NA64 SEARCHING FOR HIDDEN SECTORS AT THE CERN SPS

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The NA64 collaboration (47 researchers from 12 Institutes)


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- Proposed (P348) in 2014, first test beam in 2015 (2 weeks),
- Approved by CERN SPSC in March 2016 → NA64.
- 2016: 5 weeks, 2017: 5 weeks, 2018: 6 weeks (starting in May).
Dark Sectors

In several models (e.g. string theory, super-gravity, ...) **Dark Sectors** of particles arise naturally → interesting candidate for Dark Matter.

For a recent review of DS activities see e.g. M. Battaglieri et al., arXiv:1707.04591.

**Kinetic mixing? If YES** → **New massive boson A'** (so called Dark Photon)

**A' decay modes:**

1) Invisible: \( A' \rightarrow \chi \bar{\chi} \)

2) Visible: \( A' \rightarrow e^+e^-, \mu^+\mu^- \)
From positronium (search for massless dark photon) → NA64

Presented at Patras conference 2011:
https://bib-pubdb1.desy.de/record/295124


Signature: disappearance of 1 MeV energy
The NA64 working principle to search for $A' \rightarrow \bar{\chi} \chi$
The NA64 working principle to search for $A' \rightarrow \chi \bar{\chi}$

- DETECTED ENERGY < 50 GeV
- "BREMSSTRAHLUNG" OF $A'$

ELECTROMAGNETIC CALORIMETER (ECAL)
The NA64 working principle to search for $A' \to \chi \bar{\chi}$

Simulated $A'$ emission spectrum

**ELECTROMAGNETIC CALORIMETER (ECAL)**

**HADRONIC CALORIMETER (HCAL)**

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

$A' \to \text{MISSING ENERGY}$:
- $\text{ECAL} < 50 \text{ GeV}$
- $\text{HCAL} < 2 \text{ GeV}$

The CERN SPS H4 electron beam dumped over active target

- Up to $7 \times 10^6$ e/spill, 2-4 spill/m
- Low contamination: $\pi$ (<1%), $\mu/K$ (0.1%)
- Low energy tails (<1%)
- Beam spot of 1.5 cm (FWHM)

High hermeticity

- High hermeticity ($\sim 40 \times d_0$)
- PbSc sandwich, 6x6 matrix, cells 38x38x490 mm$^3$
- WLS fibers in spiral → suppress energy leaks
- Energy resolution $\sim 9%/\sqrt{E[GeV]}$
- Longitudinal (Pre-shower) and lateral segmentation → shower profiles (hadron rejection)
The magnetic spectrometer

Reconstruction of $e^-$ incoming momentum

Two bending magnets in series → 7 T.m field

D. Banerjee et al., NIMA881 (2018) 72-81

Tracking system: 8 XY multiplexed resistive micromegas modules and 2 GEM detectors
The Synchrotron radiation detector

Particle identification
SR emission  ~ 1/m^4

Efficiency > 95%
Suppression >10^{-5}

BGO → PbSc

E. Depero et al., NIMA 866 (2017) 196-201.
The NA64 search for $A' \rightarrow \chi\bar{\chi}$ - results (July 2016, 2 weeks)

Event Selection Criteria:
- Timing information $\rightarrow$ Pile up suppression.
- Clean incoming track: angle + single hit in all trackers, correct momentum.
- Synchrotron radiation $\rightarrow$ Hadron suppression
- Shower profile compatible with $e^-$
- No activity in Veto.

