The Future of the NA62 Experiment at CERN

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Flavour and Dark Matter
25-28 September 2017
Heidelberg
The NA62 experiment, its main goal and the detector
- Kaon rare decays $\rightarrow$ test of the SM
- Status of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ measurement
  - Highlights of the detector and its performance

The NA62 beam operation modes
- $K^+$ beam and dump

NA62 searches of New Physics at MeV-GeV scale
- Dark Photons, Axion-Like Particles, Heavy Neutral Leptons
  - Present status & future prospects

Long term future: prospects of a $K_L \rightarrow \pi^0\nu\bar{\nu}$ measurement
The NA62 Collaboration

NA62 COLLABORATION

29 institutes, more than 200 members
The NA62 Experiment

- 62nd proposed experiment in the CERN North Area
  - Successor of the NA48 experiment
  - Fixed target (Beryllium)
  - 400 GeV/c proton beam from SPS

- K$^+$ from secondary beam
  - $p_{\text{Kaon}} = 75\pm1$ GeV/c
  - Kaons decaying in flight

- 2014: first pilot run, 2015: commissioning/physics run

- 2016 physics run $\Rightarrow$ the SM sensitivity for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- Data taking until the LHC long shutdown 2 in 2018
  - $\sim 10^{13}$ $K^+$ decays to be recorded in total
Golden Rare Kaon Decays

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$: very clean FCNC processes
  - SM branching ratios $\sim 10^{-10}$
  - $K_L \rightarrow \pi^0 \nu \bar{\nu}$: completely CP-violating decay

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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

@ CERN

@ J-PARC
Relation with Unitarity Triangle

![Unitarity Triangle Diagram](image)

- New Physics models predicting different ways of violating this harmony in the two rare decays

\[
(\bar{\rho}, \bar{\eta}) \quad \alpha \\
K_L \to \pi^0 \nu \bar{\nu} \\
\gamma \quad \beta \\
(0,0) \quad (1,0)
\]


\[
\sin 2\beta \quad \epsilon_K
\]

- Alternatively, combining (III.1) and (III.15), one finds (Buras and Maniatis, 2004).

\[
\Delta m_d \quad \Delta m_s
\]

- Finally, as in the SM and more generally in all MFV models there

- It should be stressed that \(\sin^2 \theta \approx 1\) in the SM and more generally in all MFV models.

- The determination of the parameter \(\sin^2 \theta\) is determined this way depends only on two measurable branching ratios.

- As briefly discussed in Section IX and in great detail in (Ali, 2003; Buchalla, 2003;)

- The violation of this relation is much harder. As briefly discussed in

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BR($K^{+,0}_L \rightarrow \pi^{+,0} \nu \bar{\nu}$) SM Predictions

Buras et al., JHEP11 (2015) 033

- \[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \]
- \[ \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.31) \times 10^{-11} \]

- BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) and BR($K_L \rightarrow \pi^0 \nu \bar{\nu}$) uncertainties: 8% and 10%
  - Theory uncertainty: **only 2%**!
  - Excellent precision in flavour physics
The NA62 goal: BR($K^{+,0}_L \to \pi^{+,0}\bar{\nu}\bar{\nu}$) with 10% precision

- Theory uncertainty: only 2%!
  - Excellent precision in flavour physics

Experimental status: E787/E949 experiments at BNL

$$\text{BR}_{\text{exp}}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$
The NA62 Detector Hall

Detector hall + target hall = 270 m
4.5 x 10^{12} K^+ decays in the fiducial region per year

@ nominal intensity of the primary proton beam: 3 x 10^{12}/pulse
### NA62 Strategy of Measurement

#### Equation:

\[ m_{miss}^2 = \left( P_{K^+} - P_{\pi^+} \right)^2 \]
NA62 Strategy of Measurement

### Background
1. $K^+$ decay modes
2. Accidental single track matched with a $K^-$ like track

### Kaon Decays
- Accidental single tracks
- Beam interactions in the beam tracker
- Beam interactions with the residual gas in the vacuum region

### Signal
- Kinematic variable:
  \[ m_{\text{miss}} = P_\gamma - P_\mu \]

### Under pion hypothesis

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>63%</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>21%</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi\pi$</td>
<td>7%</td>
</tr>
</tbody>
</table>
Under pion hypothesis

