Searches for feebly interacting particles at the NA62 Experiment

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A Kaon Factory at CERN SPS

**NA62 Main Goal:**
the measurement of BR(K⁺→π⁺νν) with a precision better than 10% (SM BR $O(10^{-10})$)

**High intensity beam:** least $10^{13}$ K⁺ decays are required

- 400 GeV/c primary proton beam
- $3 \times 10^{12}$ protons/pulse
- 40 cm beryllium target
- 75 GeV/c unseparated hadrons beam:
  - π⁺, K⁺ (6%), protons ($Δp/p \pm 1$%)
- $4.8 \times 10^{12}$ K⁺ decays/year
The NA62 strategy

Kaons with high momentum. Decay in flight technique. Signal signature: $K^+$ track + $\pi^+$ track + missing energy

Main background sources:

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
<th>Main Rejection Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu(\gamma)$</td>
<td>63%</td>
<td>$\mu$-ID + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$</td>
<td>21%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>6%</td>
<td>multi-track + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\pi^0$</td>
<td>2%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0e^+\nu_e$</td>
<td>5%</td>
<td>$e$-ID + $\gamma$-veto</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+\nu_\mu$</td>
<td>3%</td>
<td>$\mu$-ID + $\gamma$-veto</td>
</tr>
</tbody>
</table>

Key performances to deal with the backgrounds:

- O(100 ps) timing;
- O($10^4$) background suppression with kinematics;
- O($10^7$) $\mu$-suppression;
- O($10^7$) $\gamma$-suppression;

2 signal regions, on each side of the $K^+ \rightarrow \pi^+\pi^0$ peak (to eliminate 92% of the $K^+$ width)
The NA62 detector

Final states described in this presentation:
1 downstream track and nothing else

- **LAV**: photon veto at large angles lead-glass blocks
- **GTK**: kaon tracking; 3 stations of silicon sensors
- **KTAG**: Kaon identification
  Cherenkov counter filled with N2

**STRAW**: Downstream tracking

**RICH**: Ring imaging Cherenkov
  kinematics and particle ID

**IRC, SAC**: lead and scintillator plates
  Shashlyk configuration

**MUV0, MUV3**: plastic scintillators

**Muon veto**: Hadronic calorimeters

**LKr**: quasi-homogenous ionization chamber
  27X0 deep

**CHOD**: charged hodoscope

**JINST 12 P05025 (2017), arxiv:1703.08501**
The $\pi^+\nu\nu$ interlude

$5.3$ background + $7.6$ SM signal events expected, $17$ events observed

NA62 Run1($2016 + 2017 + 2018$) result:

$Br(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (11.0^{+4.0}_{-3.5\text{ stat.}} \pm 0.3_{\text{syst.}}) \times 10^{-11}$ ($3.5\sigma$ significance)
The invisible feebly interacting particles at NA62

Searches for a new exotic particle X produced in Kaon decays through detecting missing mass:

- X decaying to invisible particles (neutrinos or dark matter)
- X So long-lived to escape the apparatus

1 track + missing mass: similar signature to the golden mode $K^+ \rightarrow \pi^+\nu\nu$

OUTLINE:

- $K^+ \rightarrow \pi^+X, X \rightarrow$ invisible/visible with the full 2016-2018 data
- $K^+ \rightarrow \pi^+\pi^0$ (or X with $m_X \sim m_\pi^0$), $X/\pi^0 \rightarrow$ invisible with 2017 data
- $K^+ \rightarrow \mu^+\nu X, X \rightarrow$ invisible with the full 2016-2018 data
- $K^+ \rightarrow lN -$ Heavy Neutral Leptons

Complementary to colliders!
The scalar portal couples the dark sector to the Higgs boson via the bilinear $H^\dagger H$ operator of the SM. The minimal scalar portal model involves one extra singlet field $S$ and two types of couplings, $\mu$ and $\lambda$:

$$L_{\text{scalar}} = L_{\text{SM}} + L_{DS} - (\mu S + \lambda S^2) H^\dagger H.$$ 

It can lead to pair-production of $S$ but cannot induce its decay.

