Missing energy experiments at positron accelerators

Pietro Bisio, Luca Marsicano

INFN-Genova

10/04/2025

Outline

1. Introduction
2. POKER/NA64-e^+
3. The JPOS-LDM experiment

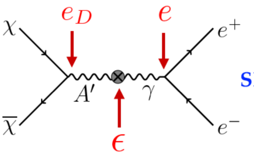
Vector mediated LDM

New massive U(1) gauge-boson (Dark Photon / A') acting as a portal between SM and DS.

"Dark – QED"

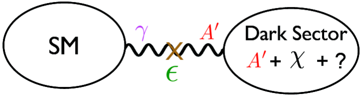
$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$

DM



SM

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

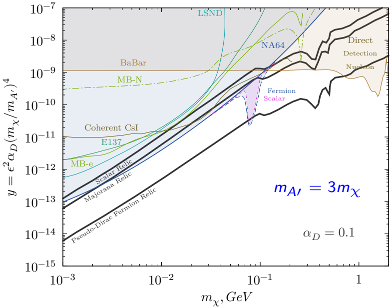


Model parameters:

- Dark Photon $m_{A'}$ and Dark Matter m_χ masses (sub-GeV)
- $A' - \chi$ coupling $e_D \simeq 1$
- $A' - \gamma$ coupling via kinetic mixing ε

Annihilation cross section ($\chi\bar{\chi} \to SM$) reads:

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

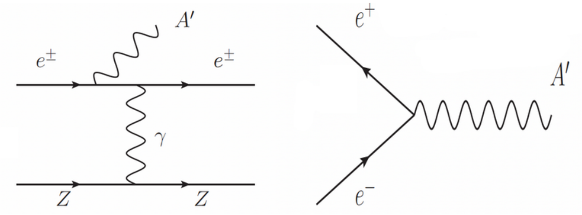


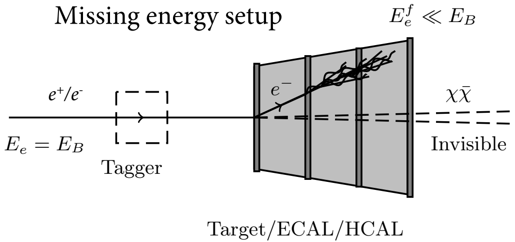
If χs make DM, the thermal origin hypothesis (freeze-out) imposes a "thermal target" $y(m_\chi)$.

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:



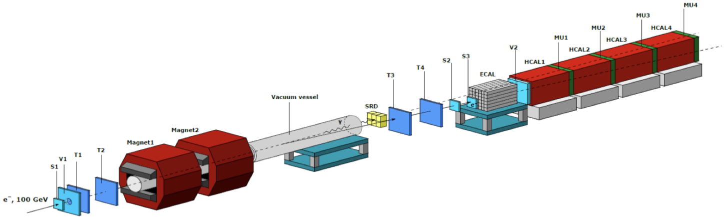


Missing Energy Signature

- 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 $E_{miss} = E_{beam} - E_{dep}$

The NA64-e experiment at CERN

- Missing-energy experiment at CERN SPS H4, 100 GeV e^- beam
- H4 beamline: $\simeq 10^7$ particles/spill, $\sigma_E < 1\%$, contamination $\sim 0.4\%$

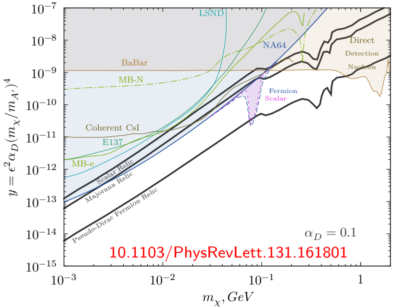


The NA64-e detector

- Active Target: 40 X_0 Pb + Sc calorimeter (ECal) with PMT readout ($\sigma_E/E \simeq 10\%/\sqrt{E} \oplus 5\%$)
- Magnetic spectrometer + SRD for beam particle tagging ($\frac{\Delta p}{p} \simeq 1\%$)
- Sc VETO + large sampling hadronic calorimeter ($\sim 30\ \lambda_I$) for hermeticity (HCal)

