Light Dark Matter search with the NA64-e Experiment and POKER at Cern SPS

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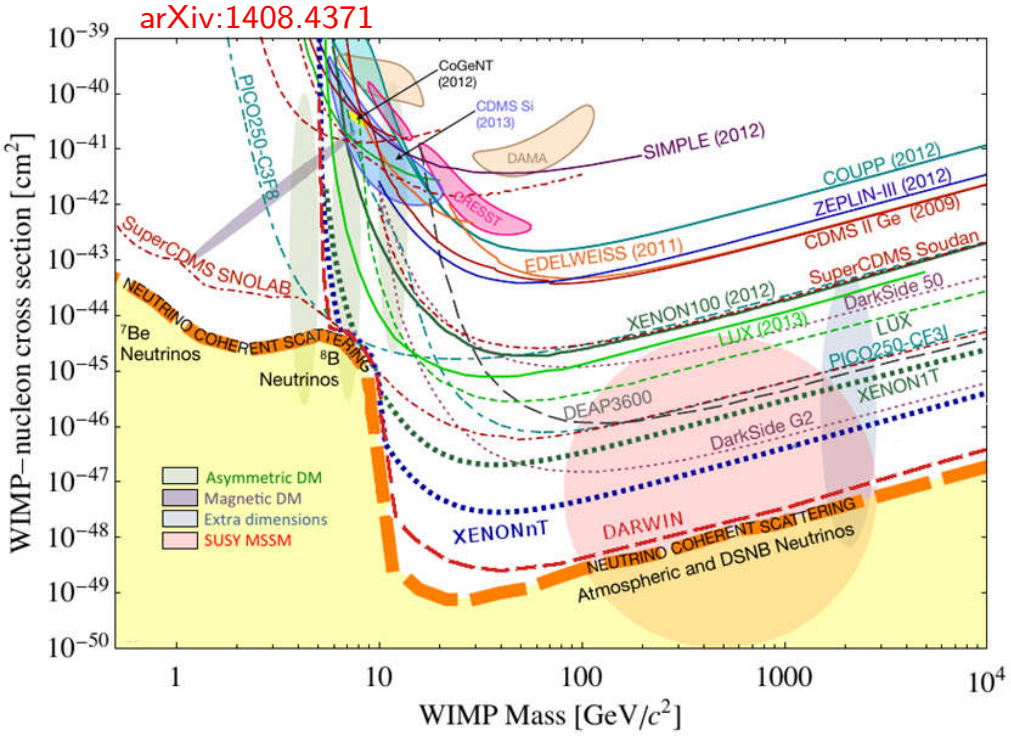
Outline

The dark sector

Dark matter: it is there, but very little is known about it! What is it? Where did it come from?

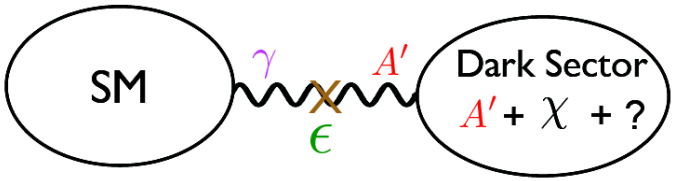
- "WIMP miracle:" electroweak scale masses ($\simeq$100 GeV) and DM annihilation cross sections (10^{-36} cm^2) give correct dark matter density / relic abundances. No need for a new interaction!
- Intense experimental program searching for a signal in this mass region. So far, no positive evidences have been found
- What about **light dark matter**, in the mass range 1 MeV $\div$ 1 GeV?



Light dark matter

The light dark matter hypothesis can explain the observed relic abundance, **provided a new interaction mechanism between SM and dark sector exists**[1]

- Simplest possibility: "vector-portal". DM-SM interaction through a new U(1) gauge-boson ("dark-photon") coupling to electric charge

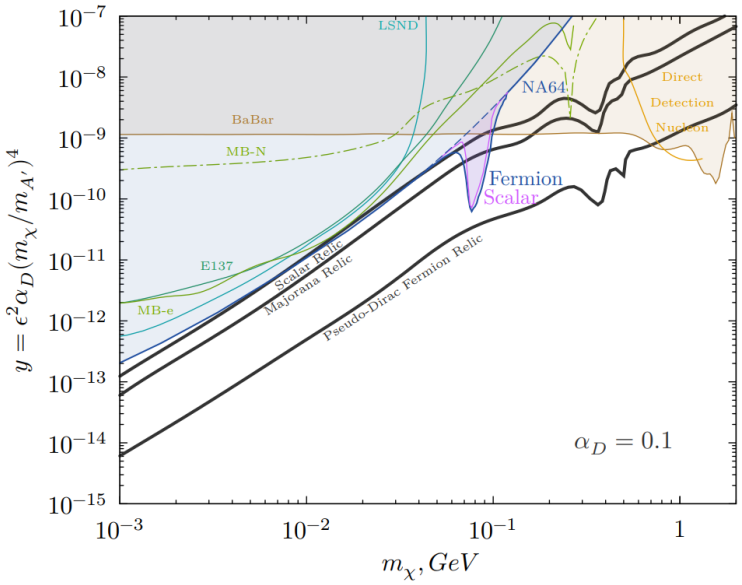


Model parameters:

