Dark Sector searches with electron and positron beams at NA64@CERN

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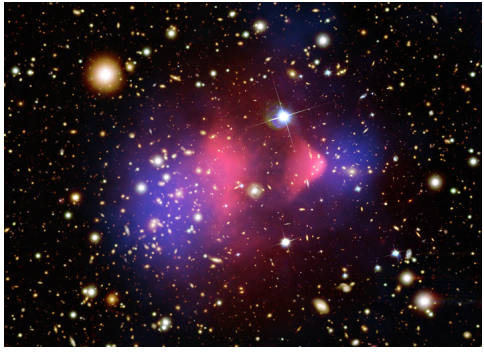
POsitron resonant annihilation into darK matter

Outline

The Dark Matter Puzzle

- Dark Matter (DM) makes up 85% of the mass of our Universe
- Focus: particle signature
- Thermal Light Dark Matter:
  - predicts a new force between DM and SM. DM and SM are in equilibrium when $T \gg m_\chi$
  - freeze-out of DM density when the temperature of the Universe is $T \ll m_\chi$
  - solid prediction of DM-SM annihilation cross-section $\langle \sigma \times v \rangle$ vs the DM relic abundance
  - m_χ in sub-GeV mass range much below the electroweak scale



X-Ray: NASA/CXC/CFA/M.Markevitch et al.
Lensing Map: NASA/STSCI; ESO WFI Magellan/U.Arizona/D.Clowe et al.
Optical: NASA/STSCI; Magellan/U.Arizona/D.Clowe et al.

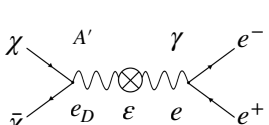
Dark Photon: the most motivated and popular model with a V mediator (massive photon)

Introduction of a new U(1) gauge-boson ("dark-photon", A'). This model includes 4 parameters:

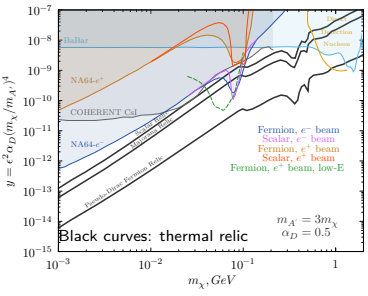
- $m_{A'}$ and m_χ
- Coupling constant α_D $(A' - \chi)$
- Kinetic mixing of A' with SM $\varepsilon << 1$

Introduction of the dimensionless parameter y:

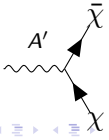
$$\alpha \equiv \frac{e^2}{4\pi} \qquad \alpha_D \equiv \frac{e_D^2}{4\pi}$$



$$\langle \sigma \times v \rangle \propto \frac{\varepsilon^2 \alpha_D m_\chi^2}{m^4 A'} = \frac{\varepsilon^2 \alpha_D m_\chi^4}{m_{A'}^4} \cdot \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$



If $m_{A'} > 2m_\chi$: invisible decay.
Convention: $m_{A'} = 3m_\chi$

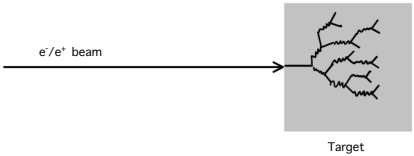


The "missing energy" technique

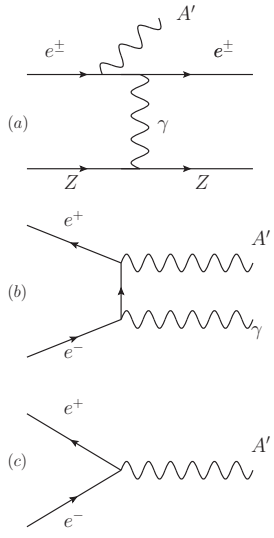
- We count each incoming beam particle
- The active target is the detector
- Beam particles hit the target one at a time to avoid pile-up
- LDM particles produced in the target following an electromagnetic shower
- Signal in the form of a missing energy, as:

$$E_{miss} = E_{beam} - E_{dep} \simeq \text{tens of GeV}$$

- Possible background sources:
  - Particles escaping the target
  - Beam hadronic contaminations