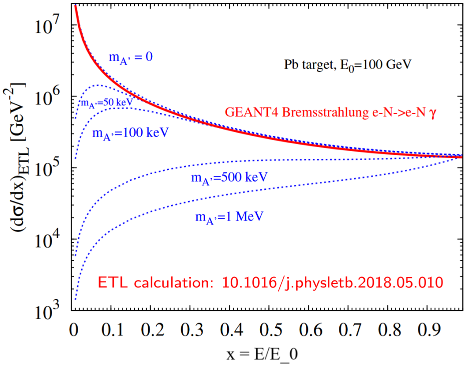
Signal signature (see A. Marini's talk):

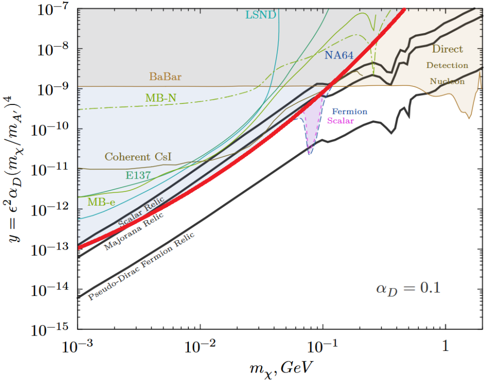
- Large missing ECal energy: $E_{miss} \gtrsim 0.5 \cdot E_{beam}$
- Well-reconstructed 100-GeV impinging e^- track
- Negligible activity in the downstream VETO and HCal



LDM yield in NA64-e: A'-Strahlung

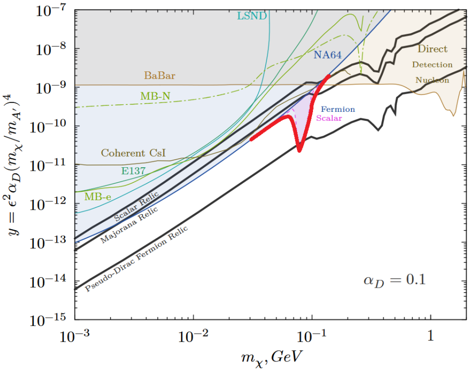
- Radiative A' emission in nucleus EM field followed by $A' \to \chi\bar{\chi}$
- Scales as $Z^2\alpha^3_{EM}$
- Forward-boosted, high-energy A' emission
- Dominant over large m_A range.

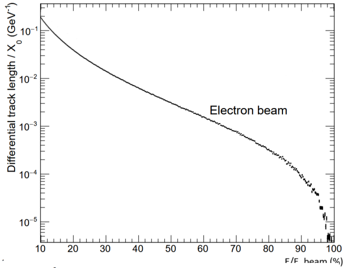


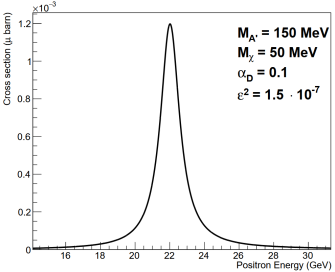


LDM yield in NA64-e: Resonant annihilation

- Resonant annihilation of secondary positrons with atomic e^-: $e^+e^- \to A' \to \chi\bar{\chi}$
- Breit Wigner-like cross section
- Scales as $Z\alpha_{EM}$
- Dominant in the $\sqrt{2m_e E_{thr}} \lesssim m'_A \lesssim \sqrt{2m_e E_{beam}}$ mass range





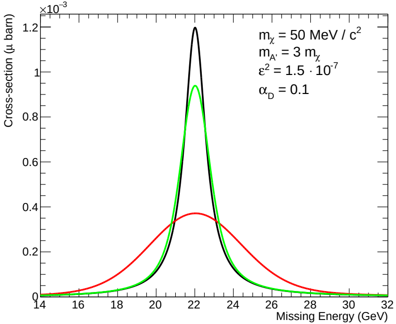


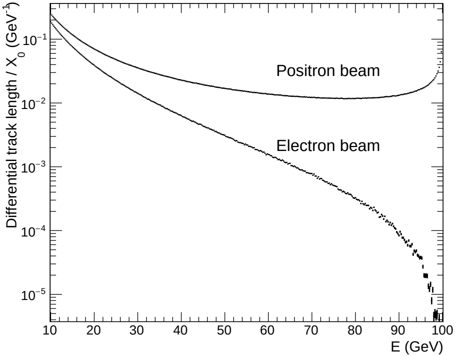
POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