- Dark-photon mass, $m_{A'}$ and coupling to electric charge ε
- Dark matter mass, m_χ and coupling to dark photon, g_D ($\alpha_D \equiv g_D^2/4\pi$)

Experimental searches:

- A comprehensive LDM experimental program must investigate **both** the existence of χ particles and of dark photons
- Experiments at accelerators at the *intensity frontier* are particularly suited to explore this paradigm



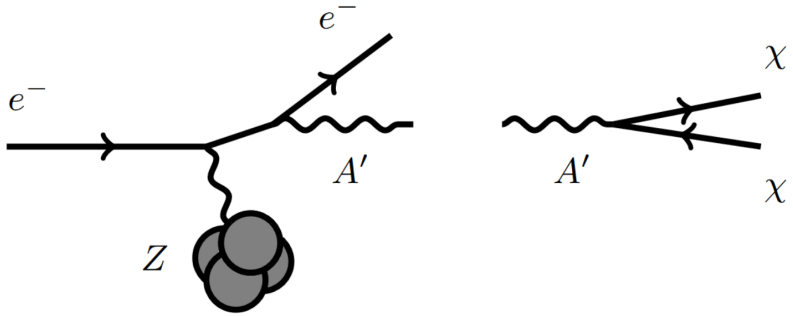
[1] For a comprehensive review: 1707.04591, 2005.01515, 2011.02157

Fixed *active* thick-target LDM searches: missing energy experiments

Missing energy approach - the *active thick target* is the detector

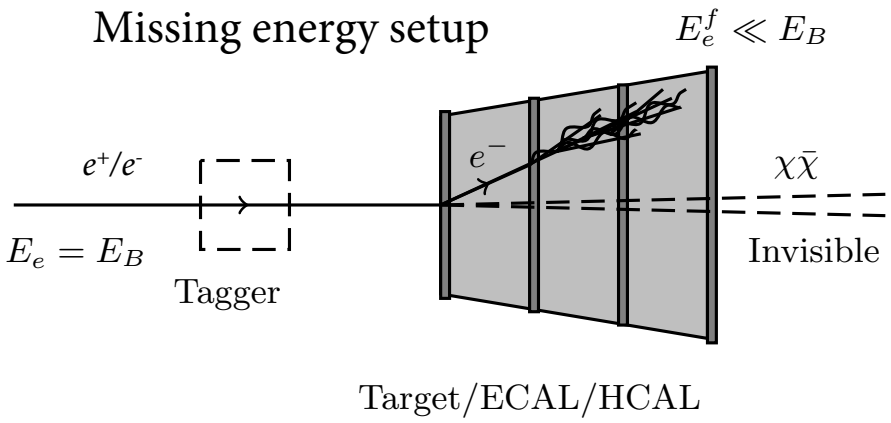
1. High intensity e^+/e^- beam impinging on thick active target $\rightarrow$ EM shower is initiated
2. A' are produced from e^+/e^- in the shower and promptly decay to LDM particles χ
3. χ particles escape the detector without interacting

A'-strahlung production mechanism:



Missing Energy Signature

- Specific beam structure: impinging particles impinging "one at a time" on the active target
- Deposited energy E_{dep} measured event-by-event
- Signal: events with large $E_{miss} = E_B - E_{dep}$
- Backgrounds: events with ν / long-lived (K_L) / highly penetrating (μ) escaping the detector



NA64$-e$ Experiment

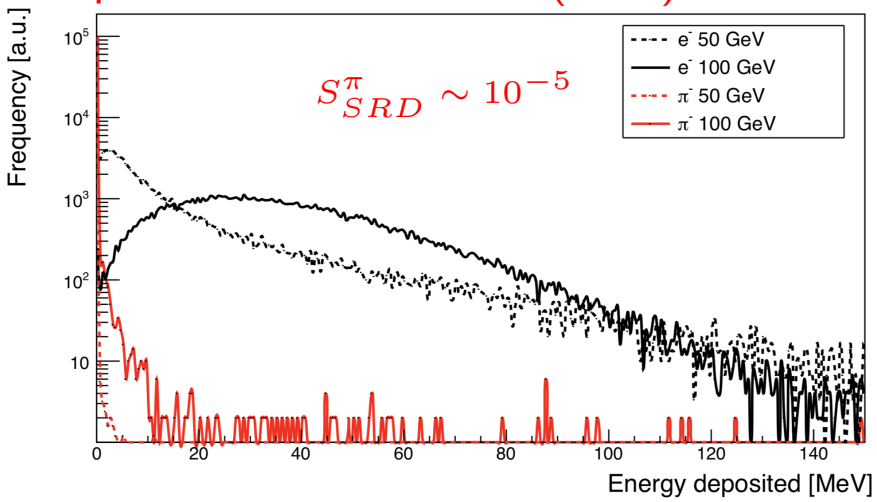
Missing energy experiment at CERN North Area H4 line - 100 GeV e^- beam[2]

