Light Dark Matter searches at accelerators

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Light DM searches at accelerators - missing energy/momentum
Can we “skip” the detection part?
Specific beam structure: particles impinging “one at a time” on the active target.

Deposited energy $E_{\text{dep}}$ measured event-by-event.

Signal: events with large $E_{\text{miss}} = E_B - E_{\text{dep}}$.

Backgrounds: events with $\nu$ / long-lived (Kl) / highly penetrating (µ) escaping the detector, beam contaminants.

Signal scaling: $\propto \varepsilon^2$
The NA64-e experiment

Missing energy experiment at CERN SPS, H4 line (CERN North Area)
NA64-e at SPS - H4 line
The H4 beam-line at Cern SPS

- $e^-$ produced starting from the 400 GeV SPS proton beam, impinging on the beryllium T2 target
- Intensity on T2 target: $2 - 3 \times 10^{12}$ protons per 4.8 s spill
- Photons from T2 selected via XTAX absorber
- $e^-$ obtained from photons converting on a downstream Pb target
- Hadron contaminants arise from neutrals produced in the T2, and decaying after the sweeping magnets

Hadron contamination at 100 GeV $e^-$ mode: ~ 0.3%
The NA64-e Detector- Upstream Trackers
MicroMegas Detector

- 6× main MM stations along the line
- 5 mm drift gap, 128 μm amplification gap; Ar-CO2 gas admixture
- Drift: 720 V/cm; amplification 43 kV/cm
Tagging $e^-$ with SRD detector

- Reject hadron with synchrotron radiation detector (SRD)
- Three modules: plastic scintillator + Pb layers, PMT readout
- Pion rejection inefficiency at 100 GeV: $10^{-4}$ - $10^{-5}$

Larmor’s formula:

$$P_\gamma = \frac{q^2}{6\pi\varepsilon_0 c^3} \frac{\alpha^2 \gamma^4}{\beta^4} = \frac{q^2 c}{6\pi\varepsilon_0} \frac{\beta^4 \gamma^4}{\rho^2}$$

Deflected beam position

~ 30 cm
The SRD detector
The NA64-e Detector - The Active Target
The Electromagnetic Calorimeter (ECal)

- EM-Calorimeter: 40 $X_0$, Pb/Sc Shashlik, PMT readout
- Readout WLS fibers go in a spiral to avoid E-leak and dead zones
- Hermeticity scan: no potential source of background is found

\[
\sigma_E/E \sim 0.1/\sqrt{E}
\]
The NA64-e Detector - Downstream
The muon VETO

- Active veto for muon and other penetrating particles produced in the ECcal
- $3 \times 51 \times 17 \times 45 \text{ mm}^3$ scintillator plates
- PMT readout
Hadronic Calorimeter (HCal)

- 4× 1-m long sandwich modules ~ 30 nuclear interaction length
- Optical fibers + PMT readout
- Pion punchthrough probability: $10^{-3}$ per module
NA64 analysis flow

- Selection cuts:
  - Clean impinging 100 GeV/c e-
  - no activity in VETO/HCAL, including HCAL4
  - EM shower-shape compatible with e- induced one (data-driven shower shape $\chi^2$ distribution)

- Signal window: E < 47-50 GeV, EHCAL < 1 GeV
- Expected background yield: ~ 0.5 events

<table>
<thead>
<tr>
<th>Background source</th>
<th>Background, $n_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Di-muons losses or decays in the target</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>2. $\mu, \pi, K \rightarrow e+...$ decays in the beam line</td>
<td>0.3 ± 0.05</td>
</tr>
<tr>
<td>3. lost neutrals ($\gamma, n, K^0$) from upstream interactions</td>
<td>0.16 ± 0.12</td>
</tr>
<tr>
<td>4. Punch-through leading $n, K^0_L$</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Total (conservatively) $n_b$</td>
<td>0.51 ± 0.13</td>
</tr>
</tbody>
</table>
Di-muon events analysis

Rare QED process $\sim 10^{-5}$/EOT:
- similar to the $A'$ production
- cross check of $A'$ yield, systematic errors
- background prediction from data
- cross check of overall efficiency

![Di-muon event data vs MC comparison](image)
NA64-e reach

- Current results based on $10^{12}$ EOT
- For $\alpha D = 0.1$, NA64-e excludes the Scalar and Majorana scenarios in a large $m_\chi$ interval.
NA64-e search for X17

\[ \tau_{X17} \sim 10^{13} \text{ s} \]

- Modified setup for X17 visible decay search
- X17 decay mostly outside WCAL
- Signature: two separated showers
- from a single e-
NA64-e search for X17

