Dark sector physics search in missing energy events with the NA64 experiment

B. Radics
(on behalf of the NA64 collaboration)
Outline

• Motivation and method of search
• The NA64 experiment
• Runs in 2016 and 2017
• Simulation of Dark Photon production
• Analysis of data
• Results
• Conclusions
Motivation

- Possible candidates for new physics: sub-GeV dark sector particles not charged under SM forces, only gravitational interaction, “portal” interactions with SM particles

- Thermal freeze-out of DM-SM could explain relic density, and put constraints on the parameter space

- May affect galactic structure formation, muon (g-2)$_\mu$, etc

- Parameter space is poorly tested

- Most accessible via portal interactions with SM: gauge kinetic mixing, MeV - GeV mass range, high intensity searches

- Most viable is interaction of DM with SM through a vector portal A’ boson

Dark Sectors 2016 Workshop: Community Report, J.Alexander et al., arxiv: 1608.8632
Motivation

- New A’ vector portal boson (dark photon) could mix kinetically with photon
  \[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{e'}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + i \bar{\chi} \gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi} \chi - e_D \bar{\chi} \gamma^\mu A'_\mu \chi \]

- A’ corresponds to new \( U(1)_D \) gauge symmetry, \( \varepsilon \ll 1 \)

- Requirement of thermal freeze-out of DM-SM annihilation through photon-A’ mixing allows to derive relations between the parameters (PRD 91,094026 (2015)).

- Rate of DM annihilation into SM fermions, allows to define signal event rate, \( y \),
  \[ \langle \sigma v \rangle \propto \alpha_{DM} \varepsilon^2 \left( \frac{m_\chi^4}{m_{A'}^4} \right) \alpha / m_\chi^2 \]
  \[ \alpha_{DM} = \frac{e_D^2}{4\pi} \]

- Decay channels: visible: e+e-, mu+mu-, hadron, …, invisible: \( A' \rightarrow \chi \bar{\chi} \) if \( m_{A'} > 2m_\chi \).
  It is dominante if \( \alpha_{DM} >> \varepsilon \).

- Production: interaction of high energy electrons in an active beam dump target
47 researchers from 11 institutes
Proposed in 2014, first test beam in 2015
Method of search for A' -> invisible

- If realised by nature, any source of photons will produce all kinematically possible massive A' states with the appropriate mixing strength: e.g. kinetic mixing with bremsstrahlung photons in the reaction of high-energy electrons from a beam absorbed in an active beam dump.

- Followed by the prompt decay A' -> invisible into DM particles: e\bar{Z} -> e\bar{Z}A'; A'->\chi\chi^{-}

- A fraction of the beam energy, f, is carried away by \chi particles, penetrating the target without interactions, \( E_{A'} = f E_0 \)

- The remaining part of the beam energy is deposited in the target: \( E_e = (1-f) E_0 \)

- Signal signature: excess of events above background with
  - single isolated energy e-m shower with energy \( E_e < E_0 \)
  - missing energy \( E_{\text{miss}} = E_{A'} = E_0 - E_e \)

- Number of A' produced per electron on target (EOT):

\[
n_{A'}(\epsilon, m_{A'}, E_0) = \frac{\rho N_A}{A_{Pb}} \sum_i n(E_0, E_e, s) \sigma^A'(E_e) \Delta s_i
\]
Simulation of $eZ \rightarrow ezA'$; $A' \rightarrow$ invisible

- Geant4 and $A'$ emission in the e-m shower development.
- Cross section from Bjorken et al. 2009.
- Sensitivity $\sim \varepsilon^2$ ($A'$ production vertex) - while for beam dump experiments $\sim \varepsilon^2 \alpha_D$ (+ $A'$ decay and $\chi$ scattering off electrons in the target detector).
- For small $\varepsilon$ mixing parameter this scheme has great advantage.
NA64 experiment setup
invisible search mode

30 August – 2 October 2017.

30 August start of run.
Installation from 9:00 30.08 up to 17:00 30.08.

31 August.
Safety inspection at 15:30.
NA64 setup for invisible mode.

1 September;
Calibration, commissioning, tuning beam and detectors.
14:00. Switch to 0 degree production, high intensity electron beam. Beam tuning by Nicos.