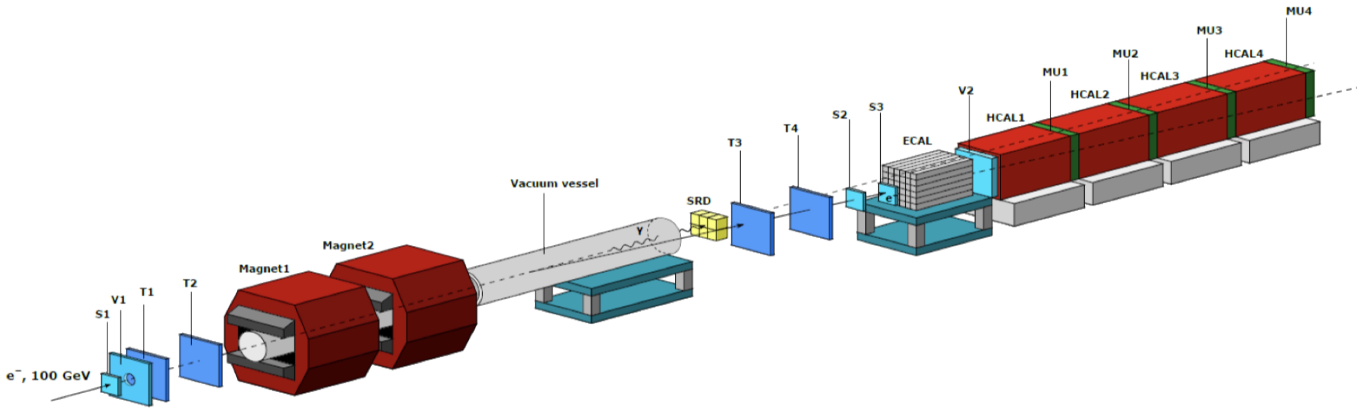
H4 line: few 10^7 e^-/spill with energy resolution $< 1\%$ and hadron contamination $\sim 0.5\%$

Experiment Setup

- Beam identification system: magnetic spectrometer and SRD tagging (MBPL magnets)
- EM-Calorimeter: $40X_0$, Pb/Sc Shashlik
- Plastic scintillator VETO
- Hadron calorimeter: 4 m, 30 λ_I

Depero et al. NIM A 866 (2017) 196-201





[2] Phys.Rev.Lett. 123 (2019) 121801

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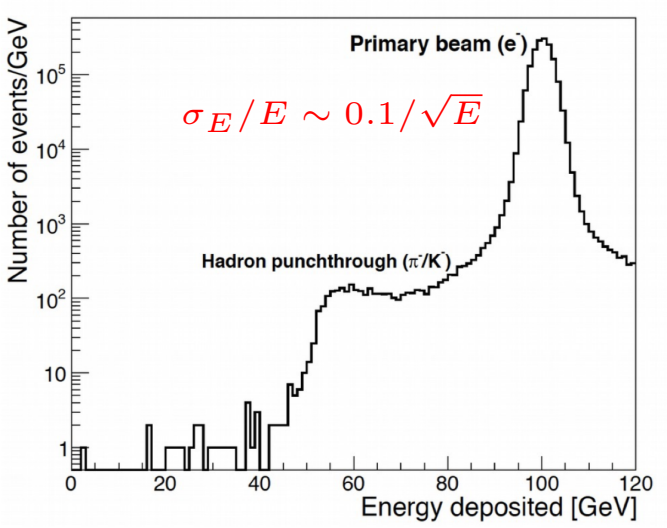

