photon veto</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi\pi$ ($K_{3\pi}$)</td>
<td>0.07</td>
<td>Kinematics, track &amp; photon veto</td>
</tr>
</tbody>
</table>
How to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$?

$m^2_{\text{miss}} \approx m^2_K (1 - \frac{P_\pi}{P_K}) + m^2_{\pi}(1 - \frac{P_K}{P_\pi}) - P_K P_\pi \theta^2_{\pi K}$

Need to measure $m^2_{\text{miss}}$ as precise as possible!

- Measurement of $K^+$ momentum.
- Measurement of $\pi^+$ momentum.
- $K^+ / \pi^+$ identification (lots of $\pi^+$ in the beam, $\mu^+$ from $K \rightarrow \mu \nu$).
- Veto for all particles (photons!) escaping the detector.
Signal Selection

Selection criteria

- Single track topology with multi-track rejection
- $15 \text{ GeV} < p_{\text{track}} < 35 \text{ GeV}$ → $E_{\text{miss}} > 40 \text{ GeV}$
- $\pi^+$ identification (RICH, MUV)
- Photon rejection

Performances:

- $\varepsilon_{\mu^+} = 1 \times 10^{-8}$ (with $\varepsilon_{\pi^+} = 64\%$)
- $\varepsilon_{\pi^0} = 3 \times 10^{-8}$
- $\sigma_{\text{time}} \sim \mathcal{O}(100 \text{ ps})$
- $\sigma(m^2_{\text{miss}}) = 1 \times 10^{-3} \text{ GeV}^2/c^4$
Background Rejection: $K^+ \rightarrow \pi^+\pi^0$

Data control sample of reconstructed $K^+ \rightarrow \pi^+\pi^0$ events is compared to:

- MC $K^+ \rightarrow \pi^+\pi^0(\gamma)$ with same selection.
- MC $K^+ \rightarrow \pi^+\pi^0(\gamma)$ with $K^+ \rightarrow \pi^+\nu\bar{\nu}$ selection, but no photon rejection.

→ Perfect data/MC agreement

In addition photon rejection measured from data

→ IB tail practically gone.
**Background Rejection: $K^+ \rightarrow \pi^+\pi^0$**

- **Estimated background from $K^+ \rightarrow \pi^+\pi^0(\gamma)$:**

  \[0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}} \text{ events}\]
Background Rejection: \( K^+ \rightarrow \mu^+\nu \)

Same method as for \( K^+ \rightarrow \pi^+\pi^0 \):

Data \( K^+ \rightarrow \mu^+\nu \) control sample is compared to:

- \( \text{MC } K^+ \rightarrow \mu^+\nu \) with same selection.
- \( \text{MC } K^+ \rightarrow \mu^+\nu \) with \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) selection, but no \( \pi^+ \) identification.
- Perfect data/MC agreement

- Remaining rejection by requiring \( \pi^+ \) identification.
Background Rejection: $K^+ \rightarrow \mu^+ \nu$

→ Estimated background from $K^+ \rightarrow \mu^+ \nu$: $0.020 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}}$ events
Background from other $K^+$ Decays

$K^+ \rightarrow \pi^+\pi^+\pi^-$

- Estimated with MC, validated by partially reconstructed $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays

  \[ 0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{syst}} \text{ events} \]

$K^+ \rightarrow \pi^+\pi^-e^+\nu$

- Branching fraction of $\mathcal{O}(10^{-5})$, but serious background with hard $\pi^-$ and slow $e^+$!
- Estimated with MC, validated by oppositely charged events

  \[ 0.013 \pm 0.017_{\text{stat}} \pm 0.009_{\text{syst}} \text{ events} \]
Upstream Background

- Accidental particles from the beam line
- Pions from interactions with beam spectrometer material
- Kaon-pion matching and geometrical cuts effective
- Data driven estimation

Estimated background from upstream background:

\[ 0.050 \pm 0.090 \text{ stat events} \]
Acceptance and Normalization

Normalization:
- $N_K$ from control triggered $K^+ \rightarrow \pi^+\pi^0$ events
- Normalization acceptance $A_{\text{norm}} = 10\%$

$N_K = 1.21(2) \times 10^{11}$

Signal acceptance
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$ acceptance: $A_{\text{signal}} = (4.0 \pm 0.1)\%$

Single Event Sensitivity:
- $(3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-10}$

- Random veto
- Definition of $\pi^+\pi^0$ region

Expected SM events:
- $0.27 \pm 0.02_{\text{exp}} \pm 0.03_{\text{ext}}$
Validation: Unblind Control Regions