**Pseudo-scalar:**
- Axion-like particles (ALPs)
- QCD axion, Axiflavon ($m \sim 0$)

Motivation: feebly interacting new particle $X$ in $K^+ \rightarrow \pi^+ X$ foreseen in several models

same analysis of $K\rightarrow \pi\nu\nu$:
- Use exactly the same selection, normalization and background evaluation;
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance and resolution in $m_{2\text{miss}}$
\( K^+ \rightarrow \pi^+X \), \( X \) invisible - the Analysis

- Normalization to \( K^+ \rightarrow \pi^+\pi^0 \) decay
- Efficiencies evaluated with data driven methods
- Data-driven background estimation
- Analysis binned in \( \pi^+ \) momentum and beam intensity
- Control regions for validation

\[
\begin{align*}
N_{\pi\pi}^{exp}(\text{region}) &= N(\pi^+\pi^0) \cdot f_{\text{kin}}(\text{region}) \\
\end{align*}
\]

Data in \( \pi^+\pi^0 \) region after \( \pi\nu\nu \) selection (including \( \pi^0 \) rejection)

Expected \( K^- \rightarrow \pi^-\pi^0 \) in signal regions after the \( \pi\nu\nu \) selection

Fraction of \( \pi^+\pi^0 \) in signal region measured on control data

arXiv: 2103.15389 [hep-ex]
$K^+ \rightarrow \pi^+ X$, $X$ invisible - the Analysis

2018 Dataset, for illustration

**Background model**
- shape: Parameterized with polynomial functions
- both in Region1 and Region2
- Background yield from $\pi\nu\nu$ analysis, including $K\rightarrow\pi\nu\nu$

**Signal model**
- shape: Gaussian
- Efficiency and normalization obtained in bins of momentum and intensity, as in $\pi\nu\nu$ analysis

Update with full dataset
arXiv: 2103.15389 [hep-ex]
Submitted to JHEP

Looking for bumps in the $m_{miss}^2$ distribution
$K^+ \rightarrow \pi^+ X$, $X$ invisible - the Analysis

**Assumption:** $X$ decays to invisible particles, or it is so long-lived to escape the apparatus

- Shape analysis on m2miss;
- Fully frequentist approach;
- Profiled likelihood test statistic;
- Combination of the 2016-2018 datasets;

Sensitivity degrades at small mX because of resolution. In particular, for axion models, half of the signal is cut away.
$K^+ \rightarrow \pi^+ X$, $X$ visible, but not seen.

Assumption: $X$ decays to visible Standard Model particles, but far from NA62. If it decays inside NA62, the products are supposed to be vetoed.

$P = e^{-\left(\frac{\Delta L}{\beta \gamma c \tau}\right)}$

$\tau$ depends on the coupling parameters and the mass.

Improved upper limit over a the range $[0,100]$ MeV and $[160,260]$ MeV.
\[ K^+ \rightarrow \pi^+ \, S \, , \, S \text{ scalar} \]

Higgs mixing model

\[ \mathcal{L}_{\text{scalar}} = - (\mu S + \lambda S^2) \, H^\dagger \, H \]

\( \lambda = 0 \)

\( \mu = \sin \theta \)

The lifetime depends on \( \sin \theta \) and \( m_S \)

S decay only in standard model particles

acceptance is reduced because the decay products (e or \( \mu \)) are vetoed

2016-2018 data
\[ K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \text{inv.} \]

- In principle \( \pi^0 \rightarrow \nu \nu \) is not forbidden because of neutrino non-zero masses, but in the SM: \( \text{BR}(\pi^0 \rightarrow \nu \nu) \sim O(10^{-24}) \)
- Any observation \( \rightarrow \text{BSM} \)
- The previous experimental limit is \( 2.7 \times 10^{-7} \) at 90\% CL, from BNL experiments

Measure possible thanks to the photon-hermeticity of NA62

With the same analysis we can also search for

\[ K^+ \rightarrow \pi^+ \chi, \chi \rightarrow \text{invisible, for } m_\chi \sim m_{\pi^0} \]

Search performed in a range of miss2 which is a background for \( \pi \nu \nu \)

\textbf{JHEP 02 (2021) 201}

2010.07644 [hep-ex]
\[ K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \text{inv.} - \text{strategy} \]

\[
\text{BR}(\pi^0 \rightarrow \text{invisible}) = \frac{\text{BR}(\pi^0 \rightarrow \gamma\gamma) \times N_s}{N_{\pi^0} \times \epsilon_{\text{sel}} \times \epsilon_{\text{trig}}} 
\]

The main background is \( K^+ \rightarrow \pi^+\pi^0, \pi^0 \rightarrow \gamma\gamma \) with undetected photons.

Counting experiment in the region: \( 25 < p_{\pi^+} < 40 \text{ GeV/c} \)
and square missing mass in \([0.015,0.021] \text{ GeV}^2/\text{c}^2\)

\[ \text{BR}(\pi^0 \rightarrow \text{invisible}) \leq 4.4 \times 10^{-9} \] at 90% C.L.

