Dark Sector searches at NA64

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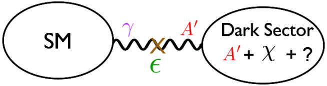
Outline

Light dark matter

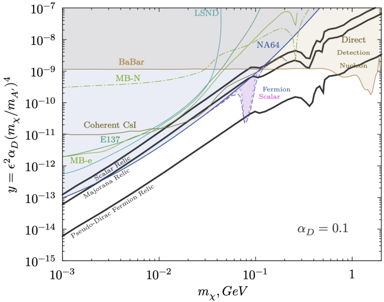
The light dark matter hypothesis predicts that DM is made by sub-GeV particles interacting with SM via a new force.[1]

Simplest possibility: "vector-portal".
DM-SM interaction trough 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 ($\alpha_D \equiv g_D^2/4\pi$)



Annihilation cross section reads:

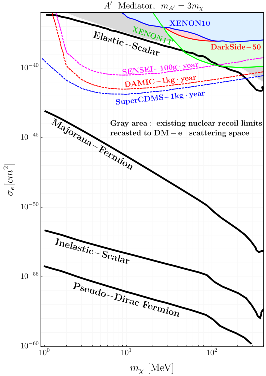
$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \frac{\varepsilon^2 \alpha_D m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

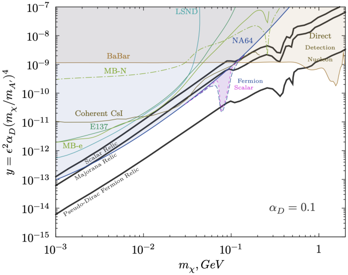
For a fixed m_χ value, the thermal origin hypothesis (DM relic density) imposes a unique value of y

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

Light dark matter searches at the intensity frontier

- Dark Matter direct detection experiments, typically optimized for $M_\chi \geq 1$ GeV, have a limited sensitivity in the sub-GeV range
  - $E_R \propto v^2 M_\chi^2 / M_N$, $v \simeq 220$ km/s $\sim 7 \cdot 10^{-4}$c
  - Many ongoing efforts to overcome this kinematic effect
- LDM-SM interaction cross section at low energy has a sizable dependence on the impinging particle velocity, with a drastic reduction for specific models





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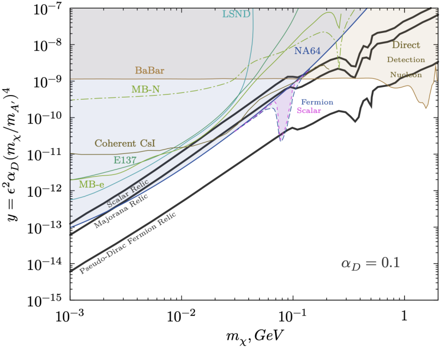


LDM at accelerators

Accelerator-based experiments at the *intensity frontier* are uniquely suited to explore the light dark matter hypothesis

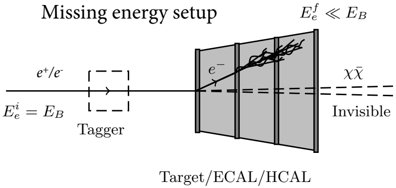
The NA64-e approach to Dark Sector search

NA64-e **approach:** missing energy measurement, high energy e^-/e^+ beam impinging on an active thick target.

Number of signal events scales as: $N_S \propto \varepsilon^2$

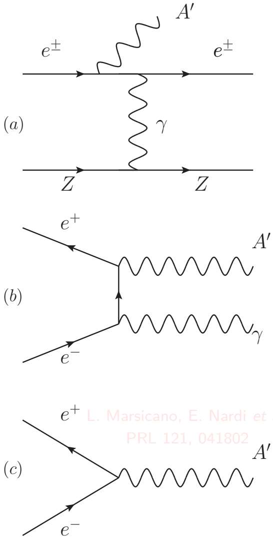
Missing Energy Experiment

- Specific beam structure: impinging particles impinging "one at 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 / eventual beam contaminants



LDM production mechanisms with lepton beams

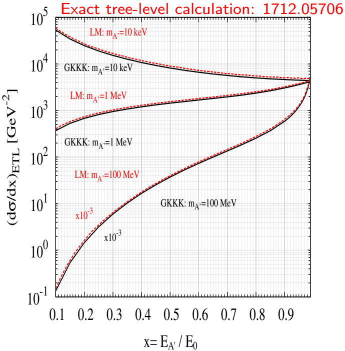
Three main LDM production mechanisms in fixed-target, lepton-beam experiments



L. Marsicano, E. Nardi *et al.*
PRL 121, 041802

a) A'-strahlung

- Radiative A' emission (nucleus EM field) followed by $A' \to \chi\overline{\chi}$
- Scales as $Z^2\alpha_{EM}^3$
- Forward-boosted, high-energy A' emission



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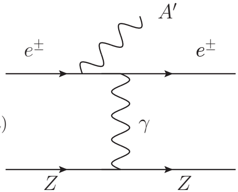

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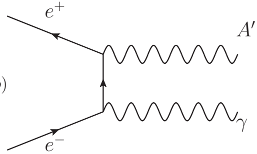
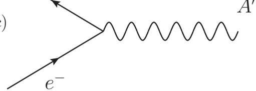