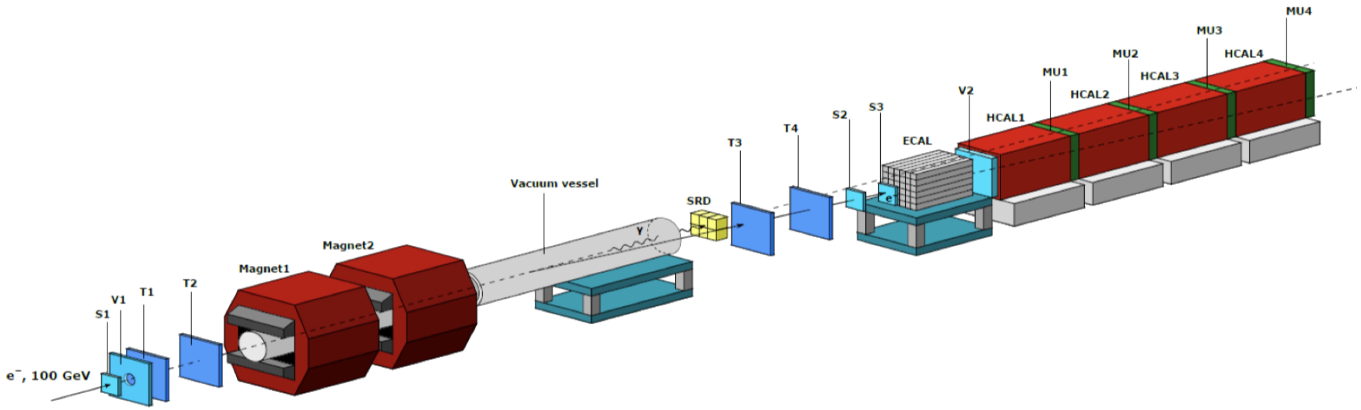

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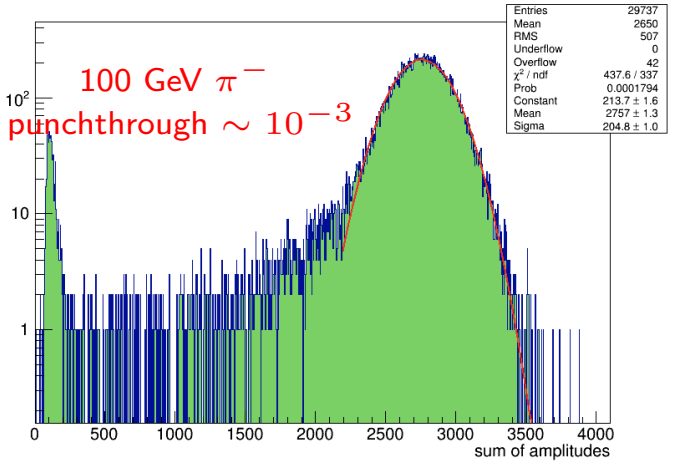

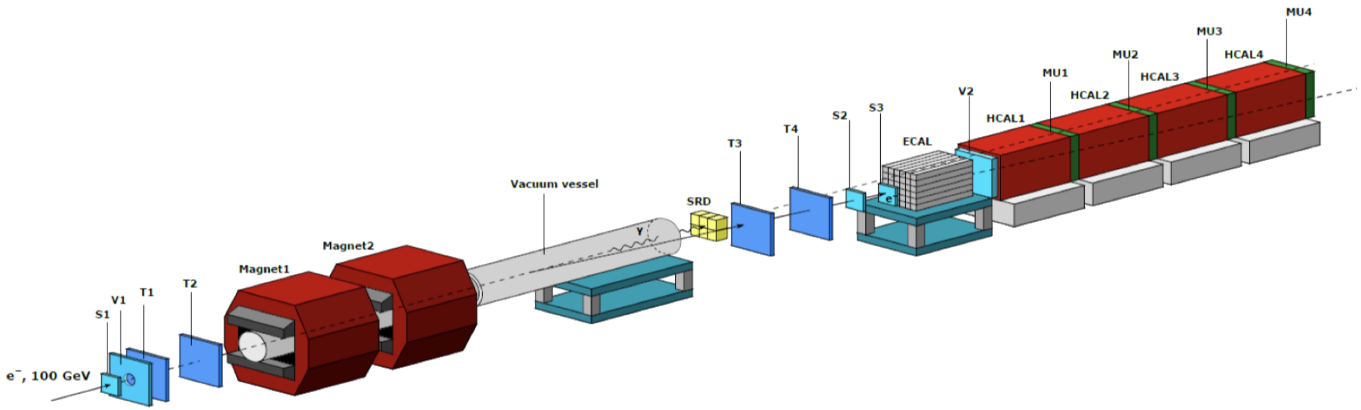

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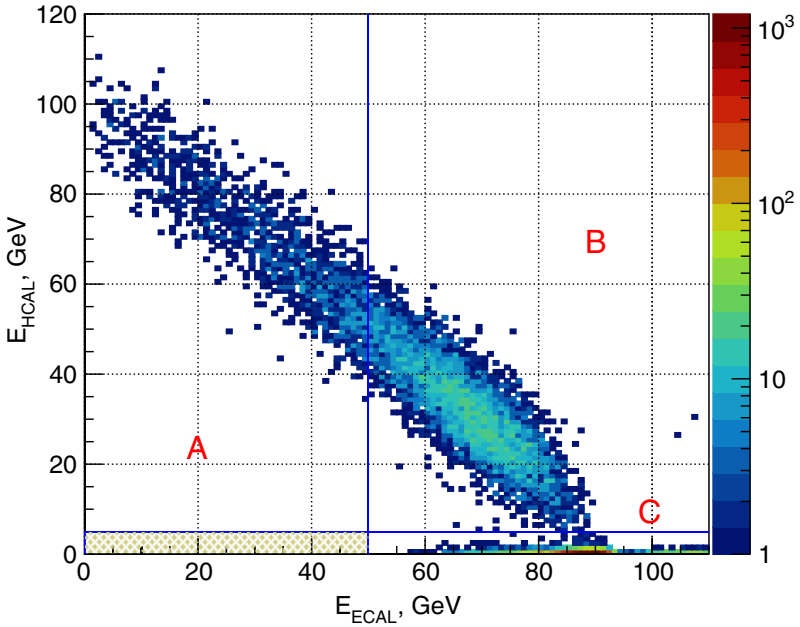
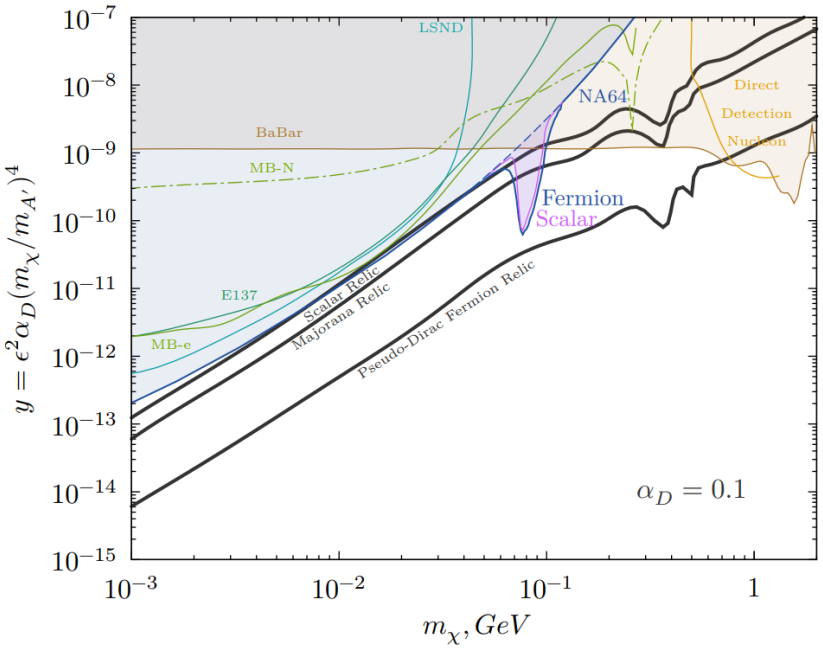
NA64$-e$ results

