Light Dark Matter Search with a Positron Beam at Jefferson Lab

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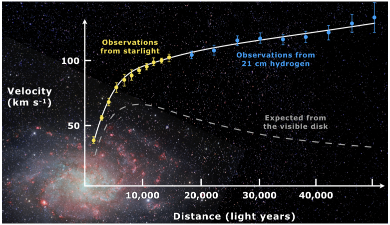
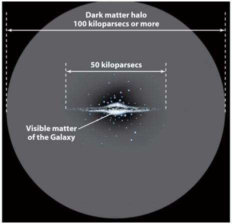
Why Dark Matter?

- Astrophysical and cosmological measurements suggest the existence of Dark Matter.
- What is it composed of? How does it interact with ordinary matter?

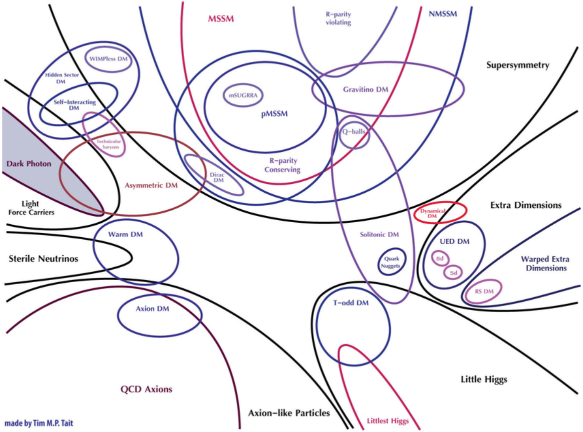




The Dark Matter

- Experimental observations do not allow us to constrain the nature of Dark Matter particles.
- There are several theoretically well-grounded models.

- WIMPs
- Axion-Like Particles
- Dark Sector
- Sterile Neutrino

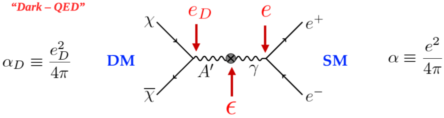


The Dark Photon

I focused on a Light Dark Matter theory ($m_\chi < 1$ GeV) that introduces a new massive vector mediator called Dark Photon (A').

Model parameters:

- Masses $m_{A'}$, m_χ
- Coupling ϵ $A' \leftrightarrow \gamma$
- Coupling α_D $A' \leftrightarrow \chi$



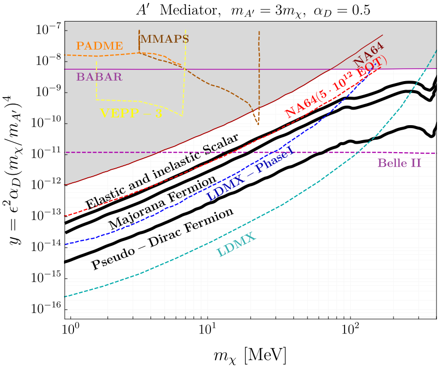
- Direct annihilation cross section (DM + DM $\rightarrow$ SM + SM) : $\sigma v \propto \frac{y}{m_\chi^2}$,

  $y \equiv \alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4$
- Dark Matter density measurement $\rightarrow$ Estimation of $< \sigma v >$ $\rightarrow$ Relation between y and m_χ $\rightarrow$ Expected curve in LDM parameter space

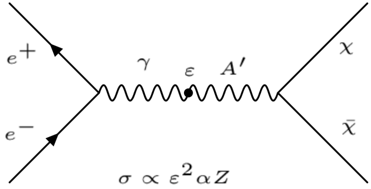
Accelerator-based experiments

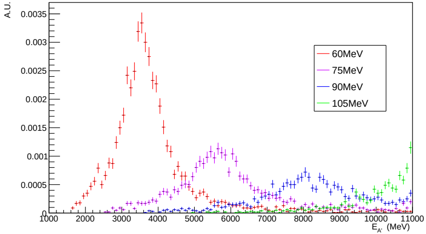
Complementary approach to direct search: production of LDM particles through Dark Photon decay at accelerators.