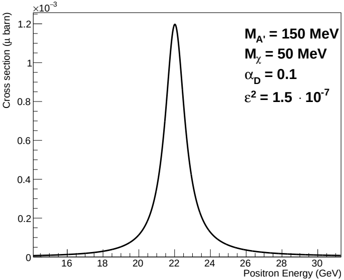
(c)



L. Marsicano, E. Nardi *et al.* PRL 121, 041802

c) Resonant e^+e^- annihilation

- $e^+e^- \to A' \to \chi\overline{\chi}$
- Scales as $Z\alpha_{EM}$
- Closed kinematics: $P_\chi + P_{\overline{\chi}} = P_{e^+} + P_{e^-}$
- Resonant, Breit-Wigner like cross section with $M_{A'} = \sqrt{2m_e E_{e^+}}$

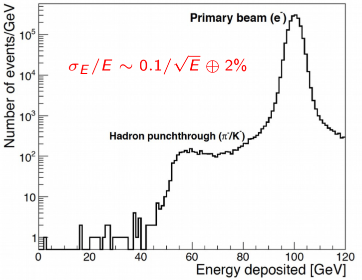


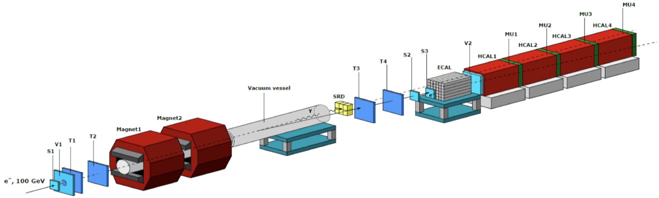
The NA64-e experiment at CERN North Area

NA64-e**:** missing energy experiment at CERN North Area, 100 GeV e^- beam[2]
H4 line: $\simeq 10^7$ e^-/spill (γ conversion). $\sigma_E < 1\%$, hadron contamination $\sim 0.5\%$

Experiment Setup

- EM-Calorimeter: $40X_0$, Pb/Sc Shashlik
- Hadron calorimeter: 4 m, 30 λ_I
- Beam identification system: SRD + MM trackers
- Plastic scintillator based scintillator counters for VETO





2 Phys. Rev. Lett. 131, 161801 (2023)

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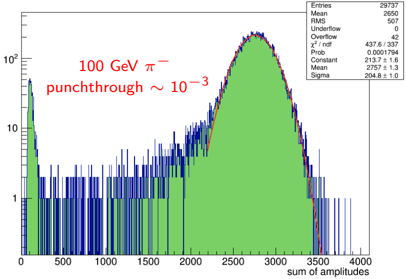

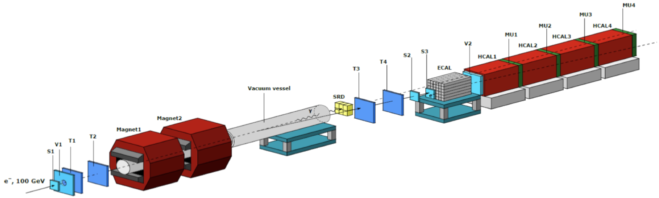

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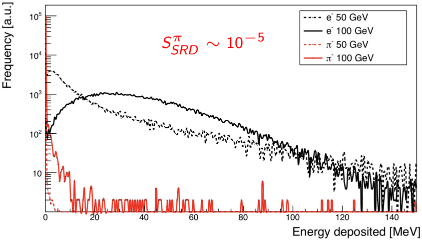
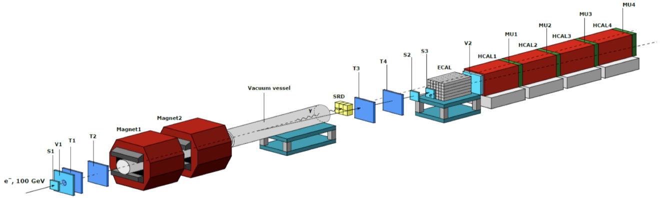




[2] Phys. Rev. Lett. 131, 161801 (2023)

NA64-e: backgrounds

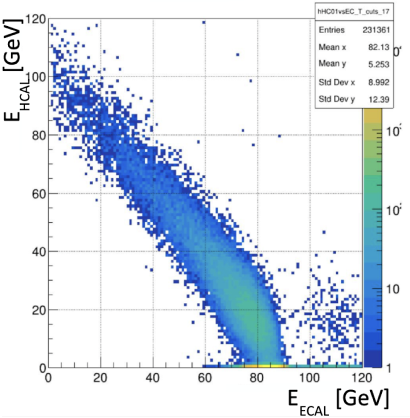
Possible background sources: production of long-lived and highly penetrating neutral SM particles upstream / within ECAL (neutrons, kaons)

(i) Di-muon events: $eZ \to eZ\mu^+\mu^-$, with one or both muons decaying or escaping without being detected by VETO/HCAL.

(ii) Decay of mis-identified contaminating hadrons to $e\nu_e$ final state.

(iii) Electro- / photo-nuclear interactions with upstream beamline materials. Critical contribution, yield estimated directly from data by side-band extrapolation.

(iv) Hadron productions in the ECAL undetected by VETO/HCAL.