2 September:
0:00; HCAL3 HV adjustment and calibration;
0 - 2 A=2445 HV=942
1 - 2 A=2470 HV=910
2 - 2 A=2380 HV=990
0 - 1 A=2501 HV=830
1 - 1 A=2423 HV=820
2 - 1 A=2540 HV=930

0 - 0 A=2528 HV=885
1 - 0 A=2501 HV=830
2 - 0 A=2400 HV=838

HCAL2 HV adjustment and calibration;
0 - 2 A=2480 HV=940
1 - 2 A=2559 HV=780
2 - 2 A=2546 HV=767
0 - 1 A=2433 HV=690
1 - 1 A=2521 HV=830
2 - 1 A=2570 HV=846
0 - 0 A=2421 HV=802
1 - 0 A=2568 HV=878
2 - 0 A=2459 HV=860

3 September:
Night shift – Ecal precalibration, HV tuning

HCAL1 HV adjustment and calibration;
0 - 1 A=2591 HV=
1 - 1 A=2450 HV=
2 - 1 A=2566 HV=

0 - 1 A=2467 HV=
1 - 1 A=2536 HV=
2 - 1 A=2558 HV=

0 - 0 A=2453 HV=
1 - 0 A=2520 HV=
2 - 0 A=2499 HV=

4 September:
Ecal calibration.
Beam tuning, beam file H4A.NA64.004 high intensity from Nicos.

COLL: 1 ±20; 2 ±40; 3 ±40; 4 ±40; 5 ±10; 6 ±35; 7 ±35; 8 ±5; 9 ±10; 10 ±10;
S0 = 3.08x10^6, S1 = 3.10x10^6, V0 = 3.9x10^5

5 September:
HCAL0 HV adjustment and calibration;
NA64 experiment setup
Key moments in reconstruction

• Synchrotron Radiation detector (SRD) made as lead - scintillator sandwich used to suppress pions and other heavier then e- particles from the beam.

• The shower profile in the ECAL is compared to profile of true electrons in order to suppress wrong particles.

• Micromegas track detectors are used to reconstruct the momentum of e- before the ECAL to suppress small fraction of soft electrons from interaction in beam line elements.
Key moments in reconstruction

- Each ECAL module is 40 $X_0$ with a 4$X_0$ preshower initial part, electron energy resolution: $dE/E \sim 0.1/\sqrt{E}$

- Requiring in-time between SRDs combined with ECAL longitudinal and lateral shower information: $\pi/e^- < 10^{-5}$, 95% e- ID efficiency (NIM A 866 (2017) 196).

- V2 after ECAL to veto charged secondaries, and HCAL ($30 \lambda_{int}, Fe+Sc$) to veto on muons or hadronic secondaries.
Data taking in 2016

• 1st Run period: 29.06-13.07 (2w)

• 2nd Run period: 12.10-09.11 (4w)

• Low intensity: \( n_{EOT} = 2.3 \times 10^{10} \) (~1.4-2\( \times 10^6 \) e- /spill)

• Medium intensity: \( n_{EOT} = 1.1 \times 10^{10} \) (~3-3.5\( \times 10^6 \) e- /spill)

• High intensity: \( n_{EOT} = 0.9 \times 10^{10} \) (~4.5-5\( \times 10^6 \) e- /spill)

• \( \text{Tr}(A') = \prod S_i \times V1 \times \text{PS}(>E_{PS}) \times \text{ECAL}(<E_{ECAL}) \)
ECAL vs HCAL energy

- Region I: dimuon events
- Region II: $E_{\text{ECAL}} + E_{\text{HCAL}} = 100$ GeV
- Region III: pile-up of e- and beam hadrons (1-20%)

Only SRD selection to be e- event
Dimuon production as reference

- Rare process gamma to muon conversion ($eZ\rightarrow eZ\gamma; \gamma \rightarrow \mu\mu$), many similarities with our signal. Available in G4, off by default.

- Can be used to estimate corrections to signal reconstruction efficiency and uncertainties in $A'$ yield calculations.

- HCAL energy around 10 GeV.