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

Project goal

- Perform a dedicated missing energy measurement in NA64-e with the SPS positron beam, replacing the existing NA64-e ECAL with a new **high resolution active target**





10.1103/PhysRevLett.121.041802

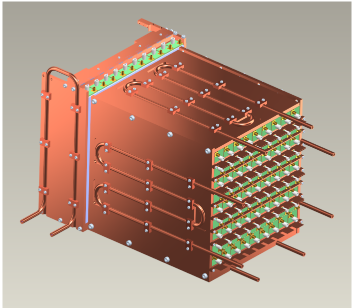
The PKR-Cal Detector

Requirements:

- Improved energy resolution ($\sigma(E)/E \simeq 2.5\%/\sqrt{E} \oplus 0.5 - 1\%$) $\rightarrow$ match the resonant peak width
- Fast response time $\rightarrow$ Reduce pile-up effects.
- High-density material $\rightarrow$ EM shower absorbed in a compact detector.
- Low passive-material volumes $\rightarrow$ Reduce spurious missing energy/improve resolution.

The new PKR-CAL detector:

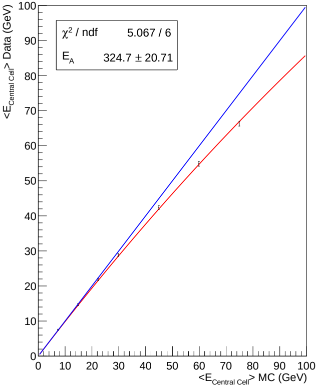
- $\sim 29\ X_0$ $PbWO_4$ calorimeter.
- 9x9 matrix of $20 \times 20 \times 220\ \mathrm{mm}^3$ crystals.
- 2 layers in front (pre-shower).
- Readout: 4x $6 \times 6\ \mathrm{mm}^2$ Hamamatsu S14160-6010 SiPM per crystal (10 $\mu\mathrm{m}$ cell size)

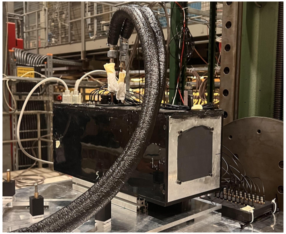


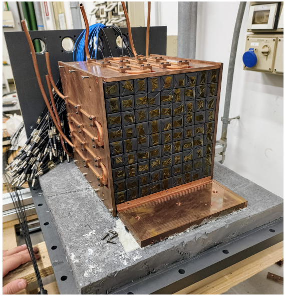
PKR-Cal R&D status

POKERINO: small-size prototype (3×3 crystals matrix) built to validate the PKR-Cal technical choices

- POKERINO test-beam performed at H8, H6 beam lines of CERN SPS
- response linearity tested in the 10 GeV - 120 GeV energy range
- measured resolution well within the PKR-Cal requirements
- crucial role of the SiPMs heating







PKR-Cal Status

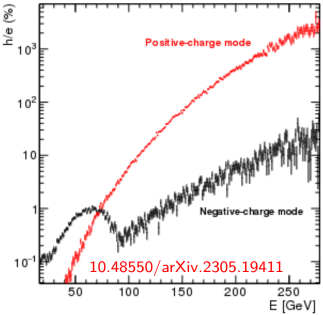
- Detector fully assembled and operational at INFN-Genova labs
- First tests with cosmic rays ongoing
- Installation in NA64-e scheduled in June 2025

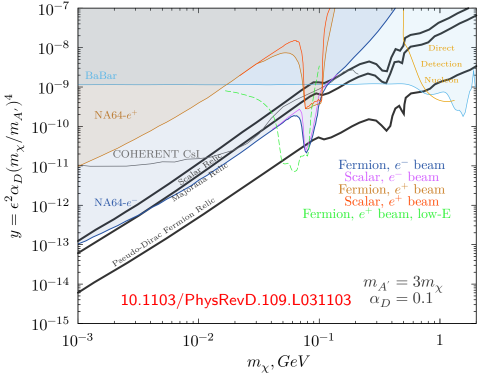
NA64-e^+ - 100 GeV measurement and post LS3 program