All selection cuts applied $\rightarrow$ no event in signal region
The NA64 search for $A' \rightarrow \chi\bar{\chi}$ - results (July 2016, 2 weeks)

$2.75 \times 10^9$ electrons on target

$\rightarrow$ exclusion of most of g-2 muon favored region


No signal observed

g-2 closed completely by BABAR results


The NA64 search for $A' \rightarrow \chi \bar{\chi}$ - results (October 2016, 3 weeks)

4 x $10^{10}$ electrons on target

NOTE: NA64 limits obtained with exact tree level cross section calculation, S. Gninenko et al. arXiv 1712.05076

No signal observed

Constraints on sub-GeV thermal DM

Good scaling for small couplings

(\sim \epsilon^2 \text{ instead of } \sim \epsilon^4 \sigma_D)
$^8$Be 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 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

**WCAL:** 30-40 $X_0$
Sandwich W-Sc

New compat Tungsten ECAL for conversion
The NA64 search for $X \rightarrow e^+e^-$ - results (2017)

Neutral events □ Signal like ■

No signal-like event in signal box

→ Increase the energy and decrease WCAL length (~$5X_0$) to cover short lived $X$-boson

**Signature:**
1) Reconstructed vertex outside WCAL
2) Reconstructed Invariant mass $\sim 16.7$ MeV
3) Double e.m. shower in ECAL

$10^{11}$ EOTS could cover the anomaly completely

$M_X=16.7$ MeV, $L_{WCAL}=5X_0$
ALPS detection in NA64

NA64 setup is capable to search for axion-like particles created through Primakov effect using decay channels $a \rightarrow yy$ and $a \rightarrow e^+ e^-$.

- Two possible decay channels to detect:
  - Visible:
    - ECAL + WCAL = 100 GeV
    - Pure neutral shower in ECAL
    - High collinearity
  - Invisible:
    - Missing energy in ECAL

Combining the two channels allow us to cover a new region of parameter space!

$10^{-4} < g_{a yy} < 10^{-2}$

$10 < m_a < 500$ MeV
### And many others!

<table>
<thead>
<tr>
<th>Process</th>
<th>New Physics</th>
<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>1. $eZ \rightarrow e^+e^- + E_{\text{miss}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- $A' \rightarrow e^+e^-$</td>
<td>Dark Sector: Dark Photons and DM</td>
<td>$10^{-3} \leq \varepsilon \leq 10^{-6}$</td>
</tr>
<tr>
<td>- $A' \rightarrow$ invisible</td>
<td>New light states ($V,S$) weakly coupled to $e^-e^-$</td>
<td>$M_{A'} \sim$ sub-GeV</td>
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<tr>
<td>- alps</td>
<td></td>
<td>$m_{Q} &lt; 10^{-5}-10^{-7}$ e</td>
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<tr>
<td>- milli-Q</td>
<td></td>
<td>$M_{\text{milli-Q}} \sim$ sub-GeV</td>
</tr>
<tr>
<td>2. $\mu^- Z \rightarrow \mu^- Z + E_{\text{miss}}$</td>
<td></td>
<td></td>
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</tbody>
</table>
| - $Z_{\mu^-} \rightarrow \nu
\nu, \mu^+\mu^-$ | $(g-2)_\mu$ anomaly, New $Z_{\mu}$ from $L_{\mu} \rightarrow L_{\tau}$ gauged symm., scalars coupled to $\mu$ | $\alpha_{\mu} < 10^{-11}-10^{-9}$ |
| - $a_{\mu}$ | | $\sigma_{\mu e}/\sigma_{\mu \mu} < 10^{-9}-10^{-8}$ |
| - $\mu \rightarrow \tau$ conversion | | |
| 3. $\pi(K)p \rightarrow M^0n + E_{\text{miss}}$ | | |
| - $K_1 \rightarrow$ invisible | CP, CPT symmetry Bell-Steinberger Unitarity, new WC particles: NHL, $\phi\phi$, VV | $\text{Br} < 10^{-8}-10^{-6}$, Complementary to $K \rightarrow \pi\nu\nu$ |
| - $K_S \rightarrow$ invisible | | $\text{Br} < 10^{-8}-10^{-7}$ |
| - $\pi^0, \eta, \eta' \rightarrow$ invisible | | |
Summary and Outlook

2016: $A' \to \bar{\nu}$
- July run: $2.75 \times 10^9$ EOT: no signal $\rightarrow$ most of g-2 muon favored region excluded (PRL118, 011802 (2017))
- October run: $4 \times 10^{10}$ EOT: no signal $\rightarrow$ new constraints on TLDM (PRD97, 072002 (2018)).