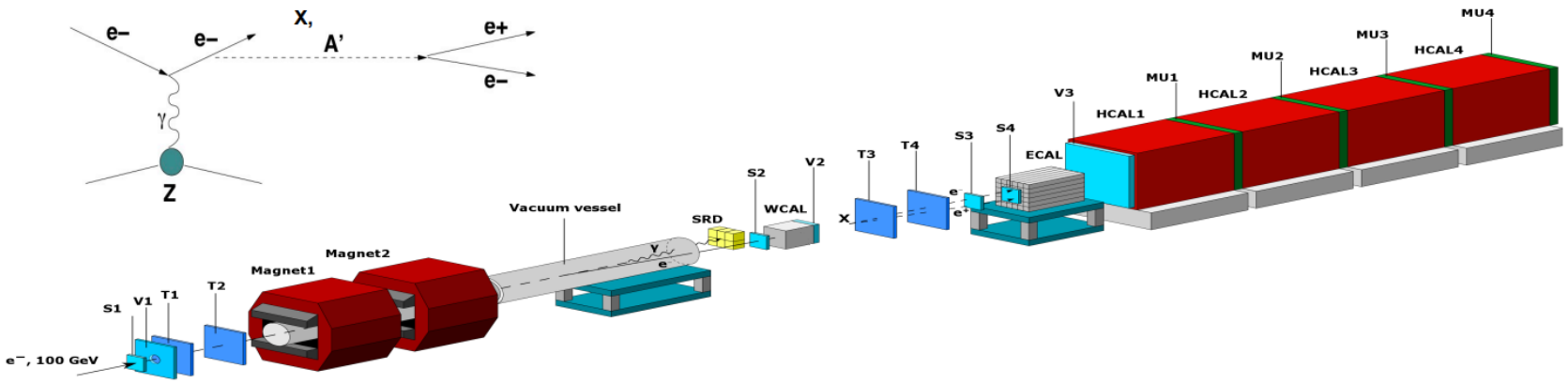
- Published NA64$-e$ results based on $2.84 \cdot 10^{11}$ EOT collected during 2016-2018
- After applying all selection cuts, no events observed in the signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV
- Expected number of background events $\sim$ 0.5 compatible with null observation
- **Most competitive exclusion limits** in large portion of the LDM parameters space
- Secondary positron annihilation contribution included in recent analysis
- Significant statistics ($\times 3$ published data) collected in 2022, analysis results expected soon.



NA64 collaboration, Phys. Rev. D 104, L091701 (2021)

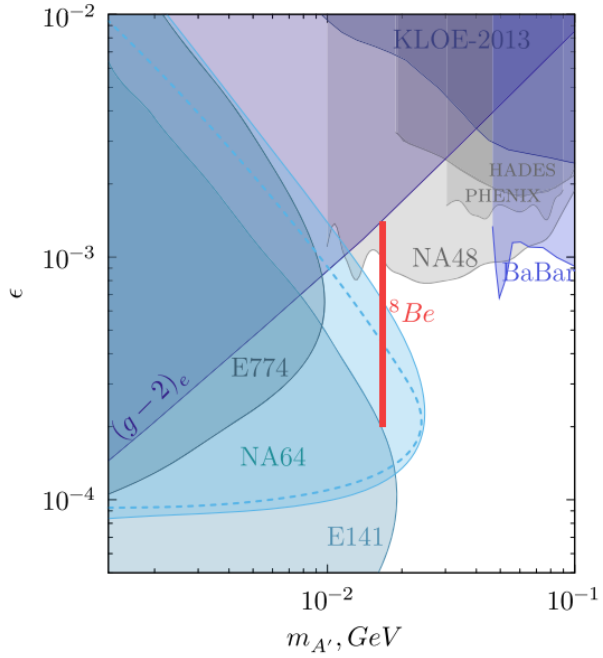


NA64$-e$ - visible mode



NA64 collaboration, Phys. Rev. D 101 (2020) no.11, 071101(R)

