Search for Light Dark Matter with POKER

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European Research Council

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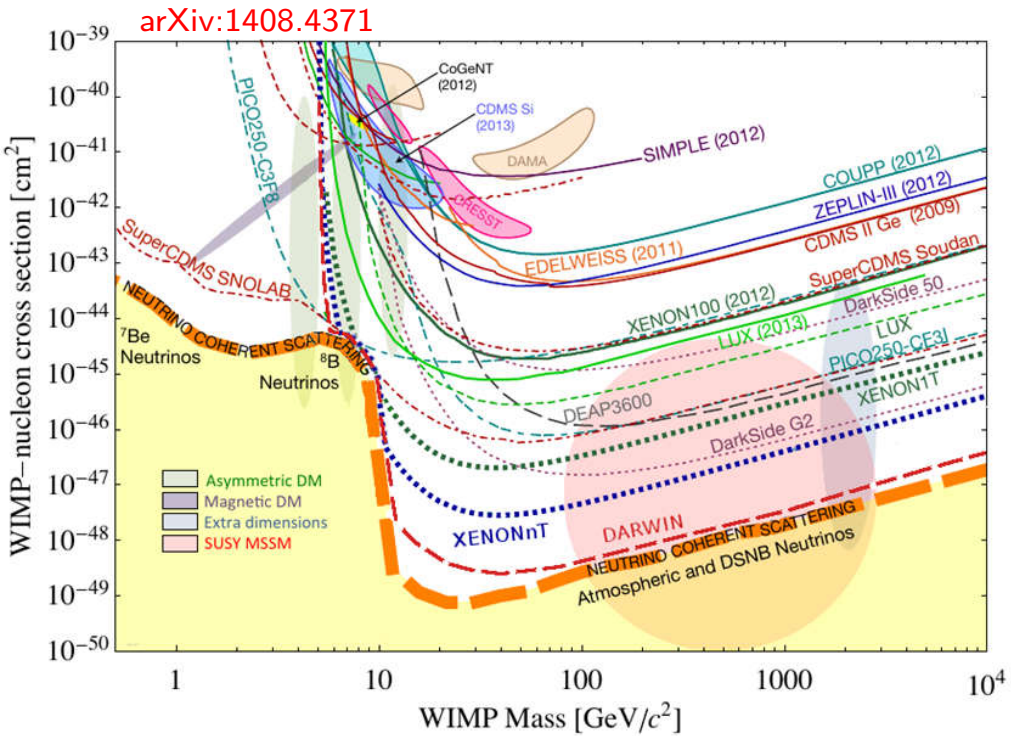
Outline

The dark matter search

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

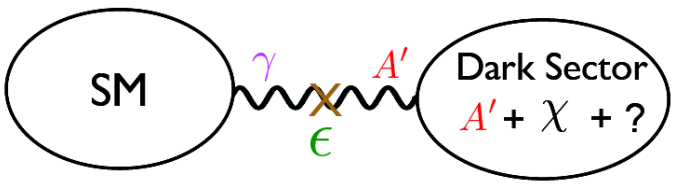
- "WIMP miracle:" electroweak scale masses ($\simeq$100 GeV) and DM annihilation cross sections (10^{-36} cm^2) give correct dark matter density / relic abundances. No need for a new interaction!
- Intense experimental program searching for a signal in this mass region. So far, no positive evidences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



Light dark matter

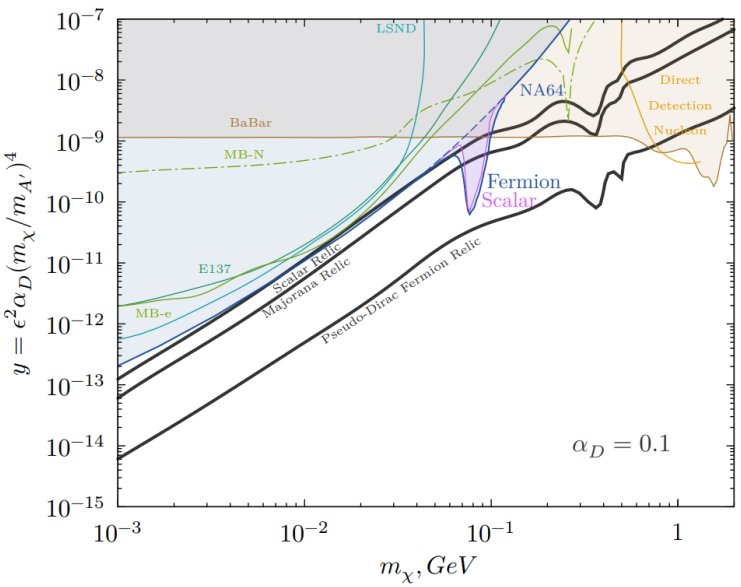
The light dark matter hypothesis can explain the observed relic abundance, **provided a new interaction mechanism between SM and dark sector exists**[1]

- 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 ($\alpha_D \equiv g_D^2/4\pi$)



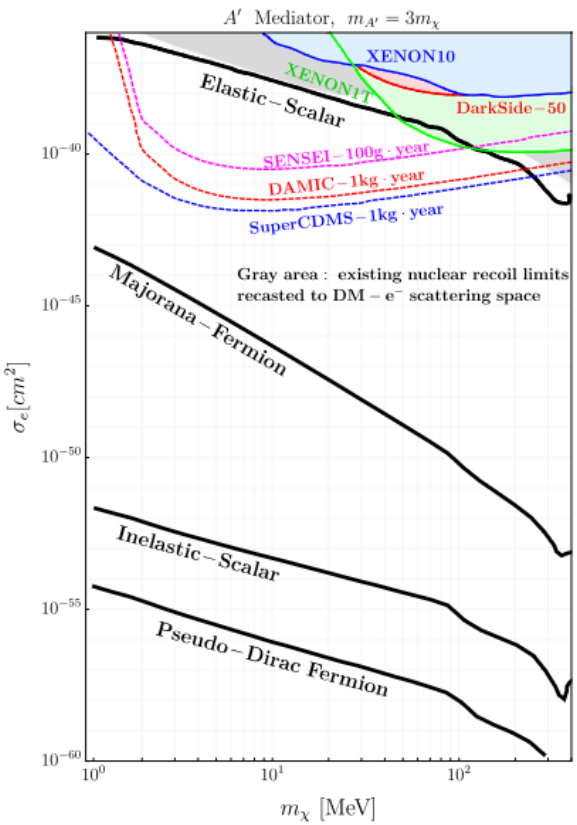
Experimental searches:

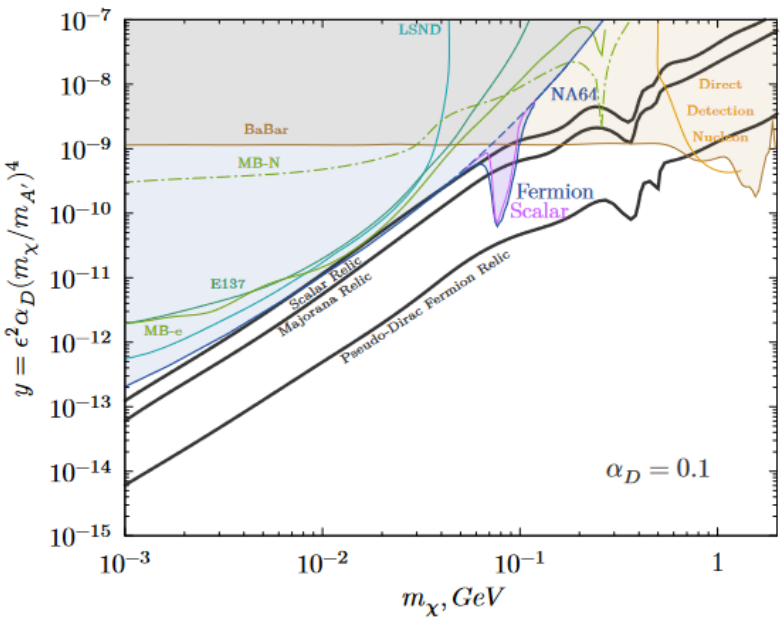
- A comprehensive LDM experimental program must investigate **both** the existence of χ particles and of dark photons
- Experiments at accelerators at the *intensity frontier* are particularly suited to explore this paradigm

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

Light dark matter search at accelerators

- Direct DM searches are typically focused one the > 1 GeV masses, have lower sensitivity in the sub-GeV mass range
  - $E_R \propto 2v^2 M_\chi^2 / M_N$, $v \simeq 3 \cdot 10^{-4} c$
  - Ongoing effort to overcome these limitations (e.g.: $\chi - e^-$ scattering).
- The low-energy LDM-SM interaction is strongly dependent from the DM velocity, with significant σ reduction depending on the details of the model





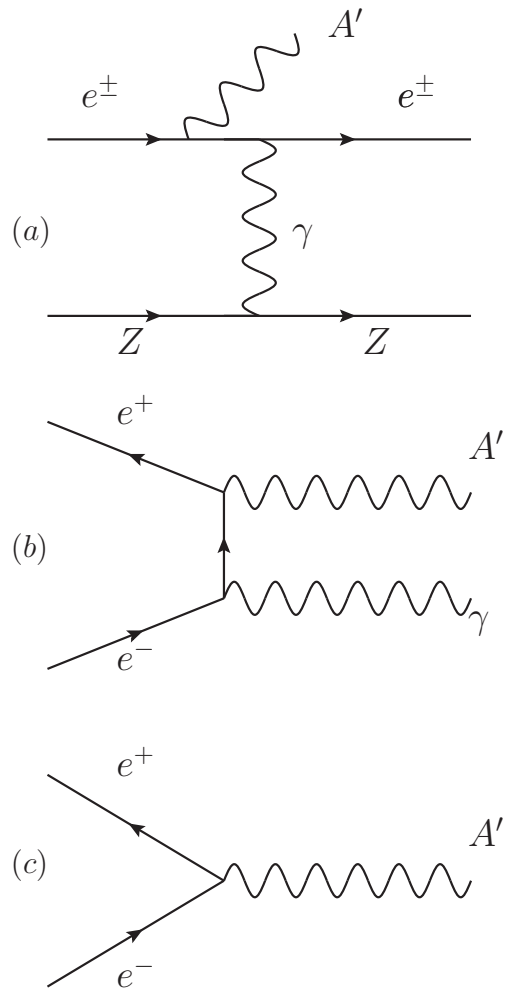
Dark photon production mechanisms with lepton beams

Three main production mechanisms with $e^+ - e^-$ beams:

(a) **A'-strahlung**
- Radiative A' emission in nucleus EM field
- forward boosted, $Z^2\alpha_{EM}^3$ scaling

(b) **Non-resonant e^+e^- annihilation**
- Forward backward emission in the CM frame
- $Z\alpha_{EM}^2$ scaling

(c) **Resonant e^+e^- annihilation**
- Resonant, Breit-Wigner like cross section with $M_{A'} = \sqrt{2m_eE}$
- $Z\alpha_{EM}$ scaling
- Most efficient LDM production process for given kinematics[2]



[2] L. Marsicano et al., Phys. Rev. Lett. 121 (2018) 041802.

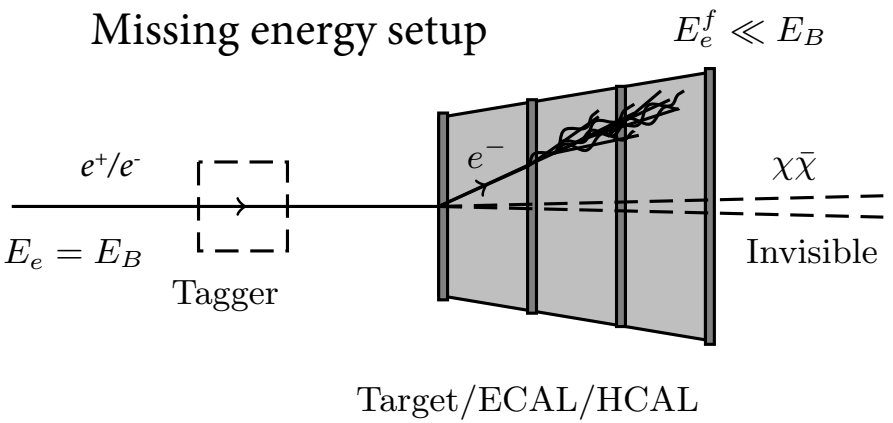
Fixed *active* thick-target LDM searches: missing energy experiments

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

Missing Energy Signature

- Specific beam structure: impinging particles impinging "one a ta 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