$\rightarrow$ active beam dump + missing-energy: very powerful tool to search for dark sector physics.

2017-2018:
- $A' \to \bar{\nu}$: goal $\sim 3 \times 10^{11}$ EOT (analysis 2017 ongoing)
- $X \to e^+e^-$: $5 \times 10^{10}$ EOT at 100 GeV (2017) arXiv 1803.07748, expected $5 \times 10^{10}$ EOT at 150 GeV (2018)

>2021 (after LS2)
- goal $5 \times 10^{12}$ EOT for $A' \to \bar{\nu}$ and explore remaining parameter space $X \to e^+e^-$
- resonant production of $A'$ with positrons (L.Marsicano et al. arXiv 1802.03794)
- Search for $Z'$ coupled to muons with M2 beamline at CERN (160 GeV/c muon), proposal in preparation
- Searches for $h,h', p0, KL, KS \rightarrow$ invisible

$\rightarrow$ Proposed searches of dark sectors in NA64 with leptonic and hadronic beams: unique sensitivities: highly complementary to similar projects.

- Contribution to the CERN PBC program after LS2
- Input to the European Strategy for Particle Physics
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The NA64 search for $A' \rightarrow \chi \chi'$ - results (July 2016, 2 weeks)

Electron selection with SRD

- **Region I:** $e^{-} Z \rightarrow e^{-} Z\gamma; \gamma \rightarrow \mu^{+}\mu^{-}$
  $\rightarrow$ benchmark for MC

- **Region II:** SM events
  $E_{ECAL} + E_{HCAL} \approx 100$ GeV

- **Region III** $\rightarrow$ pile-up events
Effects of the cuts

Trigger event

SRD, Momentum, Veto
Pileup rejection

ALL cuts applied
Constraint on light thermal Dark matter
Constraint on light thermal Dark matter

- Pseudo-Dirac Thermal DM
- Majorana Thermal DM

Graphs showing different constraints on dark matter mass and cross-section for 1 TeV Landau Pole.
The NA64 physics prospects – further correction of sensitivity?

→ Possible other corrections for the interaction $e^- \rightarrow A' \rightarrow x\bar{x}$

A' strahlung

already accounted at tree level

Aresonant production

Could be significant due to positron rich environment

Resonant production

L. Marsicano et al. arXiv 1802.03794
ALPS detection in NA64

NA64 setup is capable to search for axion-like particles created through Primankov effect using decay channels $a \to \gamma\gamma$ and $a \to e^+e^-$

$\mathcal{L}_{\text{int}} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} (\partial_{\mu} a)^2 - \frac{1}{2} m_a^2 a^2$

$\sigma_{\text{tot}}(\gamma N \to aN) = \frac{16\pi\alpha}{m_a^3} \cdot \Gamma_{a\to\gamma\gamma} \cdot [Z^2 \ln(184Z^{-1/3}) + Z \ln(1194Z^{-2/3})]$

- Decay length:
  \[ l_a = 40 \text{m} \cdot \frac{E_a}{10 \text{ GeV}} \cdot \left( \frac{g_{a\gamma\gamma}}{10^{-5} \text{ GeV}^{-1}} \right)^{-2} \cdot \left( \frac{m_a}{100 \text{ MeV}} \right)^{-4} \]

- Decay width:
  \[ \Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a}{64\pi} \]

- Signal:
  \[ N_{\text{sign}} = N_{\text{eff}}^\gamma \cdot \Delta X_{\text{eff}}^\gamma \cdot \frac{\rho N_A}{A} \cdot \sigma_{\text{tot}}(\gamma N \to aN) \exp \left( -\frac{L_{\text{dec}}}{l_a} \right) \left[ 1 - \exp \left( -\frac{L_{\text{fid}}}{l_a} \right) \right] \]
Constraint on ALPS

\[ 10^{-4} < g_{\text{ayy}} < 10^{-2} \]

\[ 10 < m_a < 500 \text{ MeV} \]