- Interest has recently grown towards A' **visible decay** $A' \to e^+e^-$ in the ~ 17 MeV mass region (X17 anomaly)
- NA64$-e$ visible mode: A' produced in **WCAL** detector (plastic and tungsten calorimeter). Search for decay products in **ECAL**
- 8.4×10^{10} EOT collected in visible mode: ruled out part of the available X17 parameter space
- The remaining space could be explored after **WCAL** detector upgrade (under discussion within the collaboration)

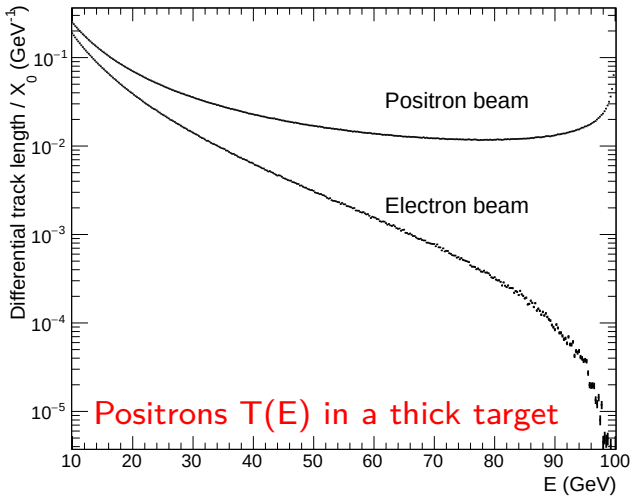


POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

An optimized light dark matter search with positrons in the NA64 framework[3]

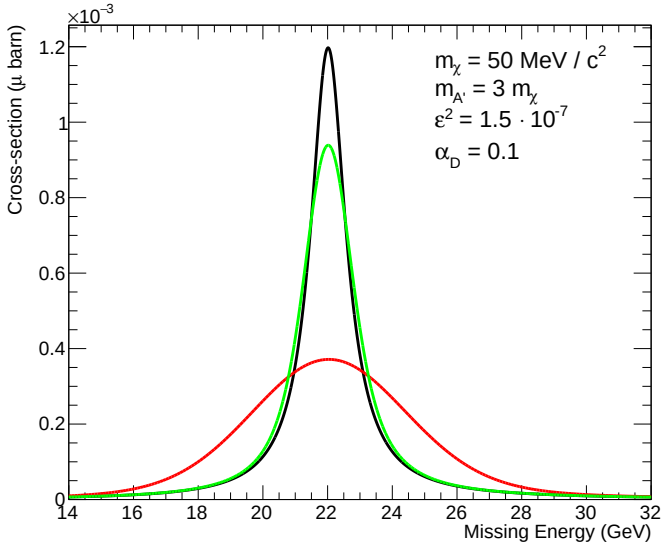
Signal production reaction: $e^+e^- \to A' \to \chi\overline{\chi}$

- Large event yield:
  $N_s^{annihil} \propto Z\alpha_{EM}$ vs
  $N_s^{brem} \propto Z^2\alpha_{EM}^3$
- Missing energy distribution shows a **peak** around $E_R = \frac{M_{A'}^2}{2m_e}$ $\to$ **clear signal signature**



Project goal

- Perform a dedicated missing energy measurement in NA64 with the SPS positron beam, replacing the existing NA64 ECAL with a new **high resolution detector ($PbWO_4$ calorimeter)**