$K^+ \rightarrow \pi^+ \pi^0(\gamma)$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ($\times 10^{10}$)

$K^+ \rightarrow \mu^+ \nu \mu(\gamma)$

$K^+ \rightarrow e^+ \pi^0 \nu_e$

$K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$

Region I

Region II

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

$\frac{d\Gamma}{\Gamma_{\text{tot}} \, dm^2_{\text{miss}}}$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$10^{-7}$
NA62 Tracking

- Silicon Pixel detector, 3 stations
  - 750 MHz total particle rate
  - Track momentum & angle resolutions: 0.2% & 16 μrad
  - Time Resolution ≈100 ps
### NA62 Tracking

**Silicon Pixel detector, 3 stations**
- **750 MHz** total particle rate
- Track momentum & angle resolutions: **0.2% & 16 μrad**
- Time Resolution $\approx 100$ ps

**4 STRAW stations with ≥3-coordinates operating in vacuum** – only $0.018X_0$ (total)

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**Deployment**
- Vacuum load for the vacuum tank.
- Integration of the tracker inside the vacuum tank.
- Capability to veto events with multiple charged particles.
- Average track efficiency near 100%.
- From these constraints follow the main requirements of the detector:

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**CoordinateViews**
- **a) x Coordinate View**
- **b) Y Coordinate View**
- **c) U Coordinate View**
- **d) A full chambers**

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**Chamber Dimensions**
- Number of Chambers: 4
- Number of Straws per View: 1'792
- Diameter: ~10 mm
- Length: 2'160 mm

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**Straw Tracker Layout**
- Chamber 1
  - Width: 101.2 mm
  - Height: 132.1 mm
- Chamber 2
  - Width: 101.2 mm
  - Height: 132.1 mm
- Chamber 3
  - Width: 101.2 mm
  - Height: 132.1 mm
- Chamber 4
  - Width: 101.2 mm
  - Height: 132.1 mm

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**Chamber 4**
- Position:
  - X: 1.2 mrad (upstream of the magnet)
  - φ: 15°

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**Hit Time Resolution**
- KTAG hit time resolution in the 2015 run.
1-track selection

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

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

7.5 Kinematic Reconstruction Performances

The fraction of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^+ \rightarrow \mu^+ \nu \bar{\nu}$ events entering in the signal regions is measured using corresponding samples of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^+ \rightarrow \mu^+ \nu \bar{\nu}$ 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 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$; the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay vertex is computed assuming that the clusters originated from $\pi^0$ decay and is required to be within $115 < Z_{\text{vertex}} < 165$ m. The $\pi^0$ selection is kept fully independent of $K^+$ and $\pi^+ \nu \bar{\nu}$ kinematic variables to avoid any bias in the reconstructed $m_{\text{miss}}^2$. The same criteria for particle identification (“particle ID”) and photon rejection in LAV, IRC and SAC used to select $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (see Sections 7.6, 7.8) are applied also to select $K^+ \rightarrow \mu^+ \nu \bar{\nu}$; a cut on the extra activity in LKr cleans the sample further. $K^+ \rightarrow \mu^+ \nu \bar{\nu}$ 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 $115 < Z_{\text{vertex}} < 165$ m is considered in the selection of this sample. Photon rejection is applied like in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection (Section 7.8).
1. track selection

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

**Figure 7:** Distribution of $m^2_{\text{miss}}$ as a function of pion momentum for kaon events selected on control data. The signal regions (red box) in the ($m^2_{\text{miss}}$, $p_\pi^+\pi^0$) plane are drawn for reference.