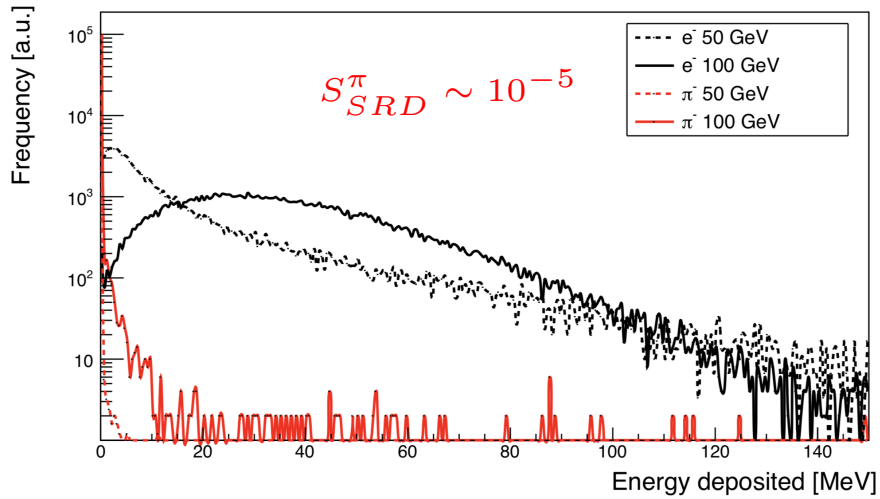


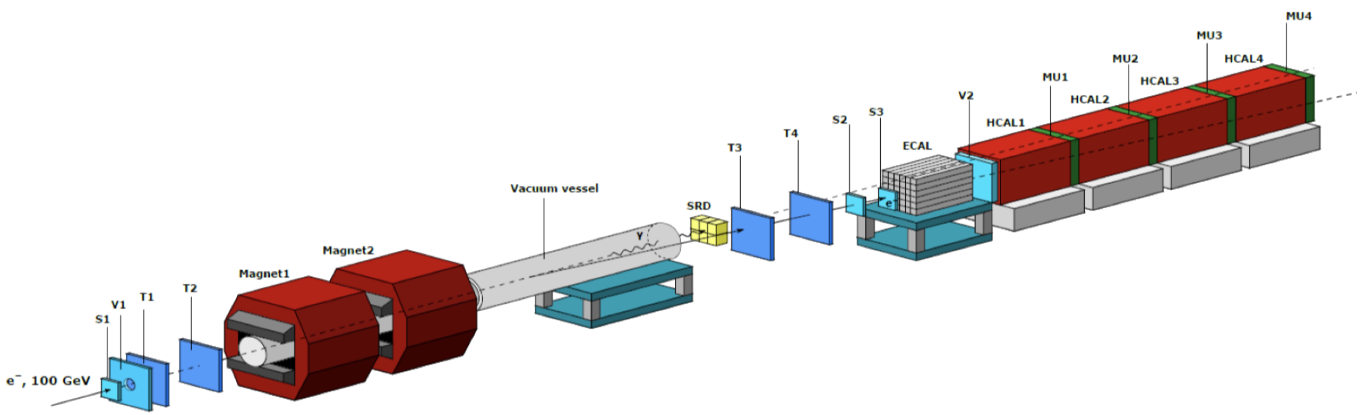
NA64 Experiment

Missing energy experiment at CERN North Area H4 line - 100 GeV e^- beam[3]
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





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

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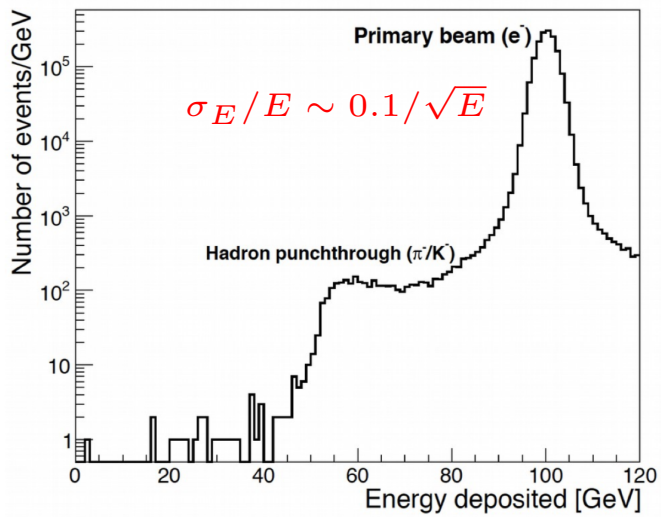

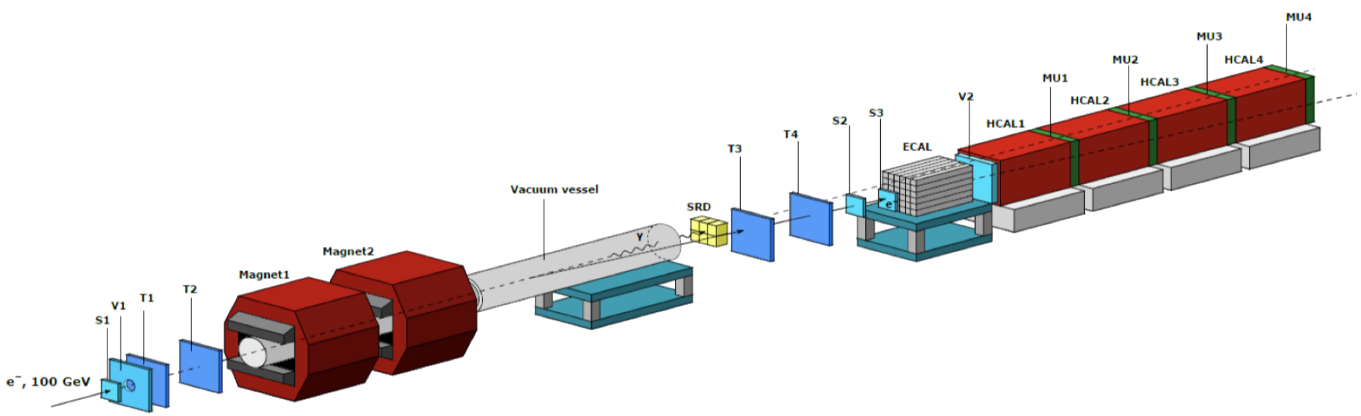

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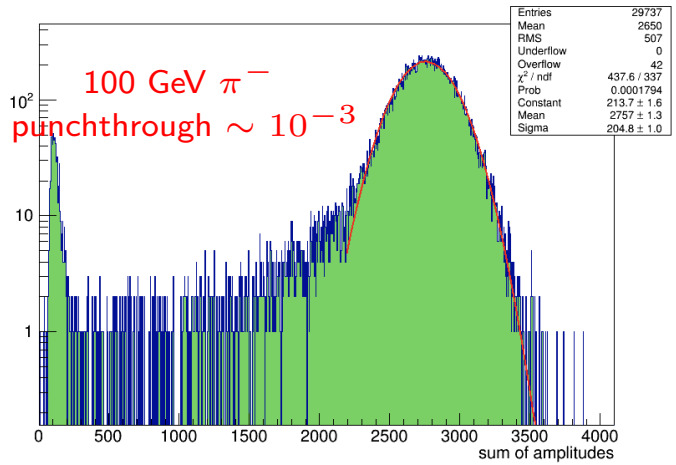

