Search for feebly interacting particles with NA62

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On behalf of the NA62 Collaboration

- Short introduction on NA62 experiment
- Three recent results on searches for feebly interacting particles
  - $K^+ \rightarrow \pi^+\chi$, $\chi \rightarrow \text{invisible}$ with the full 2016-2018 data
  - $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \text{invisible}$ with 2017 data
  - $K^+ \rightarrow \mu^+\nu\chi$, $\chi \rightarrow \text{invisible}$ with the full 2016-2018 data
~ 200 participants
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC)

The main aim is the measurement of \( BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \) with a precision better than 10%

Collected good quality data in 2016-2018
Ready to start the new data taking
Features required for the BR($K^+ \rightarrow \pi^+\nu\nu$)

The experimental apparatus has been designed in order to detect:

- Decay in flight

\[ m_{miss}^2 = (p_K - p_\pi)^2 \]

- very good kinematic reconstruction
- time measurements

<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>

- $K,\pi,\mu$ identification
- Hermetic detection of muons
- Hermetic detection of photons
NA62 Apparatus

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

**STRAW**: Downstream tracking

**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

**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
“Invisible” feebly interacting particles

NA62 is competitive in the search for FIPs at some parameter space

- High intensity beam $\Rightarrow 6 \times 10^{12}$ $K^+$ decays in fiducial volume collected in 2016-2018

Outline:

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

Signature: 1 track and missing mass

- $K^+ \rightarrow \pi^+ X$, $X \rightarrow$ invisible 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

[Also lifetime $\tau$ is an important parameter]
**Motivation:** feebly interacting new particle $X$ in $K^+ \rightarrow \pi^+X$ foreseen in several models

For example:

**Dark scalar:** mixing with the Higgs

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

$$\mu = \sin \theta \quad \lambda = 0$$

**Pseudo-scalar**

Axion-like particles (ALPs)

QCD axion, Axiflavon ($m \sim 0$)

**Analysis strategy: Same $K \rightarrow \pi \nu \nu$**

- Use exactly the same selection, normalization and background evaluation of $\pi \nu \nu$ analysis
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance and resolution in $m_\text{miss}$

Few mass points after the full selection, normalized to unity

- $m_X = 70$ MeV/c$^2$
- $m_X = 154$ MeV/c$^2$
- $m_X = 168$ MeV/c$^2$
- $m_X = 182$ MeV/c$^2$
- $m_X = 196$ MeV/c$^2$
- $m_X = 210$ MeV/c$^2$
- $m_X = 224$ MeV/c$^2$
- $m_X = 238$ MeV/c$^2$
- $m_X = 252$ MeV/c$^2$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}, \pi^+ X(\text{inv})$ analysis overview

- Normalization to $K^+ \rightarrow \pi^+ \pi^0$ decay (non-factorizing efficiencies evaluated with data driven methods)
- Data-driven background estimation
- Bins of $p(\pi^+)$ and intensity
- Control regions to validate it

4 datasets:
- 2016 data
- 2017 data
- 2018 data with old collimator (20%)
- 2018 data Run with new collimator (80%)

Details in the presentation by Bob Velghe
Flavor I session
https://indico.cern.ch/event/982783/contributions/4364555/
arXiv: 2103.15389 [hep-ex]
$K^+ \rightarrow \pi^+ X$, $X$ invisible

**Background model**
- **shape**: Parameterized with polynomial functions in R1 and R2
- **Bkg yield** from $\pi\nu\nu$ analysis, including $K \rightarrow \pi\nu\nu$ from simulation and with SM BR

**Signal model**
- **shape**: Gaussian
- **Ns** from efficiency and normalization obtained in bins of $p$ and intensity, as in $\pi\nu\nu$ analysis

Details in

*JHEP* 03 (2021) 058


Update with full dataset


Submitted to *JHEP*
$K^+ \rightarrow \pi^+ X, \; X \text{ invisible}$

- Shape analysis on $m_{\text{miss}}^2$
- Fully frequentist approach
- Profiled likelihood test statistic
- Combination of the 4 datasets

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

Sensitivity degrades at small $m_X$ because of resolution. In particular, for axion models, half of the signal is cut away.
If X decays to visible SM particles

Probability that X does not decay within the NA62 apparatus:

\[ P = e^{-\frac{\Delta L}{\beta \gamma \epsilon \tau}} \]

\(\Delta L\) depends on the coupling parameters and the mass

Comparison with BNL result
A. V. Artamonov et al. (E949 Collaboration)
Phys. Rev. D 79, 092004

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

Higgs mixing model

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

$\lambda = 0$

$\mu = \sin \theta$

(BC4 in PBC)


Used for BR computation

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

$\tau$ depends on $\sin \theta$ and $m_S$
\[ K^+ \rightarrow \pi^+\pi^0, \pi^0 \rightarrow \text{inv} \]

- \( \pi^0 \rightarrow \nu\nu \) is not forbidden because of neutrino non-zero masses, but in the SM: \( \text{BR}(\pi^0 \rightarrow \nu\nu) \sim O(10^{-24}) \), so any observation \( \Rightarrow \) BSM

- The previous experimental limit is \( 2.7 \times 10^{-7} \) at 90% CL, from BNL experiments

The hermetic photon veto in NA62, essential for \( \pi\nu\nu \) analysis, allows for the search in the Kaon decay

\[ K^+ \rightarrow \pi^+\pi^0(\gamma), \quad \pi^0 \rightarrow \text{invisible} \]