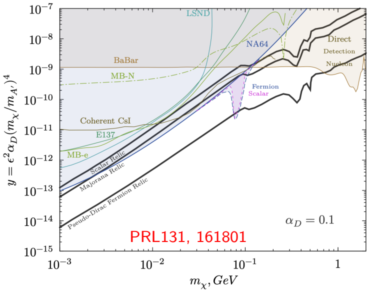


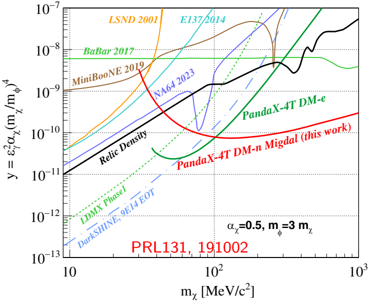
Background yield for 2021-2022 runs

Background source	Background, n_b
(i) dimuons losses or decays in the target	0.04 ± 0.01
(ii) $\mu, \pi, K \to e + ...$ decays in the beam line	0.3 ± 0.05
(iii) lost γ, n, K^0 from upstream interactions	0.16 ± 0.12
(iv) Punch-through leading n, K^0_L	< 0.01
Total n_b (conservatively)	0.51 ± 0.13

NA64-e: latest results

- Accumulated statistics $\simeq 10^{12}$ EOT (2016-2022)
- After applying all selection cuts, no events are observed in the signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV
- Expected number of background events ~ 0.5 compatible with null observation
- **Today, the most competitive exclusion limits** in large portion of the LDM parameters space.
    - Accumulate further statistics - up to 10^{13} EOT - to probe the Pseudo-Dirac Fermion Relic case for $m_{A'} \lesssim 100$ MeV.
    - New ideas are being explored to cover the large-mass region.
    - Complementarity with Direct Detection experiments - e.g. PandaX-4T (scalar LDM).





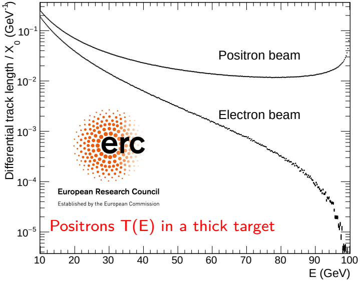
POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

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

Why positrons?

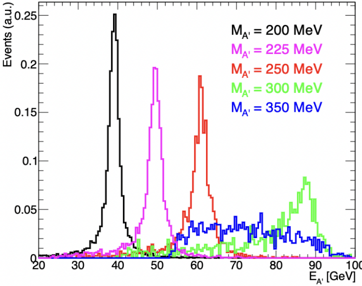
Signal production reaction: $e^+e^- \to A' \to \chi\overline{\chi}$

- 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 $E_R = \frac{M_{A'}^2}{2m_e}$



Project goal

- Perform a preliminary missing energy measurement with a positron beam, using a new high resolution / high segmentation detector replacing the current NA64 ECAL.
- Demonstrate the technique and set the basis of the first **optimized** light dark matter search at a positron-beam facility



POKER (NA64-e^+): current status

A first proof-of-concept measurement was completed in 2022 (10^{10} E^+OT at 100 GeV)

Goals: backgrounds study (higher beam hadronic contamination), resonant production characterization via the $e^+e^- \to \mu^+\mu^-$ reaction, extraction of the first upper limit with an analysis optimized for resonant LDM production.

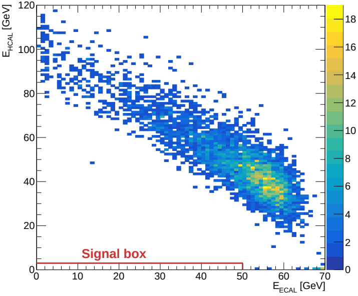
Experimental setup: as in NA64-e^-.

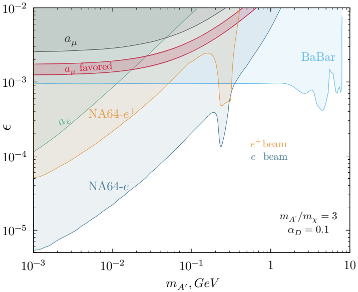
Analysis strategy: blind-analysis (signal-like region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 3$ GeV).

Main backgrounds:

- $\pi^+ \to e^+\nu_e$ + fake-SRD tag
- Upstream hadrons electro-production, soft e^+ in ECAL
- Overall expected background yield: < 0.1 events.

Results: no events observed in the signal region after unblinding, new upper limits set to the LDM parameters space.

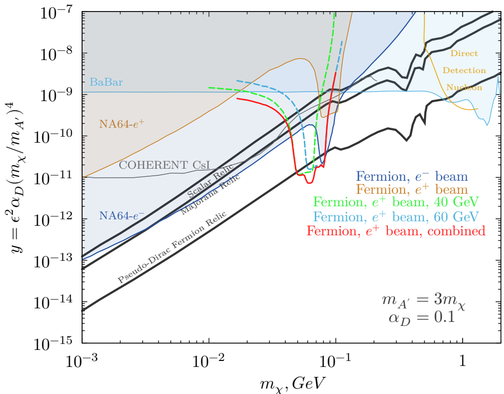




POKER (NA64-e^+): future plans

Multi-measurement program at NA64 at different e^+ beam energies.