LDM production with lepton beams

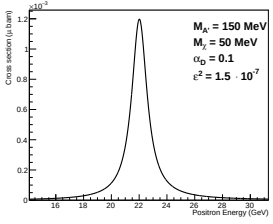


(a) A' - Strahlung

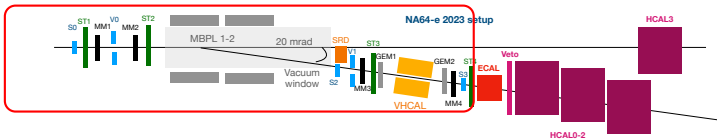
- Forward-peak A' emission
- $\sigma \propto \alpha_{EM}^3 Z^2$

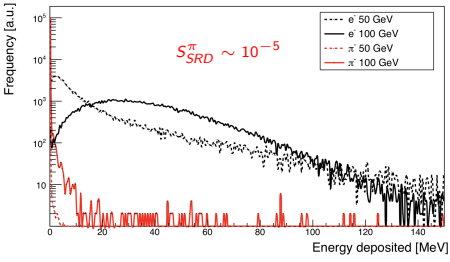
(c) Resonant annihilation

- Breit-Wigner like cross section with $m_{A'} = \sqrt{2 m_e E_{e^+}}$
- $\sigma \propto \alpha_{EM}^2 Z$



The NA64e$^-$ setup





- Located in the CERN's North Area (NA)
- Operates at line H4 of CERN SPS
- Uses a 100 GeV electron beam
- $R_{e^-} \simeq 1$ MHz
- To enhance electron/positron ID we tag each of them with an SRD signal (the SR is generated in the deflecting magnet MBPL)
- $\sigma_{E_{beam}}/E_{beam} = 1\%$
- $h/e^- = 0.5\%$

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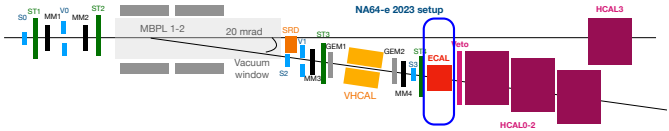

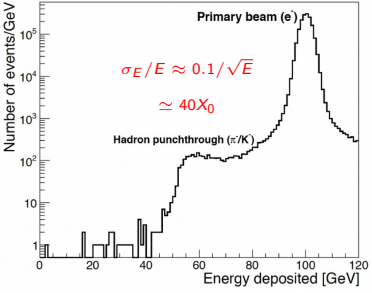

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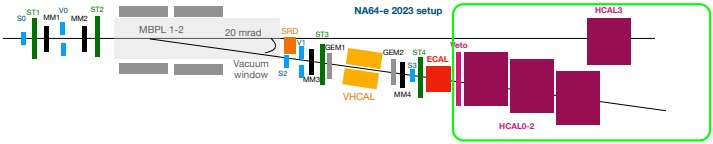

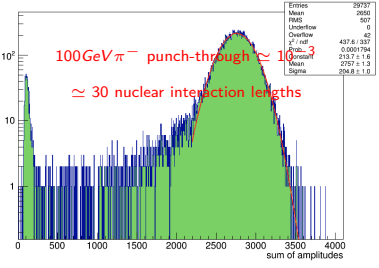

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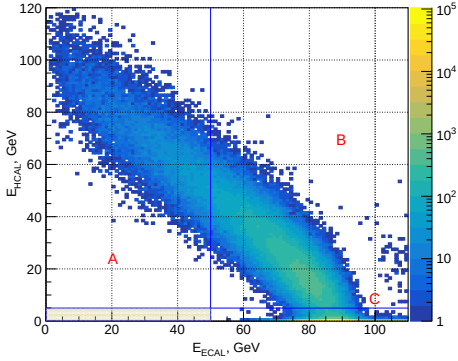
NA64e$^-$ results

- Analysis selection cuts: well-reconstructed 100 GeV/c impinging track in coincidence with SRD signal, no VETO activity
- NA64 looks the data in the form of an hermeticity plot, showing the energy deposited in the ECAL and in the HCAL
- So far, NA64 has accumulated a statistics of $9.37 \cdot 10^{11}$ e$^-$OT
- No events were observed in the Signal Window
- NA64 sets the most stringent limits in a wide mass range



