SEARCHING FOR HIDDEN/DARK SECTORS WITH THE NA64 EXPERIMENT AT THE CERN SPS

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DARK SECTOR (DS) charged under a new U(1)’ gauge symmetry and interacts with SM through kinetic mixing ($\epsilon$) of a MASSIVE VECTOR MEDIATOR (A’) with our photon.

Dark matter with mass ($m_\chi$), part of DS. Four parameters: $m_A$, $m_\chi$, $\alpha_D, \epsilon$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_\mu F'^\mu + \frac{\epsilon}{2} F'_\mu F'^\mu + \frac{m^2_A}{2} A'_\mu A'^\mu$$

$$+ i\bar{\chi}_\gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi} \chi - \alpha D_\chi_\gamma^\mu A'_\mu \chi,$$
In this framework DM can be produced thermally in the early Universe.

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

Large range for \( g_X \) and \( m_X \)

1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62...)

Flux of X generated by decays of A's produced in the dump.

**Signal:** X scattering in far detector

\[ \sigma \propto \epsilon^4 \alpha_D \]
2) NA64/LDMX APPROACH

NA64 **missing energy**: produced A's carry away energy form the active dump used to measure recoil e- energy

\[ \sigma \propto \epsilon^2 \]
EXPLICIT TARGET FOR NA64 ($y, m_X$) DM PARAMETER SPACE

$y = \epsilon^2 \alpha_D (m_X/m_{A'})^4$

Cross sections DM $\to$ SM annihilation is $\sim Y$, useful variable to compare exp. sensitivities

Solid lines predictions from DM relic abundance

Recent review [https://arxiv.org/pdf/1707.04591.pdf]

**EXPLICIT TARGET FOR NA64 \((y,m_X)\) DM PARAMETER SPACE**

**NA64**

\[ y = \epsilon^2 \alpha_D \left( \frac{m_X}{m_{A'}} \right)^4 \]

**Probed**

Solid lines predictions from DM relic abundance

**NA64e TARGET**

Higher mass region could be covered by NA64mu (pilot run in 2021)

*PLB796, 117 (2019)*
The NA64 method to search for $A' \rightarrow \chi \overline{\chi}$

**Diagram:***

- **TAGGED 100 GeV**
- **Requested ECAL ENERGY < 50 GeV**
- **“BREMSSTRAHLUNG” OF A’**

**Active Dump**

**ELECTROMAGNETIC CALORIMETER (ECAL)**

$\sqrt{\alpha_D} = g \chi$

Paolo Crivelli | 26.05.2020 | 8
Signature for the invisible decay $A' \rightarrow \chi \bar{\chi}$ - large missing energy

\[
\gamma \rightarrow e^+e^- A'
\]

ELECTROMAGNETIC CALORIMETER (ECAL)

HADRONIC CALORIMETER (HCAL)

STANDARD MODEL:
$E_{\text{ECAL}} + E_{\text{HCAL}} = 100 \text{ GeV}$

$A' \rightarrow \text{MISSING ENERGY}:
\begin{align*}
\text{ECAL} &< 50 \text{ GeV} \\
\text{HCAL} &< 2 \text{ GeV}
\end{align*}$
The Electromagnetic Calorimeter (ECAL)

- Active target

- High hermeticity (\(\sim 40 \times 0\))
- PbSc sandwich, 6x6 matrix, cells 38x38x490 mm³
- WLS fibers in spiral → suppress energy leaks
- Energy resolution \(\sim 9\%/\sqrt{(E[GeV])}\)
- Longitudinal (Pre-shower) and lateral segmentation → shower profiles (hadron rejection)

100 GeV electrons (tagged with \(S_{1,2,3}\))
The Hadronic Calorimeter (HCAL)

- High hermeticity due to Lorentz boost

- High hermeticity: 4 HCAL (~7 λ/module)
- FeSc sandwich 3x3 matrix, cells 19.4x19.2x150 cm³
- WLS fibers in spiral → suppress energy leaks
- Energy resolution ~ 60%/√(E[GeV])
The magnetic spectrometer

D. Banerjee et al., Advances in HEP, 105730 (2015)

Reconstruction of e⁻ incoming momentum

Two bending magnets in series → 7 T.m field

D. Banerjee et al., NIMA881 (2018) 72-81
The Synchrotron radiation detector (e- tagging)

Particle identification
SR emission $\sim 1/m^4$

e- efficiency > 95%
Suppression $\pi$, $K>10^{-5}$

E. Depero et al., NIMA 866 (2017) 196-201.
The NA64 search for $A' \rightarrow \chi \bar{\chi}$ - results (July + October 2016, 5 weeks)

- $4 \times 10^{10}$ electrons on target
- No event in signal box
- → exclusion of most of g-2 muon favored region
- g-2 closed completely by BABAR results

