Search for dark matter & dark sectors at fixed target
with some focus on NA62

Babette Döbrich (CERN) for NA62

Vulcano, 25/05/2018
Dark Matter from the viewpoint of a particle physicist

want to produce DM
or something ‘mediating’ it

Energy, Mass
Small Coupling
Known collider
Flavour
Fixed T
Precision, Intensity

E.g. Axion
lab-scale
++
direct DM
short lifetime
long lifetime
++
++

Some models of Dark Matter propose MeV mass, very weakly-coupled particles e.g. [1502.06000] production needs sufficiently high energy & high intensity & long detection volumes

fixed target facility is an obvious choice

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Beam energy & type \((e, p, \mu)\), number of beam particles shot on target, composition of target material

‘shield length’ and length & volume of the decay region

background rejection by shield or detector capabilities

detector types for decay products: charged/neutral Standard Model Particles or scattering of DM itself

timeline of data-taking and cost
Constraints from past experiments: ALP-example

\[
N_{\text{det}} \sim \left[ \exp \left( -\frac{D}{\gamma \beta \tau} \right) - \exp \left( -\frac{D + L}{\gamma \beta \tau} \right) \right]
\]

- decay length $\gamma \beta \tau$, ALP lifetime \( \Gamma = \tau^{-1} = g_{a\gamma}^2 m_a^3 / (64\pi) \)

exclusion through dumps

- **CHARM** 400 GeV, \( N_{\text{pot}} = 2.4 \times 10^{18} \) on copper, \( D = 480 \text{m}, L = 35 \text{m} \) (off-axis: 7-12 mrad)
- **NuCal** 70 GeV, \( N_{\text{pot}} = 1.7 \times 10^{18} \) on iron, \( D = 64 \text{m}, L = 23 \text{m}, \text{on-axis 0-15 mrad} \)
- **SLAC141** 9 GeV, \( N_{\text{eot}} = 2 \times 10^{15} \) on tungsten, \( D = 35 \text{m} \)
- **SLAC137** 20 GeV, \( N_{\text{eot}} = 2 \times 10^{20} \) on aluminum, \( D = 200 \text{m} \)

Plot from 1512.03069 with updates from 1709.00009
<table>
<thead>
<tr>
<th>Experiment</th>
<th>type</th>
<th>geometry</th>
<th>sensitivity</th>
<th>timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA62 at CERN</td>
<td>400 GeV POT</td>
<td>$d \simeq 80m$, $L \simeq 65m$</td>
<td>charged + neutral SM</td>
<td>now + 2021 ff.</td>
</tr>
<tr>
<td>Seaquest at Fermilab</td>
<td>120GeV POT</td>
<td>$d \simeq 5$, $L \simeq 15m$</td>
<td>charged + neutral SM</td>
<td>now, approved for $\mathcal{O}(10^{18})$</td>
</tr>
<tr>
<td>ShiP at CERN</td>
<td>400 GeV POT</td>
<td>$d \simeq 60$, $L \simeq 50m$</td>
<td>charged + neutral SM + DM</td>
<td>design phase</td>
</tr>
<tr>
<td>HPS + LDMX at SLAC</td>
<td>4-10 GeV EOT</td>
<td>$\mathcal{O}(some \ m)$</td>
<td>bump (HPS) + missing $p$ (LDMX)</td>
<td>HPS: first data, LDMX: design</td>
</tr>
<tr>
<td>NA64</td>
<td>100 GeV EOT</td>
<td>$\mathcal{O}(some \ m)$</td>
<td>missing $p$</td>
<td>now</td>
</tr>
<tr>
<td>PADME</td>
<td>0.5 GeV EOT</td>
<td>$\mathcal{O}(some \ m)$</td>
<td>missing $p$</td>
<td>M. Raggi</td>
</tr>
</tbody>
</table>

in addition proposals parastic at LHC with overlapping program ... focus in the following: NA62 (only exotic part)!
NA62 at CERN see talk by G. Ruggiero in the afternoon for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
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protons on target (POT) $\searrow$

beam collimator (TAX) ‘open’

$\Rightarrow K^+$ to detector $\downarrow$

main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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protons on target (POT) ↘

beam collimator (TAX) ‘open’ ⇒ $K^+$ to detector ↓

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1) Kaon decay with exotic

2) parasitically: e.g. exotic → $l^+ l^-$ + exotic away from beamline

beam collimator closed → dump ⇒ exotics to detector ↓ with much reduced backgrounds

3) dedicated data-taking e.g. axion → $\gamma \gamma$

some examples will follow!
NA62 at CERN see talk by G. Ruggiero in the afternoon for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

protons on target (POT) \(\searrow\) can produce exotics

\[\text{main measurement:} \quad \text{BR } \mathcal{O}(10^{-10}): \quad K^+ \rightarrow \pi^+\nu\bar{\nu}\]

1) Kaon decay with exotic

2) parasitically:

\[\text{e.g. exotic } \rightarrow l^+l^-\]

\[\leftarrow \text{beam collimator (TAX) ‘open’} \quad \Rightarrow \quad K^+ \text{ to detector } \downarrow\]

