



# The NA64-e experiment at CERN: status and perspectives

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# Outline

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- 1 The physics case
- 2 The NA64-e experiment
- 3 NA64-e Run3 results
- 4 Looking forward & conclusions



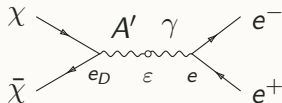
## Dark Photon model

LDM:  $m_\chi$  naturally lies in the sub-GeV mass range. The Freeze out scenario leads to the introduction of a new interaction between LDM and SM, the dark photon  $A'$  a new U(1) **massive vector gauge boson**, which is one of the most motivated LDM mediators.

- ▶ masses  $m_{A'}$  and  $m_\chi$ ;
- ▶ dark-sector coupling  $\alpha_D$ ;
- ▶ kinetic mixing with the SM photon,  $\varepsilon \ll 1$ .

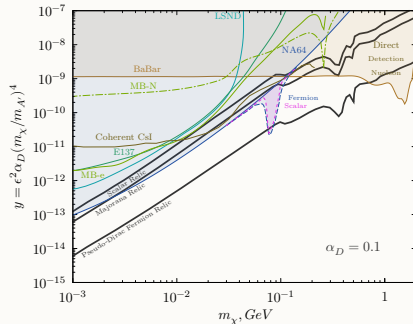
Introducing the thermal target parameter

$$y \equiv \varepsilon^2 \alpha_D \left( \frac{m_\chi}{m_{A'}} \right)^4$$



$$\alpha = \frac{e^2}{4\pi}, \quad \alpha_D = \frac{e_D^2}{4\pi}$$

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



Black curves: thermal relic targets.

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

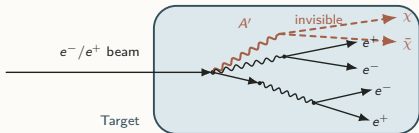
# Missing energy and LDM production

## Principle

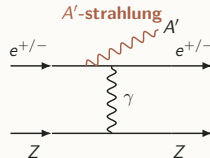
- ▶ Each incoming beam particle is tagged individually.
- ▶ The active ECAL target is the detector itself.
- ▶ The beam intensity is kept sufficiently low to ensure negligible pile-up.
- ▶ LDM particles are produced in the target in the electromagnetic reactions ( $A'$ -strahlung in  $e$ -Z scattering, or of  $e^+e^- \rightarrow \text{annih.}$ )
- ▶ The signal is a large missing energy:

$$E_{\text{miss}} = E_{\text{beam}} - E_{\text{dep}} \simeq \mathcal{O}(10 \text{ GeV}).$$

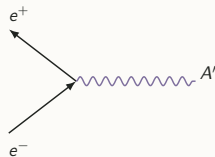
- ▶ Main background for  $e^-$  at 100 GeV search: Escaping secondary neutrals from hadron electro-production on beam materials



## Dark Photon production



### Resonant annihilation

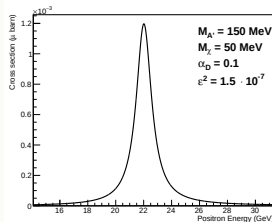


### A'-strahlung

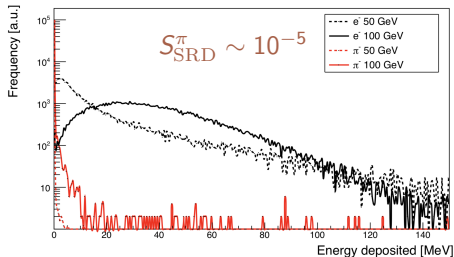
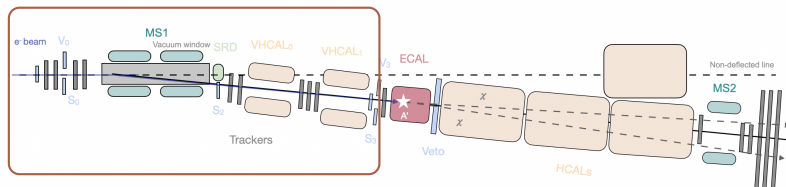
- ▶ Forward-peaked  $A'$  emission.
- ▶  $\sigma \propto \alpha_{\text{EM}}^3 Z^2$ .