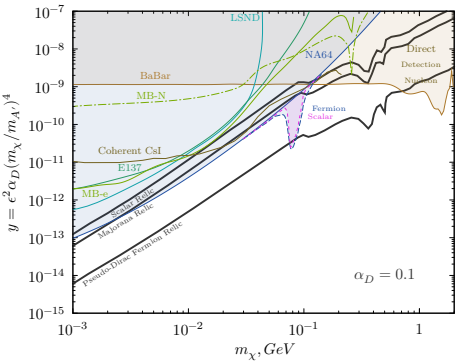
Yu. M. Andreev et al. (NA64 Collaboration)
Search for Light Dark Matter with NA64 at CERN.
Phys. Rev. Lett. 131, 161801 – Published 16 October 2023.

NA64e$^-$ results

Background source	Background [n_b]
dimuon losses or decays in the target	0.04 ± 0.01
μ, π, K decays in the beam line	0.3 ± 0.05
Upstream e^+/e^- interactions	0.16 ± 0.12
Punchthrough	< 0.01
Comprehensive background (conservative)	0.51 ± 0.13

Additional strategies for the background suppression:

- Installation of a massive Veto HCAL against large-angle hadronic secondaries from upstream interactions
- A new LYSO matrix-based Synchrotron Radiation Detector to reject μ, π, K decays
- Beam tests are currently ongoing for both the sub-detectors



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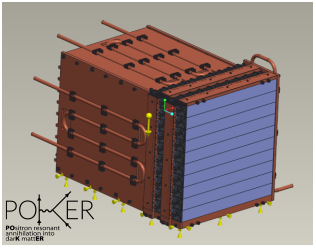
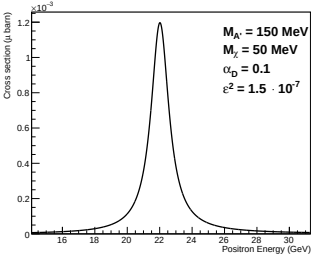
Dark sector searches with e^+ beams in NA64

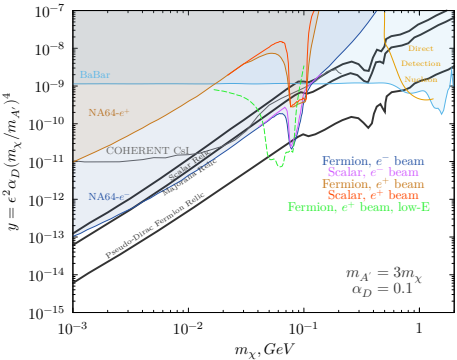
- To enhance the annihilation signature, the POKER project proposed the use positron beams, operating at low energies (60-40 GeV)
- To do so, it is necessary to use a novel electromagnetic calorimeter (PKR-Cal) with improved energy resolution.
- The PKR-Cal consists of a 9×9 22 cm long PWO crystals.
- The required energy resolution is: $\sigma_E/E \sim 2.5\%/\sqrt{E} \oplus 0.5\%$





The 100 GeV e^+ measurement

- A pilot run was acquired during Summer 2022 with the NA64 Pb-Sc calorimeter with a 100 GeV positron beam
- A statistics of $1.017 \cdot 10^{10}$ e^+OT was accumulated.
- The results look very promising!



Yu. M. Andreev et al. (NA64 Collaboration)
Probing light dark matter with positron beams at NA64.
Phys. Rev. D 109, L031103 – Published 23 February 2024.

Wrapping up and conclusions

- NA64 is a world-leading LDM search experiment operating at line H4 of CERN SPS
- In this context, the missing energy technique is exploited, using 100 GeV e^- beams
- NA64 sets the most stringent limits on the $m_\chi = 10^{-3} - 10^{-1}$ GeV parameters space
- POKER is an ERC-funded project aiming at the LDM detection using lower-energies e^+ beams, enhancing the resonant annihilation LDM production
- To validate the technique, during Summer 2022 we performed a 100 GeV e^+ measurement
- During Summer 2023 we performed a 70 GeV e^+ beam measurement, acquiring a statistics of $1.596 \cdot 10^{10}$ e^+OT
- The analysis of this measurement is finalized, the results will be published soon