POKER
POsitron resonant annihilation into darK matter

INFN
Istituto Nazionale di Fisica Nucleare

The NA64 experiment at CERN

Anna Marini, on behalf of the NA64 collaboration

INFN-Genova

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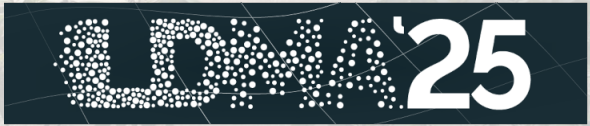
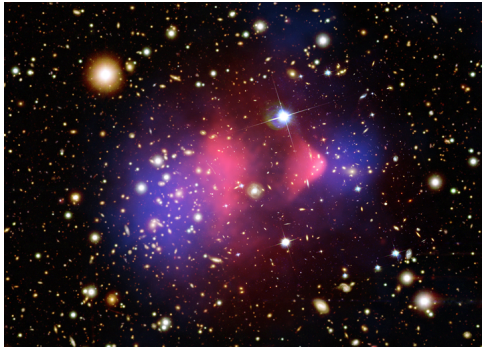
erc
European Research Council
Established by the European Commission



Outline

The Dark Matter Puzzle

- Dark Matter (DM) makes up 85% of the mass of our Universe
- Hypothesis: DM is made of particles
- 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



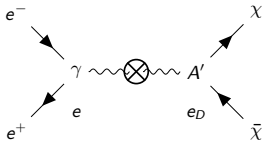
X-Ray: NASA/CXC/CFA/M.Markevitch et al.
Lensing Map: NASA/STSCI; ESO WFI Magellan/U.Arizona/D.Clowe et al.
Optical: NASA/STSCI; Magellan/U.Arizona/D.Clowe et al.

Dark Photon: a well 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 $\varepsilon << 1$

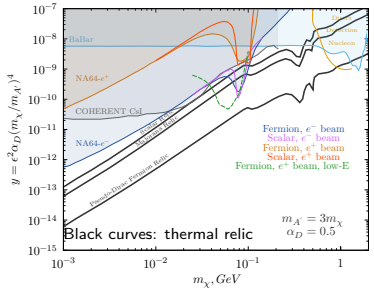
Introduction of the dimensionless parameter y:



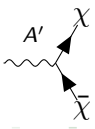
$\alpha \equiv \frac{e^2}{4\pi}$

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

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



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



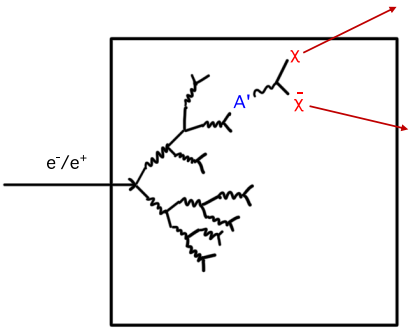
The "missing energy" technique

- We count each incoming beam particle
- The active target is a calorimeter
- Beam particles hit the target one at a time to avoid pile-up
- LDM particles produced in the target by the incoming particle or a secondary one in the EM shower
- Signal in the form of a missing energy, as:

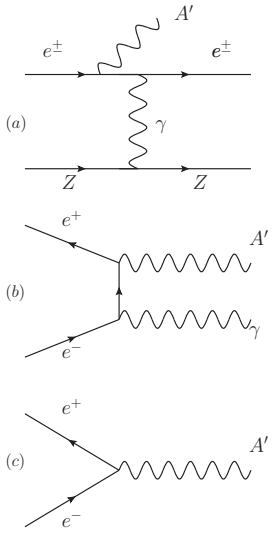
$$E_{miss} = E_{beam} - E_{dep} \simeq \text{tens of GeV}$$

E_{miss} is carried away by LDM particles

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



LDM production with lepton beams

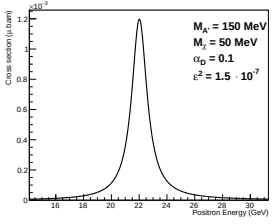


(a) A' - Strahlung

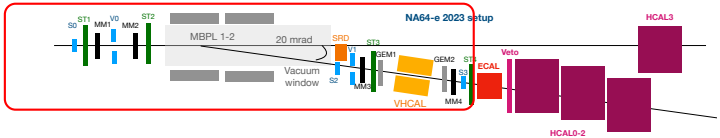
- Forward-peak A' emission
- $\sigma \propto \alpha_{EM}^3 Z^2$