- The high-energy experiments sensitivity is not significantly affected by the theory details.
- **Experiments at accelerators** can test multiple LDM models simultaneously.
- Controlled environment allows optimised studies in certain regions of the parameter space.



A' production via e^+ beam impinging on a fixed target





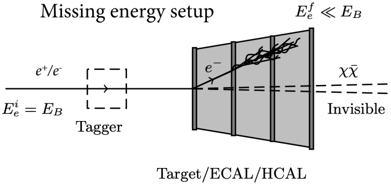
Resonant annihilation process

$$e^+e^- \rightarrow A' \rightarrow \bar{\chi}\chi$$

- Most intense production channel
- The cross section presents a Breit-Wigner distribution
- Resonance energy: $E_R = \frac{m_{A'}^2}{2m_e}$

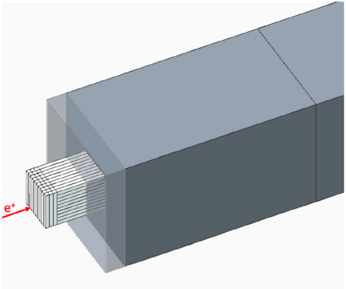
Experimental technique

The produced A' decays into $\chi\bar{\chi}$ which escape from the target without interacting.
$\rightarrow$ **Missing energy measurement**.



- **Setup:** positrons impinging on a thick active target. ECAL
- **Thick target:**
  - Electromagnetic shower
  - Secondary positrons ($E_{e^+} < E_{Beam}$)
  - Large $m_{A'}$ range exploration
- **Active target:**
  - Measure the energy deposited by each impinging positron (E_{Dep})
  - $E_{Miss} \equiv E_{Beam} - E_{Dep}$
- **Current:** limited to reduce pile-up effects

Experimental technique

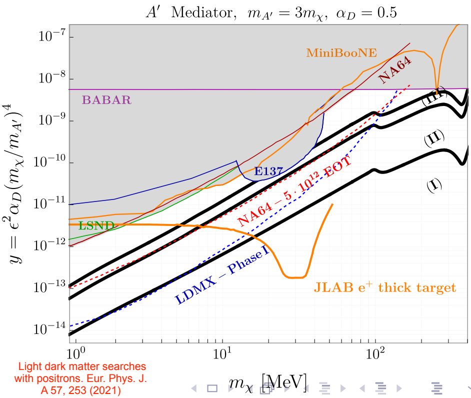


- **Signal:** events with high missing energy
  - Threshold $E_{MISS}^{CUT} \sim E_{Beam}/2$
- **Backgrounds:** events with high energy particles leaving the detector (μ, π, n, K_L)
  - External veto: HCAL

JPOS: proposal for a physics program based on e^+ at JLAB.

JPOS-LDM:

- Beam: e^+ 11 GeV
- Statistic: $1e^+/\mu s \times 1y = 10^{13}$ POT
- I performed a preliminary semi-analytical evaluation of the sensitivity, zero background



Light dark matter searches with positrons. Eur. Phys. J. A 57, 253 (2021)

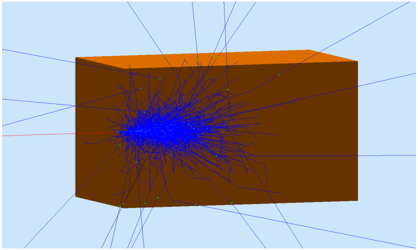
Goal of the analysis

- **Objective:** feasibility study and setup optimization through Monte Carlo simulations of signal and background.
- **Computational limitations**. Long computation time makes it critical to simulate $\sim 10^{13}$ events.
  - I used **extrapolations** and **multi-step simulations** to estimate the expected number of background events.
- **Simulation precision**. The description of some phenomena within the code is approximate and may deviate from reality (high statistic, single event study).
  - **Comparative studies**. Comparison of different simulations to determine the experiment **critical parameters** that significantly affect the experimental sensitivity.

