Latest results and future prospects of NA64

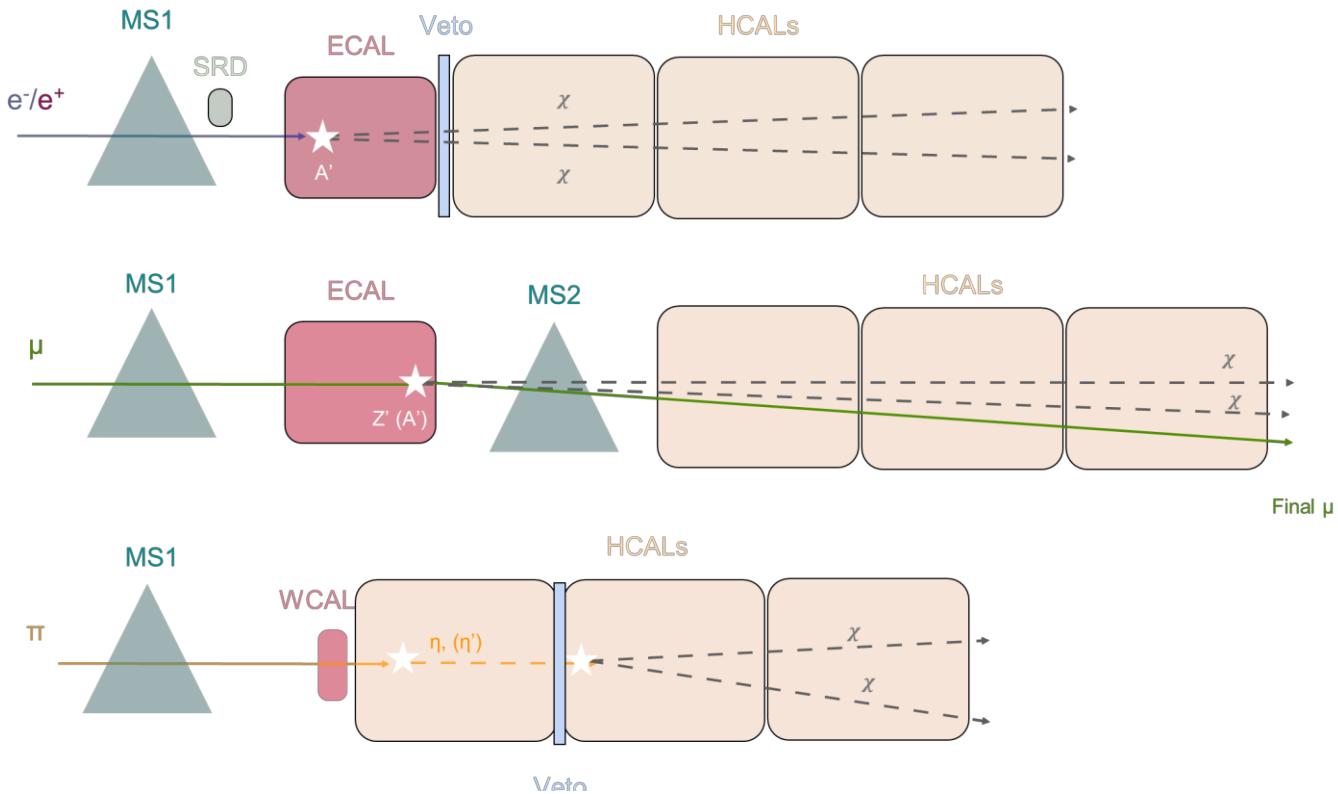
LDW2025 - Madrid, 17.9.2025

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics on behalf of NA64 collaboration

The NA64 experiment

Fixed target experiment at the intensity frontier, searching for Dark Sector physics below the electroweak scale with the *missing energy/momentum* technique