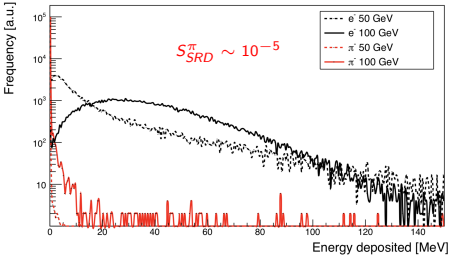
(c) Resonant annihilation

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



The NA64e$^-$ setup





NA64 experiment @CERN SPS:

- Operates at H4 beamline with a 100 GeV/c electron beam with $\sigma_{E_{beam}}/E_{beam} = 1\%$ spread
- $R_{e^-} \sim 5$ MHz
- Beam contamination $h/e^- = 0.5\%$

The NA64 detector:

- SRD to enhance electron/positron ID (the SR is generated in the deflecting magnet MBPL)
- The core is a Pb-Sc Shashlik-type ECAL
- The latter part is a large Fe-Sc HCAL to tag hadronic secondaries

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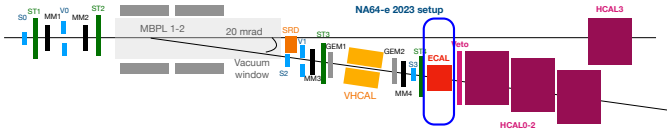

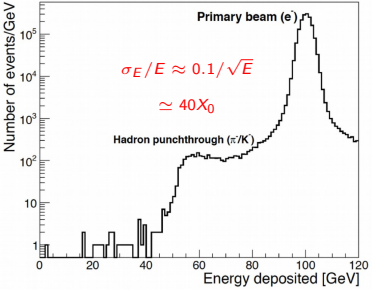

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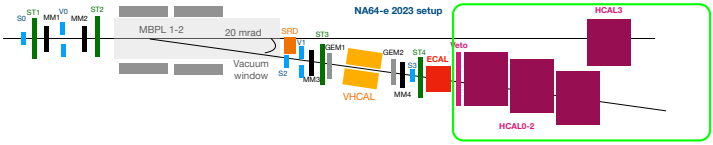

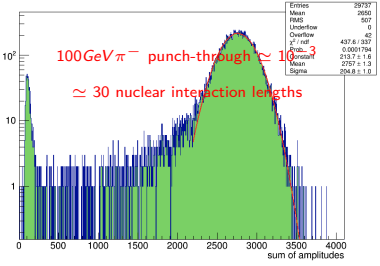

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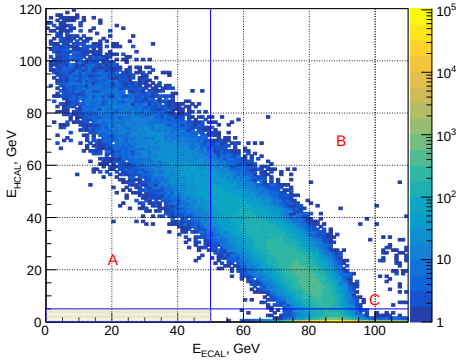
NA64e$^-$ results

- 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.