<table>
<thead>
<tr>
<th>CR</th>
<th>( \pi^+\pi^0 )</th>
<th>( \mu^+\nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>( 0.52 \pm 0.08_{\text{stat}} \pm 0.03_{\text{syst}} )</td>
<td>( 1.02 \pm 0.16_{\text{stat}} )</td>
</tr>
<tr>
<td>CR2</td>
<td>( 0.94 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}} )</td>
<td></td>
</tr>
</tbody>
</table>

1 event observed

2 events observed
Result

1 event observed
Result

1 event observed

\[ \mathbf{m}^2_{\text{miss}} [\text{GeV}^2/c^4] \]

\[ K^+ \rightarrow \pi^+\nu\bar{\nu} \text{ MC} \]

\[ \text{data} \]

\[ \text{RICH} \]

\[ \text{expected rings} \]

\[ P = 15.3 \text{ GeV/c} \]

\[ \text{Likelihood under different mass hypotheses} \]

\[ 0.000 \]

\[ 0.000 \]

\[ 1.000 \]
Result

Single Event Sensitivity: \( (3.15 \pm 0.24) \times 10^{-10} \)

→ SM expectation: \( 0.27 \pm 0.04 \) events

Expected background: \( 0.15 \pm 0.09 \) events

Observed: 1 event

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ at } 95 \% \text{ CL} \]

(PLB 791 (2019) 156)

For comparison:

- Expected limit: \( 10 \times 10^{-10} \text{ at } 95 \% \text{ CL} \)
- 68 % CL region: \( (2.8^{+4.4}_{-2.3}) \times 10^{-10} \)
- E787/949: \( (1.7 \pm 1.1) \times 10^{-10} \)
- SM expectation: \( (0.8 \pm 0.1) \times 10^{-10} \)
Look into 2017 Data

- **Several improvements**
  (e.g. 40% better $\pi^0$ rejection)

- **Expectations (preliminary):**

  **Kaon decays:** $(13 \pm 1) \times 10^{13}$
  
  **SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events:** $2.5 \pm 0.4$

  **Background events:** $0.8 \pm 0.1$
  (without upstream background)

### 2017 background expectation

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events in signal regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ IB</td>
<td>$0.35 \pm 0.02_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu(\gamma)$ IB</td>
<td>$0.16 \pm 0.01_{\text{stat}} \pm 0.05_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$</td>
<td>$0.22 \pm 0.08_{\text{stat}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^+ \pi^-$</td>
<td>$0.015 \pm 0.008_{\text{stat}} \pm 0.015_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \gamma \gamma$</td>
<td>$0.005 \pm 0.005_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow l^+ \pi^0 \nu_l$</td>
<td>$0.012 \pm 0.012_{\text{syst}}$</td>
</tr>
<tr>
<td>Upstream Background</td>
<td>Analysis on-going</td>
</tr>
</tbody>
</table>

Rainer Wanke, *BSM Physics with Kaons*, Flavor 2019, May 21st, 2019
Search for Lepton Number Violation
Search for Lepton Number Violation

Lepton Flavour Violation may occur e.g. via Majorana neutrinos, leading to decays with $\Delta L = 2$.

- In Kaon decays: $K^+ \rightarrow \pi^- e^+ e^+$ and $K^+ \rightarrow \pi^- \mu^+ \mu^+$

NA62:

- Collection of di-electron, di-muon, and multi-track events simultaneously with $\pi^+ \nu \bar{\nu}$ via dedicated, downscaled triggers (Downscaling: $ee = 8$, $\mu\mu = 2$, multi-track = 100).

- Data sample: $\sim$ 3 months of 2017 data (3× more still to come).
Search for Lepton Number Violation

\( K^+ \rightarrow \pi^- e^+ e^+ \):
- \( N_K \approx 2 \times 10^{11} \)
- \( N_{\text{background}} = 0.16 \pm 0.03 \)
- \( N_{\text{signal}} = 0 \)
\[ \Rightarrow \mathcal{B} < 2.2 \times 10^{-10} \text{ at 90\% CL} \]

\( K^+ \rightarrow \pi^- \mu^+ \mu^+ \):
- \( N_K \approx 8 \times 10^{11} \)
- \( N_{\text{background}} = 0.9 \pm 0.4 \)
- \( N_{\text{signal}} = 1 \)
\[ \Rightarrow \mathcal{B} < 4.2 \times 10^{-11} \text{ at 90\% CL} \]

\( \text{PDG: } < 6.4 \times 10^{-10} \)

\( \text{PDG: } < 8.6 \times 10^{-11} \)

\( \text{(arXiv:1905.07770)} \)
Search for Dark Photons in $\pi^0$ Decays
Dark Photons

- Fields $A'_\mu$ with strength $F'_{\mu\nu}$, mixing with coupling $\epsilon$ with electroweak field $F^\mu_\nu$.