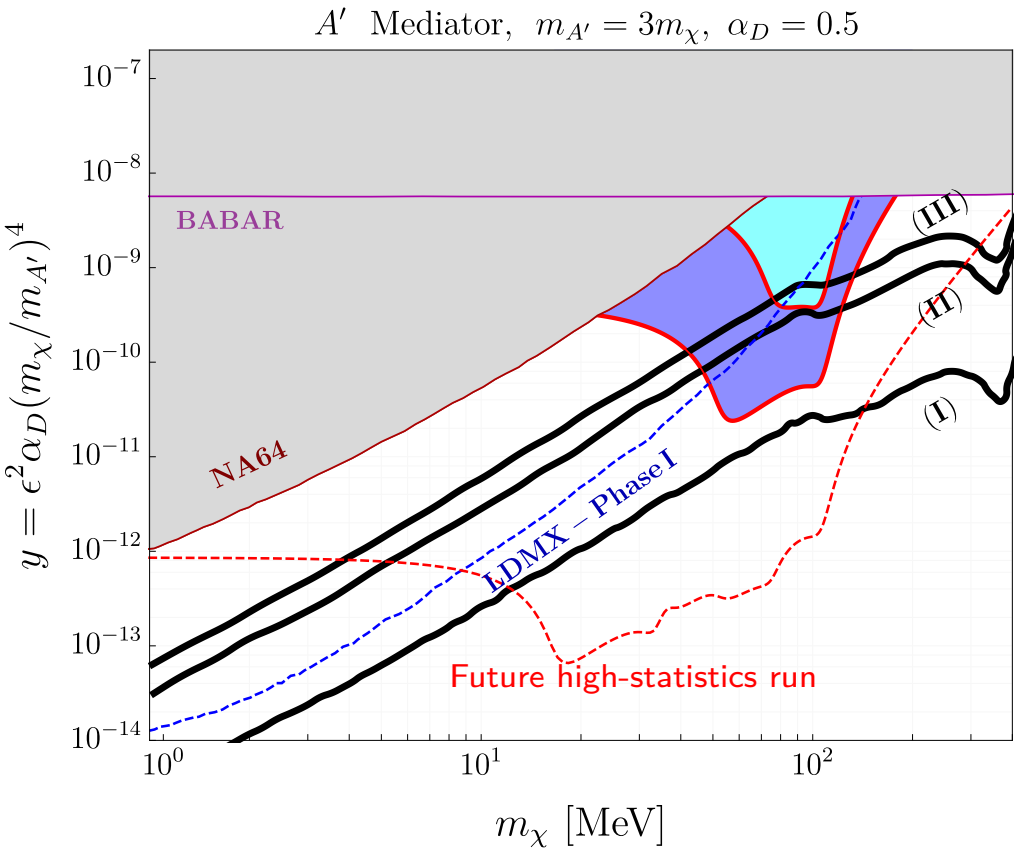
[3] Project funded by ERC grant

POKER sensitivity to LDM

Pilot measurement at the H4 beamline with 100 GeV e^+ beam[4]

- **Baseline scenario:** $5 \cdot 10^{10}$ e^+OT, 50 GeV missing energy threshold
- **Aggressive scenario:** $3 \cdot 10^{11}$ e^+OT, 25 GeV missing energy threshold
- Future experimental program with multiple 10^{13} e^+OT runs at different energies

Pilot run sensitivity - 0 bck

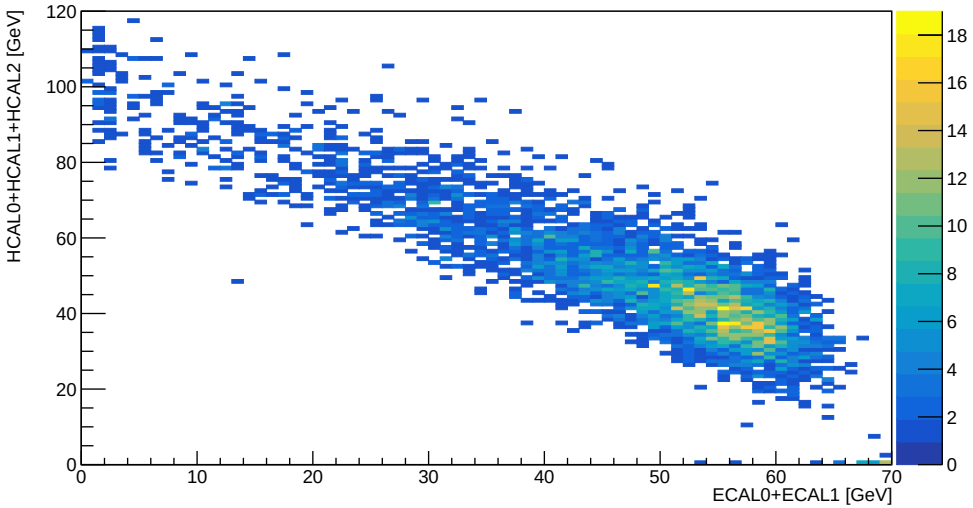


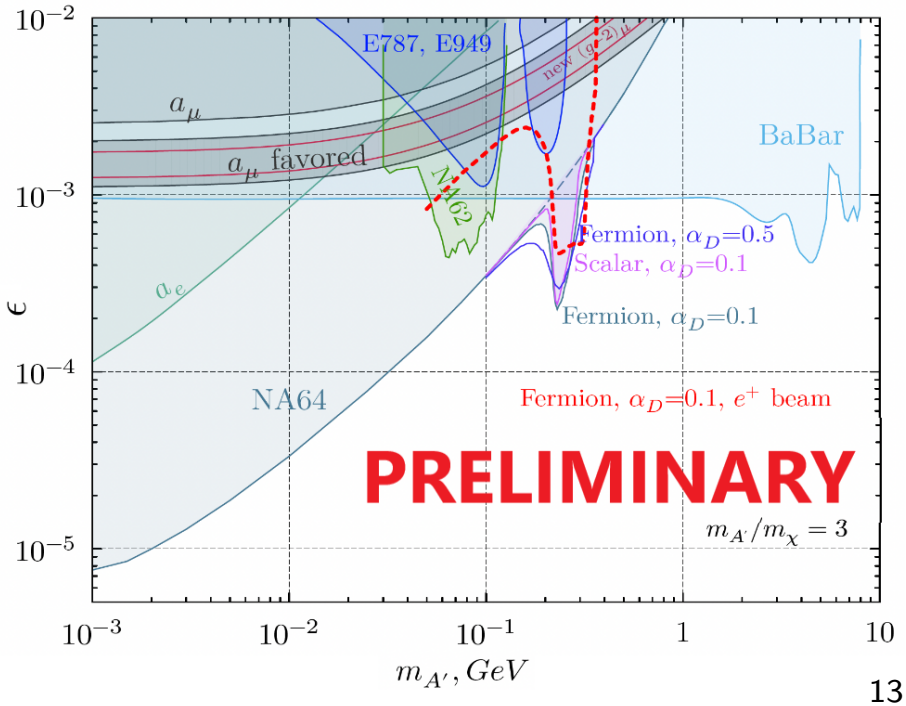
[4] NA64 addendum in preparation to be submitted to next SPSC