- $\sim 10^4$ dimuon pairs detected in HCAL in 2016 run period.

- MC simulation: cross section have been biased in G4 by a factor of 200 to have good statistics.

- MC compared with Data.
Dimuon reconstruction

### Data sample

<table>
<thead>
<tr>
<th>Data sample</th>
<th>beam intensity, $10^6$</th>
<th>$n_{tot}, 10^6$</th>
<th>$n_{2\mu}^{MC}$</th>
<th>$n_{2\mu}^{data}$</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>run I</td>
<td>1.8</td>
<td>171</td>
<td>1223</td>
<td>1124</td>
<td>0.92</td>
</tr>
<tr>
<td>run II</td>
<td>3.2</td>
<td>208.5</td>
<td>1491</td>
<td>1268</td>
<td>0.85</td>
</tr>
<tr>
<td>run III</td>
<td>4.6</td>
<td>597</td>
<td>4271</td>
<td>3417</td>
<td>0.81</td>
</tr>
</tbody>
</table>
Analysis: efficiency and uncertainties

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Value, uncertainty</th>
<th>sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of collected EOT, $n_{EOT}$</td>
<td>1 ± 0.02</td>
<td>$e^-$ Data</td>
</tr>
<tr>
<td>incoming $e^-$ selection cuts, $\epsilon_e$</td>
<td>0.58 ± 0.03</td>
<td>$e^-$ Data</td>
</tr>
<tr>
<td>$A'$ yield, $\epsilon_{A'}$</td>
<td>$\epsilon$, $m_{A'}$ dependent, 10%</td>
<td>MC, Dimuons</td>
</tr>
<tr>
<td>ECAL selection cuts, $\epsilon_{ECAL}$</td>
<td>0.93 ± 0.06</td>
<td>Data, Dimuons</td>
</tr>
<tr>
<td>Veto cut, $\epsilon_V$</td>
<td>0.94 ± 0.03</td>
<td>Data, MC</td>
</tr>
<tr>
<td>HCAL selection cuts, $\epsilon_{HCAL}$</td>
<td>0.98 ± 0.02</td>
<td>Data, MC</td>
</tr>
<tr>
<td>Total</td>
<td>0.50 ± 0.13</td>
<td></td>
</tr>
</tbody>
</table>

- Values correspond to high-intensity run.
- Total efficiency varying 0.73±0.12 to 0.50±0.13.
- ECAL and incoming e- selection most rate dependent.
The simulation of this reaction on nuclei is a well-known reaction in particle physics. It is expected to be an important cross-check of dimuon results with the NA64 code. However, we anticipate that comparison simulation for decays and propagation of muons through detectors will be facilitated by the use of Geant4 and a code developed by NA64. Here, we briefly review the description of the gamma conversion into a muon-antimuon pair implemented in Geant4. The dimuon production was also used as a reference for the simulation of dark photon production. The gamma conversion into a muon-antimuon pair is rewritten in the form of the differential cross section. The differential cross section can be differential in the energy fraction of muons. For hydrogen, the values of the classical radius of muon and atomic number of the nuclei are used. For other nuclei, those are expected to be larger by a factor of five.

### Analysis cuts

- **Left:** only SRD cut to be e- events
- **Middle:** all selection but cut against upstream interactions (Tracker hit multiplicity, and lateral energy spread and time spread in HCAL cells)
- **Right:** final event selection

---

**FIG. 6:** Event distribution in the $(E_{\text{ECAL}}, E_{\text{HCAL}})$ plane from the runs II (top row) and III (bottom row) data. The left panels show the analysis cuts. The middle panels include all selection but cut against upstream interactions (Tracker hit multiplicity, and lateral energy spread and time spread in HCAL cells). The right panels show the final event selection.
Backgrounds

• Leak of energy through holes, cracks in the detector
  • X-Y scan of ECAL and HCAL - no significant E leak found

• Detector hermeticity: photo-nuclear reaction producing neutrons, charged hadrons escaping detection in HCAL (non-herm)
  • pion beam test, Data-MC comparison, single hadron prod. prob. $< 10^{-4}$, non hermeticity $< 10^{-9}$, overall negligible $< 10^{-13}$