- **NA64e, NA64e+**
  - Search for vector-mediated (A') Light Dark Matter using electrons and positrons at H4
- **NA64μ**:
  - Phase 1: L_μ-L_τ Z' as a solution to the (g-2) μ anomaly and LDM
  - Phase 2: Complementary LDM searches
- **NA64h**:
  - Search for leptophobic DS coupled to light SM quarks



NA64 research program - input to EPPSU 2026

LS3 Run 4 LS4

2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

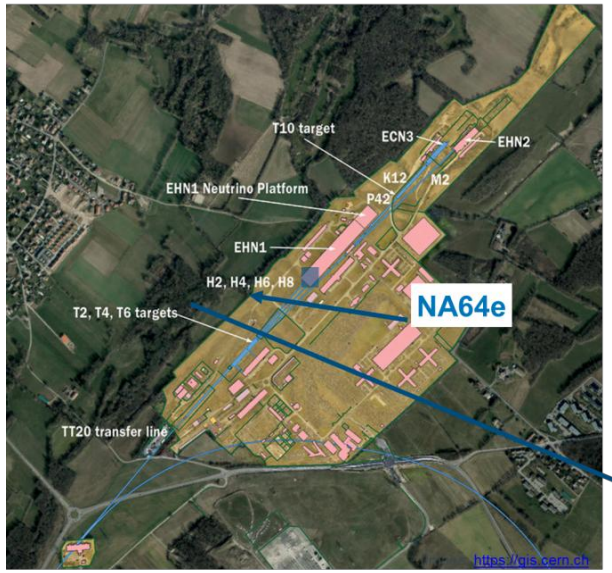
Beamline	Particle	Motivation	Latest results	Current statistics	2025	2026 (preliminary plans)	Run 4 [particles on target]
H4	NA64e⁻	*Leptophilic Dark Sectors coupled to e⁻: LDM, inelastic DM, ALPs, scalar, Z', X17 …*	9.37×10^{11}	2×10^{12}	**5.9×10^{11}**	8×10^{11}	**10^{13}**
	NA64e⁺	*LDM (higher masses <0.25 GeV, several mediators axial, vector, pseudoscalar, scalar),…*	100 GeV: 10^{10} 70 GeV: 1.3×10^{10}	100 GeV: 10^{10} 70 GeV: 1.3×10^{10}	**45 GeV:3.24×10^{9} 40 GeV: 6.39×10^{9}**	**40, 45, 60 GeV**	**> 10^{11} for different energies**
M2	NA64μ	*Leptophilic DS coupled to μ: LDM (higher masses > 0.1 GeV, ALPs, Z', muon g-2, millicharge, μ→τ…*	1.98×10^{10}	3.5×10^{11}			**2×10^{13}**
	NA64h	*Hadrophilic DS* *Invisible η, η', K_0 decays*	Addenda to be prepared next year **Proof-of-principle published! Phys. Rev. Lett. 133, 121803 (2024).**				

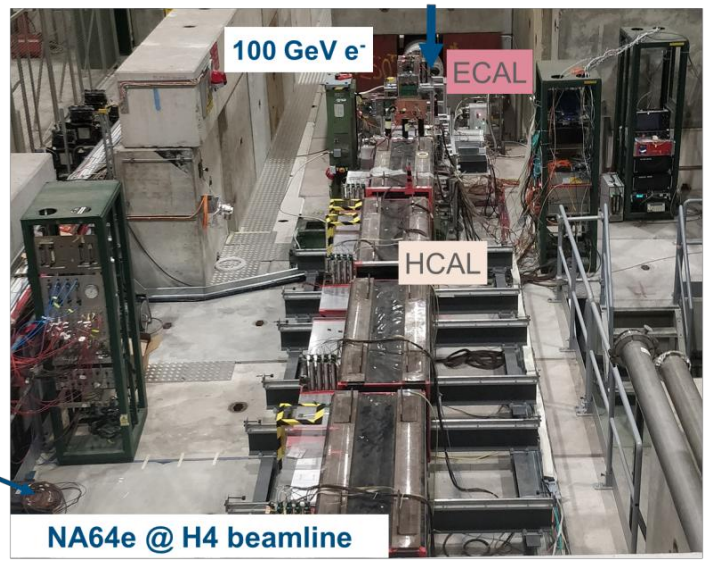
NA64 post LS3 program submitted as an input to ESPPU (arXiv:2505.14291)