- Two measurements at 60 GeV and 40 GeV will allow to probe the LDM parameters space down to the thermal targets.
- 10^{11} E^+OT requested, 2x 1-week data-taking runs.
- Modest detector upgrades: new SRD detector (possibly: new active target)
- Very positive feedback from the SPSC



POKER (NA64-e^+): new LYSO-based SRD detector

At low beam energy, the SR emission drops significantly $E_{SR} \propto E^4_{beam}$: an optimized SRD detector is necessary.
Possible option: LYSO-based homogeneus detector.

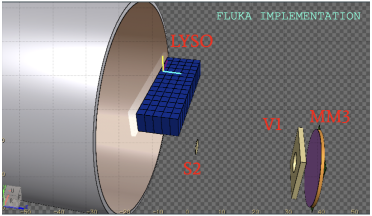
LYSO key properties:

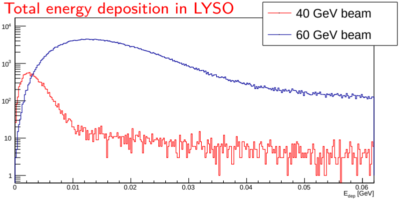
- Large density: $\simeq$7 g/cm^3
- High light yield: $\simeq 3 \cdot 10^4 \gamma$/MeV
- Very fast response: $\tau \simeq 40$ ns

Possible critical items for false-positives:

- Lu intrinsic radioactivity
- Afterglow effects

Detector design currently being optimized through MC simulations.
Preliminary results demonstrate that e^+ detection efficiencies up to 99% (60 GeV) / 89% (40 GeV) can be reached, with minimal rate of false-positives.





NA64 program

Electron Beam:

- NA64-e: $\simeq 10^{12}$ EOT already measured
- Additional $\sim 6 \times 10^{11}$ EOT collected in 2023 (data analysis ongoing), after detector upgrade (electronics, straw detectors and veto hadron calorimeter)
- **Already probed significant part of the A' invisible parameter space up to the thermal relic targets**

Positron Beam:

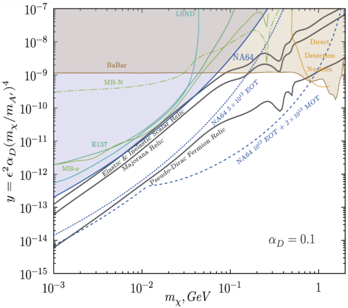
- Primary e^+ beam allows to exploit the enhanced resonant annihilation cross section $\rightarrow$ **high sensitivity to large A' masses**
- **Dedicated short e^+ run in 2022**: 10^{10} e^+OT accumulated at 100 GeV
- Multi-measurement program at lower energies: dedicated R&D in 2024-2025, long data taking post-LS3.

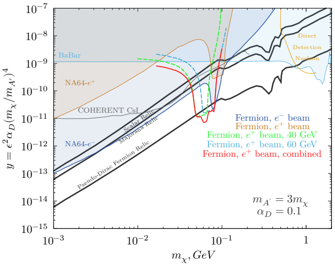
Muon Beam:

- NA64-μ: missing momentum and energy experiment with a muon beam
- Ongoing parallel effort of the NA64 collaboration, data-taking at M2 beamline

Hadron Beam

- Explore light mesons fully invisible decay modes
- First ideas are currently being developed

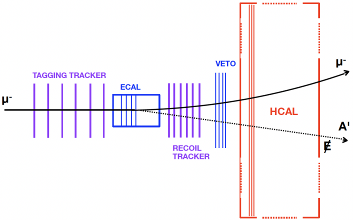




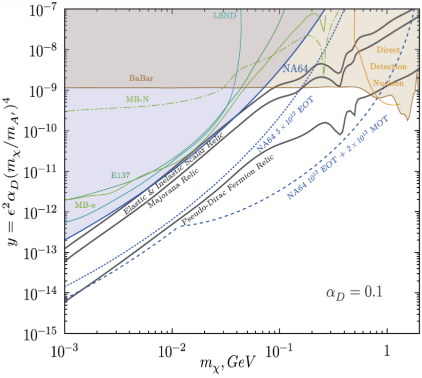
NA64 short-term future: NA64−μ: experimental technique

LDM search with a **muon beam** impinging on a fixed target, complementary to $e^{\pm}$ searches in the high-mass region.

- **Signal production:** A' radiative emission by beam muons impinging on an active target (ECAL).
- **Signal signature:** ***missing momentum.*** Well-identified impinging beam track and final-state low-energy deflected track. No additional activity in downstream detectors (VETO / hadronic calorimeters).



Combined sensitivity of NA64-e (10^{13} EOT) and NA64-μ (2×10^{13} MOT).