ECAL and signal efficiency

JPOS-LDM active thick target:

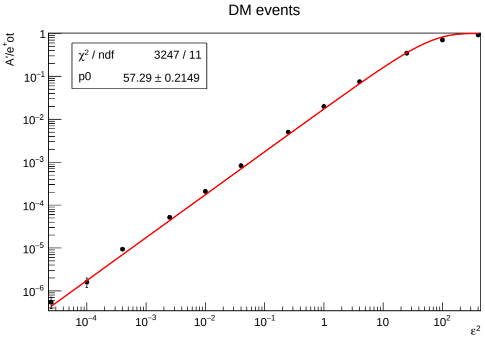
- Fast response time → Reduces pile-up effects
- Large volume → Full electromagnetic shower absorption
- High density material → Compact detector



- $PbWO_4$ crystals
  - Fast scintillation time ($\sim$ 20 ns)
  - High density ($\sim$ 8.3 g/cm^3)
  - Strong radiation hardness
- Signal events simulation → ECAL geometry optimization

Signal simulation: coupling/linearity

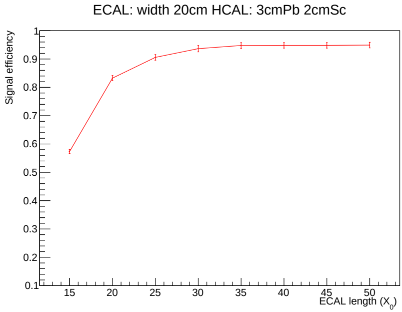
- I implemented the χ and A' particles and their production into the GEANT4 code.
- I chose best ε^2 parameter to perform signal simulations (cross section biasing).

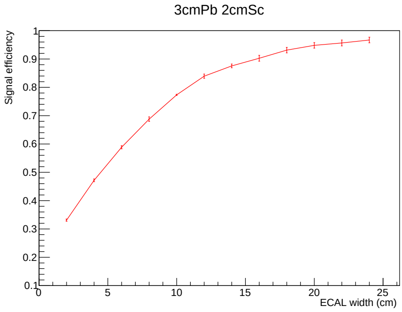


- $\varepsilon^2 \lesssim 1$, **linear region**.
- $\varepsilon^2 \gg 1$, **asymptotic region**.
- I set $\varepsilon^2 = 1$ to perform the ECAL geometry study.

Signal simulation: ECAL geometry

- Signal efficiency as a function of target geometry.

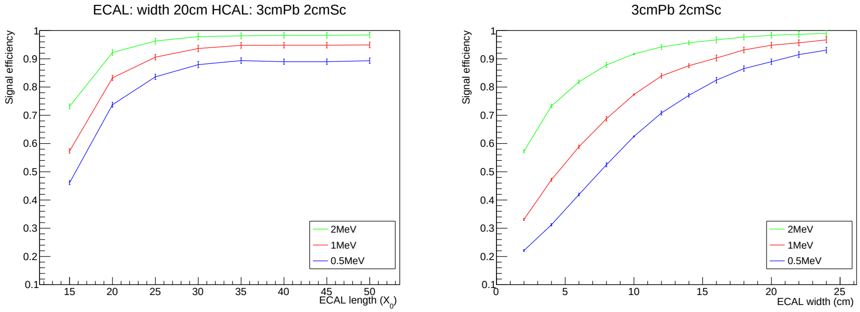




Length $\simeq 40X_0$, width 20×20 cm^2 $\leftrightarrow$ Signal efficiency $\sim 90\%$

Signal simulation: ECAL geometry

- Signal efficiency as a function of target geometry.
- Veto parameters moderately affects the results.