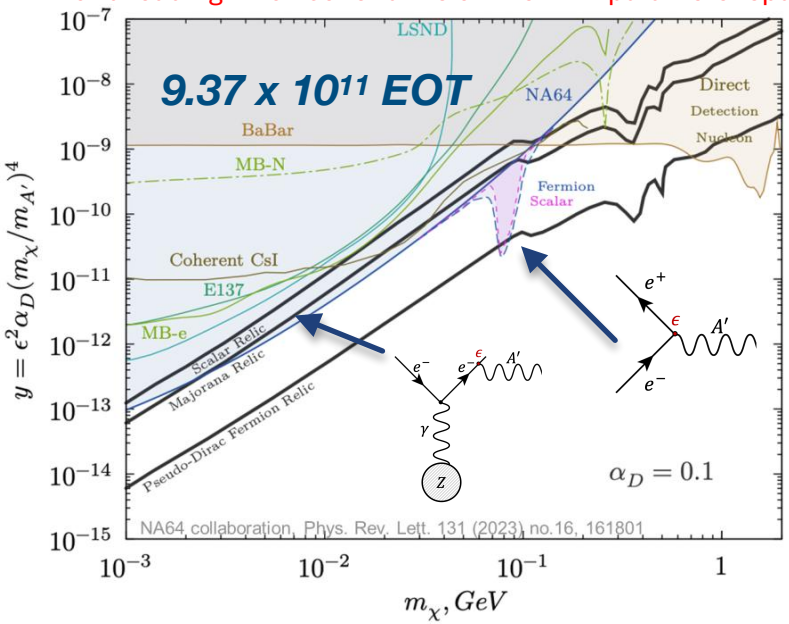
NA64 LDM latest results (2016-2022)

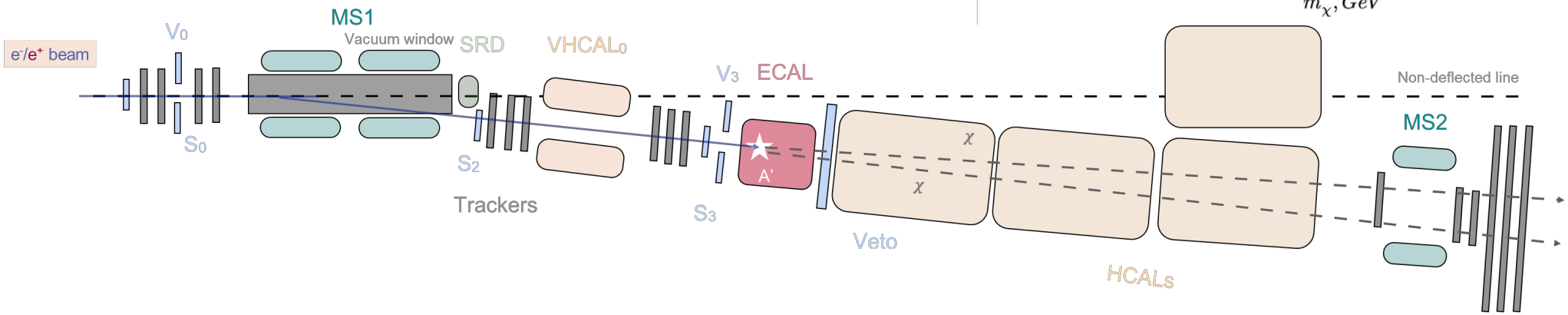
NA64, Phys. Rev. Lett. **131**, 161801 (2023)