NA64 short-term future: NA64−μ. Experimental setup

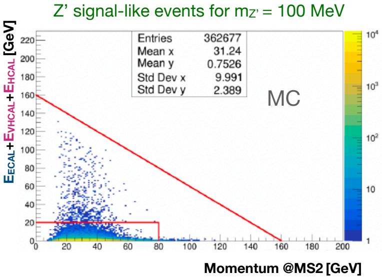
NA64-μ experiment: muon beam missing energy + momentum search

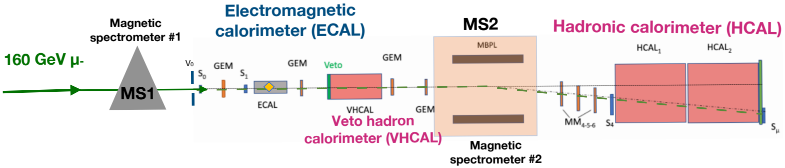
Beam: M2 beamline at CERN SPS, 160 GeV μ^-, $10^5 - 10^7$ μ/s.

Detector:

- Two magnetic spectrometers, MS1 (impinging μ) / MS2 (scattered μ)
- Three calorimeters: ECAL (active target), VHCAL, HCAL
- Beam-defining plastic scintillator counters

Signal signature: $P_1 \simeq 160$ GeV, $P_2 < 80$ GeV, $E_{CAL} \simeq$MIP.





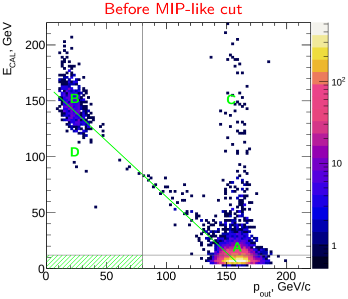
NA64$-\mu$: status

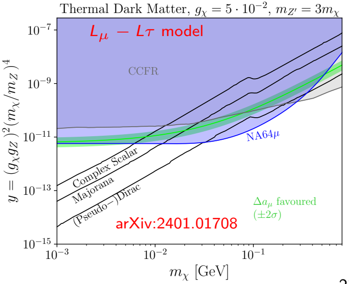
Three test runs have already been performed in 2021 (5x10^9 MOT), 2022 (2x10^{10} MOT), and 2023 (10^{11} MOT)

- Very successful runs, *efficient use of the M2 beam thanks to the positive coordination with the Compass / AMBER experiment.*
- Results from 2022 data analysis: $\simeq 3 \times 10^{-12}$ background events expected per MOT. No events observed in the signal region:
  - Well identified 160 GeV/c impinging μ^-
  - Reconstructed scattered muon track with $p < 80$ GeV/c
  - MIP-like energy deposition in the all calorimeters.
- 2023 data analysis in progress.

Possibility for a long physics run in 2024

- Detector optimization in progress.
- Final goal: 5×10^{12} MOT.

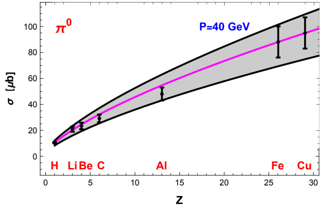


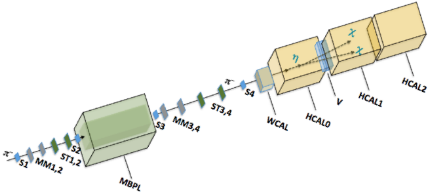


NA64-h

Search for fully-invisible decay of neutral pseudo-scalar mesons as a probe for new physics: dark sector with predominant coupling to quarks. SM prediction: $BR \simeq (M_\nu/M_S)^2 \lesssim 10^{-16}$.

- **NA64 approach:** use a $\simeq$ 50 GeV/c π^- beam. Exploit the charge-exchange process $\pi^- N \to SN'$ as a source of secondary high energy $\pi^0/\eta/\eta'$ particles.
- Missing-energy measurement: $E_{WCAL} \simeq E_{MIP}$, $E_{HCAL} \simeq 0$, $E_{VETO} \simeq 0$.
- First test in 2023 with $\simeq 2.9 \times 10^{10}$ π^-OT (50 GeV/c) - analysis still in progress. Main systematic uncertainty from the total charge-exchange cross section, $\simeq 30\%$. *We're currently defining a strategy to measure this.*





Conclusions

- Light dark matter scenario (MeV-to-GeV range) is largely unexplored
  - Can efficiently explain DM relic density.
  - Theoretically founded as the WIMP DM paradigm, assuming a **new** DM-SM interaction mechanics exists.
- The NA64 experiment at CERN aims to investigate the Dark Sector through missing-energy/momentum measurements, exploiting different probes:
  - Electron beam: $1.6\text{x}10^{12}$ EOT already accumulated, most stringent limits in the low-mass LDM region. Complementarity with Direct Detection.
  - Positron beam: exploit resonant LDM production (high signal yield, clear kinematic signature) - POKER project.
  - Muon beam: focus on the high mass region. Three test runs completed, first results are very promising.
  - Hadron beam: first ideas being developed.

This work is part of a project that received funding from the European Research council under the European Union's Horizon 2020 research and innovation programme, Grant agreement No. 947715 (POKER).