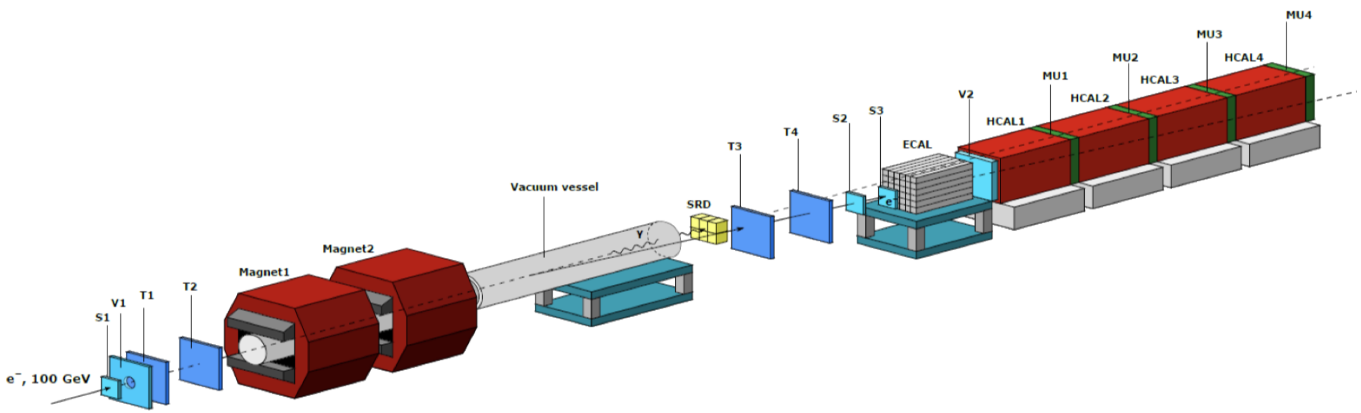

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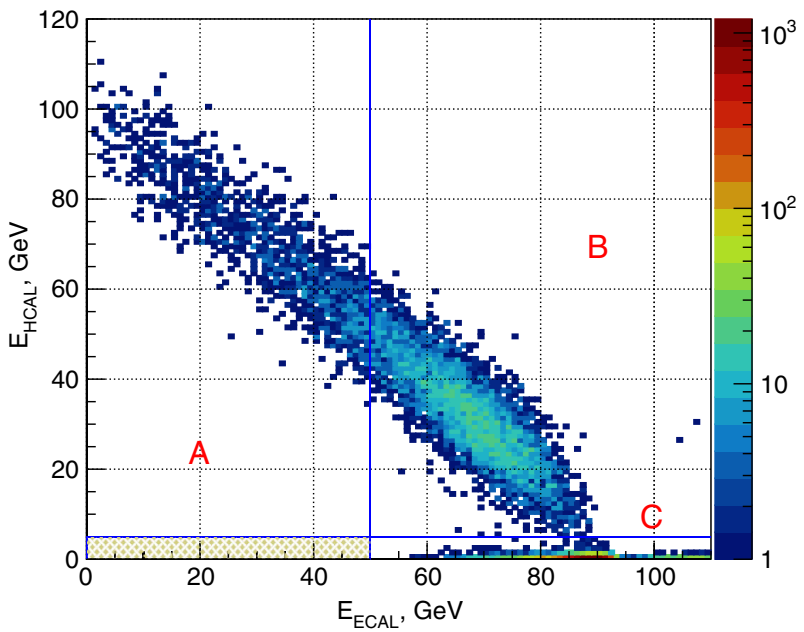
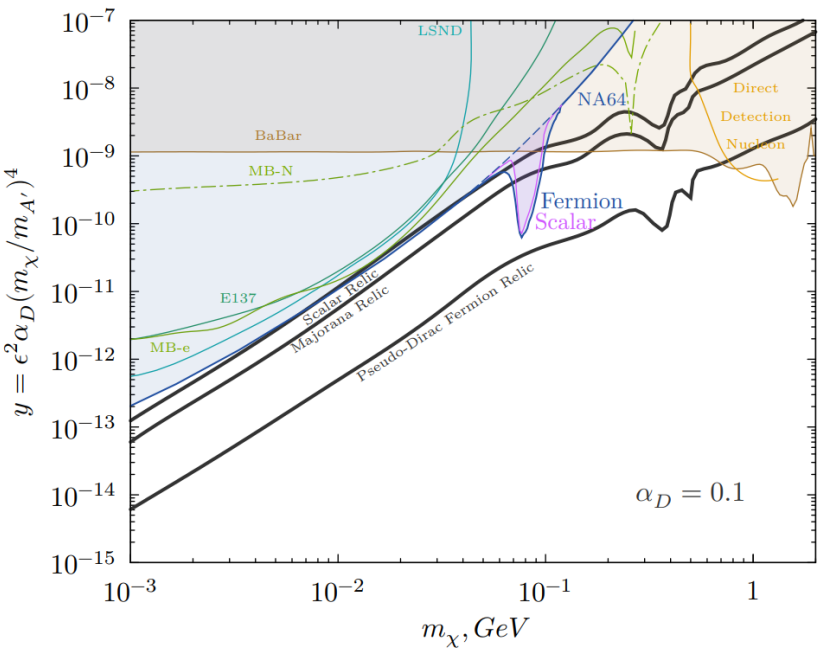
NA64$-e$ results

- NA64 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 ~ 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 ongoing.