World leading NA64 constraints on the LDM parameter space

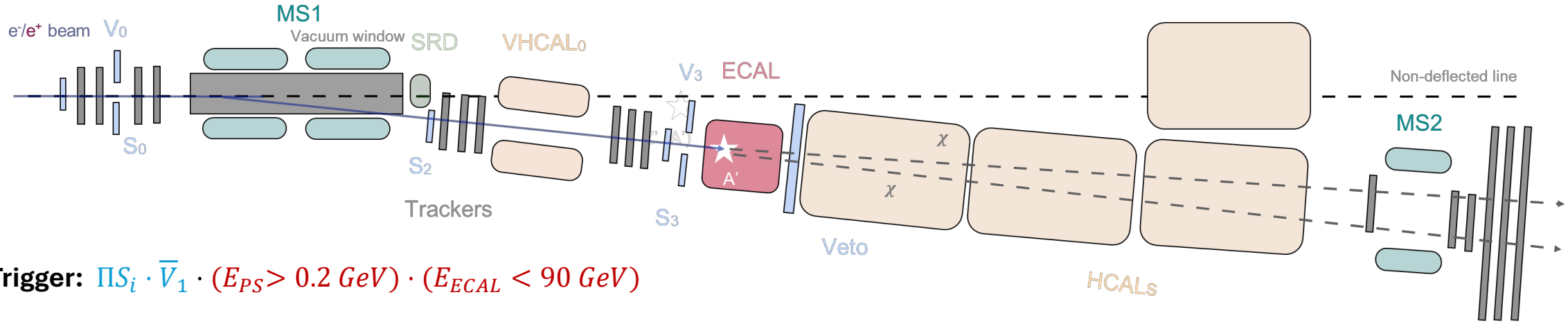








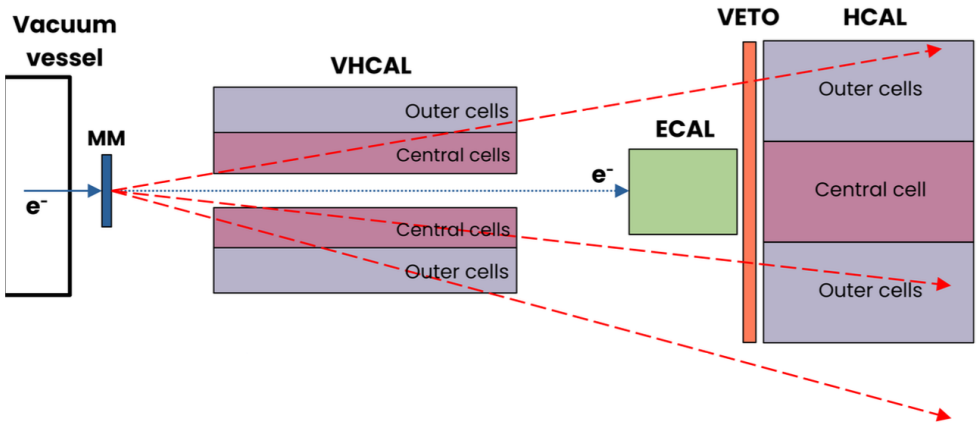
Status of NA64e

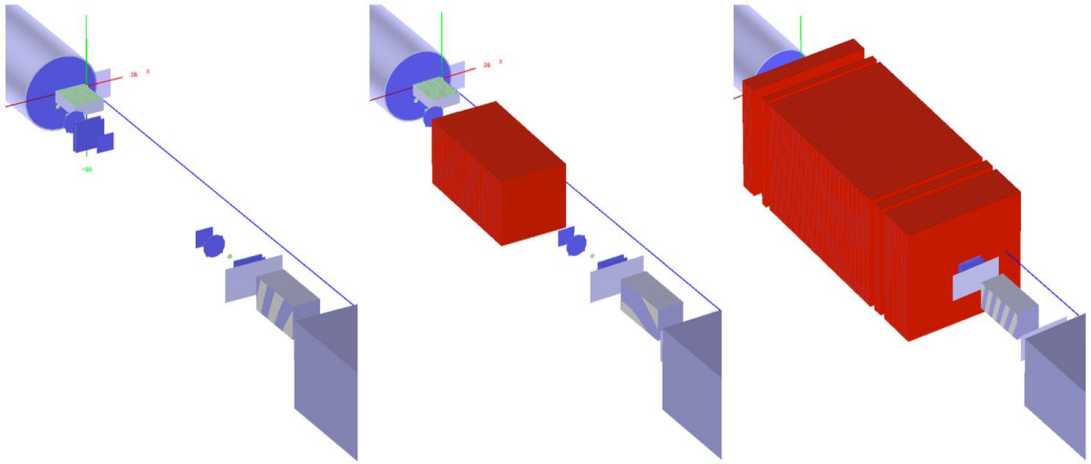


- **Trigger:** $\Pi S_i \cdot \overline{V}_1 \cdot (E_{PS} > 0.2\ GeV) \cdot (E_{ECAL} < 90\ GeV)$
- **Momentum reconstruction and PID**:
  - Magnetic spectrometer (MS1) + Synchrotron Radiation Detector (SRD)
- **Hermeticity**
