Latest Results of NA64 searching for Dark Sectors at the CERN SPS

Benjamin Banto Oberhauser, Group P. Crivelli, on behalf of the NA64 collaboration
Focus in this talk: **Hidden-sector Dark Matter**

- Interesting framework to explain the origin of DM
- Vector portal: new force carrier, **Dark Photon A'**

Lagrangian described by **4 parameters**:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{e}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'^{\mu} A'^{\mu}$$

$$+ i\bar{\chi}\gamma^\mu \partial_\mu \chi - m_{\chi} \bar{\chi} \chi - e_{D} \bar{\chi} \gamma^\mu A'^{\mu} \chi.$$  

Useful parameter for comparison

Proportional to DM-SM annihilation cross-section

$$y = e^2 \alpha_D \left(\frac{m_{\chi}}{m_{A'}}\right)^4$$
The NA64 Collaboration

- Fixed target experiment at the CERN Super-Proton Synchrotron (SPS) aiming at probing Dark Sector physics

- International collaboration: ~50 researchers from 16 Institutes

- Broad physics program
  - See Henri Sieber’s talk for NA64 muon beam configuration (after this talk)
How to produce Dark Photons?

Annihilation

Bremsstrahlung

Meson decay
How to detect Dark Photons?

Decay:

**Invisible**

\[ m_{A'} > 2m_\chi \]

**Visible**

\[ m_{A'} < 2m_\chi \]

**Signature:**
- Missing energy
- SM particles
How to detect Dark Photons?

NA64 Invisible setup

- Beam:
  - 100 GeV $e^-$ beam
- Tagging system:
  - Trackers (MM, GEM, Straw Tubes)
  - SRD
- Hermeticity (Calorimeters):
  - ECAL ($\sim 40 \, X_0$)
  - HCAL ($\sim 28 \, \lambda$)

Momentum reconstruction and $e^-$ identification:

- Micromegas: D. Banerjee et al., NIMA 881 (2018) 72-81
- SRD: E. Depero et al., NIMA 866 (2017) 196-201
How to **detect** Dark Photons?

### Electromagnetic Calorimeter (ECAL)

*Standard Model:* 

\[ E_{\text{ECAL}} + E_{\text{HCAL}} = 100 \text{ GeV} \]

### Hadronic Calorimeter (HCAL)

\[ A' \rightarrow \text{Missing energy!} \]
Results: Combined 2016-2018 invisible searches \((2.84 \times 10^{11} \text{ EOT})\)

- **Leading** constraints for \(m < 0.1 \text{ GeV}\) in beam dump experiments

\((g-2)_\mu\) region completely excluded by NA64 and BaBar

Predictions from DM Relic Abundance
Recent search led by ETHZ group: Semi-visible Channel

**Semi-visible Decay**
Alternative model for $A'$ decay

$$m_{\chi_2} > m_{\chi_1} \text{ and } m_{A'} > 2m_{\chi_1}$$

$$\Delta = m_{\chi_2} - m_{\chi_1}$$

**Signature**
Missing energy + SM particles

\[ e^- Z \rightarrow e^- Z A' \]
\[ A' \rightarrow \chi_1 \chi_2 \]
\[ \chi_2 \rightarrow \chi_1 e^+ e^- \]

Explanation of $(g-2)_{\mu}$ anomaly and DM relic density

G. Mohlabeng, PRD 99, 115001 (2019)
Y. Tsai, et al., PRL126, 181801 (2021)
Results: Semi-visible decay and $(g-2)_\mu$

- **NA64 Collaboration, arXiv:2107.02021v2**
  - Submitted to EPJC
- **Covering** unexplored parameter space for $(g-2)_\mu$ and LDM
- A large region **remains uncharted!**
  - Aim for future runs
Current Status of new NA64 dedicated beam area

July 2021
Beam data taking ongoing!

- **Permanent place** in H4 beamline
- **Upgrade** in detectors and electronics
  - Higher granularity SRD
  - MM: Improved design and reduced material budget (ETHZ Group)
- **New Calorimeters (ZDCAL and VHCAL)** for **more background suppression**
The search continues!