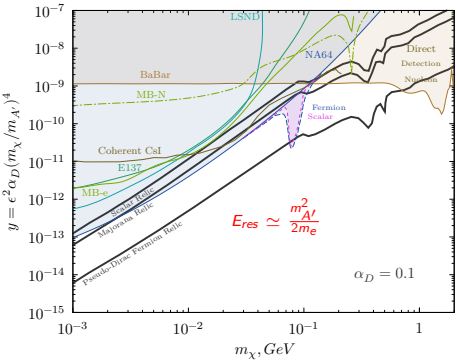
Background source	Background [n_b]
dimuon losses or decays in the target	0.04 ± 0.01
μ, π, K decays in the beam line	0.3 ± 0.05
Upstream e$^+$/e$^-$ interactions	0.16 ± 0.12
Punchthrough	< 0.01
Comprehensive background (conservative)	0.51 ± 0.13

NA64e$^-$ results

Additional strategies for the background suppression and sensitivity increase:

- Improvement of the setup hermeticity: installation of a massive Veto HCAL against large-angle hadronic secondaries from upstream interactions
- Better beam particle ID: a new LYSO matrix-based Synchrotron Radiation Detector to reject μ, π, K decays
- Increase of statistics by running at higher intensity: replacement of the readout electronic with a faster one

Beam tests are currently ongoing for all these upgrades.



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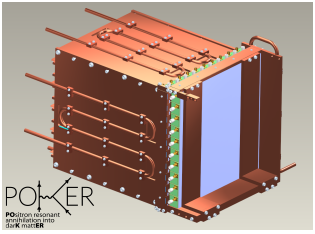
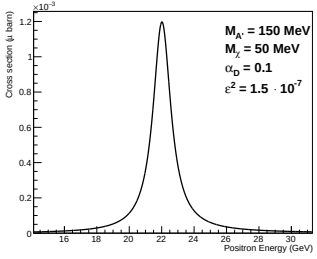
Dark sector searches with e^+ beams in NA64

- To enhance the annihilation signature, the POKER project proposed the use positron beams, operating at low energies (70-40 GeV)
- First pilot runs with 100 and 70 GeV/c with the current NA64 detector have already been finalized: Phys. Rev. D 109, L031103 and arXiv:2502.04053
- To exploit lower energies, 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: $\sigma_E/E \sim 2.5\%/\sqrt{E} \oplus 0.5\%$

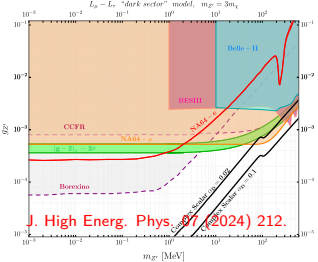
See Dr. Marsicano and Dr. Bisio talks!



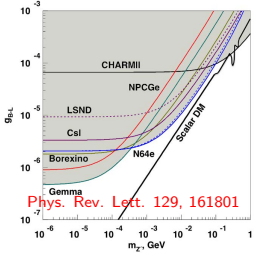


Other Beyond Standard Model searches

The collected data have been re-analyzed to explore other Beyond Standard Model scenarios:



J. High Energ. Phys. 07 (2024) 212.



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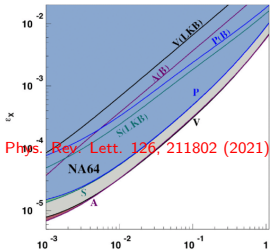
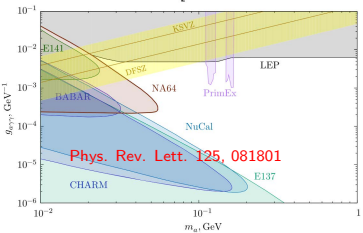


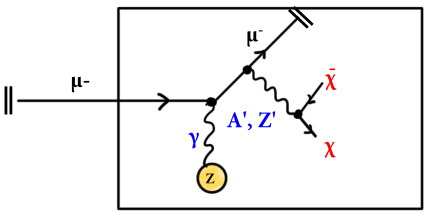
Phys. Rev. Lett. 126, 211802 (2021)



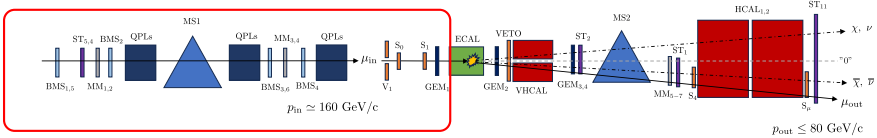
Phys. Rev. Lett. 125, 081801

The NA64μ program

- Complementary program to NA64e
- Search for higher mass Dark Photons
- The goal is to search for muon-philic dark sector particles, which could also explain the muon (g-2)$_\mu$ anomaly, such as a new light vector $L_\mu - L_\tau$ Z′ boson
- 160 GeV/c muon beam at CERN SPS M2
- In this context, the missing-momentum technique is exploited

