NA64: searching for hidden sectors at the CERN SPS

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Dark Matter

- Several cosmological observations suggest the existence of Dark Matter, e.g. galaxy rotation curves\textsuperscript{1}, gravitational lensing and spectrum of CMBR.
- In addition to the most popular models like WIMP-SUSY various DM models motivate "light" new physics that could be observed in low energy experiments.
- One possibility is a dark sector of SM singlets coupled to ordinary matter by gravity and possibly other very weak forces. An extra (broken) U(1)’ symmetry would implies a new massive boson A’ (Dark Photon).

Introduction

Dark Matter

- One possibility is a dark sector of SM singlets coupled to ordinary matter by gravity and possibly other very weak forces. An extra (broken) U(1)’ symmetry would imply a new massive boson A’ (Dark Photon)

Dark Photon features

- $\Delta L = \epsilon F^{\mu\nu} A'_{\mu\nu}$ kinetic mixing
  - $\gamma$-A’, $\epsilon$ coupling strength
- natural coupling $\epsilon \sim 10^{-3} - 10^{-4}$, $M_{A'} \sim \epsilon^{1/2} M_Z$

Decay Modes

1. Visible: $A' \rightarrow e^- e^+, \mu^- \mu^+$
2. Invisible: $A' \rightarrow \chi \bar{\chi}$
Dark Matter

- One possibility is a dark sector of SM singlets coupled to ordinary matter by gravity and possibly other very weak forces. An extra (broken) U(1)’ symmetry would imply a new massive boson $A’$ (Dark Photon)

**Decay Modes**

1. **Visible:** $A’ \rightarrow e^- e^+, \mu^- \mu^+$
2. **Invisible:** $A’ \rightarrow \chi \bar{\chi}$ NA64 focus

**Motivations**

1. if $M_{A’} \geq 2M_{DM}$ and $\alpha_{DM} \gg \epsilon^2 \alpha$ invisible decay is the most relevant
2. can explain $(g-2)_\mu$ hint$^2$

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Dark photon signal

Dark photon is produced through kinetic mixing of a Bremstrahlung-γ in the ECAL. The Dark photon would escape then the setup undetected through the invisible decay $A' \rightarrow \chi \bar{\chi}$

**Dark Photon signal:**
- Particle ID: 100 GeV electron
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Dark Photon signal:
- Particle ID: 100 GeV electron
- Missing energy in the ECAL ($E_{ECAL} \leq E_{thresh}$)
- no activity in VETO and HCAL
Dark Photon signal

Pre-shower  |  ECAL
---|---
\(e^-\)  |  \(\gamma\)  |  \(A'\)

Scattering with Nuclei  |  Kinetic mixing

Veto

\(\chi\)  |  \(\bar{\chi}\)

Missing momentum signature

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Standard model  |  With Dark photon

Events

\(E_{\text{HCAL}}\), GeV  |  \(E_{\text{ECAL}}\), GeV

100  |  90  |  80  |  70  |  60  |  50  |  40  |  30  |  20  |  10  |  0

100  |  90  |  80  |  70  |  60  |  50  |  40  |  30  |  20  |  10  |  0
The NA64 experiment

Timeline:
2014: Proposal
2015: First test beam
2016: Approval

Over 40 participants!
→ 6 from ETH

30 m

NA64 setup - Key features
The NA64 experiment

NA64 setup - Key features

Beam features:

- **High energy particle to trigger the reaction**: 100 GeV $e^-$ from CERN SPS
- **Main impurities of H4 beam**: $\pi^-$, low energy $e^-$ ($\sim$1%) $\mu^-$ and $K^-$ ($\leq$0.1%)
Electromagnetic calorimeter:

- **High hermeticity**: $6 \times 6$ ECAL PbSc sandwich matrix longitudinally segmented, $38 \times 38 \times 445 \text{ mm}^3$ ($\sim 40 X_0$) with WLS fiber inserted in spiral and $9\% (E[\text{GeV}])^{-1/2}$ energy resolution
NA64 setup - Key features

Hadronic calorimeter:

- **High hermeticity**: 4 HCAL FeSc sandwich $3 \times 3$ modules, $60 \times 60 \times 150$ cm$^3$ ($\sim 7 \lambda$ for each module) with WLS fiber and $60\% (E[GeV])^{-1/2}$ energy resolution
The NA64 experiment

ETH group contribution

NA64 setup - Key features

Magnetic spectrometer:

- **Measure momentum**: Tracking system made of 8 XY-multiplexed MicroMegas modules and 4 GEM detectors together with 2 MPBL magnet.