- Many other physics results:
  - Axion-like particles (ALPs) search: \( \text{Phys. Rev. Lett. 125, 081801 (2020)} \)
  - Constraints on New Physics in \((g-2)_e\): \( \text{Phys. Rev. Lett. 126, 211802 (2021)} \)

- Main prospects until 2025 (CERN Long Shutdown 3)
  - Fully exploit experimental potential and explore remaining parameter space motivated by DM relic abundance
  - First pilot + first physics run with NA64\(\mu\) (Henri Sieber’s talk)
Acknowledgements

The NA64 Collaboration, in particular P. Crivelli and S. Gninenko
The ETH Zurich group, in particular P. Crivelli, E. Depero, L. Molina Bueno and H. Sieber
SNSF Grant No. 197346
Back-up
\[ L = L_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \frac{e}{2} F'_{\mu\nu} F^{\mu\nu} + i \bar{\chi} \gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi} \chi - e_D \bar{\chi} \gamma^\mu A'_\mu \chi \]

- **Standard Model Lagrangian**
- **A' massive vector field associated with the U'(1) broken symmetry**
- **Kinetic mixing term with the standard photon \( \gamma \)**
- **\( \chi \): DM candidate, it can be pseudo-Dirac, scalar or Majorana fermion**

For simplicity during the talk
NA64 invisible setup

Momentum reconstruction: \( \frac{dp}{p} \sim 1\% \)

Tagging of 100 GeV electrons

H4 beam from CERN SPS:
- \( \leq 10^7 \) e\(^-\)/spill, 5s spill duration, 2-4 spill/min
- Hadron contamination \( \pi/e \leq 1\% \)
NA64 invisible setup

**Trackers:**
- Straw Tubes
- MicroMegas (MM)
- Gas Electron Multiplier (GEM)

**Synchrotron Radiation Detector:**
- Efficiency ~95%
- Suppression ~$10^{-5}$

Synchrotron radiation ~ $1/m^4$
NA64 invisible setup

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

Missing energy!

ECAL:
- Pb/Scintillator
- High hermeticity (~40 $X_0$)

HCAL (4 modules):
- Fe/Scintillator
- High hermeticity (~28 $\lambda$)
Sources of Background in invisible mode setup

<table>
<thead>
<tr>
<th>Background source</th>
<th>Background, n_b</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Dimuons</td>
<td>0.024 ± 0.007</td>
</tr>
<tr>
<td>(ii) $\pi, K \rightarrow e\nu, K_{e_3}$ decays</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>(iii) $e^-$ hadron interactions in the beam line</td>
<td>0.43 ± 0.16</td>
</tr>
<tr>
<td>(iv) $e^-$ hadron interactions in the target</td>
<td>&lt;0.044</td>
</tr>
<tr>
<td>(v) Punch-through $\gamma$’s, cracks, holes</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total $n_b$ (conservatively)</td>
<td>0.53 ± 0.17</td>
</tr>
</tbody>
</table>
Prospects for NA64

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

NA64e $10^{13}$

+ NA64\(\mu\) $2 \times 10^{13}$

\(\alpha_D = 0.1\)

\[ m_X, \text{GeV} \]

S. N. Gninenko et al., PLB 796, 117-122 (2019)
# 2016-2018 invisible runs analysis: event candidate selections

Selection criteria:
1. **Single track** with momentum 100±3 GeV (clean track)
2. **In time** trigger and energy deposit in SRD compatible with an e⁻ (timing information and electron identification)
3. Longitudinal and lateral shape of EM shower in ECAL consistent with an e
4. No activity in the VETO and HCAL (no punch-through)

Regions:

I. Dimuon production through
\[ e^−Z \rightarrow e^−Zγ; \gamma \rightarrow μ^+μ^- \]

II. SM events with hadron electroproduction in ECAL satisfying (within detector resolutions)
\[ E_{ECAL} + E_{HCAL} = 100 \text{ GeV} \]

Regions:
A. Pure neutral hadronic secondaries produced in ECAL
B. e⁻ hadronic interaction in the target
C. e⁻ hadronic interactions downstream the beam line (SRD) with large transverse fluctuations in hadronic secondaries
Byproducts of our searches: ALPs search

Axion-like Particles (ALP)
- Production via Primakoff effect

Signature
HCAL1 as veto
Results: ALPs search

- **NA64 collaboration PRL 125, 081801 (2020)**
- NA64 closed the gap between beam dump and collider experiments
- Under study:
  - Combining ALP with A' searches
2016-2018 invisible runs analysis: ALP event candidate selections

