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

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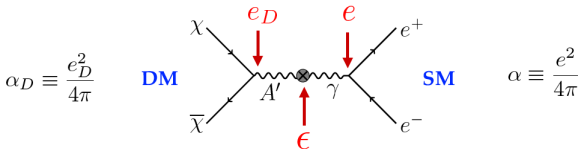
September 7th 2023, Bari -1st General Meeting of COSMIC WISPers COST Action

NA64 main physics case: the Dark Sector

"Light Dark Matter" hypothesis: DM made of sub-GeV particles χ, part of a new "dark sector". LDM-SM interaction mediated by a new massive $U(1)$ gauge boson, the dark photon

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

- "Dark Photon" (A') portal, parameters:
  - A' and LDM masses
  - Coupling $A' - \chi$: $e_D \simeq 1$
  - Coupling $A' - SM$ con kinetic mixing, $\varepsilon \ll 1$

- Annihilation cross section:
$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 \alpha_D \, m_\chi^2}{m_{A'}^4} = \frac{\varepsilon^2 \alpha_D \, m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$
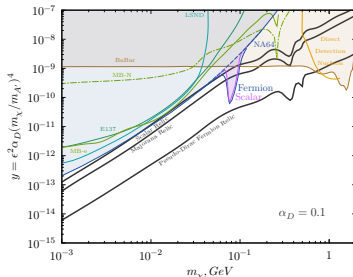

For a given m_χ value, y value is fixed by cosmology - $\mathcal{O}(1)$ variations depending on the fine details of the model.

The *missing energy* technique

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 χ particles - **"invisible decay"**
3. χs escape the detector without interacting
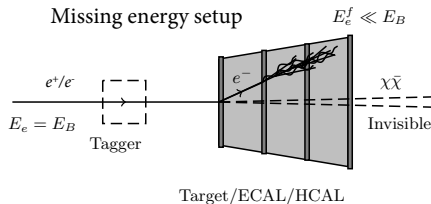
Main A' production mechanisms:
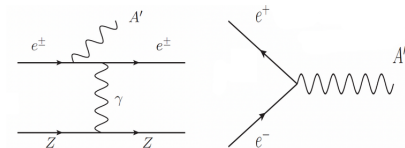
Missing Energy Signature

- Specific beam structure: 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

Missing energy setup

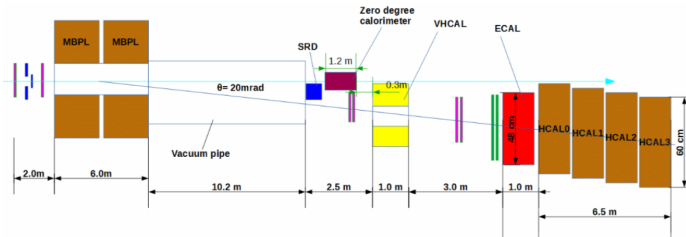Target/ECAL/HCAL

NA64 Experiment

Missing energy experiment at CERN North Area H4 line - 100 GeV e^- beam
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
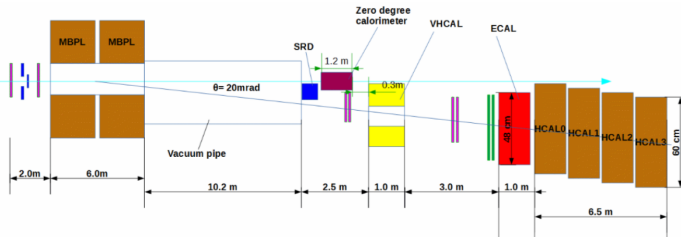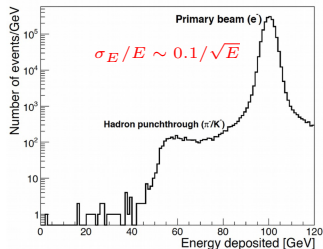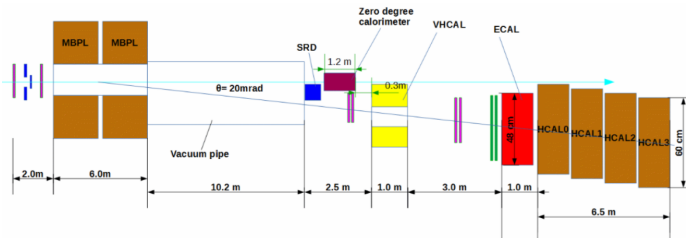- Hadron calorimeter: 4 m, 30 λ_I

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Introduction
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The NA64 experiment
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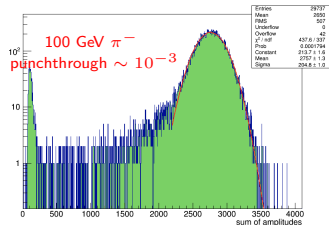The POKER project
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Conclusions
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100 GeV π^-
punchthrough $\sim 10^{-3}$

Data analysis of 2021-2022 runs

Accumulated statistics: 6×10^{10} (2021) + 6.3×10^{11} (2022) → 9.37×10^{11} e^- on target (EOT) in total (2016-2022).