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

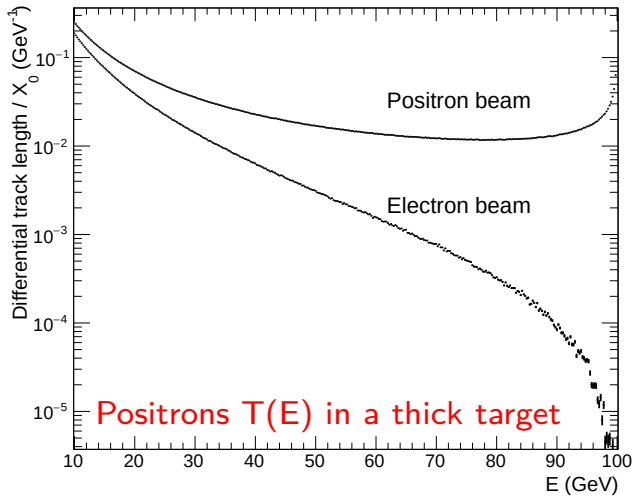


POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

An optimized light dark matter search with positrons in the NA64 framework[4]

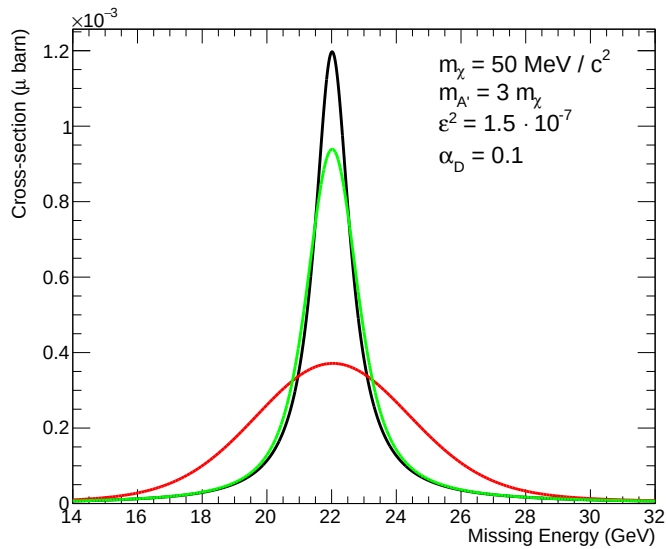
Signal production reaction: $e^+e^- \to A' \to \chi\overline{\chi}$

- 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 preliminary missing energy measurement with a positron beam, using a new **high resolution detector ($PbWO_4$ calorimeter)** replacing the existing NA64 ECAL
- Demonstrate the technique and set the basis of the first **optimized** light dark matter search at a positron-beam facility



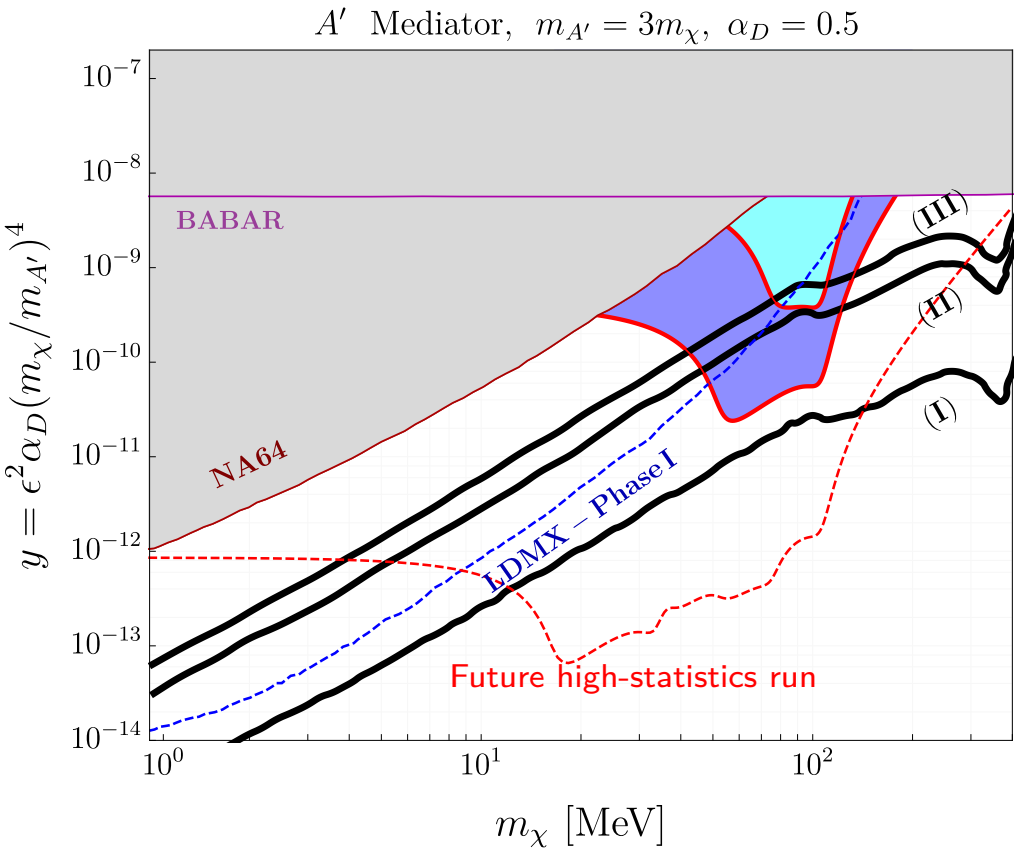
[4] Project funded by ERC grant

POKER sensitivity to LDM

Pilot run sensitivity - 0 bck

Pilot measurement at the H4 beamline with 100 GeV e^+ beam[5]

- **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



[5] Currently discussing within NA64 and SPSC to possibly run the pilot measurement in 2024