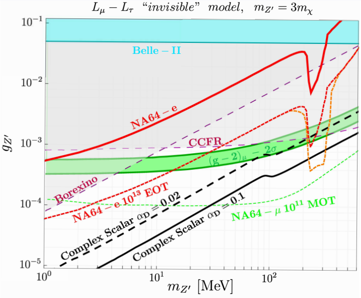
Backup slides

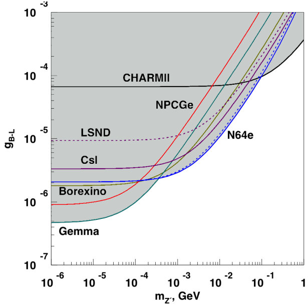
Light Z' search in the $L_\mu - L_\tau$ scenario

- Re-analysis of the 2016-2018 dataset searching for a new gauge boson coupling predominantly to muons and taus
- Ad-hoc calculation of the loop-induced coupling to photons (kinetic mixing)
- Results are more stringent than Belle-II limits, and compatible with exclusion contours from the re-analysis of neutrino experiments

Search for a new B-L Z' gauge boson

- First NA64 analysis using the 2021 dataset
- New constraints on the Z' parameters space, more stringent compared to those obtained from the neutrino-electron scattering data for the 0.3-100 MeV mass range
- Results can be re-casted to A' space via $g_{B-L} \leftrightarrow \varepsilon e$.

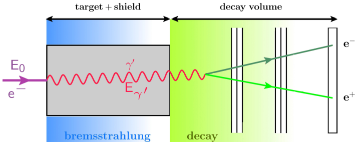




A' production and visible decay detection in a fixed thick-target setup

Reaction topology:

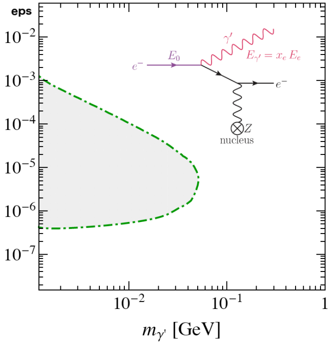
- A' production: radiative A' emission
  $e^- N \to e^- N A'$
- A' propagation: for low ε values ($\lesssim 10^{-5}$) the A' is long-lived, resulting to a detached decay vertex.
- A' detection: measurement of the $e^+ \, e^-$ decay pair in a downstream detector.



Number of events:
Dependence on main parameters[3]:

$$N \sim N_{eot} n_{sh} \int dE' dE_e dt I_e(E_e, t) \frac{d\sigma}{dE'} e^{-L_{sh}/\lambda}(1 - e^{-L_d/\lambda})$$

- Upper bound:
  $N_{evt} \propto \varepsilon^2 e^{-L_{sh}/l_{A'}}, \; l_{A'} \propto E_0/\varepsilon^2$
- Lower bound:
  $N_{evt} \propto \varepsilon^2 L_d / l_{A'} \propto \varepsilon^4$

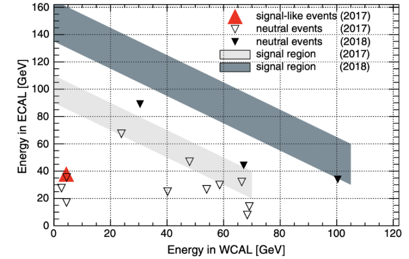


[3] For a review: S. Andreas, Phys.Rev. D86 (2012) 095019

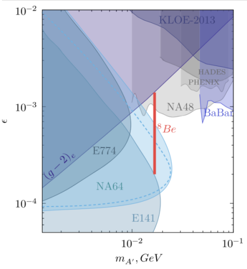
Visible A' search at NA64

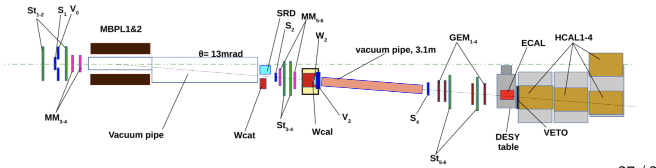
A' production by radiative emission in compact WCAL active target and decay to e^+e^- in vacuum pipe

- Clean impinging e^- with $P \simeq P_0$
- No activity in W2 and V2 veto counters
- MIP-like signature in S4, signals in trackers
- No activity in VETO and HCAL
- Energy deposition in WCAL and ECAL, with $E_{WCAL} + E_{ECAL} = E_0$



Combined analysis of 2017 ($5.4 \cdot 10^{10}$ EOT, 100 GeV/c) and 2018 ($3 \cdot 10^{10}$ EOT, 150 GeV/c) data: *no signal-like events observed in the signal region*



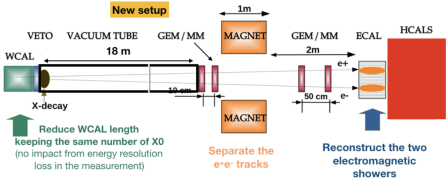


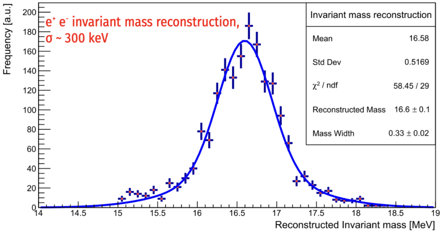
Future prospects for post-2023 run: improved setup with e^+e^- invariant mass reconstruction.

Detector upgrades:

- New compact tungsten calorimeter (same X_0) to measure short-lived A' and improve sensitivity to large ε
- New SRD optimized for 150 GeV beam energy
- New larger transverse size MM
- New ECAL with larger transverse dimensions

With these modifications, 20 days of beam time at 150 GeV/c will be required to fully scrutinize the still-unexplored X17 parameters space.





