FIRST RESULTS FOR SEARCHES OF EXOTIC DECAYS WITH NA62 IN BEAM-DUMP MODE

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on behalf of the NA62 collaboration

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Search Motivation

- Several extensions of the Standard Model (SM):
  - **Vector portal → Dark Photons (DP)**
  - **Scalar portal → Dark Scalars**
  - **Neutrino portal → Heavy Neutral Leptons**
  - **Axion portal → Axion-like particles**

- The Dark Photon model introduces a new vector field $F_{\mu\nu}$ symmetric under a new U(1) symmetry feebly interacting with the SM fields

- A specific constrained model: kinetic mixing interaction with the SM hypercharge,
  \[ \varepsilon \cos \theta_W F_{\mu\nu} B^{\mu\nu} \]

- Mass $M_{A'}$ of the DP and coupling $\varepsilon$: free parameters

Decay width dominated by lepton-antilepton final states for $M_{A'} < 700$ MeV

16/09/22 KAON 2022 International Conference
The NA62 experiment at the CERN SPS

Broad physics program:
• Main goal: measurement of the $K^+ \rightarrow \pi\nu\nu$ branching ratio
• Rare and forbidden decays
• Precision measurements
• Exotic searches (beam-dump mode): DP, HNLs, ALPs, DSs

Timeline of the NA62 experiment

Primary beam:
400 GeV/c SPS protons, 
$\sim 1.1 \times 10^{12}$ ppp/s

Secondary beam:
75 GeV $K^+(6\%)$ $p(24\%)$ $\pi^+(70\%)$ $\sim 750$MHz at GTK

2008 NA62 approval
2009-2014 detector R&D, installation
2016-2018 Physis Run
2019-2021 LS2 upgrades
2021-2025 Physics Run
NA62 in beam-dump mode

3.2 m long Cu-Fe movable collimators (TAX)

400 GeV/c protons

Z=23 m

STRAW: tracking of charged particles

CHOD: fast detector used for trigger $\sigma_T \sim 600$ ps

MUV3: muon veto/ID detector

LKr: e.m. calorimeter for PID and photon identification

LAV: Large angle photon veto detectors

Target removed

Target removed

Setup for beam-dump data taking:

- TAXes closed and target removed
- Improved sweeping from dipoles downstream of TAXes
- Beam intensity 1.5 times higher than the nominal
Data sample

$(1.40\pm0.28) \times 10^{17}$ POT collected in ~ 10 days of data taking

POT measured by beam secondary emission monitor

Two trigger lines for charged final states:

- **Single-track trigger**, one or more CHOD hits:
  
  $Q1/D$, $D = 20 \rightarrow 14 \text{kHz}$

- **Two-track trigger**, >1 in-time CHOD hits:
  
  $H2 \rightarrow 18 \text{kHz}$

Control trigger LKr-based to measure efficiency of the charged triggers, $1\text{MeV}$ threshold $\rightarrow 4\text{kHz}$

$Q1$ trigger efficiency = 99.8%

$H2$ trigger efficiency = 98%
Expected sensitivity: geometrical acceptance

Two production mechanisms are in action in proton-nucleus interaction scenario:

- Bremsstrahlung production: \( pN \rightarrow X A' \)
- Meson-mediated production: \( pN \rightarrow X M, M \rightarrow A' \gamma (\pi^0) \), where \( M = \pi^0, \eta, \rho, \omega, \) etc.

Sensitivity per production mechanism assuming 0 observed events in \( 1.4 \times 10^{17} \) POT

Sensitivity per decay mode assuming 0 observed events in \( 1.4 \times 10^{17} \) POT

*The grey underlying area is adapted by PBC, originally based on: Phys. Rev. Lett. 126, no. 18, 181801(2021)
Analysis Strategy

Signal signature:
- Lepton-antilepton vertex reconstructed within the NA62 fiducial volume, a primary vertex close to the proton beam impact at the TAXes

Event selection:
- One vertex in FV from two reconstructed tracks of good quality
- Track times consistent with trigger and with each other (10 ns window)
- Muon id with calorimeter and muon detector
- No in-time activity at large angle veto (LAV) to reduce possible selection of vertices by interaction of incoming muons with the material in the LAVs
- Extrapolation of di-lepton momentum to TAX

CR = control region
SR = signal region

**Signal MC**

**CDA_{TAX}**: closest distance of approach between the beam direction at the TAX entrance and the lepton-antilepton pair direction, $\sigma_{CDA} = 7$ mm

**$Z_{TAX}$**: longitudinal primary vertex position, $\sigma_{Z} = 5.5$ m

CR and SR kept blind up to analysis approval

SR: $CDA_{TAX} < 20$ mm & $6 < Z_{TAX} < 40$ m
Improvements w.r.t. 2018 data taking

2018 data: $2.6 \times 10^{16}$ POT

2021 data: $1.4 \times 10^{17}$ POT

Thanks to beam optimization, background reduction $\times 200$ despite higher intensity
Selection efficiency and signal yield

\[ N_{\text{exp}} = \text{POT} \times \chi(pN \rightarrow A') \times \text{BR}(A' \rightarrow \mu\mu) \times P_{\text{rd}}(\varepsilon) \times A_{\text{acc}} \times A_{\text{trig}} \]