During the R&D of the POKER active target, a first measurement with a 100 GeV e^+ beam, using the current NA64-e setup has been performed in 2022: $\sim 10^{10}$ e^+OT collected

No events in the signal region after data unblinding

- **Goals:** background studies, first upper limit optimized for resonant A' production
- **Blind-analysis approach**: signal region $E_{ECal} < 50$ GeV, $E_{HCal} < 1$ GeV
- **Main expected backgrounds**: decay of K and π contaminants in the beam (larger contamination in positron mode), beam upstream interactions

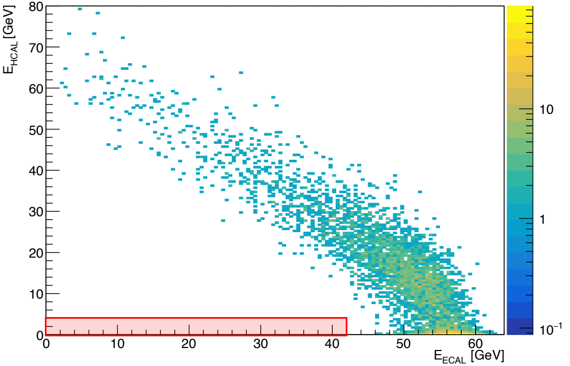


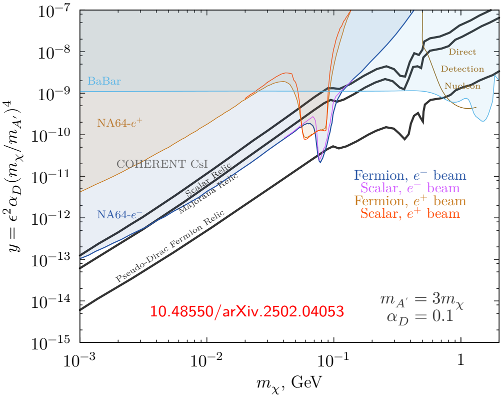


- Results motivated the collaboration to propose to SPSC a future program with 40 GeV and 60 GeV e^+ beams at H4 beamline (CERN-SPSC-2024-003 ; SPSC-P-348-ADD-4)
- Tentative schedule including two runs of 10^{11} e^+OT each to be performed after LS3

NA64-e^+ - 70 GeV measurement and post LS3 program

- Preliminary measurement at 70 GeV, in view of future post-LS3 program, performed in 2023; $\sim 1.5 \times 10^{10}$ e^+OT collected
- Improved setup including new veto HCal (VHCal) for better hermeticity
- Reduced hadron contamination w.r.t. the 100 GeV measurement
- Signal window: $E_{ECal} < 42$ GeV, $E_{HCal} < 1$ GeV
- No event observed in the signal box after unblinding





The Ce$^+$BAF Proposal

Jefferson Lab (Newport News, Virginia, USA) hosts the Continuous Electron Beam Accelerator Facility (**CEBAF**), which accelerates electrons up to 12 GeV.

In recent years, the JLAB community has investigated a **positron-beam upgrade** (Ce$^+$BAF) to complement the laboratory's physics program.

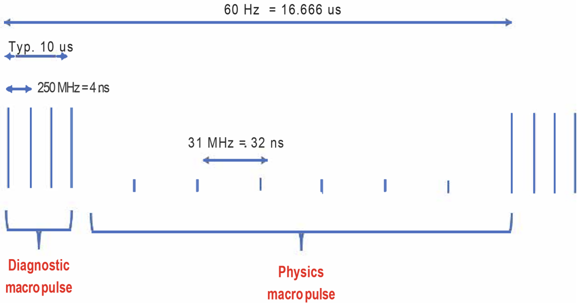
- Primary $\sim$ 12 GeV e^+ beam with negligible particle contamination.
- Highly-collimated beam: $\sigma_x, \sigma_y < 300\ \mu$m
- Continuous time-structure.

Missing-energy technique requires e^+ to impinge "one at a time" $\rightarrow$ A dedicated solution is needed

$\sim$ MHz Positron Beam at Ce$^+$BAF

A low beam current ($\sim$ 0.1 pA) is incompatible with the diagnostic tools that control the CEBAF beam. A "**mixed operation mode**" was considered:

- High-intensity macro-pulses are injected in the CEBAF at 60 Hz to operate the beam diagnostic systems.
- In between, low-intensity physics pulses, populated on average by less than 1 e^+, are injected using an ad-hoc laser system (R&D is needed).