Selection cuts:
- Clean impinging 100 GeV e^-, no activity in VETO/HCAL,
- shower-shape compatible with e- induced one (data-driven shower shape χ^2 distribution)

Signal window: $E_{ECAL} <$ 47-50 GeV, $E_{HCAL} <$ 1 GeV, depending on the run conditions and detector performances

Expected background yield: $\sim$ 0.5 events (contribution of upstream electro-nuclear reactions extrapolated from data via sideband fit)

Sideband-fit example (2022 run, sub-run period #2)
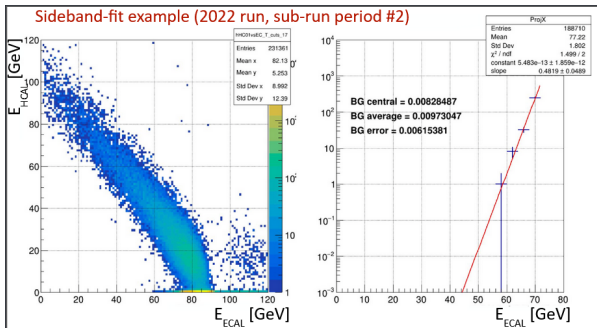
NA64 results from all runs ($\sim 10^{12}$ EOT)

- No signal observed in $\sim 10^{12}$ EOT collected

- For $\alpha_{\rm D} = 0.1$, NA64 excludes the Scalar and Majorana scenarios in a large m_χ interval.

- Thanks to e+e- resonant enhancement, the Pseudo-Dirac Fermion scenario is touched in a narrow m_χ region.
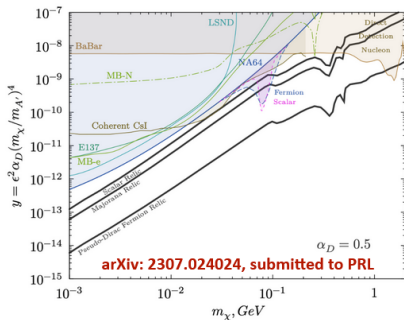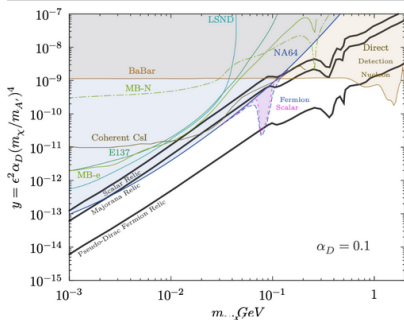
Search for Z' with NA64

- Dark Sector - SM interaction mediated by a light Z' boson with dominant coupling to μ and τ

- Data collected in 2016-2018 re-analyzed for the Z' search ($\sim 3 \times 10^{11}$ EOT)

- Loop-induced mixing between the SM photon and Z' - effective coupling implemented in signal simulation (MadGraph5)

- Resulting limits touch the preferred $g - 2$ region for $m_{Z'}$ 1 MeV. Collecting 10^{13} EOT would allow to explore a significant part of the $g - 2$ band.
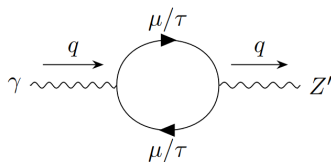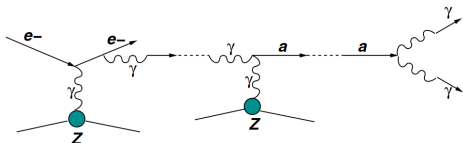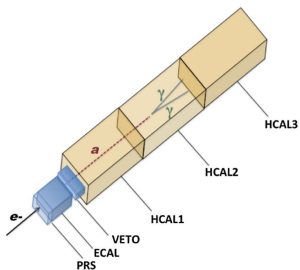