First e^+ measurement at NA64

While the POKER active target is being built, a preliminary measurement with a 100 GeV e^+ beam, using the current NA64$-e$ setup has been performed in 2022

- **Goals:** background studies, first upper limit optimized for resonant A' production
- $\sim 10^{10}$ e^+OT collected
- **Blind-analysis approach**: signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV
- **Main expected background source**: decay of misidentified K and π contaminants in the beam
- No events in the signal region after data unblinding





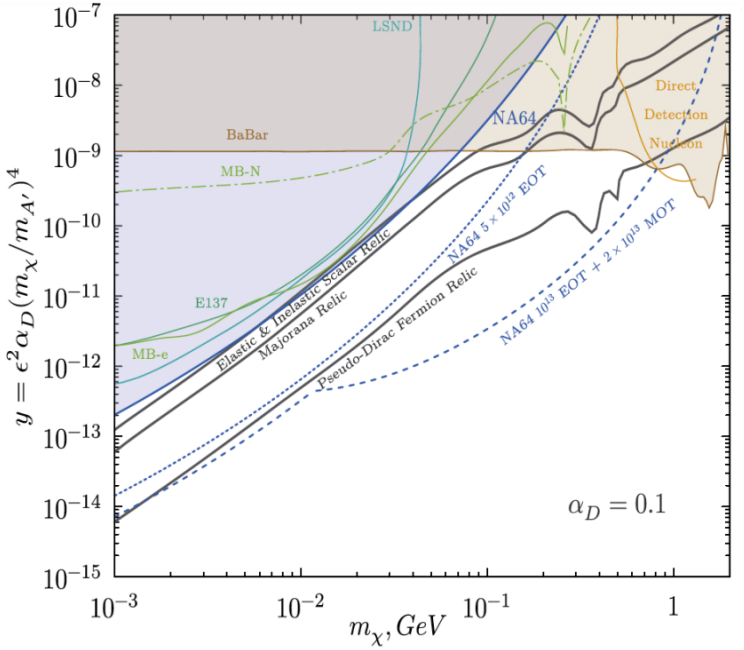
NA64 future prospects

Electron Beam:

- High statistic run in 2022 collected $\sim 10^{12}$ EOT; first results unveiled in the next weeks
- Up to $\sim 3 \times 10^{12}$ EOT collected by LS3: **probe significant part of the A' invisible parameter space and many BSM extensions such as ALPs, Z' in Lmu-Ltau, B-L models**

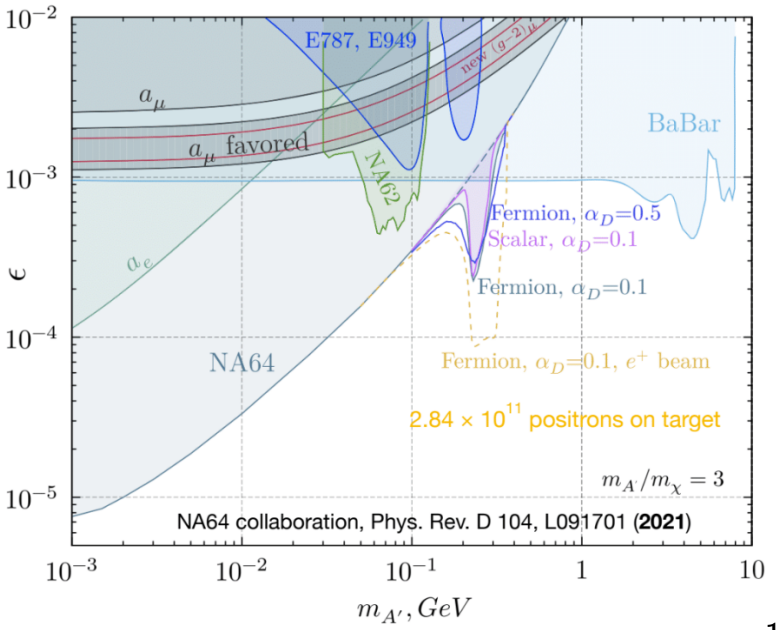
Muon Beam:

- NA64-μ: missing momentum and energy experiment with a muon beam
- Ongoing parallel effort of the NA64 collaboration



Positron Beam:

- Primary e^+ beam allows to exploit the enhanced resonant annihilation cross section $\rightarrow$ **high sensitivity to large A' masses**
- First dedicated e^+ run performed in Fall 2022: $\sim 10^{10}$ e^+OT collected
- Possibility of a future **multi-energy measurement program** is being investigated (POKER project)



Conclusions

- Light dark matter scenario (MeV-to-GeV range) is largely unexplored and theoretically well motivated
- NA64-e is an electron-beam missing-energy experiment at CERN
  - NA64 produced several important results in the search for dark photon, both in the visible and invisible decay scenario
  - The high statistics 2022 run will allow to probe a significant part of the preferred LDM parameter space (analysis results expected soon)
  - First test run with a positron beam performed in 2022
- POKER is an ERC funded project, aiming to perform an optimized missing energy measurement with a positron beam
  - The project foresees the realization of a high-resolution active target to be implemented in the NA64 setup
  - Studies on hadron contamination and detector R&D currently ongoing - possibility to run the pilot measurement in 2024 currently discussed