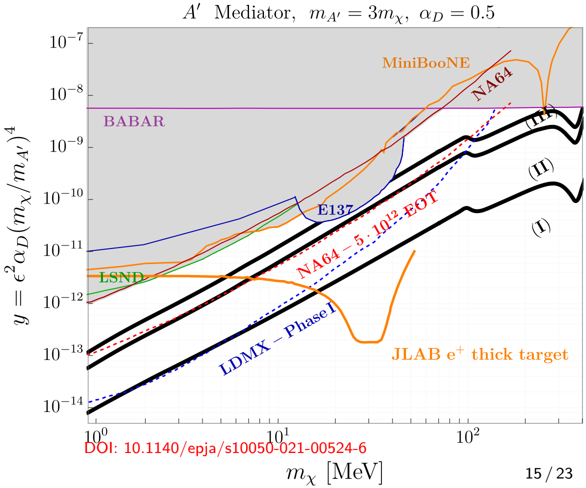
- The experiment acquires data only during low-intensity pulses in which e^+ impinge on the detector, on average, every 500 ns.
- To reduce the radiation dose in the active target, a fast magnetic deflector can transport the high-current pulses to a beam dump.

Preliminary Sensitivity Evaluation

Preliminary, semi-analytical evaluation for the sensitivity of a missing-energy experiment searching for LDM with a future ~ 10 GeV positron beam at JLAB.

Assumptions:

- 11 GeV e^+ beam
- $1\ e^+/\mu s \times 1y \simeq 10^{13}$ POT
- Missing energy threshold $= 5.5$ GeV
- Zero background events
- Signal efficiency $\sim 50\%$
- A' produced only through the resonant annihilation channel



DOI: 10.1140/epja/s10050-021-00524-6

Conceptual Design Studies

This promising result motivated a **conceptual design study**, based on **Monte Carlo** simulations, to assess the experiment's feasibility and perform a preliminary setup optimization.

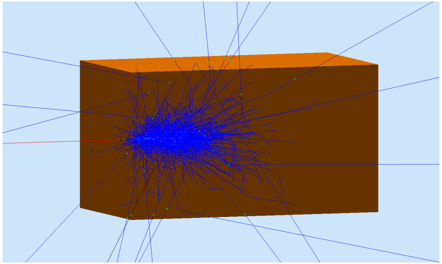
- **Computational limitations**: it is critical to adopt a brute-force approach and simulate $\sim 10^{13}$ events.
- **Extrapolations** and **multi-step simulations** were used to estimate background events.

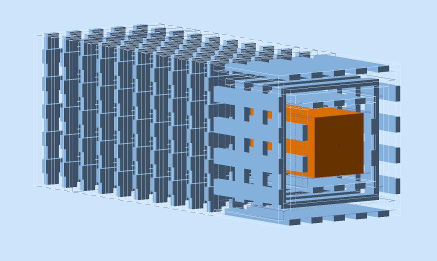
- **Single-event study and simulation precision**: the implementation of some phenomena (e.g. large-angle bremsstrahlung) within the code is based on approximation and assumptions. Results may deviate from reality for rare events.
- A **comparative approach** between different simulations was adopted to determine critical parameters that affect the experimental sensitivity.

The Simulated Setup

Homogeneous $PbWO_4$ crystals **ECAL**

- Fast scintillation time ($\sim$ 20 ns)
- High density ($\sim$ 8.3 g/cm^3)
- Strong radiation hardness
- Segmentation allows shower-shape studies to reject backgrounds