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The top-row plots in Figure 8 show the distribution of $K^+\rightarrow\pi^+\pi^0\nu\bar{\nu}$ control events with $15 < p_{\pi^+} < 35$ GeV/c in the ($m^2_{\text{miss}} (\text{No GTK})$, $m^2_{\text{miss}} (\text{RICH})$) and ($m^2_{\text{miss}} (\text{No GTK})$, $m^2_{\text{miss}} (\text{RICH})$) samples.
Summary of the Performance

- $\sim 10^4$ kinematic suppression of the background
  - GTK, STRAW

- Highly effective photon veto system, $\sim 10^8 \pi^0$ rejection
  - LAV (large angle vetos), LKr (as a medium angle veto), IRC and SAC (small angle vetos, down to 0 radian)

- $\sim 10^7$ muon suppression from particle identification with calorimeters, fast muon veto (MUV3) and RICH
  - LKr+MUVs: $10^5$ muon rejection @ $\sim 80\%$ pion efficiency
  - RICH: $\sim 10^2$ muon rejection in range $15 \text{ GeV/c} < p_{\text{track}} < 35 \text{ GeV/c}$

- Good time resolution: $\sim 100 \text{ ps}$
\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) Analysis in Data 2016

- After particle ID and photon veto cuts
  - 2.3\times10^{10} K^+ decays (5% of 2016 data) used

- Expected signal: 0.064, expected background: 0.057, observed: 0 events
  - (The event in the box fails \( m^2_{\text{miss}}(\text{w/o GTK}) \) cut)
  - Signal acceptance: 3.3%
    - Will be improved
After particle ID and photon veto cuts

- **2.3×10 K⁺ decays (5% of 2016 data) used**

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- (The event in the box fails $m^2_{\text{miss}(\text{w/o GTK})}$ cut)

- **Signal acceptance:** 3.3%
  - Will be improved

**The SM sensitivity, BR<10⁻⁹, expected to be reached using the ~full 2016 data**

**Expected ~15 signal events in 2017 data**
NA62 Beam Operation Modes

SPS beam and users

T2 wobbling

T4 wobbling

T6

P42

M2

Cedar

NA61

H2

H4

H6

H8

P6

K12

NA62

COMPASS
NA62 Beam Operation Modes

- 75 GeV/c $K^+$ beam or proton dump modes using “TAXes”
- Easily switchable modes in the current beam setup of NA62
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  - Easily switchable modes in the current beam setup of NA62

SPS beam and users

NA62 beam-line from target to decay volume

- TAXes: movable copper + iron made collimators of ~22λ, total thickness
NP Searches in Dump Mode: ALP

- Long-lived Axion-like particles created by photon fusion
  - Copper TAX $\rightarrow$ coherent $Z^2$ enhancement of production rate

- ALP lifetime dependence on its mass and coupling with photon
  \[ \tau \sim \frac{1}{(g_{a\gamma}^2 m_a^3)} \]

- Expected limits on the mass and coupling assuming 1 day/1 month of data taking in the dump mode
NP Searches in Dump Mode: ALP

- ~1 day NA62 data from running in dump mode already sensitive to ALPs at 90% CL
  - Large proton energy, 400 GeV
  - Long decay volume, 65 m
  - Assume 0 background
    - Rather realistic

- Dependence of the projected limits on
  - Production differential cross section of ALPs and lifetime
  - Acceptance photons in the LKr electromagnetic calorimeter
NP Searches in Dump Mode: $A'$

- Search for displaced di-lepton decays: $A' \rightarrow e^+ e^-, A' \rightarrow \mu^+ \mu^-$
  - $2 \times 10^{18}$ protons on target (~2 years)
  - Limits at 90% CL, 0 background
    - Production only in target, no TAXes

$|A' \text{ coupling to ordinary } \gamma|^2$

- Higher sensitivity is expected considering direct QCD production of $A'$ and dump on TAXes
Search for visible decays of long-lived HNL → πe, πμ

- Limits depend on the relation of HNL couplings with the SM leptons, $U_e:U_\mu:U_\tau$
- $2 \times 10^{18}$ protons on target (~2 years)
- Limits at 90% CL, 0 background
NA62 in Run 2, 3 and 4

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

- 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, HNL single track decays
      - All benefit from the same trigger signature
  - In proton dump mode:
    - ALPs, $A' \rightarrow$ visible, HNL

- Run 4: there are some ideas...
KLEVER for $K_L \rightarrow \pi^0 \nu \bar{\nu}$ Measurement

- Complementary search of KOTO with the high energy of $\pi^0$, $p_{\pi^0} = 70$ GeV/c
  - ~60 Standard Model events in 5 years of running
    - 5x$10^{19}$ protons on target
  - Boosted photons from $K_L \rightarrow \pi^0\pi^0$ decays (main background), easy for vetoing