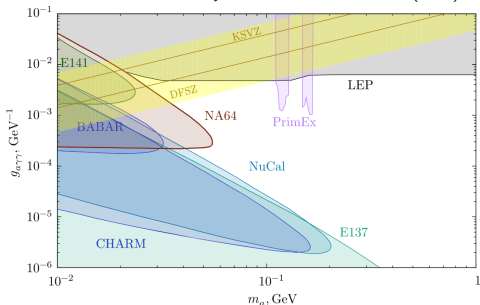The NA64 Collaboration, Phys. Rev. D 106, 032015
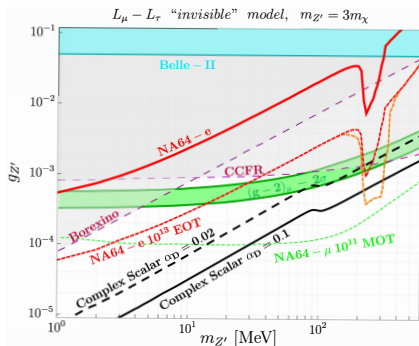
Search for ALPs and scalars

- ALPs produced via Primakoff effect from hard bremsstrahlung photons in the ECAL
- **HCAL fist module used as a veto**
- signal defined as: 1) $E_{ECAL} < 85$ GeV, $E_{HCAL23} > 15$ GeV or 2) $E_{ECAL} < 50$ GeV, $E_{HCAL23} \simeq 0$ GeV
- NO events observed in 2016-2018 data (compatible with expected background B $\simeq 0.17$)

The NA64 collaboration Phys. Rev. Lett. 125, 081801 (2020)

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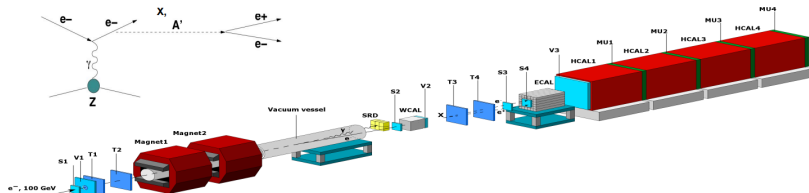
NA64 collaboration, Phys. Rev. D 101 (2020) no.11,
071101(R)

- Interest has recently grown towards A' **visible decay** $A' \to e^+e^-$ in the ~ 17 MeV mass region (X17 anomaly)

- NA64 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

- **WCAL** detector upgrade necessary to improve reach
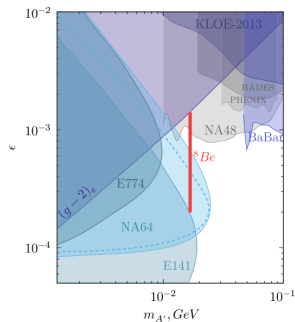
NA64 visible - future upgrade

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 $X17 \to e^+ e^-$ decay
$\rightarrow$ **new setup under consideration**

- New WCAL geometry for improved signal efficiency
- Dipole magnet $+ \sim 18$ 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
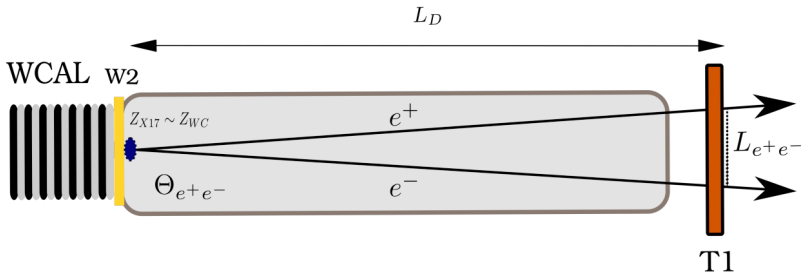
POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

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

Exploit the LDM production process:
$e^+e^- \to A' \to \chi\overline{\chi}$[1]

- Large event yield:

  $N_s^{annihil} \propto Z\alpha_{EM}$ vs
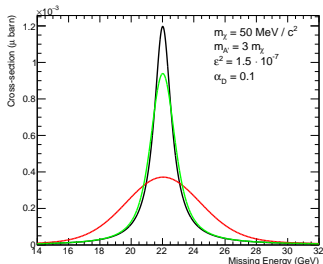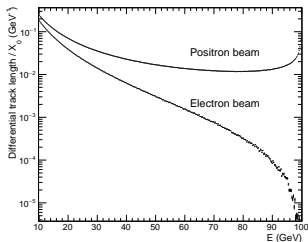 $N_s^{brem} \propto Z^2\alpha_{EM}^3$