Selection criteria:
1. Single track with momentum 100±3 GeV (clean track)
2. In time trigger and energy deposit in SRD compatible with an e (timing information and electron identification)
3. Longitudinal and lateral shape of EM shower in ECAL consistent with an e
4. No activity in the VETO
5. No activity in HCAL (signature 2)
6. No activity in HCAL1 and EM-like shower in HCAL2,3 (R-cut)

R-cut: using shower lateral shape in HCAL to discriminate e-induced shower from hadron's

\[ R = \frac{E_{HCAL} - E_{HCAL}^c}{E_{HCAL}} \]

<table>
<thead>
<tr>
<th>3x10^4 events</th>
<th>7x10^3 events</th>
<th>12 events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRD electron identification</td>
<td>No activity in VETO</td>
<td>All selection criteria (+R &gt; 0.06)</td>
</tr>
</tbody>
</table>

D. Banerjee et al., PRL 125, 061801 (2020)
NA64 visible setup

Addition of WCAL:
- Tungsten Calorimeter (W/Scintillator)
- High hermeticity (~40 $X_0$)

Visible decay of Mediator X

Signature as **missing energy**:
- Two EM showers
  - One in the dump (WCAL)
  - One in the ECAL
- $E_{\text{WCAL}} + E_{\text{ECAL}} = E_{\text{beam}}$
Results: Visible searches for $^8$Be anomaly

- Goal for 2022 with **updated visible setup**:
  - Perform invariant mass reconstruction
  - Cover full parameter space

Selection criteria:
1. Single track entering the dump
2. In time trigger and energy deposit in SRD compatible with an e⁻ (timing information and electron identification)
3. No energy in V2 (0.5 MIP)
4. Signal in S4 counter compatible with 2 MIPs
5. Two EM-like showers in WCAL and ECAL with $E_{\text{Beam}} = E_{\text{WCAL}} + E_{\text{ECAL}}$
6. No energy deposit on VETO and HCAL
### Physics program of NA64 collaboration

<table>
<thead>
<tr>
<th>Process</th>
<th>New Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^- \text{ beam}$</td>
<td></td>
</tr>
<tr>
<td>$A' \rightarrow e^+e^-$</td>
<td>Dark photon</td>
</tr>
<tr>
<td>$A' \rightarrow \text{invisible}$</td>
<td>sub-GeV Dark Matter ($\chi$)</td>
</tr>
<tr>
<td>$A' \rightarrow \bar{\chi}\chi$</td>
<td>new gauge $X$-boson</td>
</tr>
<tr>
<td>$X \rightarrow e^+e^-$</td>
<td>Dark Sector, charge quantisation</td>
</tr>
<tr>
<td>milliQ particles</td>
<td>Axion-like particle</td>
</tr>
<tr>
<td>$a \rightarrow \gamma\gamma$, invisible</td>
<td></td>
</tr>
<tr>
<td>$\mu^- \text{ beam}$</td>
<td></td>
</tr>
<tr>
<td>$Z_\mu \rightarrow \bar{\nu}\nu$</td>
<td>gauge $Z_\mu$-boson of $L_\mu - L_\tau &lt; 2m_\mu$</td>
</tr>
<tr>
<td>$Z_\mu \rightarrow \bar{\chi}\chi$</td>
<td>$L_\mu - L_\tau$ charged Dark matter ($\chi$)</td>
</tr>
<tr>
<td>milliQ</td>
<td>Dark Sector, charge quantisation</td>
</tr>
<tr>
<td>$a_\mu \rightarrow \text{invisible}$</td>
<td>non-universal ALP coupling</td>
</tr>
<tr>
<td>$\mu - \tau$ conversion</td>
<td>Lepton Flavour Violation</td>
</tr>
<tr>
<td>$\pi^-, K^- \text{ beam}$</td>
<td>Current limits, PDG 2018</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \text{invisible}$</td>
<td>$Br(\pi^0 \rightarrow \text{invisible}) &lt; 2.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \text{invisible}$</td>
<td>$Br(\eta \rightarrow \text{invisible}) &lt; 1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta' \rightarrow \text{invisible}$</td>
<td>$Br(\eta' \rightarrow \text{invisible}) &lt; 5.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K^0_S \rightarrow \text{invisible}$</td>
<td>no limits</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \text{invisible}$</td>
<td>no limits</td>
</tr>
<tr>
<td>$e^+ \text{ beam}$</td>
<td></td>
</tr>
</tbody>
</table>
Current invisible setup
Upgraded MM trackers for NA64 by ETHZ group

- Reduced material budget
- New larger design for alternative setups
- Characterized and ready