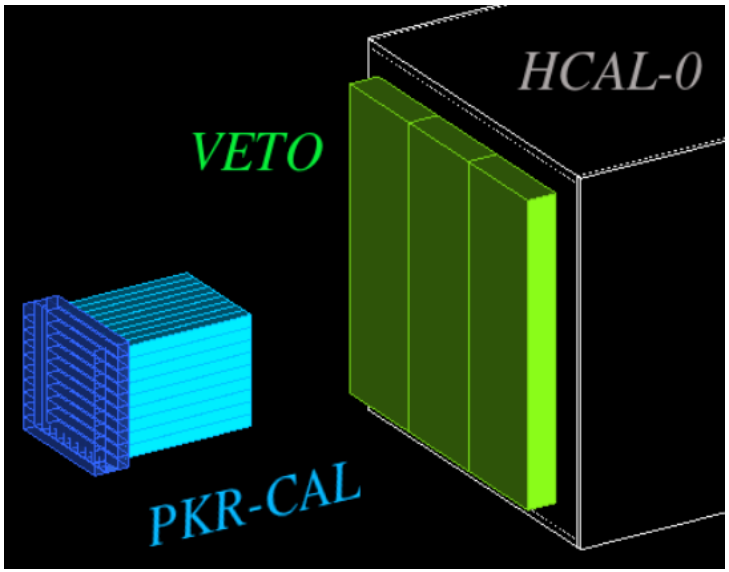
POKER: Active Target

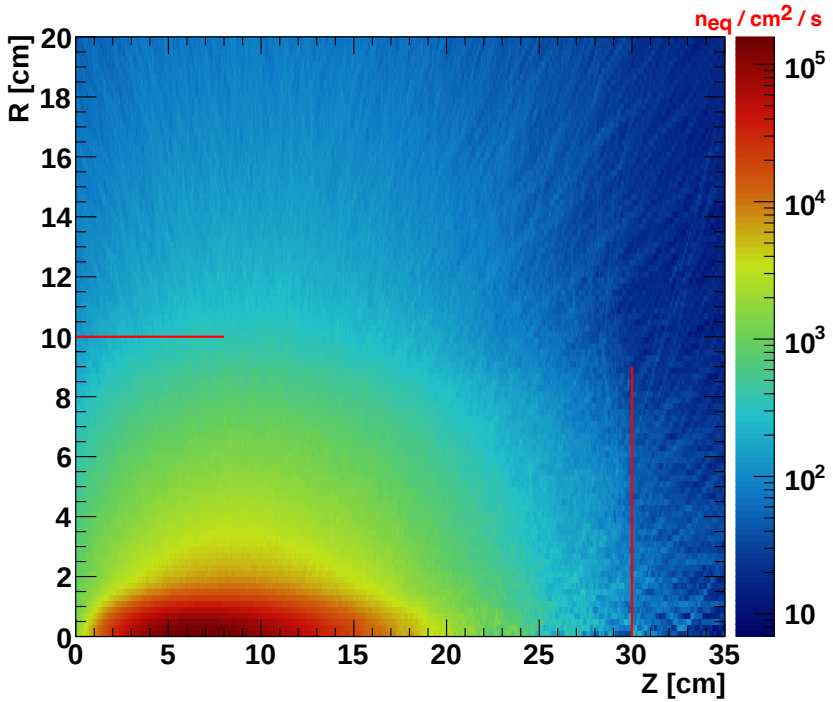
Calorimeter in $PbWO_4$ crystals, SiPM readout

- 9×9 matrix of $20 \times 20 \times 220$ mm^3 with 4-layers pre-shower ($20 \times 20 \times 20$ mm^3 crystals): total 33.7 X_0
- Energy resolution: $\frac{\sigma_E}{E} \sim 2.5\%/\sqrt{E} \oplus (0.5 \div 1)\%$
- $LY \sim 2.5\,\mathrm{phe}/MeV$: 4x SiPM 6x6 mm^2, 10 μm cell.

Critical aspect: radiation damage

- EM dose up to 200 $\frac{\mathrm{rad}}{\mathrm{h}}$ (CMS ecal max 500 $\frac{\mathrm{rad}}{\mathrm{h}}$)
- Possible solutions: Light induced annealing, beam-spot rastering
- $\phi_n \leq 10^3$ n_{eq} $cm^{-2}s^{-1}$ - no significant effect expected



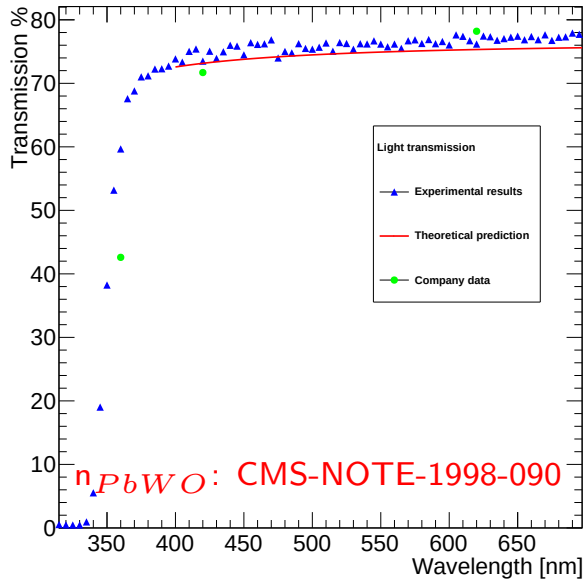


$PbWO_4$ crystals characterization

Characterization campaign of crystal samples from Crytur

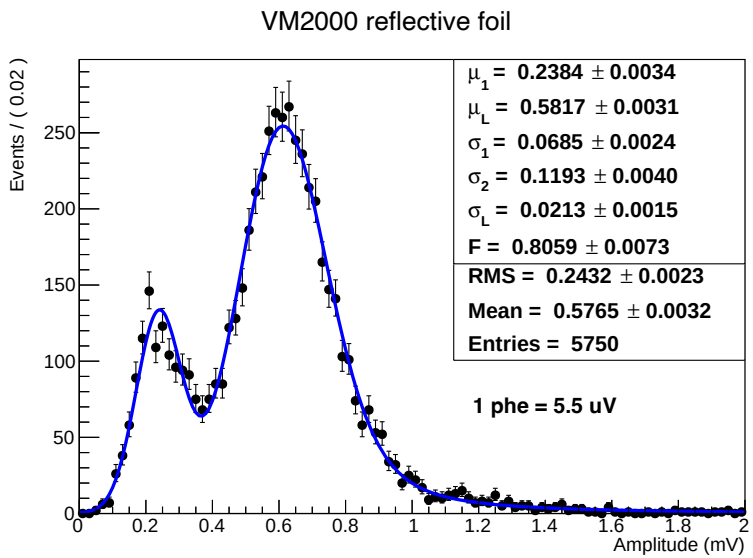
Longitudinal transmittance

- Measurement performed with spectrophotometer (CERN, Crystals Clear lab)
- Results: $T > 70\%$ at $\lambda = 450$ nm for all tested samples



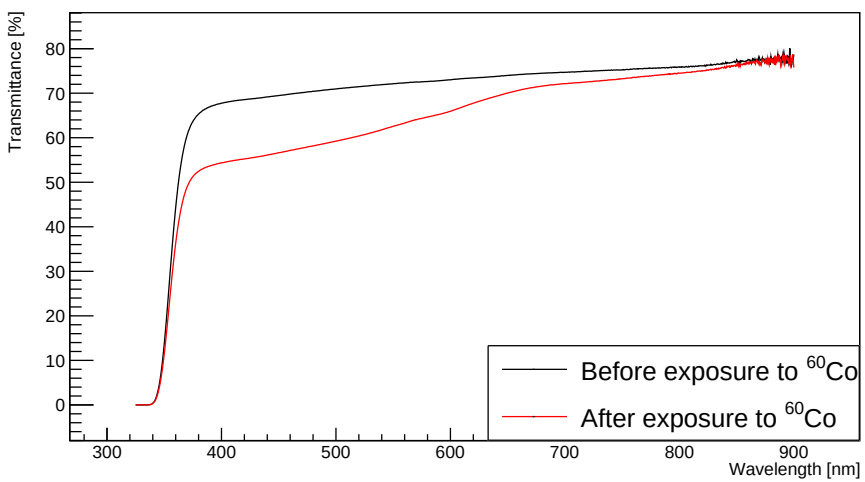
Light Yield

- LY measurement with cosmic rays: telescope with plastic scintillator counters, thermostated crystals ($18°$)
- Readout: 4x S14160-6010 SiPM (6x6 mm^2, 10 μm pixel size)
- Single phe amplitude measured with laser pulser
- Resulting LY $\simeq 5\ phe/MeV$