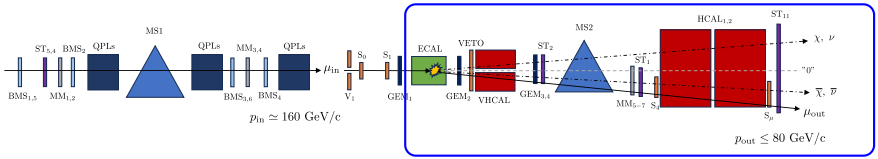


The NA64μ setup



- The incoming muon momentum is reconstructed through a magnetic spectrometer (MS1) consisting of:
  - three $5\,\mathrm{T}\cdot\mathrm{m}$ bending magnets,
  - four $8 \times 8\,\mathrm{cm}^2$ micromesh gas detectors (micromegas, MM1–4),
  - two $20 \times 20\,\mathrm{cm}^2$ straw tube chambers (ST5;4),
  - six variable-sized scintillator hodoscopes,
  - the beam momentum stations (BMS1–6).
- The obtained momentum resolution is $\sigma_{p_{in}}/p_{in} \simeq 3.8\%$.

The NA64μ setup



- The target (ECAL) is followed by:
  - a large $55 \times 55\,\mathrm{cm}^2$ high-efficiency veto counter (VETO),
  - a $5\lambda_{\mathrm{int}}$ copper-scintillator hadronic calorimeter (VHCAL) with a hole in its middle.
- The outgoing muon momentum is reconstructed through a second magnetic spectrometer (MS2).
- The achieved momentum resolution is $\sigma_{p_{\mathrm{out}}}/p_{\mathrm{out}} \simeq 4.4\%$.
- To identify and remove any residuals from interactions upstream of MS2 and ensure maximal hermeticity, two large $120 \times 60\,\mathrm{cm}^2$, $\lambda_{\mathrm{int}} \simeq 15$ HCAL modules (HCAL1;2) are placed at the end of the setup, together with a $120 \times 60\,\mathrm{cm}^2$ straw tube chamber (ST11).

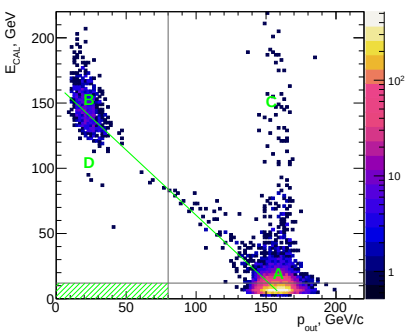
NA64μ results

To minimize the background, the following set of selection criteria is used:

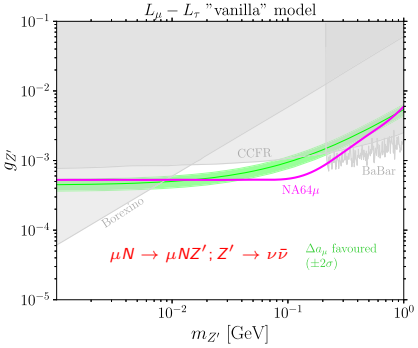
- We require a single incoming muon passing the whole setup (MS1 and MS2) with initial momentum in the range 160 ± 20 GeV/c.
- At most one hit is reconstructed in MM5–7 and ST1 (no multiple hits)
- The corresponding extrapolated track to the HCAL face is compatible with a MIP energy deposit in the expected cell (suppression of upstream interactions).
- The energy deposit in the calorimeters and the veto should be compatible with a MIP.