 Dark Photon $A'$

- Same quantum numbers as normal photon, but massive.
- If $\gamma$ mixes into dark photon:

  Missing energy may reveal its presence (e.g. in $\pi^0$ decay)
Search for $\pi^0 \rightarrow \gamma A'$ with $A' \rightarrow \text{invisible}$

Analysis principle:

- Select sample of tagged $\pi^0$ from $K^+ \rightarrow \pi^+\pi^0$ decays, with exactly one $\gamma$ detected (parasitic to $\pi\nu\bar{\nu}$ trigger + small forward energy).
- Signal signature: 1 track, 1 photon + $E_{\text{miss}}$
- Peak search in

$$m_{\text{miss}}^2 = (p_K - p_\pi - p_\gamma)^2.$$ 
- Background:

Only $\pi^0 \rightarrow \gamma\gamma$ with 1 lost $\gamma$, determined from data by using $\gamma$ conversions.
Search for $\pi^0 \rightarrow \gamma A'$ with $A' \rightarrow \text{invisible}$

Data sample:

- Search performed with $\approx 1.5 \times 10^{10} K^+$ decays (subsample of 2016 data).
- No excess observed.
Search for $\pi^0 \rightarrow \gamma A'$ with $A' \rightarrow \text{invisible}$

No observation $\rightarrow$ exclusion limits:

- Limits on $\epsilon^2$ of $\mathcal{O}(\text{few } 10^{-7})$ for $60 \text{ MeV} < m_{A'} < 110 \text{ MeV}$.

Side result:

- Limit on $\pi^0 \rightarrow \gamma \nu \bar{\nu}$: $\mathcal{B}(\pi^0 \rightarrow \gamma \nu \bar{\nu}) < 1.9 \times 10^{-7}$ at 90 % CL

(arXiv:1903.08767, accepted by PLB)
Conclusions & Outlook

NA62 experiment:

- **General aim:** Measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ to a 10% level.
  
  First $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ result published, 20× more data on tape.

- **Large sensitivities to further BSM physics like LNV/LFV, Hidden sector particle searches, ...**
  
  First results on small data sets published.

- **Further plans:**
  
  - Take more data for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ after LS2.
  
  - Special runs for LFV/LNV and/or in beam-dump mode for the search of long-lived neutral hidden sector particles.
Backup
$K^+ \rightarrow \pi^+ \nu \bar{\nu} :$ Experimental Status

$K_L \rightarrow \pi^0 \nu \bar{\nu}$

- **E931a (KEK):** (PRD 81 (2010) 072004)

- **E787/E949 (BNL):** (PRL 101 (2008) 191802)

**BR < 2.6 \times 10^{-8} \quad (90\% \text{ CL})**

**SM:** $(3.4 \pm 0.6) \times 10^{-11}$

**BR \approx (17 \pm 11) \times 10^{-11}**

**SM:** $(8.4 \pm 1.0) \times 10^{-11}$
Kaon Identification

Principle:

- $K^+$ have lower velocity than $\pi^+$
- Identification with a Threshold Cherenkov counter.
- Cherenkov light is reflected to PMT arrays with 48 PMTs each.
NA62 Beam Spectrometer

Missing mass resolution:

- Need precise K⁺ momentum
- Three Si-Pixel stations in 750 MHz beam.

**GigaTracker**

- On-sensor TDC with channel cooling
- $X/X_0 < 0.5\% / \text{station}$
- Momentum resolution 0.15 GeV/c
- $\sigma(t_{\text{beam particle}}) \sim 200$ ps

*Fully completed in Sep 2016!*
NA62 Magnet Spectrometer

Old NA48 spectrometer:

- Straw chambers operated in vacuum.
- No multiple scattering on helium and entry window.
- No acceptance loss due to the beam pipe.