$PbWO_4$ crystals- radiation hardness characterization

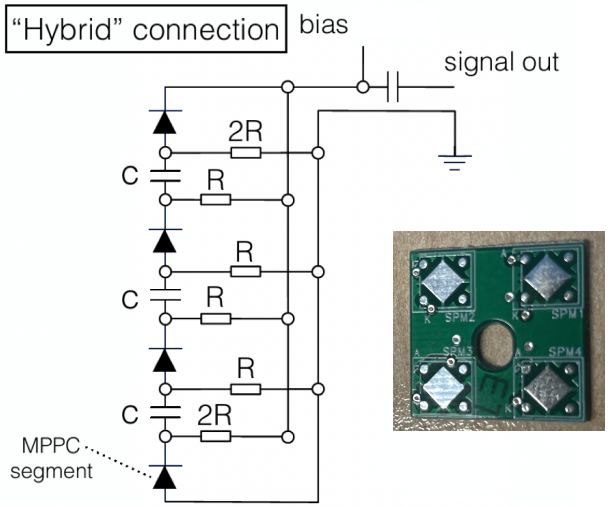
- 90x $2 \times 2 \times 22$ cm^3 crystals and 45x $2 \times 2 \times 20$ cm^3 crystals tested at the "Strahlenzentrum" of Gießen
- crystals exposed to intense ^{60}Co radioactive source - **absorbed dose: ∼30 Gy**
- Light transmission measured with Hitachi spectrophotometer before and after exposure; evaluated radiation damage $d_k = \frac{1}{L} \cdot \ln \frac{T_{\text{before}}}{T_{\text{after}}}$
- 20-cm crystals compatible with Crytur specifications, 22-cm crystals slightly worse -"best" crystals selected for the core of the POKER active target

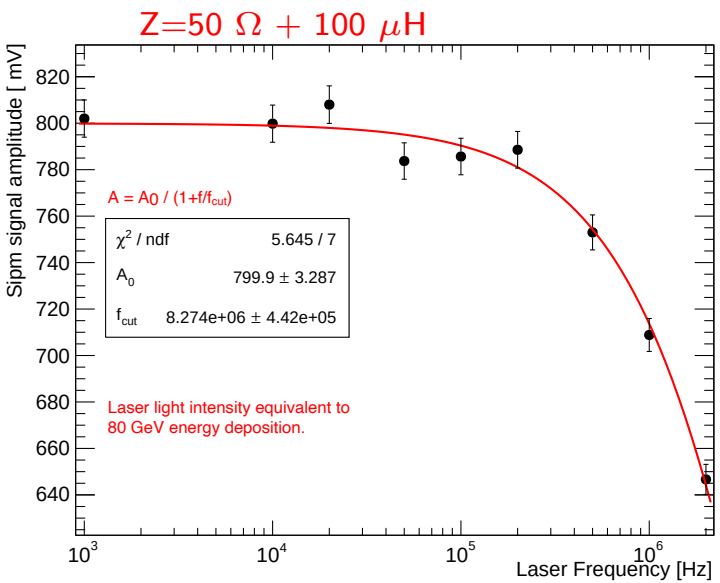


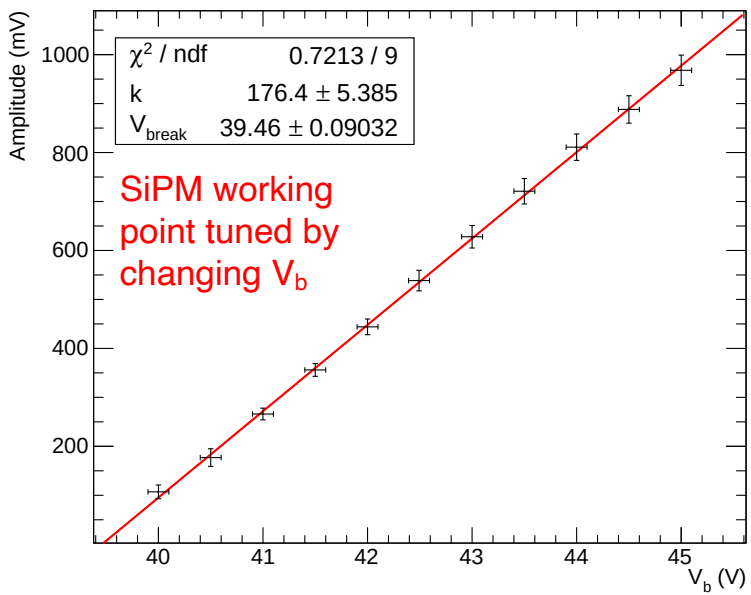
Crystals annealed in oven after the characterization

Light readout: SiPMs

- POKER readout: 4 SiPMs per crystal. 10 μm pixel size to mitigate saturation effects
- Custom HV supply chain to minimize gain variations due to bias current. Ad-hoc PCB design.







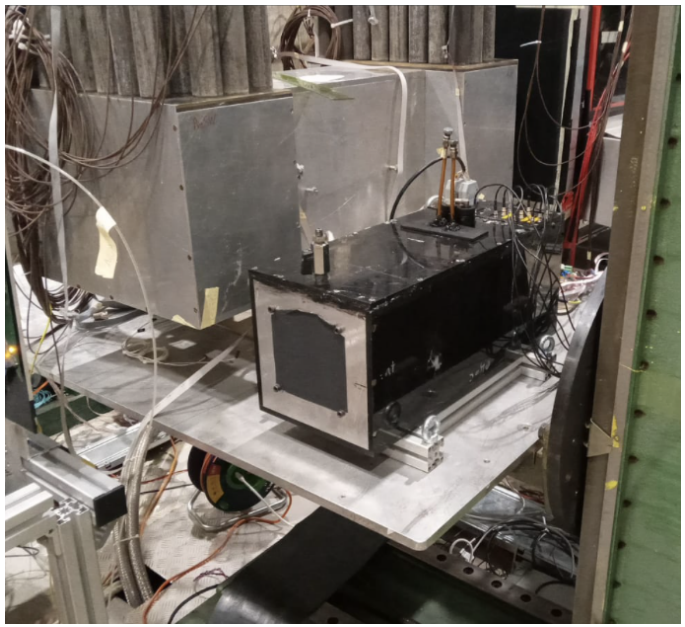
The POKERINO prototype

POKERINO: 3×3 crystals prototype, readout by SiPMs, to validate design and technical solutions adopted for the POKER active target (mechanics, light readout, electronics) and evaluate performance