POKER (NA64-e^+): new active target

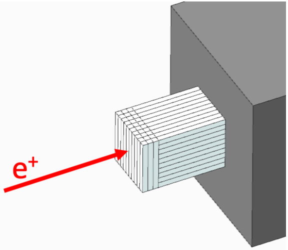
To properly measure the A' signal resonant line shape, a new active target with optimized energy resolution is required: **new PKR-CAL detector**.

Baseline design: 33.5 X_0 $PbWO_4$ calorimeter with SiPM readout

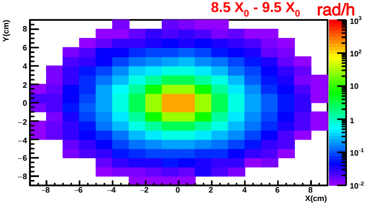
- 9x9 matrix of 20x20x220 mm^3 crystals + 4 layers in front (pre-shower): 31.5 X_0
  - Fully absorb EM shower with minimal longitudinal/transverse energy leakage
- Required $\sigma_E/E \sim 2.5\%/\sqrt{E} \oplus 0.5\%$
  - $LY \sim 2.5\,\mathrm{phe}/MeV$
  - Use four 6x6 mm^2 SiPMs, 10 μm cell coupled to each crystal

Radiation levels are critical

- EM dose up to 200 rad/h (CMS ECAL max: 500 rad/h)
  - Light-induced annealing
  - Beam-spot rastering: factor $\simeq$5 reduction
- $\phi_n \leq 10^3$ n_{eq} $cm^{-2}s^{-1}$: no significant effects expected



100 kHz 100 GeV e^+: radiation dose

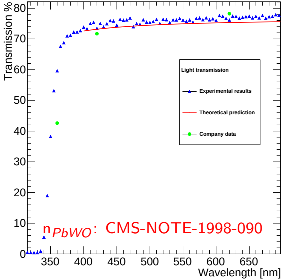


POKER (NA64-e^+): $PbWO_4$ R&D

Massive characterization of $PbWO_4$ main properties (producer: CRYTUR)

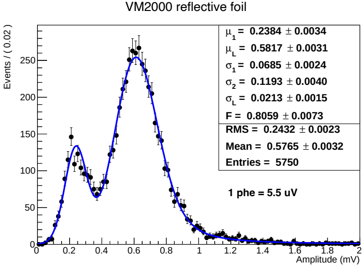
Longitudinal light transmission vs λ:

- Spectrophotometer-based setup
- Measurements reproducibility better than 1%.
- $T > 70\%$ at $\lambda = 450$ nm for all samples.



Absolute light yield

- Setup:
  - Cosmic-ray telescope with plastic-scintillator counters
  - Crystal temperature stabilized at +18 °C
  - Readout: 4x S14160-6010 SiPM (6x6 mm^2, 10 μm pixel size)
- Single-phe amplitude obtained from a pulsed-laser measurement
- LY from energy distribution fit $\simeq 5$ phe/MeV for all samples



POKER (NA64-e^+): new FADC digitizer

Development of a new FADC, possibly based on the Waveboard platform (INFN-Roma1), to replace the existing NA64 digitizers (MSADC from Compass).

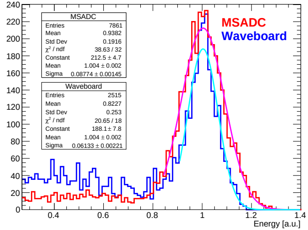
Requirements:

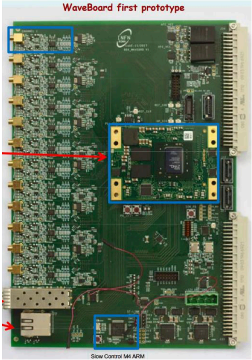
- At least 250 MHz sampling frequency
- Support for digital trigger logic

The use of the Waveboard in NA64 has already been validated with standalone measurements:

- Single-channel response
- Multiple-channels response

Ongoing R&D: Waveboard integration in NA64 (UCF protocol)



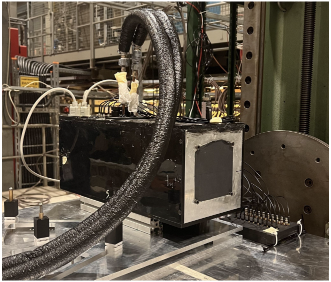


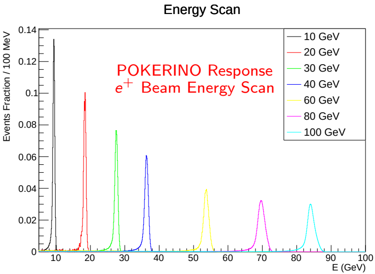
F. Ameli *et al.*, NIMA 936

POKERINO: 3x3 $PbWO_4$ matrix with SiPM readout.
Goal: characterize the prototype response to cosmic rays / beam to validate the technical choices and measure the detector performances
Measurements:

- Cosmic-ray measurements with EEE setup in Genova: commissioning / LY measurement and uniformity studies.
- August 2023: characterization with high-energy e^+ (10...120 GeV) at CERN, H8 beamline.