### Resonant annihilation

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

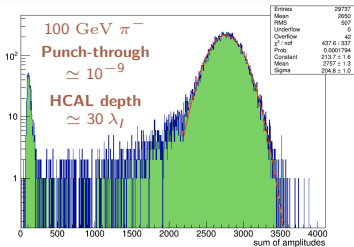
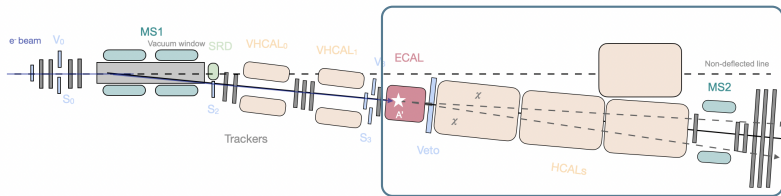
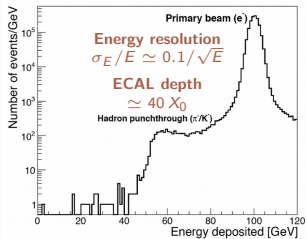


# The NA64-e<sup>-</sup> setup



- ▶ Located in CERN's North Area.
- ▶ Operates at line H4 of CERN SPS.
- ▶ Uses a 100 GeV electron beam.
- ▶  $R_{e^-} \simeq 1$  MHz.
- ▶ Electron/positron ID through the SRD signal.
- ▶  $\sigma_{E_{\text{beam}}}/E_{\text{beam}} = 1\%$ .
- ▶  $h/e^- = 0.5\%$ .
- ▶ Reducing beam material + increasing VHCAL+HCAL acceptance is a solution to the background problem for e<sup>-</sup> search at 100 GeV
- ▶ Beam hadronic contamination could be suppressed by a new SRD

# The NA64-e<sup>-</sup> setup

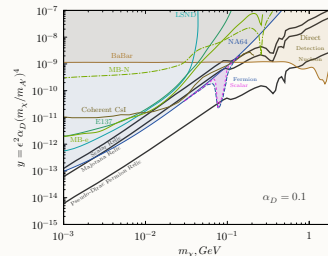
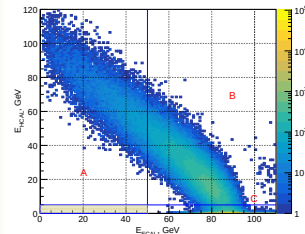


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## NA64-e latest results

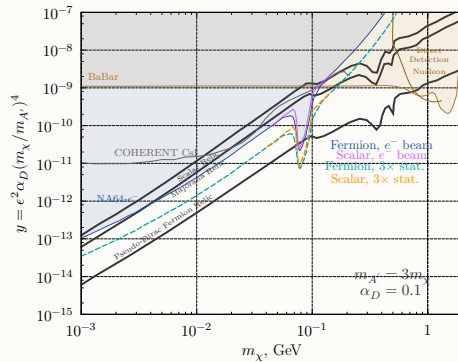
- Analysis selection cuts: well-reconstructed 100 GeV/c impinging track in coincidence with SRD signal, no VETO activity
- NA64 is looking for signal events in the hermeticity plot, showing the energy deposited in the HCAL vs ECAL energy SM events occupy plot diagonal due to the energy conservation, while signal is an event with missing energy in the HCAL and energy deposit only in ECAL  $< 50$ -60 GeV.
- So far, NA64 has accumulated a statistics of  $9.37 \times 10^{11} \text{ e}^- \text{OT}$
- No events were observed in the Signal Window
- NA64 sets the most stringent limits in a wide mass range
- Results are published in: [Phys. Rev. Lett. 131, 161801 \(2023\)](#)

| Background source                              | Background [ $n_b$ ] |
|------------------------------------------------|----------------------|
| dimuon losses or decays in the target          | $0.04 \pm 0.01$      |
| $\mu$ , $\pi$ , K decays in the beam line      | $0.3 \pm 0.05$       |
| Upstream $\text{e}^+/\text{e}^-$ interactions  | $0.16 \pm 0.12$      |
| Punchthrough                                   | $< 0.01$             |
| <b>Comprehensive background (conservative)</b> | $0.51 \pm 0.13$      |