  - Hadronic calorimeter (HCAL), veto hadron calorimeter (VHCAL) + Veto
- **Signature of the signal event**: well-reconstructed 100-GeV electron track, E_{miss}> 50 GeV, NO activity in the Veto, HCALs and VHCALs

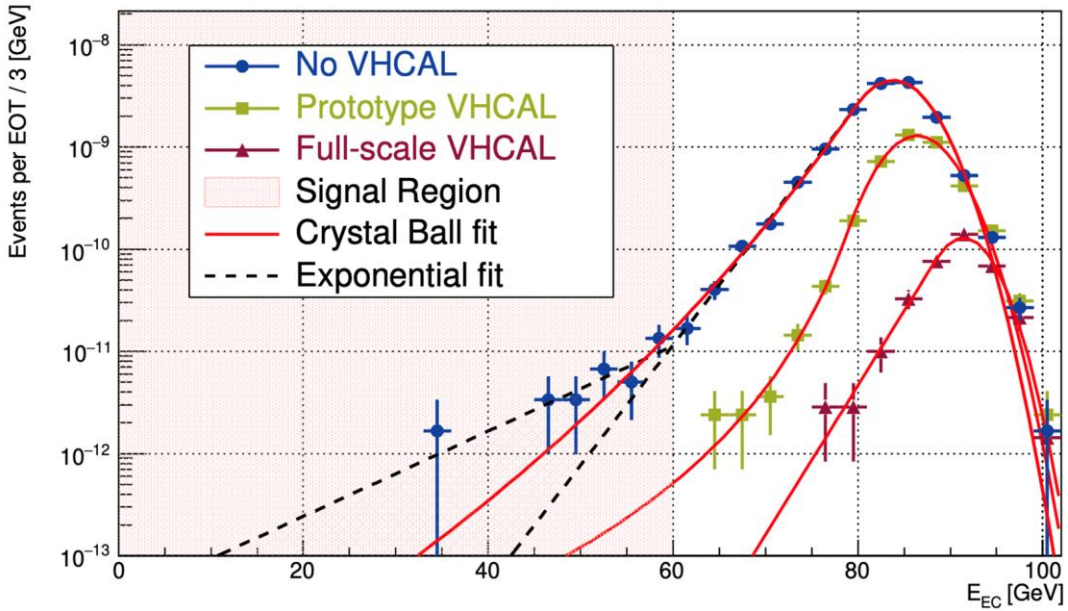
- ~1.6 10^{12} eOT collected in the same setup between 2023 and 2024
- Blinded data analysis ongoing
- Goal: LDM exploration and prove feasibility of post-LS3 program
- Plan: publish together 2023-2026 data