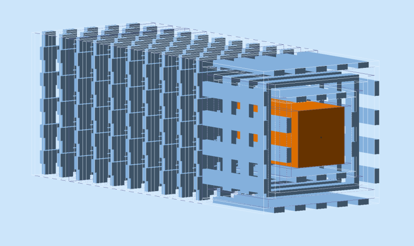


Length $\simeq 40X_0$, width 20×20 cm^2 $\leftrightarrow$ Signal efficiency $\sim 90\%$

HCAL and background rejection

The external veto detects energetic particles escaping from the target.

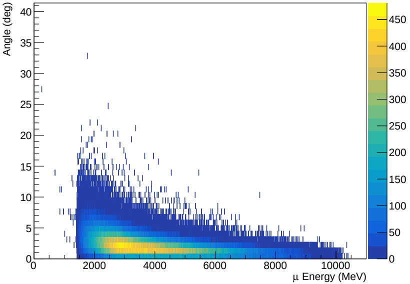
- **High hermetic veto** $\rightarrow$ Detects long-lived neutral hadrons (n, K^0_L) and penetrating particles ($\mu^{\pm}$, $\pi^{\pm}$).
- **Fast response time** $\rightarrow$ Measurement in coincidence with ECAL
- **Compact design** $\rightarrow$ Minimise total detector size.

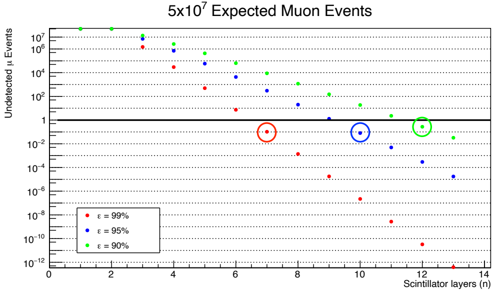


- Sampling hadronic calorimeter
- Lead (Pb) + Plastic scintillator (Sc)
- Background simulations $\rightarrow$ Veto design optimisation

Background simulations: muon pair photo-production

Dedicated simulation with cross section biasing.
Collected statistic is equivalent to 10^{12} POT.



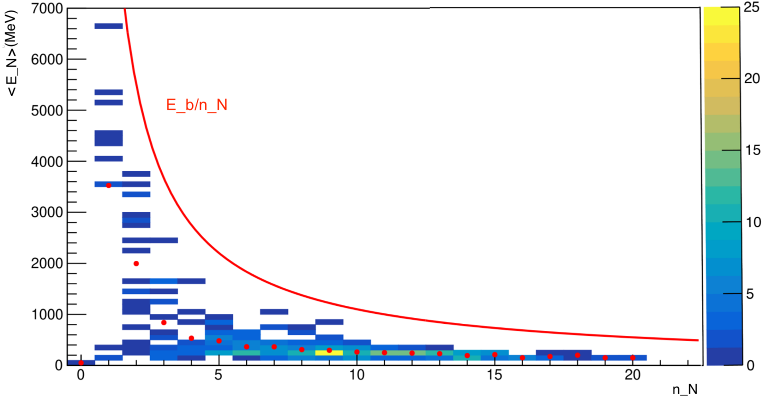


- $\sim$ 1 event every 10^6 POT
- Muons mostly produced at forward angles

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

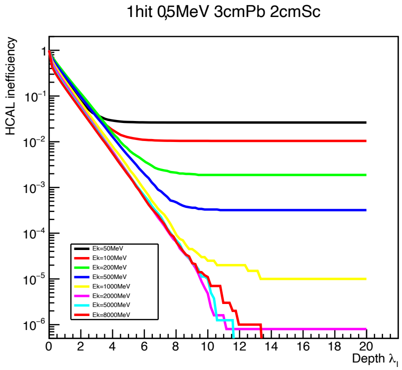
Background simulations: hadrons, ”neutral events” - Sampling