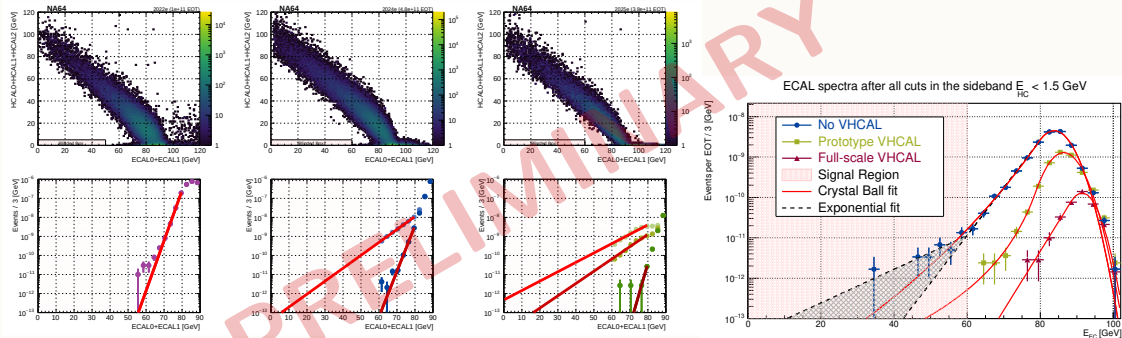


## NA64-e<sup>-</sup> achievements during Run3

- ▶ NA64-e has completed the pre-LS3 program, acquiring a statistic of  $3 \times 10^{12}$  eOT
- ▶ During Run 3 (2024-2026), the detector was upgraded to improve background rejection and increase signal efficiency:
  - The installation of a new LYSO-based synchrotron radiation detector
  - The installation of an additional veto-hadronic calorimeter (VHCAL) to tag secondary particles induced by upstream interactions



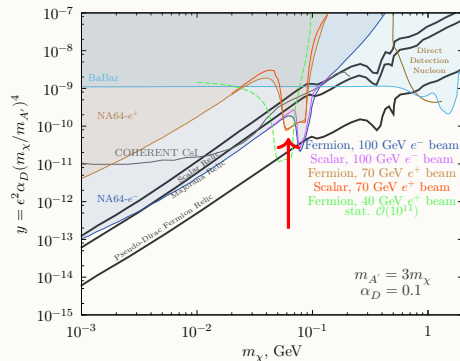
## NA64-e upgrades



The introduction of the VHCAI detector (one module in 2024 and two modules in 2025–2026) extended the geometric acceptance of the experiment and significantly reduced the background arising from beam interactions with upstream elements of the beamline.

## NA64- $e^+$ results

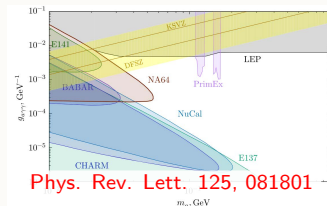
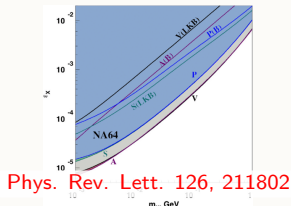
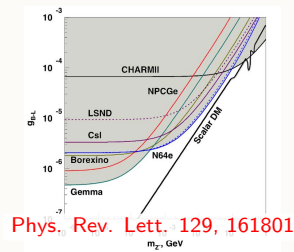
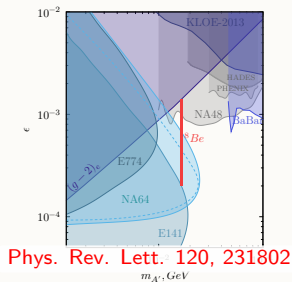
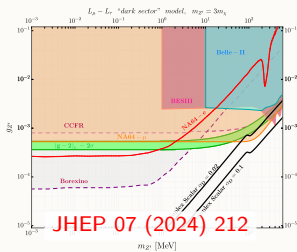
- ▶ To enhance the annihilation signature, the POKER project proposed the use positron beams, operating at low energies (60-40 GeV)
- ▶ A pilot run was acquired during Summer 2022 with a 100 GeV positron beam, acquiring a statistics of  $1.017 \times 10^{10} e^+OT$  was accumulated ([Phys. Rev. D 109, L031103](#)).
- ▶ In 2023 we acquired  $1.596 \times 10^{10} e^+OT$  using 70 GeV positrons ([J. High Energy Phys. 2025, 256 \(2025\)](#)).