New NA62 spectrometer:
NA62 Straw Tracker

- 4 chambers with 1 cm straws.
- 0.5% $X_0$ per station.

a) X Coordinate View

b) Y Coordinate View

c) U Coordinate View

d) Overlay of four Views

Figure 221. Schematic drawing of the four “Views” that compose each straw chamber. a) the x-coordinate view with vertical straws, b) Y-coordinate View with horizontal straws, c) the U-coordinate view (the V-coordinate view is rotate by 90 degrees compared U-coordinate), d) A full chambers consisting of the X,Y,U and V Views; the active area of the chamber covers a diameter of 2.1m. The gap near the middle of each layer is kept free for the beam passage.

From these constrains follow the main requirements of the detector:

- Spatial resolution $\leq 130 \text{ pm}$ per coordinate
- $\leq 80 \text{ pm}$ per space point
- $\leq 0.5\%$ of a radiation length ($X_0$) for each chamber
- Installation inside the vacuum tank ($P = 10^{-5}$ mbar) with minimum gas load for the vacuum system ($\text{Leak rate } \leq 10^{-5} \text{ mbar} \cdot \text{l/s}$)

Rainer Wanke, BSM Physics with Kaons, Flavor 2019, May 21st, 2019
3.5 Straw Tracker

3.5.4 Chamber Design, Construction and Installation

3.5.4.1 Detector Geometry and Layout

The detector consists of four stations and each station has four views and gives four measuring points (x, y, u, v) as shown in Figure 249.

The mechanical structure of the chambers requires good dimensional stability, rigidity, and strength. The active volume of the detector is 2.1 m x 2.1 m and each straw plane has a 12 cm wide region for the beam in the middle of the frame without straws. A 3D drawing of a chamber is shown in Figure 250.

Figure 249. Layout of the straw spectrometer in ECN3 with the straw chambers marked 1, 2, 3 and 4.

Figure 250. One chamber consisting of two modules (left). Detail of the straw fixation beam (right).
NA62 RICH Detector

- Vessel ~17 m long, Ne gas at atm. pressure
- Mirror mosaic (17 m focal length)
- Beam pipe
- 2 × ~1000 PMTs
NA62 RICH Detector
NA62 RICH Detector
NA62 RICH Detector

One-track selection

RICH performance in 2016:
- 0.8% $\mu$ mis-ID with
- 90% pion efficiency
→ $O(10^2)$ $\pi/\mu$ separation
Photon Vetos

Target → CEDAR → GTK

- Large Angle Veto (LAV)
- Small Angle Vetos (IRC, SAC)

- LKr Calorimeter

Decay Region 65m

50 mrad

8.5 mrad

CHANTI
Charged Particle Veto
Large Angle Vetos (LAV)

Station 1

Station 12

OPAL lead glasses

Table 7

<table>
<thead>
<tr>
<th>Stations</th>
<th>Diameter [mm]</th>
<th>Block radius [mm]</th>
<th>Layers</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1–A5</td>
<td>2168</td>
<td>537</td>
<td>907</td>
<td>5</td>
</tr>
<tr>
<td>A6–A8</td>
<td>2662</td>
<td>767</td>
<td>1137</td>
<td>5</td>
</tr>
<tr>
<td>A9–A11</td>
<td>3060</td>
<td>980</td>
<td>1350</td>
<td>4</td>
</tr>
<tr>
<td>A12</td>
<td>3320</td>
<td>1070</td>
<td>1440</td>
<td>4</td>
</tr>
</tbody>
</table>

Each block is read out at the back side by a Hamamatsu R2238 76-mm PM, which is optically coupled via a 4-cm long cylindrical light guide of SF57 of the same diameter as the PM. The rear face of the glass block is glued to a 1-cm thick stainless-steel mounting flange featuring a circular cutout for the light guide. A complete module is the monolithic assembly of a block, PM, and light guide, as shown in Figure 28. Each block is made by arranging these blocks around the perimeter of the sensitive volume of the experiment, with the blocks aligned radially to form an inward-facing ring. Multiple rings are used in each station in order to provide the depth required for the efficient detection of incident particles. The blocks in successive rings are staggered in azimuth; the rings are spaced out longitudinally by about 1 cm.
Liquid-Krypton Calorimeter

- Quasi-homogeneous liquid-krypton calorimeter (from NA48).
- Completely new 14-bit FADC readout (~13500 channels).
- Inefficiency measured from $K^+ \rightarrow \pi^+\pi^0$ decays:

\[ \sim 7 \times 10^{-6} \text{ for } E_\gamma > 10 \text{ GeV} \]
Hadron Calorimeter/Muon Veto System

- **Hadron calorimeter**: Two iron-scintillator-strip sandwich calorimeters (*MUV1/MUV2*).
- **Fast Muon Veto** for Level 0 trigger (*MUV3*).