- \( \chi(pN \rightarrow A') \): DP production probability
- \( \text{BR}(A' \rightarrow \mu\mu) \): decay branching fraction
- \( P_{\text{rd}}(\varepsilon) \): probability for DP to reach the NA62 fiducial volume and decay therein
- \( A_{\text{acc}} \): selection efficiency
- \( A_{\text{trig}} \): trigger efficiency
Invariant mass resolution

Possible signals can be precisely identified from the two-track invariant mass

Differences in expected yield, acceptance, and invariant mass resolution due to kinematics of production modes
Background sources

The difference of track times suggests two main concurring background mechanisms

Before LAV veto is applied (CR and SR blinded)

Full selection (CR and SR blinded)
Background evaluation

Combinatorial background

- Background from random superposition of two uncorrelated “halo” muons
- Selected single tracks in a data sample orthogonal to the one used for the analysis
- Track pairs are artificially built to emulate a random superposition
- Each track pair weighted to account for the 10 ns time window → independent on the intensity
- Powerful statistical accuracy from combinatorial enhancement

Prompt (in-time) background

- Background from secondaries of muon interactions with the traversed material (hadron photo-production)
- Muon kinematic distributions extracted from selected single muons in data (backwards MC)
- To correct the spread induced by the backward-forward process (straggling, MS), an unfolding technique is applied to better reproduce the data distributions
- Relative uncertainty of MC expectation ~ 100%

Prompt background negligible w.r.t. combinatorial (UL at 90% CL is 30% of combinatorial)
### Data-MC comparison: control samples

#### Outside CR

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{exp}} \pm \delta N_{\text{exp}}$</th>
<th>$N_{\text{obs}}$</th>
<th>$p (N \geq N_{\text{obs}})$</th>
<th>$p (L \leq L_{\text{obs}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>0.46 ± 0.07</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SR</td>
<td>0.040 ± 0.006</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

#### CR

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{exp}} \pm \delta N_{\text{exp}}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>0.050 ± 0.007</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SR</td>
<td>0.005 ± 0.001</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

#### SR

**16/09/22**

KAON 2022 International Conference
Data-MC comparison: signal sample, CRs opened

Probability for a non-zero observation in SR is 1.59%

<table>
<thead>
<tr>
<th>CR</th>
<th>N_{exp} \pm \delta N_{exp}</th>
<th>N_{obs}</th>
<th>p (N \geq N_{obs})</th>
<th>p (L \leq L_{obs})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside CR</td>
<td>26.3 \pm 3.4</td>
<td>28</td>
<td>0.41</td>
<td>0.74</td>
</tr>
<tr>
<td>CR1</td>
<td>0.29 \pm 0.04</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>CR2</td>
<td>0.58 \pm 0.07</td>
<td>1</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>CR3</td>
<td>1.70 \pm 0.22</td>
<td>2</td>
<td>0.50</td>
<td>0.68</td>
</tr>
<tr>
<td>CR1+2+3</td>
<td>2.57 \pm 0.33</td>
<td>4</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>CR</td>
<td>0.17 \pm 0.02</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SR</td>
<td>0.016 \pm 0.002</td>
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</tr>
</tbody>
</table>
Data-MC comparison: signal sample, SR opened

1 event observed
Counting experiment with $2.4\sigma$ significance

Signal shape not taken into account for the significance
The region enclosed by the contour is excluded.
Conclusions and prospects

- The first preliminary result on search for production and decay of an exotic particle from data collected by the NA62 experiment in beam-dump mode has been presented.

- A cut-based counting experiment blind analysis to search for $A' \rightarrow \mu^+\mu^-$ has been performed on the data collected in 2021.

- With $(1.4 \pm 0.28) \times 10^{17}$ POT, a 90% CL upper limit has been set, exploring a new region of the parameter space.

- Search for decays of exotic particles to $e^+e^-$, $\gamma\gamma$, $\pi^+\pi^-\gamma$, and other hadronic final states using the data collected in 2021, are ongoing.

- NA62 intends to collect $10^{18}$ POT in beam-dump in 2022-2025 with interesting perspectives on dark photons, ALPs, dark scalars and HNLs.
Backup
Information on the observed event in SR

- $M_{\mu\mu} = 411$ MeV
- $\Delta T = -1.69$ ns
- $P(\mu^+) = 99.5$ GeV
- $P(\mu^-) = 39.5$ GeV
- $Z_{FV} = 157.8$ m
- $CDA_{FV} = 382$ mm
- $Z_{TAX} = 17$ mm
- $E/P(\mu^+) = 0.008$
- $E/P(\mu^-) = 0.018$

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16/09/22
Prompt background from MC

Expected background before LAV veto

NA62 Preliminary
### Expected background summary for CR and SR

<table>
<thead>
<tr>
<th>Region</th>
<th>Combinatorial</th>
<th>Prompt</th>
<th>Upstream-prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>0.17 ± 0.02</td>
<td>&lt; 0.033*</td>
<td>&lt; 0.052*</td>
</tr>
<tr>
<td>SR</td>
<td>0.016 ± 0.002</td>
<td>&lt; 0.003*</td>
<td>&lt; 0.005*</td>
</tr>
</tbody>
</table>

*Limits defined at 90% CL