+ exotic away from beamline

\[\Rightarrow \quad \text{exotics to detector } \downarrow\]

with much reduced backgrounds

some examples will follow!
protons on target (POT) can produce exotics

main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
1) Kaon decay with exotic
2) parasitically:
e.g. exotic $\rightarrow l^+ l^-$
3) dedicated data-taking
e.g. axion $\rightarrow \gamma \gamma$
some examples will follow!
A Kaon’s life:
- $\text{BR}(K^+ \rightarrow \pi^+\pi^0) \simeq 0.21$
- $\text{BR}(K^+ \rightarrow \mu^+\nu) \simeq 0.64$
- $\text{BR}(K^+ \rightarrow \pi^+\pi^-\pi^+) \simeq 0.06$

Detector system
- Kaon: KTAG, GTK, CHANTI
- Pion: STRAW, CHOD, RICH
- $\gamma$ Vetoes: LAV, IRC, SAC, LKr
- MUV system: $\mu$ & Hadron

unseparated 750 MHz beam at GTK3
(6.6% Kaons at 75 GeV, 1% bite)
1) Kaon decay with exotic: results

Trigger band width shared by $\pi^+\bar{\nu}\nu$
+ other Kaon & non-Kaon modes
example Kaon: $K^+ \rightarrow N + l^+$,

N: ‘stable’ Heavy Neutrino
2015 data: PLB 778 137 (2018)
based on $\sim 3 \times 10^8$ Kaon decays
1) Kaon decay with exotic: results

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from 2016 data:

invisibly decaying Dark Photon
$K^+ \rightarrow \pi^0\pi^+$ with $\pi^0 \rightarrow A' + \gamma$
(prelim: paper in preparation)

search peak in missing mass of

$$m_{\text{miss}}^2 = (P_K - P_\pi - P_\gamma)^2$$
Parasitic to $\pi\nu\bar{\nu}$: invisible Dark Photons, heavy Neutrinos... as seen before

Trigger Parasitic to $\pi\nu\bar{\nu}$: $\mu\pi + \mu\mu$ away from beamline: 2017: $\mathcal{O}(10^{17})$ POT, sizable statistics $\mathcal{O}(10^{18})$ POT possible this year

dump-mode: sizable statistics $\mathcal{O}(10^{18})$ reserved for future, but some channels discovery potential with moderate statistics (e.g. ALP $\mathcal{O}(10^{16})$)

⇒ In the following: ”long-lived” prospects at $\mathcal{O}(10^{18})$ POT
ALPs coupled to photons

\[ \mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{f_\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu}. \]

ALP = Axion-like particle (name derives from QCD axion)

- good properties
- as dark matter mediator

see e.g. 1709.00009

- Assume \(10^{18}\) 400-GeV POT
- projection based on Primakov production and 0 background
Dark Photons

minimalistic NP:
Extra U(1) mixing
kinematically with EM
or hypercharge

Sensitivity expected to be higher than shown:
1. including direct QCD production of $A'$
2. Including $A'$ production in the dump (here, only target)

- Assume $10^{18}$ 400-GeV POT
- Study DP production (meson decays, bremsstrahlung) from interaction on target, search for $ee$, $\mu\mu$
- Assume zero background, expected 90%-CL exclusion plot
Dark Scalars

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

in this model we assume \( \lambda = 0 \)

real

singlet

scalar

coupled

with

Higgs

Assume \( 10^{18} \) 400-GeV POT

sensitivity to hidden scalars charged decays search for \( ee, \mu\mu, \pi\pi, KK \)
two-track final states originating at the TAX

assume zero background, expected 90%-CL exclusion plot

NA62 projected sensitivity dominated by beauty production
Heavy Neutral Leptons

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_\alpha I(\bar{L}_\alpha H)N_I \]

- e.g. \( \nu_{\text{MSM}} \rightarrow \) neutrino masses, (warm) DM candidate and baryon asymmetry
- separately address 3 extreme coupling scenarios [Shaposhnikov, Gorbunov arXiv:0705.1729]
- Assume \( 10^{18} \) 400-GeV POT: search for two-track final states originang at the TAX sensivity includes open channels, assuming 0 background
- assume zero background, evaluate expected 90%-CL exclusion plot
Background rejection NA62: 2016 data $\mathcal{O}(10^{15})$ POT

- **Track quality** (association with CHOD, LKr hits in time) + **acceptance** (CHOD, LKr, MUV3)
- **Vertex quality**: two-track-distance $< 1$ cm, vertex-position $105 < z < 165$ m
- Further veto (rhs): $E_{\text{LKr, additional}} < 2$ GeV; IRC, SAC, LAV no hits with $\pm$ 5 ns, CHANTI no candidate within $\pm$ 5 ns
- No events in signal region at TAX even with standard $K^+$ beam at $\mathcal{O}(10^{15})$ POT, background rejection OK for $\mathcal{O}(10^{15})$ POT in standard conditions and $4 \times \mathcal{O}(10^{15})$ in dump
Summary: ‘DM’ at fixed target

Potential roads to discovery in particle physics

Fixed-target experiments explore MeV-GeV very weakly coupled new physics

NA62: 2016 data analyzed for $K^+ \rightarrow \pi^+ \bar{\nu} \nu$, 2017 analysis on the way, 2018 data taking ongoing.

In addition,

- before LS2: $\pi \bar{\nu} \nu$-parasitic triggers/searches + short dedicated beam-dump runs
- after LS2, a year-long data taking would provide sensitivity to various LLPs

Thank you for your attention!