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**ETH group contribution**

**NA64 setup - Key features**

**Synchrotron radiation detector:**

- **Suppress hadronic background:**
  Synchrotron radiation tagging system (BGO scintillator) to reject $\mu^-, \pi^-$ and $K^-$ decay in flight \(^4\)

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\(^4\)E.Depero,P.Crivelli,D.Banerjee et al., High purity 100 GeV electron identification with synchrotron radiation, NIM A866, 196-201 (2017)
Main tasks of the PhD thesis

## Hardware
- Maintenance and upgrades of XY-multiplexed Micromegas modules
- Design of mechanical support for trackers
- Testing new solution for trackers: ⇒ **Pixel sensor** for vertex reconstruction will be tested in 2018 run in collaboration with Dr. Malte Backhaus

## Analysis
- **Background Rejection**: Synchrotron radiation and shower profile analysis
- Analysis of tracking and vertex reconstruction of XY-multiplexed Micromegas in high flux environments
- Analysis of data acquired in beam time

## Feasibility studies
- Visible mode \( A \rightarrow e^+ + e^- \) with short Tungsten calorimeter
- \( \mu^- Z \rightarrow \mu^- Z + E_{\text{miss}} \) with muon beam

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5 F.J. Munoz et al., NIM A845, 132 - 135 (2017)
Main tasks of the PhD thesis

Hardware

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Analysis

- **Background Rejection**: Synchrotron radiation and shower profile analysis ↔ focus of presentation
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Feasibility studies

- Visible mode $A \rightarrow e^+ + e^-$ with short Tungsten calorimeter
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5 F.J. Munoz et al., NIM A845, 132 - 135 (2017)
In NA64 hadrons and muons can leave a fake signal by decay or neutral punchthrough.

**Example of background**: Decay of Kaon $K^- \rightarrow \pi^0 + e^- + \bar{\nu}_e$ signature lies in the signal region.
Synchrotron radiation and shower profile analysis for background rejection
The radiated power per meter:

\[ P = \frac{e^2 c}{6\pi \epsilon_0 (mc^2)^4} \frac{E^4}{R^2} \]

(1)

Properties

- \( P \sim E^4 \) ⇒ performs best for high \( e^- \) momentum
- \( P \sim m^{-4} \) ⇒ high separation between \( e^- \) and other charged particles
Synchrotron radiation

Simulation

30 MeV peak

High energy ionization

Frequency [a.u.]

Energy deposited [MeV]
Synchrotron radiation

Rejection of high energy ionization achieved by exploiting spatial distribution of synchrotron radiation

Bending magnet

Primary beam axis

ECAL+HCAL

30 MeV peak

High energy ionization

Simulation

Energy deposited [MeV]

Frequency [a.u.]
efficiency of 95% with suppression of $10^{-5}$ achieved with BGO crystals\textsuperscript{7}

\textsuperscript{7}E.Depero,P.Crivelli,D.Banerjee et al., NIM A866, 196-201 (2017)
Shower profile analysis

- Distinguish electrons from hadron through signature in the ECAL
- Improve suppression factor for hadrons by $\sim 10^3$
- Simple three steps algorithm structure

![Gamma shower](image1.png) ![Hadronic shower](image2.png)
Shower profile analysis

- Distinguish electrons from hadron through signature in the ECAL
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- Simple three steps algorithm structure

[Diagram showing ECAL for gamma shower and hadronic shower]
Shower profile analysis algorithm

- Extrapolate particle arrival point \((X_{ECAL}, Y_{ECAL})\) in the electromagnetic calorimeter

![Segmented electromagnetic calorimeter with Micromegas trackers](image-url)
Shower profile analysis

Shower profile analysis algorithm

- Extrapolate particle arrival point \((X_{ECAL}, Y_{ECAL})\) in the electromagnetic calorimeter
- Compute predicted energy deposition in each cell as function of \((X_{ECAL}, Y_{ECAL})\)

Cells layout:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>2,4</td>
<td>3,4</td>
<td>4,4</td>
</tr>
</tbody>
</table>