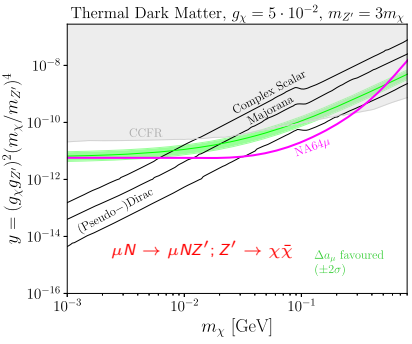
We accumulated a statistics of $(1.98 \pm 0.02) \times 10^{10}$ MOT. After unblinding, no events were found in the signal region

Background source	**Background [n_b]**
Momentum misreconstruction	0.05 ± 0.03
$K \to \mu + \nu + \cdots$ in-flight decays	0.010 ± 0.001
Calorimeter non-hermeticity	<0.01
Comprehensive background (conservative)	0.07 ± 0.03



NA64μ results

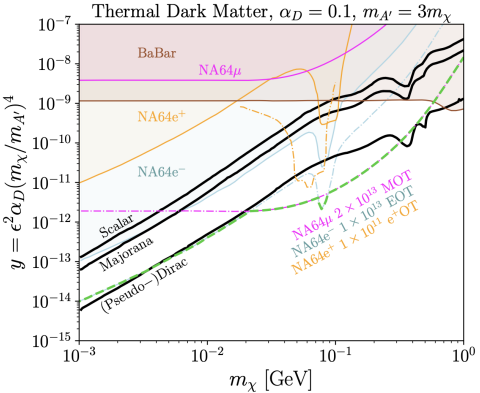




- See: Phys. Rev. Lett. 132, 211803
- See: Phys. Rev. D 110, 112015

Future prospects

- NA64e plans to reach a statistics of $\sim 10^{13}$ EOT by the end of CERN Run4, to further improve its limits on Dark Photon searches, Z′ and ALPs
- In addition, we plan to accumulate a $\sim 1.3 \times 10^{12}$ statistics with (40-70) GeV/c positron beams
- NA64μ aims to reach a statistics of $\sim 2 \times 10^{13}$ MOT bu the end of CERN Run4, to further explore the parameter space for heavier Dark Photons, ALPs, Z′...



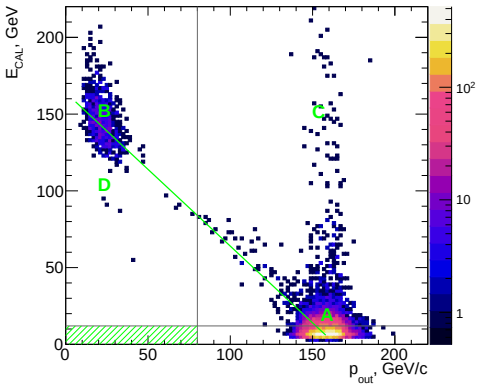
Wrapping up and conclusions

NA64 is a world-leading Dark-Sector search experiment operating at CERN SPS with the primary goal of either discovering LDM, or disproving its most motivated models.

- NA64e exploits the missing energy technique, using 100 GeV e^- beams
- NA64e sets the most stringent limits on the A' search with $m_\chi = 10^{-3} - 10^{-1}$ GeV parameters space with a total statistics of 0.937×10^{12} EOT.
- This accumulated statistics have been re-analyzed to explore other BSM scenarios, such as L$\mu-$ Lτ,B-L and ALPs

- NA64μ exploits the missing momentum technique, using 160 GeV μ^- beams
- NA64μ observed no event falling within the signal region with $(1.98 \pm 0.02) \times 10^{10}$ MOT, allowing to set 90% C.L. upper limits in the $(m_{Z'}, Z')$ parameter space of the L$\mu-$ Lτ vanilla model.
- New constraints on light thermal DM for values $y \gtrsim 6 \times 10^{12}$ for $m_\chi \gtrsim 40$ MeV are also obtained.

Hermeticity plot - NA64μ



- Region A: MIP-compatible events: muons traversing the full setup with little to no deflection in MS2.
- Region B: Hard scattering or bremsstrahlung events (final state has low-momentum muons)
- Region A to C: Quasi-total muon energy deposition in HCAL due to muon nuclear interactions in the HCAL modules.
- Region D: Muon nuclear interactions in ECAL. These events deviate from the expected energy-momentum conservation diagonal and leak into the signal region.