- New large angle photon veto (LAV) detectors
Summary

- NA62 experiment at CERN to measure $K^+$ rare (BR $\sim 10^{-11}$) decay $K^+ \rightarrow \pi^+\bar{\nu}\bar{\nu}$

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

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

- Possible long term future: measurement of $K_L \rightarrow \pi^0\nu\bar{\nu}$
  - $K_{L\text{EVE}}$: modified beam-line, upgraded detector
    - After long shutdown 3 (2027)
    - The experiment logo will be changed
Amplitude $\sim m^2_{u,c,t} / m^2_W \rightarrow$ short-distance dynamics
- Negligible up-quark contribution
- Effective theory framework for calculation of the decay amplitude

$$H_{\text{eff}}^{\text{SM}} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \sum_{l=e,\mu,\tau} \left( V_{cs}^* V_{cd} X_{\text{NL}}^l + V_{ts}^* V_{td} X(x_t) \right) \left( \bar{s}d \right)_{V-A} \left( \bar{\nu}_l \nu_l \right)_{V-A}$$

- Theoretically calculable $X_{\text{NL}}^l$ and $X(x_t)$ loop functions
  - Remarkable progress over the last decade
**Photon Rejection with Vetos**

- \( K^+ \rightarrow \pi^+\pi^0 \) selection requiring 2\(\gamma \) in LKr compatible with \( \pi^0 \)
  - No photons in other sub-detectors

![Graph showing \( \sigma(m^2_{\text{miss}})[\text{GeV}^2/c^4] \) as a function of \( p_{\pi^+} [\text{GeV}/c] \)]

- Data
- Analytical interpolation
- Contribution from \( P_{\pi^+} \)
- Contribution from \( \theta_{\pi^+} \)
- Contribution from \( P_K \)
- Contribution from \( \theta_K \)

NA62 Preliminary

Data 2016

\( \sigma(m^2_{\text{miss}})[\text{GeV}^2/c^4] \)

- \( 10 \) to \( 55 \text{ GeV}/c \)
- \( 0 \) to \( 2 \times 10^{-3} \)
Performance of RICH

- $\sim 10^2$ muon suppression factor
  - $15 \text{ GeV} / c < p_{\text{track}} < 35 \text{ GeV} / c$

NA62 preliminary 2015 data
Calorimeter Performance

- Total energy = LKr + MUV1 + MUV2

- $10^5$ muon rejection is reached at 80% pion efficiency
  - On-going study to increase the efficiency up to 90%
NA62 Sensitivity to $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})$

- Monte-Carlo simulation
  - 10% signal acceptance

<table>
<thead>
<tr>
<th>Decay</th>
<th>SM events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>45</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu\mu(\gamma)$</td>
<td>1.5</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$</td>
<td>7.5</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Others</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$\Sigma$ background</td>
<td>$&lt;$10</td>
</tr>
</tbody>
</table>

- 10% precision after 2 years of data taking
NP Searches with $K^+$ Beam: $A'$

- Dark Photon: $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma A'$ and $A' \rightarrow \chi \chi$
  - Same trigger signature as the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decays

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

- Minimum bias data: 2 $\gamma$ on LKr, simulate 1$\gamma$ loss
- MC:
  - $m_{A'} = 30$ MeV
  - $m_{A'} = 60$ MeV
  - $m_{A'} = 90$ MeV

- Improved limits at 90% CL (preliminary) in DP mass range: $\sim 50$ MeV/c$^2 < m_{A'} < 90$ MeV/c$^2$
  - Data used: $1.5\times10^{10}$ $K^+$ decays (small fraction of 2016 sample)
NP Searches with $K^+$ Beam: HNL

- Heavy Neutrino from Neutrino Minimal SM (νMSM)
  - Three right-handed neutrinos: the lightest $N_1$ – dark matter candidate

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l+\nu_l) \rho_l(m_N)}$$

- $K^+ \to \mu^+ N$: NA62 2007 data (arXiv:1705.07510)
- $K^+ \to e^+ N$: NA62 2015 data (paper in preparation)
  - Improved limits on $|U_{e4}|^2$ in the $m_N$ range ~ 170 MeV/c$^2$ – 450 MeV/c$^2$

See Letizia Peruzzo’s talk on Monday