$8.4 \times 10^{10}$ EOT collected in visible mode: ruled out part of the available X17 parameter space
NA64-e upgrades for the X17 search

- The sensitivity to the X17 in the NA64 visible mode is limited by the WCAL length ($\gamma c \tau_{X17} \sim 30$ mm) and the capability to separate the very close tracks of the $X17 \rightarrow e^+e^- \rightarrow \text{new setup under consideration}$
- New WCAL geometry for improved signal efficiency
- Dipole magnet + ~ 18 m vacuum pipe for tracks separation
- GEM trackers + ECAL for invariant mass measurement (10% invariant mass resolution)
- Possible to probe significant part of the X17 parameter space in a ~ 20 days run
NA64-μ exploring the $L_\mu - L_\tau$ scenario

- LDM Model variation: $Z'$ as a portal to DM sector
- $Z'$: light boson coupled to the second generation leptons ($\mu, \tau$) in the $L_\mu - L_\tau$ scenario
- Possible low mass explanation of the (g-2)$_\mu$ (the muon anomaly)
- NA64-μ: Missing momentum search for $Z'$ using the 160-GeV muon beam by the M2 line at Cern
NA64-$\mu$

Signal Signature:

- in: clean 160 GeV $\mu$- track
- out: $< \sim 80$ GeV $\mu$- track
- no energy in the ECAL, Veto, HCAL
NA64-\(\mu\) analysis cut-flow

Cut-flow:
1. HCAL modules in-time
2. Single-hit per tracker
3. Reconstructed momenta range
4. Quality cut on downstream momenta
5. Energy compatible with MIP energy in calorimeters and veto
NA64-$\mu$ limits

- Total statistic of $(1.98 \pm 0.02) \times 10^{10}$ muons on target
- No events observed
- Almost completely excluded the explanation of the (g-2)$\mu$ in this particular model

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<td>(I) Momentum mis-reconstruction</td>
<td>$0.05 \pm 0.03$</td>
</tr>
<tr>
<td>(II) $K \rightarrow \mu + \nu$, ... in-flight decays</td>
<td>$0.010 \pm 0.001$</td>
</tr>
<tr>
<td>(III) Calorimeter non-hermeticity</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Total $n_b$ (conservatively)</td>
<td>$0.07 \pm 0.03$</td>
</tr>
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NA64-\(\mu\) projected reach in the \(A'\) scenario

- Optimal sensitivity for \(A'\) with mass \(>10\) MeV
- Complementary to NA64-e
The Light Dark Matter eXperiment (LDMX)
LDMX - Experimental approach

- 4 - 8 GeV electron beam on thin target
- measure momentum before and after the interaction in the target
- **signal signature:** low energy $e^-$ with detectable transverse missing momentum - NO other activity in the ECAL/HCAL

- Beam temporal structure allowing for one-by-one tagging of electrons
Beam Facility

Beam provided by SLAC:

- Planning on 4 GeV and 8 GeV runs
- low current, high repetition rate of 37 MHz

Signal Identification

- DM bremsstrahlung VS SM bremsstrahlung: different kinematics

[Graphs showing electron recoil energy distributions and electron transverse momentum distributions, with markers for different energy levels.]
LDMX Detector Concept

- Fast, low mass tagging and recoil trackers
- Fast, granular and radiation hard electromagnetic calorimeter enclosed by hermetic hadronic calorimeter.
- Trigger scintillator for counting incoming e-
Tracker

- **Tagger tracker**
  - 7 double-sided low mass silicon strip (~0.7 $X_0$)

- **Recoil tracker**
  - 6 low-mass layers
  - Efficient reconstruction of 50MeV - 1.2 GeV recoil $e^-$

- **Tungsten Target**
  - ~0.1 $X_0$ good compromise between rate and momentum resolution
  - Scintillator pads in the front/back

arXiv:1808.05219
Electromagnetic Calorimeter

- Si-W sampling calorimeter, with high granularity and shower containment (~40 $X_0$)
- ECal signal used in the trigger
LDMX - Reach

- Final goal $10^{16}$ EOT
- Capable to explore all the thermal targets
- Sensitivity to all targets even accounting for up to ~10 background events
Summary

❖ Vector mediated LDM is a well motivated model giving rise to a rich phenomenology at accelerator experiments
❖ Many radically different ideas proposed in the years
  ➢ Searches at colliders (prompt/detached vertices, electron/proton colliders)
  ➢ Fixed target experiments
    ■ Thin target: HPS, PADME...
    ■ Beam-dump: E137, BDX, SHiP...
  ➢ Missing energy/momentum: NA64, LDMX...
❖ The parameter space will be intensely explored in the next years.....stay tuned!
Thanks of the attention!!