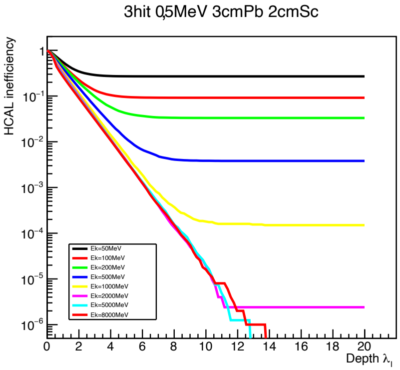
- I selected most the critical background events:
  - $E_{Miss} > 5$ GeV
  - No charged particles leaving the ECAL with kinetic energy greater than 500 MeV
- I computed the average kinetic energy of the **neutral hadrons** (n, K_L) as a function of their multiplicity.



Background simulations: hadrons, ”neutral events” - Inefficiency

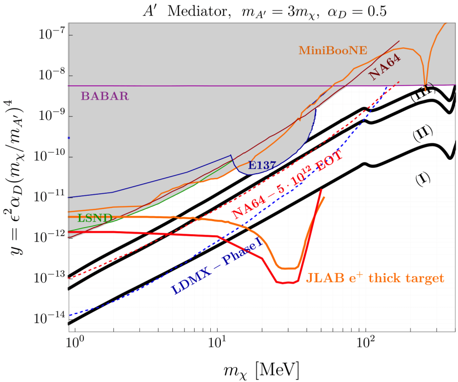
- Only HCAL simulations → Veto inefficiency for a single neutral hadron
- Sampling → Total veto inefficiency, expected background events
- I studied different geometries (layers thickness) and measurement conditions (thresholds, number of hits) → Critical parameters and setup optimisation





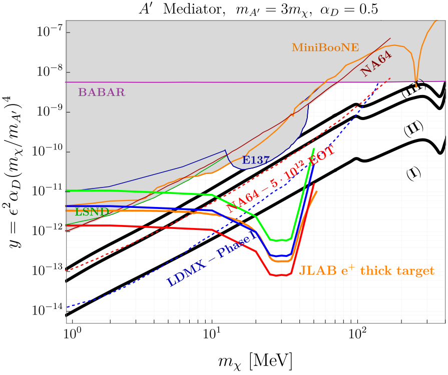
Sensitivity (90% CL)

- 10^{13} POT
- $E_{Miss}^{CUT} = 5$ GeV
- Signal efficiency $\sim$ 90%
- There is a set up in which expected background events = 0
  - Layers thickness: 3 cm Pb + 2 cm Sc
  - Hit HCAL: 1
  - Threshold Sc tile: 0.5 MeV

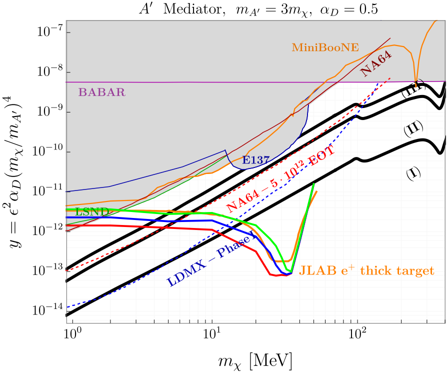


Sensitivity: systematic studies

- E_{Miss}^{CUT}: 5 GeV
- 0, 10, 100 background events



- E_{Miss}^{CUT}: 5 GeV, 7 GeV, 9 GeV
- 0 background events



Conclusions

- **LDM** theories can be efficiently studied with experiments at **accelerators**.
- Thanks to the resonant annihilation process, positron-beam missing energy experiments play a unique role in this field.
- JPOS-LDM is the **first experiment** that searches for LDM through this technique in the multi-GeV energy range.
- The construction of the detector will necessarily proceed in stages (low statistics, modular detector a-la-NA64).
- I determined the **critical parameters** affecting experiment sensitivity.
- This work has **confirmed the JPOS preliminary results** and represents the **starting point** for a possible future implementation of the experiment.