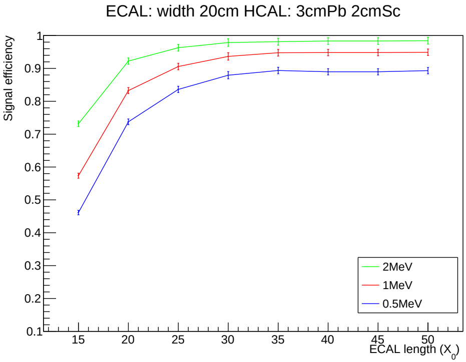


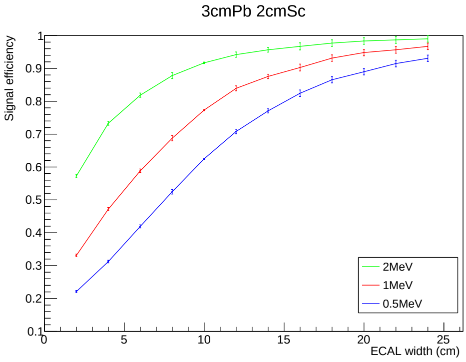
Sampling **hadronic calorimeter** (Sc + Pb)

- Plastic scintillator is divided into tiles
- Covering all the target's faces
- Modular design

Signal simulation: ECAL Geometry

- **Signal efficiency** ($E_{miss} > 5$ GeV, veto not activated) as a function of the target geometry.
- HCAL geometry and energy thresholds moderately affect the results.

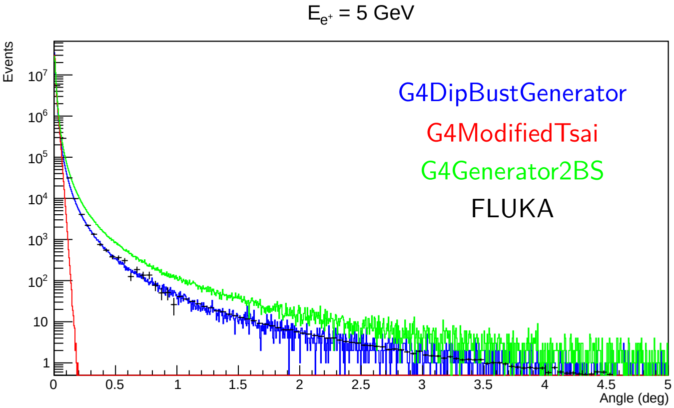




- ECAL length $\simeq 35X_0$, width 20×20 cm^2 $\rightarrow$ Signal efficiency $\sim 90\%$

Background Simulations: EM Events - Large-Angle Bremsstrahlung

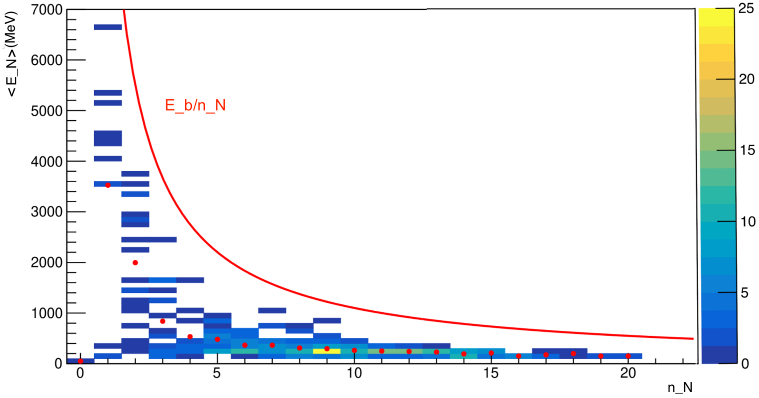
- In $\sim 50/10^{10}$ EM shower simulation, an **energetic photon** is emitted **backward** ($E_\gamma > 2$ GeV, $\theta > 90^\circ$), escaping from the target.
- A cavity in the target can shift the beam impact point inside the calorimeter.



- Few experimental data available → **MC depend on assumptions in the implementation**.
- Experimental **measurements are needed** to investigate this background.

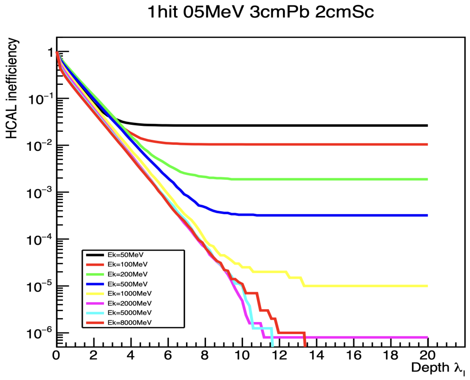
Background simulations: Neutral Hadronic Events - Sampling