Improvement of a factor 60 with respect to the previous experiments.

2017 data

BKG estimation

Observed data
\[ K^+ \to \pi^+ X, \ mX \sim m_{\pi^0} \]

Model independent analysis for the upper limit of BR(K\(\to\)\(\pi^+\)X)

If X decays to visible particles inside the apparatus, the acceptance is reduced and the upper limit is weaker.

Acceptance of the cut on \(m_{\text{miss}}^2\) depends on the mass hypothesis.

2017 data
$K^+ \rightarrow \pi^+ a$, the ALP hypothesis

Pseudoscalar axion-like particle

$$\mathcal{L}_{SM} = \frac{\partial_\mu a}{f_\ell} \sum_\alpha \bar{\ell}_\alpha \gamma_\mu \gamma_5 \ell_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

$[ f_q = f_\ell ]$

If $a$ decays to invisible particles, or it is so long-lived to escape the apparatus.

If $a$ decays to visible SM particles the acceptance is reduced because the decay products ($e$ or $\mu$) are vetoed.


2101.12304 [hep-ex]

M. J. Dolan et al., JHEP 03 (2015) 171
Used for BR and lifetime computation.

\[ K^+ \rightarrow \mu^+ \nu X, \ X \rightarrow \text{invisible} \]

A possible explanation of the anomalous muon magnetic momentum \( g-2 \) is the existence of a new light gauge boson


In a scenario with dark matter freeze out, it could be a scalar or vector mediator of an hidden sector decaying to Dark Matter \( X \rightarrow \chi \chi \)

\[ K^+ \rightarrow \mu^+ \nu X, \ \text{with} \ X \rightarrow \text{invisible} , \ \gamma \gamma, \ \mu^+ \mu^- \]

Work in progress

Same final state as
\( K^+ \rightarrow \mu^+ N, \ N: \text{Heavy Neutral Lepton} \)

One \( \mu^+ \) and missing mass


2101.12304 [hep-ex]
$K^+ \rightarrow \mu^+ \nu X$, $X \rightarrow \text{invisible}$

3 body decay $\rightarrow$ looking for modifications of the

$$m_{\text{miss}}^2 = (p_K - p_\mu)^2$$

Counting experiment with lower cut on m2miss optimized independently for each mass hypothesis, requiring the strongest upper limit
$K^+ \rightarrow \mu^+ \nu X$, $X \rightarrow \text{invisible}$

Tested mass hypotheses from 10 to 370 MeV

In the model with **scalar mediator**, the mean value of the $m_2\text{miss}$ is larger compared to the **vector mediator**

This results in a stronger upper limit for the **scalar X model**

New upper limit for the ultra-rare decay:

$\mathcal{B}(K^+ \rightarrow \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6}$ at 90% CL
Heavy Neutral Leptons

$K^+ \to lN$, with $l = e$ or $\mu$: two body decays looking for bumps

$$\text{BR}(P^+ \to lN) = \text{BR}(P^+ \to l\nu) \times \rho_l(m_N) \times |U_{l4}|^2$$

- HNL production is enhanced kinematically wrt SM decays
- Helicity suppression relaxed in the $K \to eN$ case: factor $O(10^5)$ enhancement
Conclusions

- NA62 is a detector built to measure the very rare decay $K^+ \rightarrow \pi^0 + vv$.
  - Nevertheless its characteristics and the beam intensity are such that stronger limits on feebly interacting particles are possible;
- New Limits on:
  - $K^+ \rightarrow \pi^+ X$, $X \rightarrow$ invisible, in almost the full the mass range $\sim [0, 250]$ MeV
  - $K^+ \rightarrow \pi^+ \pi^0$ (or $X$ with $m_X \sim m_{\pi^0}$), $X/\pi^0 \rightarrow$ invisible
  - $K^+ \rightarrow \mu^+ v X$, $X \rightarrow$invisible in the mass range $[10, 370]$ MeV
  - Heavy Neutral Leptons: new limits in electron and muon flavors
- Ongoing analyses to finalize other searches with 2016-2018 dataset
- NA62 is ready for the new data taking (Kaon beam and beam dump), starting soon (July 2021)
NA62 in Dump Mode

**Beam dump mode**

B and D instantaneously decay to exotic mediators and SM particles which are stopped/deviated

\[ B,D \rightarrow X(\text{exotic mediator}) \]

\[ X \rightarrow 2 \text{ tracks} \]

p 400 GeV

Also $\gamma\gamma$ signature to search for ALPs from Primakoff

Slide from Roberta Volpe