• Large transverse fluctuations from hadronic showers, long lived neutral emitted at large angles: similar to previous estimates

• Upstream interactions: requires precise knowledge of dead material in the beam line
  • SRD, V2, tracker suppression of secondaries
  • HCAL: lateral E and time spread compared with that expected from single electrons interacting in the ECAL target
  • estimation from data control regions

• Particle in-flight decays
  • SRD, ECAL energy and incoming track angle
Backgrounds

<table>
<thead>
<tr>
<th>Background source</th>
<th>Estimated number of events, $n_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>hermeticity: punchthrough $\gamma$'s, cracks, ..</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>loss of hadrons from $e^- Z \rightarrow e^- + hadrons$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>loss of muons from $e^- Z \rightarrow e^- Z \gamma; \gamma \rightarrow \mu^+ \mu^-$</td>
<td>$0.005 \pm 0.001$</td>
</tr>
<tr>
<td>$\mu \rightarrow e \nu \nu, \pi, K \rightarrow e \nu, K_{e3}$ decays</td>
<td>$0.02 \pm 0.004$</td>
</tr>
<tr>
<td>$e^-$ interactions in the beam line materials</td>
<td>$0.09 \pm 0.03$</td>
</tr>
<tr>
<td>$\mu, \pi, K$ interactions in the target</td>
<td>$0.008 \pm 0.002$</td>
</tr>
<tr>
<td>accidental SR tag and $e^-$ from $\mu, \pi, K$ decays</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Total $n_b</td>
<td>$0.12 \pm 0.04$</td>
</tr>
</tbody>
</table>

- Dominant contribution from upstream interactions
- 30% uncertainty also mainly due to upstream interactions
- Estimated from extrapolation of background control regions to signal region
Analysis

• Data collected from 2016 runs are divided in 3 bins: low, medium and high intensity beam.

• For each bin the background, efficiency corrections and uncertainties are estimated.

• A cut optimisation for the maximum sensitivity was performed for ECAL cut.

• The expected sensitivity was calculated with the Profile Likelihood method with RooStats, using the PL as test statistics, and taking the asymptotic approximation.

\[
N_{A'} = \sum_{i=1}^{3} N_{A'}^i = \sum_{i=1}^{3} n_{EOT}^i \epsilon_{tot}^i n_{A'}^i (\epsilon, m_{A'}, \Delta E_e)
\]

• Each ith entry for each data: simulating signal events for beam conditions and reconstructing w/ selection criteria, and efficiency corrections.

• Results also cross checked with simple limit from Poisson signal model with log-normal used for systematic uncertainty terms. Results agree within %.
Results on $A'$ parameters

- Best limits in the region 0.001 - 0.1 GeV.
- Muon g-2 favoured parameter region for vector mediator model excluded.
Results on light thermal dark matter

- LTDM models can be classified into spin and mass of DM and mediators, here only considering vector mediator.

- Assuming limits from prev. slide, constraints on DM annihilation freeze out.

- Results obtained for LSND, E137 and MiniBoone with $10^{22}$, $10^{19}$ and $10^{20}$ POT.

- NA64 obtained with only $\sim 4 \times 10^{10}$ EOT. With $\sim 4 \times 10^{11}$ EOT NA64 can cover all beam dump exclusion areas.
Conclusions

• Search is performed for sub-GeV dark photon mediated production of dark matter by NA64, using $4.3 \times 10^{10}$ 100 GeV electrons.

• No evidence of such events found.

• Derived upper limits on $A' \gamma$ mixing strength in the mass range 1-500 MeV, allowing to exclude vector mediator model solution for the muon g-2 anomaly.

• Assuming these limits and constraints on DM ann. freeze out NA64 managed to exceed also limits on LTDM scenarios.

• NA64 continues to increase statistics in the near future and extend searches for dark matter and new physics at CERN SPS.

• Just finished our 2017 run, collecting additional $5 \times 10^{10}$ electrons:
  
  • Runs finished both with invisible and visible mode, sensitivity to exclude $\varepsilon = [5 \times 10^{-5}, 10^{-3}]$, covering light X boson ($^{8}$Be) favoured parameter region

  • Data under evaluation