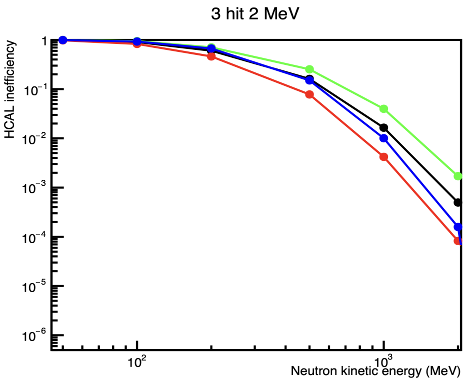
- ECAL simulation $\rightarrow$ we selected critical **neutral hadronic events**:
  - $E_{Miss} > 5$ GeV
  - No charged particles exit the ECAL with kinetic energy > 500 MeV
- Average kinetic energy of escaping neutrons (K_L) as a function of their multiplicity:



Background simulations: Neutral Hadronic Events - Inefficiency

- HCAL simulations → **veto inefficiency** for a single, neutral hadron
- Different geometries (layers thickness), veto conditions (energy threshold, number of hits) and MC physics lists were tested

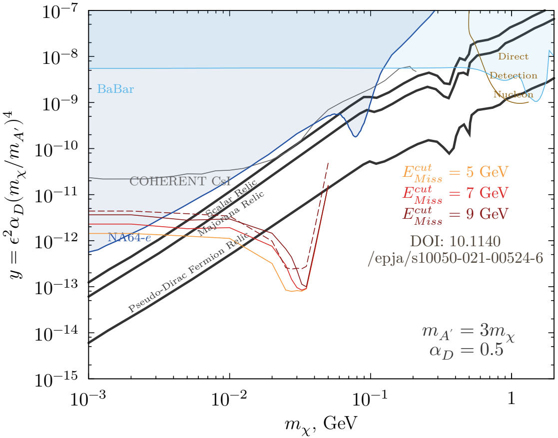




- HCAL length $\simeq 20\ \lambda_I$, **few MeV veto threshold** → Expected bkg < 1

Estimated Sensitivity (90% CL)

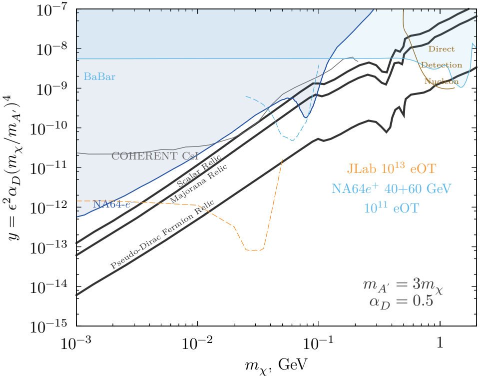
- 11 GeV e^+ beam
- 10^{13} POT
- E_{Miss}^{CUT}: 5 GeV, 7 GeV,9 GeV
- Signal efficiency $\sim$ 90%
- No background events
- A' produced only through the resonant annihilation channel



- **Starting point:** further steps forward must be based on experimental measurements.
- The construction a **modular detector** will necessarily proceed in steps.
- MC will be **tuned with experimental results** starting from low-statistics, preliminary runs.

Conclusions

- Positron resonant annihilation is a powerful mechanism to search for vector-mediated LDM. Fixed-target missing-energy experiments can fully exploit this production process.
- The **POKER project** aims to perform an optimized LDM search with e^+ beams at CERN SPS, within the NA64-e experimental context
    - A new improved active target, to be included in the NA64-e detector, will be soon tested on beam (summer 2025)
    - Preliminary measurements performed with the current NA64-e apparatus support the feasibility of a post LS3 program with multi-energy e^+ beams
- We performed a **conceptual design study** for a missing-energy experiment, searching for LDM with an **11 GeV positron beam at JLAB**.
    - This study represents a first confirmation of the potential and feasibility of such project