Improvement of setup for 2018 run

HCAL0: Rejection of events with hard neutral from upstream e- interactions

ST1,2: New straw-tube trackers: VETO against hadron electro-production in the beam material upstream the ECAL.
Combined results (2016-2018)

NEW constraints on sub-GeV DM parameter space (2016-2018)

First time NA64 constraints on light thermal DM exceeding sensitivity of beam dump exp. (suppressed by $\epsilon^2\alpha_D$)

Current bounds on thermal relic DM & projected NA64 sensitivity

\[ \alpha_D = 0.1 \]
\[ m_{A'} = 3m_\chi \]

**New VHCAL**: to improve detector hermiticity and reject high-p\(_T\) hadronic secondaries from beam interactions upstream the ECAL dump. Search expected to be BKG free up to \( \sim 10^{13} \) EOT
2) The NA64 search for $X/A' \rightarrow e^+e^-$

VISIBLE DECAY MODE \[ m'_{A} < 2m_{X} \]

Pair production of SM particles
8Be anomaly and X boson

Could be explained by new ‘protophobic’ gauge boson X with mass around 17 MeV


The NA64 search for $X \rightarrow e^+e^-$ - experimental setup

Addition of W calorimeter
Short in length to allow X to escape

Zooming in (next slide)
The NA64 search for $X \rightarrow e^+e^-$ - experimental signature

Signature:
1) $E_{\text{WCAL}} + E_{\text{ECAL}} = 100$ GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL
The NA64 search for $X \rightarrow e^+e^-$ - results (2017-2018)

No signal-like event in signal box

~ $8 \times 10^{10}$ EOT

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020
The NA64 search for $X \rightarrow e^+e^-$ - prospects (2021)

Feasibility under study

NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) 2020
The NA64 search for ALP

**Production via Primakoff effect**

\[ e^- Z \rightarrow e^- Z \gamma; \gamma Z \rightarrow a Z; a \rightarrow \gamma \gamma \]

Closing the gap between beam dump and colliders

Search expected to be BKG free up to \( ~5 \times 10^{12} \) EOT

The NA64 physics prospects

<table>
<thead>
<tr>
<th>Process</th>
<th>New Physics</th>
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<tbody>
<tr>
<td>$e^-$ beam</td>
<td></td>
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<tr>
<td>$A' \to e^+e^-$, and $A' \to invisible$</td>
<td>Dark photon</td>
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<tr>
<td>$X \to e^+e^-$</td>
<td>Dark Sector, charge quantisation</td>
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<tr>
<td>milliQ particles</td>
<td>Axion-like particles</td>
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<tr>
<td>$\mu^-$ beam</td>
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<tr>
<td>$Z_\mu \to \nu\nu$</td>
<td>gauge $Z_\mu$-boson of $L_\mu - L_\tau &lt; 2m_\mu$</td>
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<tr>
<td>$Z_\mu \to \chi\chi$</td>
<td>$L_\mu - L_\tau$ charged Dark Matter ($\chi$)</td>
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<td>milliQ</td>
<td>Dark Sector, charge quantisation</td>
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<tr>
<td>$a_\mu \to invisible$</td>
<td>non-universal ALP coupling</td>
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<tr>
<td>$\mu - \tau$ conversion</td>
<td>Lepton Flavour Violation</td>
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<td>$\pi^-, K^-$ beams</td>
<td>Current limits, PDG'2018</td>
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<tr>
<td>$\pi^0 \to invisible$</td>
<td>$Br(\pi^0 \to invisible) &lt; 2.7 \times 10^{-7}$</td>
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<tr>
<td>$\eta \to invisible$</td>
<td>$Br(\eta \to invisible) &lt; 1.0 \times 10^{-4}$</td>
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<tr>
<td>$\eta' \to invisible$</td>
<td>$Br(\eta' \to invisible) &lt; 5 \times 10^{-4}$</td>
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<tr>
<td>$K_S^0 \to invisible$</td>
<td>no limits</td>
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<tr>
<td>$K_L^0 \to invisible$</td>
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Could provide an explanation of (g-2)$_\mu$ anomaly

CERN-PBC-REPORT-2018-007

NA64 program: submitted as input to the European Strategy Group in the context of the PBC

CERN Council Open Symposium on the Update of European Strategy for Particle Physics
13-16 May 2019 - Granada, Spain
Summary and Outlook

- NA64: Active beam dump + missing-energy approach is very powerful probe for Dark Sector physics.
- Experiment exceeded sensitivity of previous beam dump exps. to thermal light dark matter.
- To fully exploit NA64 potential probing most of the remaining parameter space predicted by the DM relic density accumulate $5 \times 10^{12}$ EOT for $A' \rightarrow \chi \bar{\chi}$ after LS2
- Exploration of the remaining parameter space $X \rightarrow e^+e^-$
- New permanent location being prepared with active participation of NA64.
- Proposed searches in NA64 with leptonic and hadronic beams: unique sensitivities highly competitive/complementary to similar projects.