Emilio Depero (IPA – ETHZ)
Shower profile analysis

Shower profile analysis algorithm

- Extrapolate particle arrival point \((X_{ECAL}, Y_{ECAL})\) in the electromagnetic calorimeter
- Compute predicted energy deposition in each cell as function of \((X_{ECAL}, Y_{ECAL})\)
- Compute compatibility with measured shower

\[
\Rightarrow \text{Check compatibility using a } \chi^2\text{-test:}
\]

\[
\chi^2 = \sum_{i}^{N} \left( \frac{E_{pred}^{i}(X_{ECAL}, Y_{ECAL}) - E_{mes}^{i}}{\sigma_{pred}^{i}(X_{ECAL}, Y_{ECAL})} \right)^2
\]  

\[\text{(2)}\]
- $4.3 \times 10^{10}$ electrons on target collected and analyzed in 2016\textsuperscript{8}
- Muon (g-2) anomaly nearly completely covered in 2016, now completely excluded by Babar
- New setup is being tested! $5.4 \times 10^{10}$ EOT in the visible mode $A' \rightarrow e^+ + e^-$ analyzed and soon to be published

\textsuperscript{8}NA64 collaboration, Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS, Phys. Rev. Lett. 118,011802(2017)

\textsuperscript{8}NA64 collaboration, Search for vector mediator of Dark Matter production in invisible decay mode, arXiv:1710.00971 (2017)
Outlook

- Collected data in 2017 ($\sim 1 \times 10^{11}$) currently under analysis
- New run in May 2018 before LS2. $\sim 10^{11}$ EOT will be collected to be cover parameter space justified by relic densities of dark matter\(^9\)
- Expand sensitivity of visible mode $A' \rightarrow e^+ + e^-$ in the parameter space of X-boson\(^10\) in 2018 using pixel sensor and improved setup
- One week of charge exchange measurements to estimate invisible branching ratio of $K_L, K_S, \pi^0, \eta$
- Many possibility to investigate for future experiments after LS2

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Many more possibilities for **NA64**!

<table>
<thead>
<tr>
<th>Process</th>
<th>New Physics</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+Z \rightarrow e^+Z + E_{\text{miss}}$</td>
<td>Dark photons, Hidden sectors, $(g-2)_\mu$ new particles, milli-q</td>
<td>$10^{-4} &lt; \epsilon &lt; 10^{-5}$, $M_{A'} \sim \text{sub-GeV}$, $e' &lt; 10^{-5}$-10^{-7}$</td>
</tr>
<tr>
<td>$\mu^+Z \rightarrow \mu^+Z + E_{\text{miss}}$</td>
<td>$(g-2)<em>\mu$, gauged $L</em>\mu-L_\tau$, L-phobic boson $Z_\mu$, LFV</td>
<td>$\alpha_\mu &lt; 10^{-11}$-10^{-9}$, $&lt; 10^{-9}$-10^{-8}/\mu$</td>
</tr>
<tr>
<td>$\pi(K)p \rightarrow M^0n \rightarrow E_{\text{miss}}$</td>
<td>Bell-Steinberger Unitarity, CP, CPT, NHL, 2HDM</td>
<td>$\sim 10^{-5}$, $Br &lt; 10^{-8}$, $&lt; 10^{-8}$-10^{-7}$</td>
</tr>
<tr>
<td>$pA \rightarrow X + E_{\text{miss}}$</td>
<td>leptophobic X +h</td>
<td>$\sim \text{GeV DM}$, $&lt; 10^{-7}$-10^{-8}/p$</td>
</tr>
</tbody>
</table>

1. **On detection of narrow angle $e^+e^-$ pairs from dark photon decays**
   - A.V. Dermenev, S.V. Donskov, S.N. Gninenko et al

2. **The K_L invisible decays as a probe of new physics**
   - S.N. Gninenko and N.V. Krasnikov

3. **Search for invisible decays of $\pi^0$, $\eta$, $\eta'$, K_S and K_L: A probe of new physics and test using the Bell-Steinberger relation**
   - S.N. Gninenko
   - Phys. Rev. D91 (2015) 015004;

4. **Muon g-2 and searches for a new leptophobic sub-GeV dark boson in a missing-energy experiment at CERN**
   - S.N. Gninenko, N.V. Krasnikov, V.A. Matveev
   - Phys. Rev. D91 (2015) 095015;