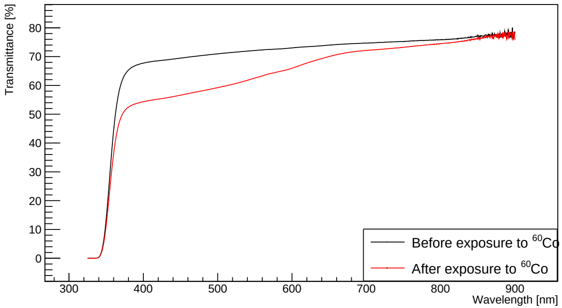
Backup Slides

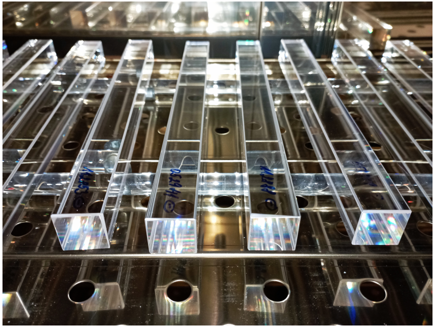
PKR-Cal R&D - radiation tolerance

- Radiation dose during PKR-Cal operation estimated via FLUKA simulations
- Maximum dose in the central crystal at $\sim 9X_0$ depth: 200 $\mathrm{rad/h}$ (dose for CMS $PbWO_4$ calorimeter: $\sim$ 500 rad/h)
- Crystals exposed to $\sim$ 30 Gy from $^{60}\mathrm{Co}$ at the "Strahlenzentrum" (Gießen), to assess radiation tolerance (loss in transparency).

Mitigation Strategies

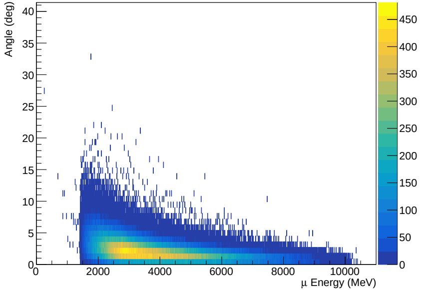
- Most radiation-tolerant crystals placed in the center of the PKR-Cal
- Beam rastering
- Monitor transparency with laser system
- Crystals annealing

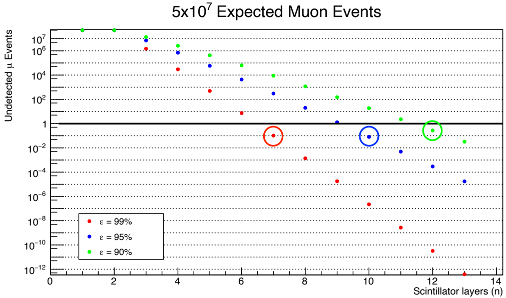




Background: Muon Pair Photoproduction

Cross-section biasing: collected statistics equivalent to 10^{12} POT.





- $\sim$ 1 event every 10^6 POT
- Muons mostly produced at forward angles

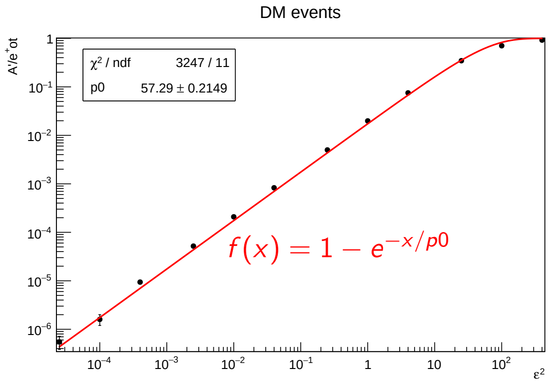
- Analytical calculation to evaluate the required veto layers
- n $\sim$ 12 results in less than 1 background event for 10^{13} POT

12 GeV Ce^+BAF : Polarized Electron or Polarized Positron Beams

Machine Parameter	Electrons	Positrons
Hall Multiplicity	4	1 or 2
Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 µA	> 1 µA
Polarized Intensity	170 µA	> 50 nA
Beam Polarization	> 85%	> 60%
Fast/Slow Helicity Reversal	1920 Hz/Yes	1920 Hz/Yes

Signal Simulation: Cross-Section Biasing

- We implemented the χ, A' particles and their interactions in GEANT4 code.
- **Best** ε^2 **value** (DM-SM coupling) in Monte Carlo: minimizes computational time without distorting the simulations of Standard Model processes.



A' produced per positron on target vs ε^2:

- $\varepsilon^2 \ll p0$ linear region.
- $\varepsilon^2 \gg p0$ asymptotic region.
- $\varepsilon^2 = 1$ was set to perform the signal efficiency studies.