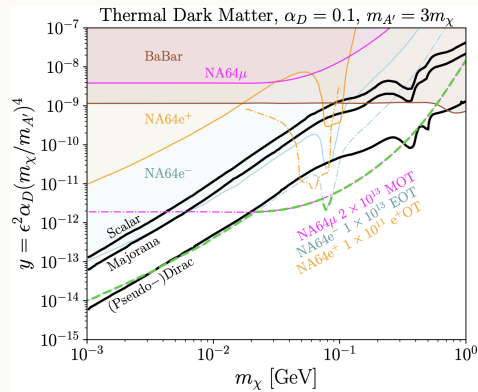
# NA64 potential for other physics cases

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



## Next Steps

- ▶ Finalize the 2024-2025-2026 data analysis and publish the results
- ▶ Work on detector updates for Run4 (DAQ, tracking, etc.)
- ▶ During Run4 we plan to reach a comprehensive statistic of  $10^{13}$  eOT
- ▶ Exploit resonant dark photon production using positron beams through a scan of the beam energy.



NA64 also operates in muon and hadron mode! For the latest results and future program, please see the talk by Dr. Molina Bueno and Dr. Ayala Torres!

## Conclusions

- ▶ NA64 is a world-leading LDM search experiment operating at the CERN SPS H4 beam line. It exploits the missing-energy technique using 100 GeV electron beams.
- ▶ NA64 sets some of the most stringent limits in the  $m_\chi = 10^{-3}$ – $10^{-1}$  GeV mass range.
- ▶ NA64 completed its pre-LS3 programme with  $3 \times 10^{12}$  eOT.
- ▶ Detector upgrades, including the VHCAL, substantially reduced the expected background. The LYSO-based SRD enabled the low-energy positron programme.
- ▶ During Run 4, NA64 aims to collect  $10^{13}$  eOT, significantly improving its sensitivity to LDM and several other new-physics scenarios.

Backup slides

# The Dark Matter Puzzle

## Why Dark Matter?

- ▶ Dark Matter makes up about 85% of the mass of our Universe.
- ▶ Experimental focus: search for a particle signature.
- ▶ Thermal Light Dark Matter:
  - DM and SM are in equilibrium for  $T \gg m_\chi$ ;
  - freeze-out occurs for  $T \ll m_\chi$ ;
  - perturbative relation between  $\langle\sigma v\rangle$  and the relic abundance;
  - $m_\chi$  naturally lies in the sub-GeV mass range.

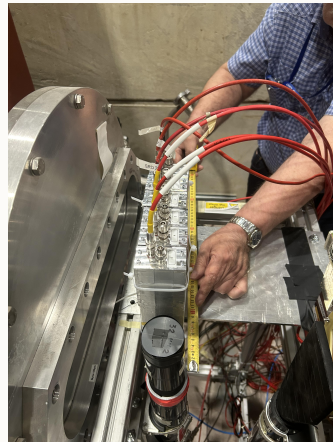
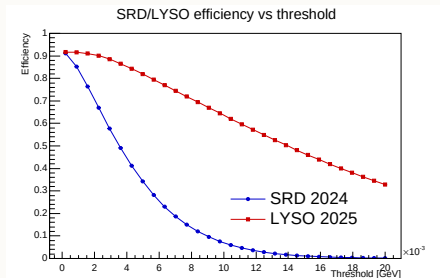


X-Ray: NASA/CXC/CFA/M. Markevitch et al.  
Lensing Map: NASA/STScI; ESO WFI Magellan/U.  
Arizona/D. Clowe et al.  
Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al.

Light dark-sector models provide experimentally accessible signatures in fixed-target missing-energy searches.

## NA64-e upgrades

- ▶ During Run 3, NA64 explored the possibility to run with lower-energy beams ( $E_0 \sim 40$ ) GeV
- ▶ In these conditions, the current Pb-Sc Synchrotron Radiation Detector (SRD) is not optimal, since it was specifically designed for a 100 GeV beam
- ▶ Therefore, we implemented a novel LYSO-based SRD
- ▶ This new detector was tested during 2024. We then introduced it into our setup for 2025-2026 runs



# Search for $A'$ with positron beams

- Enhanced production cross section:  
 $N_s^{annihil} \propto Z\alpha_{EM}$  vs  
 $N_s^{brem} \propto Z^2\alpha_{EM}^3$
- The missing-energy distribution exhibits a peak centered at  

$$E_R = \frac{M_{A'}^2}{2m_e}$$
- Sensitivity in the mass range  
 $\sqrt{2m_e E_{thr}} < M_{A'} < \sqrt{2m_e E_0}$