- 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)**

[1] L. Marsicano, E. Nardi et al. Phys. Rev. Lett. 121, 041802

The PKR-Cal Detector

- **Electromagnetic calorimeter**: 9×9 matrix of $2 \times 2 \times 20$ cm^3 PbWO$_4$ crystals + 4-layers pre-shower (total ~ 120 crystals)
- **SiPM-based readout**: 4x 6×6 mm^2 Hamamatsu S14160-6010 SiPM per crystal (10 μm cell size)
- Expected resolution from MC simulations: $\sigma_E/E \sim 2.5\%/\sqrt{E} \oplus (0.5 \div 1)\%$
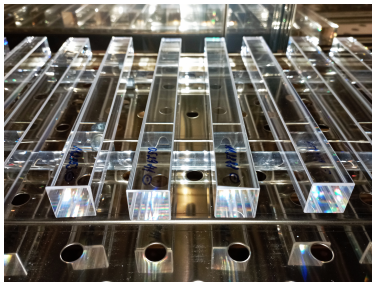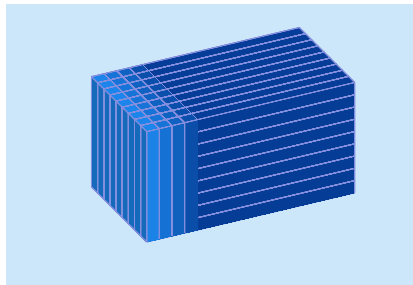

PKR-Cal R&D status:

- Crystals characterization (**light yield, light transmission, radiation hardness**) performed
- small-size (3X3 crystals) prototype built and tested at H8 line @CERN, to validate technical choices (data analysis ongoing)
- PKR-Cal mechanical structure design ongoing

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 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
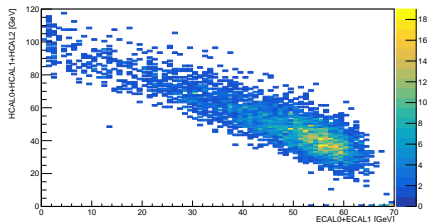


arXiv:2308.15612 - submitted to PRL
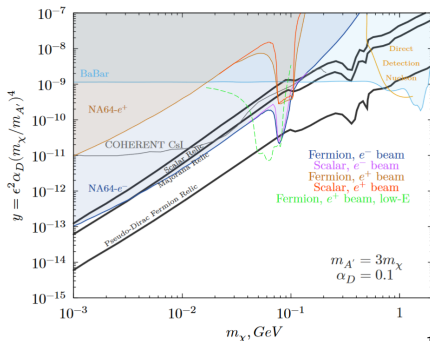
NA64 future prospects

Electron Beam:

- High statistic run in 2022 collected $\sim 10^{12}$ EOT; analysis results submitted to PRL
- 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**
- Possibility to upgrade the detector "visible mode" to enhance the sensitivity in the X17 paramter space is currently being discussed
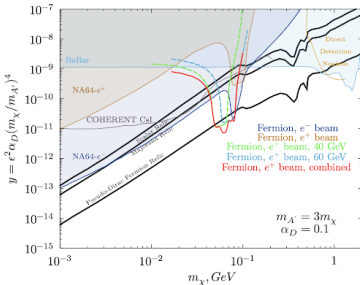
Muon Beam:

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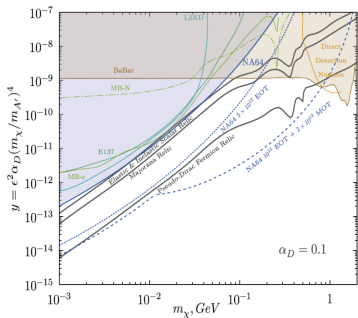
Positron Beam:

- 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

- NA64 is an electron-beam missing-energy experiment at CERN searching for Dark Sector particles in the Dark Photon paradigm
  - The high-statistics 2022 run allowed to set stringent limits in the "invisible decay" dark photon parameter space ($A' \to \chi\bar{\chi}$)
  - In addition to the A' "invisible decay" scenario, NA64 set limits on ALPs,Z', visible A' decay (X17) and B-L.

- POKER is an ERC funded project, aiming to perform an optimized missing energy measurement with a positron beam
  - The project includes the realization of a high-resolution active target to be implemented in the NA64 setup
  - First test run with a positron beam performed in 2022, with the original NA64 setup
  - Studies on hadron contamination and detector R&D currently ongoing - possibility to run the pilot measurement in 2024 currently discussed

thanks for the attention!