With the same analysis we can also search for

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

Search in the \( m^2_{\text{miss}} \) range which is a background region for the \( K \rightarrow \pi\nu\nu \) analysis

[2017 Data]
Analysis strategy:

\[ \text{BR}(\pi^0 \to \text{invisible}) = \text{BR}(\pi^0 \to \gamma\gamma) \times \frac{N_8}{N_{\pi^0} \times \epsilon_{\text{sel}} \times \epsilon_{\text{trig}}} \]

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

Counting experiment in the region:
25<\(p<40\) GeV/c and square missing mass in [0.015,0.021] GeV\(^2/c^4\)

\[ \text{Veto inefficiency} \]

\[ \text{Events/(5 GeV/c)} \]

\[ \text{BR}(\pi^0 \to \text{invisible}) \leq 4.4 \times 10^{-9} \text{ at 90\% C.L.} \]
Search for $K^+ \rightarrow \pi^+ X$, $m_X \sim m_{\pi 0}$

Model independent upper limit to BR($K^+ \rightarrow \pi X$)

$$BR(K^+ \rightarrow \pi^+ X) = \frac{N_s}{N_{K^+} \times R(m_X) \times \varepsilon_{\text{sel}} \times \varepsilon_{\text{trig}}}$$

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

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

2017 Data

JHEP 02 (2021) 201
2010.07644 [hep-ex]
$K^+ \rightarrow \pi^+ a, a: ALP$

Pseudoscalar axion-like particle

$$\mathcal{L}_{\text{SM}} = \frac{\partial \mu a}{f \ell} \sum_\alpha \bar{\ell}_\alpha \gamma \gamma_5 \ell_\alpha + \frac{\partial \mu a}{f q} \sum_\beta \bar{q}_\beta \gamma \gamma_5 q_\beta$$

(BC10 in PBC) [J. Beacham et al., J. Phys. G 47 (2020) 010501] $f_q = f \ell$

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

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

**2017 Data**

**JHEP 02 (2021) 201**
2010.07644 [hep-ex]
Motivation

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 $X \rightarrow \chi \chi$


$\textbf{K}^+ \rightarrow \mu^+ \nu X, \ X \rightarrow \text{invisible}$

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

One $\mu^+$ and missing mass

Details in the presentation by 
Marco Mirra, Neutrino I session 
https://indico.cern.ch/event/982783/contributions/4362325/
$K^+ \rightarrow \mu^+\nu X, \ X \rightarrow \text{invisible}$

3 body decay, the signal has a broad distribution in

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

background estimation from MC:

- Counting experiment with lower cut on $m^2_{\text{miss}}$
  - optimized independently for each mass hypothesis, requiring the strongest upper limit

Good Data/MC agreement

2016-2018 Data

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

\[ N_K = \frac{N_{SM}}{A_{SM} \cdot B(K^+ \rightarrow \mu^+ \nu)} = (1.14 \pm 0.02) \times 10^{10} \]

Tested mass hypotheses from 10 to 370 MeV

In the model with scalar mediator
the mean value of $m_{miss}^2$
is larger compared to the vector mediator.

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

Also an upper limit to the very rare SM decay has been established:

\[ B(K^+ \rightarrow \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6} \text{ at 90\% CL} \]
Conclusions

☑ Improved bounds on feebly interacting particles $X$ with the signatures:

- $K^+ \rightarrow \pi^+ X, X \rightarrow \text{invisible, in almost the full the mass range } \sim [0, 250] \text{ MeV}$

- $K^+ \rightarrow \mu^+ \nu X, X \rightarrow \text{invisible, in the mass range } [10, 370] \text{ MeV}$

☐ Ongoing analyses to finalize other searches with 2016-2018 dataset

☐ Getting ready for the new data taking (Kaon beam and beam dump), starting soon (July 2021)

Stay tuned!

Thank you for your attention
Spares
$K^+ \rightarrow \pi^+ S$, S: scalar

2017 dataset

https://www.hepdata.net/record/ins1832447
https://www.hepdata.net/record/ins1822910

HEPData

$JHEP$ 03 (2021) 058
$K^+ \rightarrow \pi^+ a, a: ALP$

2017 dataset

https://www.hepdata.net/record/ins1832447
https://www.hepdata.net/record/ins1822910
Assumption: the non-Gaussian tails of the $m_{\text{miss}}^2$ spectrum are left-right symmetrical.

A “tail” component is added to the estimated background in each $m_{\text{miss}}^2$ bin in the region $m_{\text{miss}}^2 > 0$ equal to the difference between the data and simulated spectra in the symmetric mass bin with respect to $m_{\text{miss}}^2 = 0$.

A 100% uncertainty is conservatively assigned to this component to account for the above assumption.
Not-only Kaons

A large Kaon sample is ready to be analyzed but:
searches for exotic particles are limited by the kaon mass

**Standard kaon mode**

\[
p, \pi, K \quad 75 \text{ GeV}
\]

\[
p, \pi, K \quad 75 \text{ GeV}
\]
Not-only Kaons

**Beam dump mode**
B and D instantaneously decay to exotic mediators and SM particles which are stopped/deviated

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

\[ p \rightarrow 400 \text{ GeV} \]

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

Also \( \gamma \gamma \) signature to search for ALPs from Primakoff