Data analysis currently in progress, first results are promising.

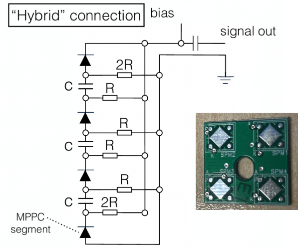


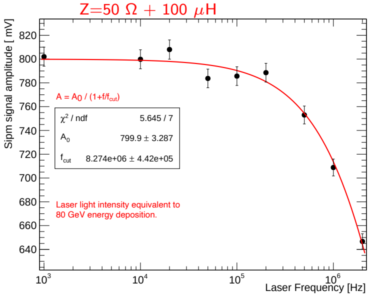


POKER (NA64-e^+): SiPM and readout R&D

Current readout scheme:

- 4x 6x6 mm^2 SiPMS coupled to each crystal to maximize light collection. Pixel size: 10 μm to minimize saturation effect (Hamamatsu S14160-6010)
- Hybrid-connection to minimize capacitance toward readout amplifier while keeping low bias voltage.
- Ad-hoc biasing scheme (LC network) to minimize bias current-induced gain variations.
- Ad-hoc connection circuit with embedded thermal-dissipation planes.





NA64 long-term future: NA64-h. Invisible K^0 decay.

- The Standard Model prediction for $S \to \mathrm{invisible}$ is extremely small, $\lesssim 10^{-16}$
  - $S \to \nu\bar{\nu}$ is rigorously forbidden by helicity conservation if neutrino is massless.
  - $BR \simeq (M_\nu / M_S)^2$ due to finite neutrino mass.
  - $S \to 4\nu$ suppressed by $(G_F M_S^2)^4$.
- Any observation of these processes would be an unambiguous signal for the presence of new BSM physics.
- No upper limit exist today for $K^0_{S,L} \to \mathrm{invisible}$
- This challenging search is complementary to existing and planned efforts for $K^0_{S,L} \to \pi^0 + \mathrm{invisible}$ (KOTO, Klever) and $K^{\pm} \to \pi^{\pm} + \mathrm{invisible}$ (NA62)

S	$BR(\mathrm{invisible})$	
π^0	$< 4.4 \cdot 10^{-9}$	NA62[4]
η	$< 1.0 \cdot 10^{-4}$	BESIII[5]
η'	$< 6 \cdot 10^{-4}$	BESIII
$K^0_{S,L}$	NO	

[4] JHEP 02 (2021) 201

[5] PRL 97 (2006) 202002

NA64 long-term future: NA64-h. Experimental setup

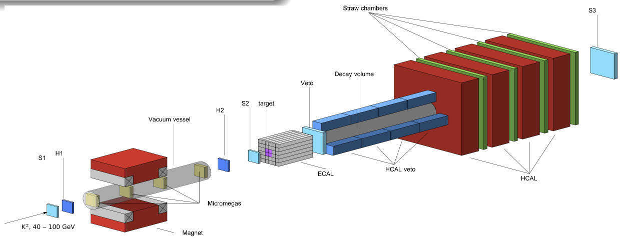
NA64-*h* approach: exploit the charge-exchange reaction $K^- p \to K^0 n$ as a source of a secondary neutral kaons, and search for the $K^0_{S,L}$ invisible decay.
Unique experimental signature: complete disappearance of the beam energy.

Experiment setup

- Low-Z active target surrounded by an hermetic EM calorimeter
- High-efficiency veto counters
- Massive HCAL around and downstream a decay vessel
- Upstream beam tracking/tagging

Signal signature

- Well-defined impinging track
- MIP-like energy deposition in the active target
- No activity in ECAL or VETO
- No activity in the HCAL



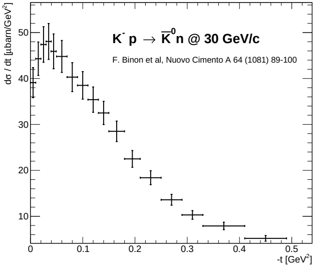
The number of signal events is proportional to:

- The number of K^-OT N_{K-}
- The p numerical density in the active target n
- The charge-exchange cross section $\frac{d\sigma_{CE}}{dt}$
- The decay probability in the decay vessel length L
- The signal efficiency ε
- The invisible channel branching fraction BF_I

Charge-exchange cross section:

- Data for 30 GeV/c K^- beam available from IHEP-70 measurement
- Regge-based model, $\rho + a_2$ $t-$channel exchange: energy dependence $\sim s^{\alpha(0)-1}$. $Z-$dependence $\sim Z^{2/3\div1}$.

$$N_S = N_{K^-}\, n \cdot \int dt \frac{d\sigma_{CE}}{dt} \cdot \varepsilon(t) \left[1 - \exp\left(-\frac{L}{\gamma(t)c\tau}\right)\right] BF_I$$



NA64-h sensitivity for 10^{12} K^-OT

Assuming zero background events, from $N_S = N_{K_L} + N_{K_S} < N_{up}^{90\%CL}$:

- $\mathrm{Br}(K_S \rightarrow \text{invisible}) \lesssim 10^{-8}$
- $\mathrm{Br}(K_L \rightarrow \text{invisible}) \lesssim 10^{-6}$