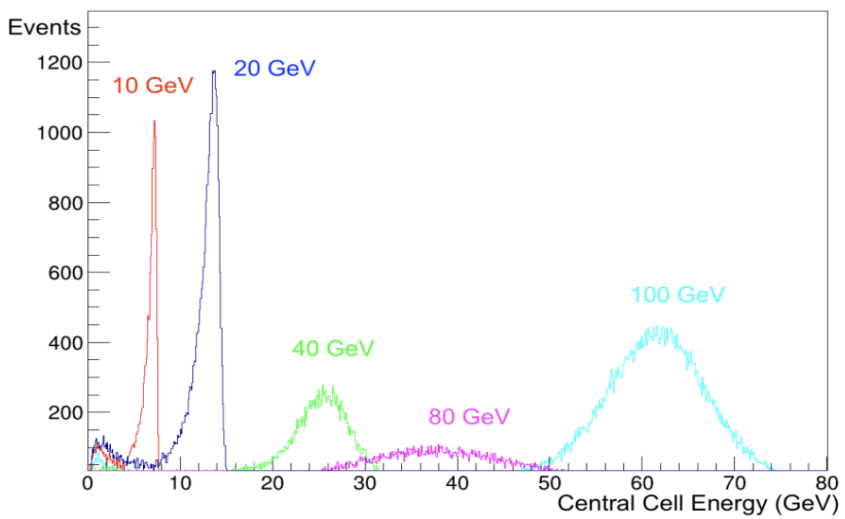
Performed tests:

- LY measurements and response uniformity tests with cosmic rays @INFN-Genova (EEE setup)
- Summer 2022: first measurement on beam at CERN H4 (4h test, courtesy of NA64) → critical effect of power supply (CAEN A1539P), when SiPMs are operated with high-frequency stochastic pulses

Future tests: summer 2023, 1 week dedicated measurement at CERN H8



Different current for each beam energy value

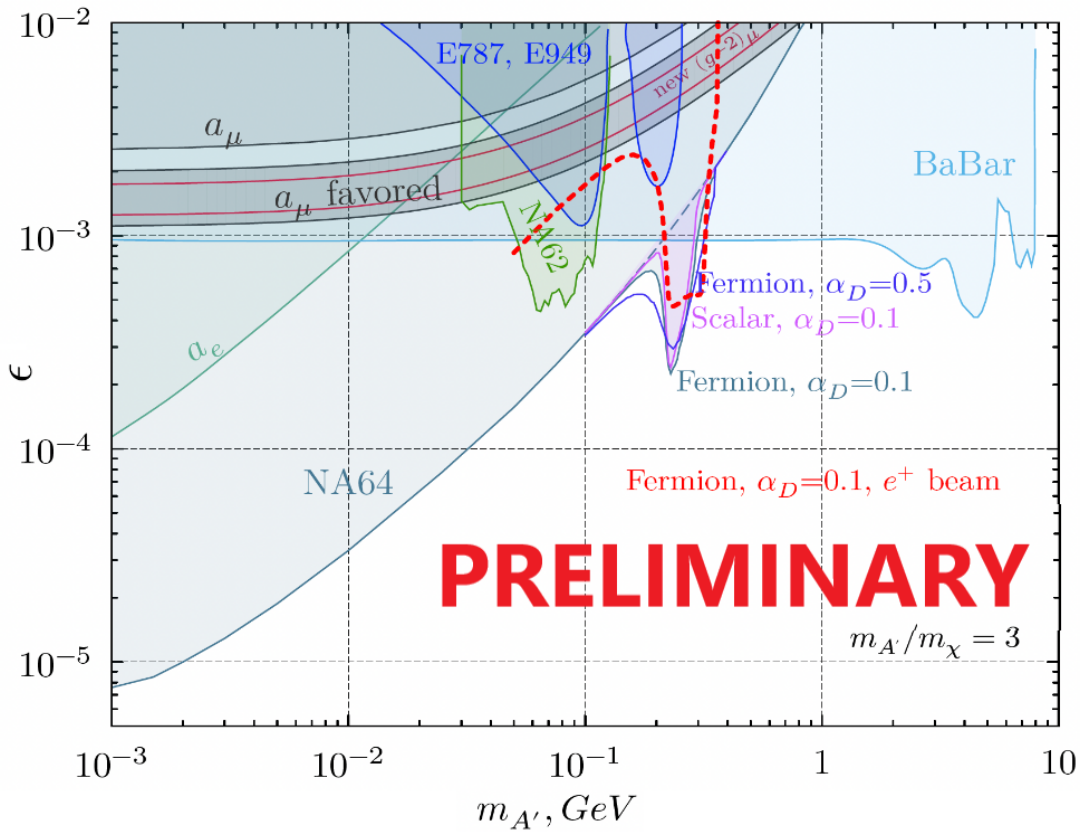


First e^+ beam measurement at NA64

While POKER R&D is ongoing, a first measurement with a 100 GeV positron beam has beam performed with the current NA64 setup

Aim of the measurement: background studies (large hadron contamination in positron mode), first upper limit optimized for the resonant annihilation channel

- NA64 "invisible setup", missing energy threshold $E_{miss} \lesssim 60$ GeV
- Blind-analysis strategy (signal-like region EECAL < 50 GeV, EHCAL < 3 GeV)
- expected background: 0.1 events - main contribution from hadron beam contaminants $k^+ \to e^+ \pi_0 \nu_e$ + fake-SRD tag



Data unblinding in the next few weeks

Conclusions

- Light dark matter scenario (MeV-to-GeV range) is largely unexplored and theoretically well motivated
  - A collection of complementary searches exploring this paradigm is required. Among these, searches at accelerator play a key role.
- NA64 is an electron-beam missing-energy experiment at CERN
  - NA64 produced several important results in the search for dark photon: its sensitivity could be further improved by using a positron beam
- POKER is an ERC funded project, aiming to perform the first 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
  - Detector R&D is currently ongoing, including crystals characterization, SiPM and electronics studies
  - The possibility to run the pilot measurement in 2024 is currently being discussed
  - NA64 has performed a preliminary measurement with a positron beam. Data are currently being analyzed.

Thanks for your attention!