Studying the main background: upstream hadron electro-production





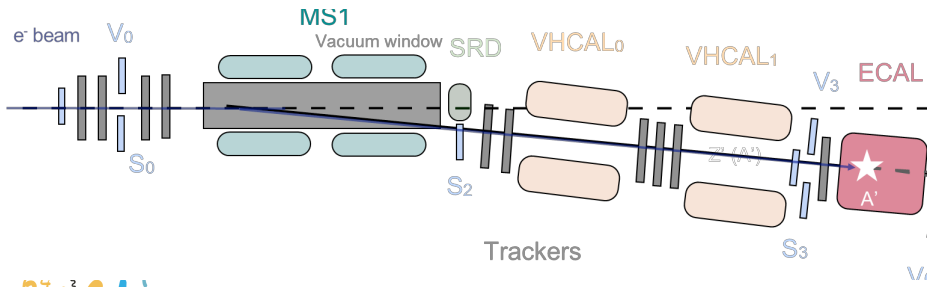
- 2023 preliminary analysis and Monte Carlo developments demonstrated our understanding of electro-nuclear and photo-nuclear (NIM A 1081 (2026), 170830).
- Prototype VHCAL introduced in 2023 effectively suppresses this background by more than an order of magnitude.
- Further setup optimization in 2025 with 2nd VHCAL introduction
- Results driving the design of finalized VHCAL to be implemented during LS3



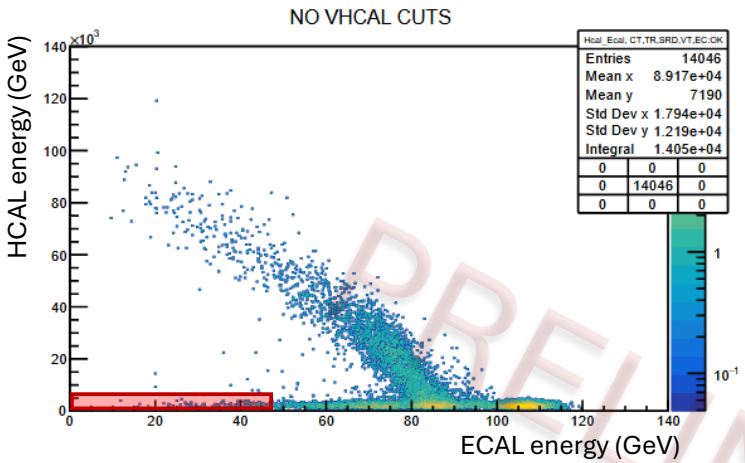
First look at the 2025 data

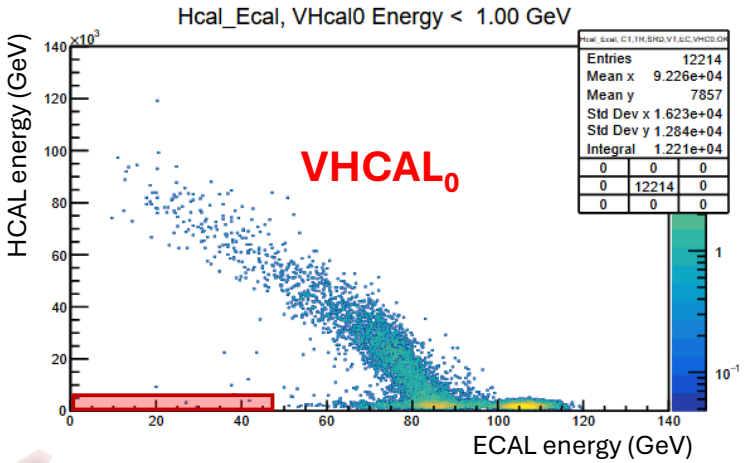
- ~5.9 × 10^{11} eOT collected during 2025 with improved setup (additional VHCAL module)
- Encouraging results from a "quick look" at data (the run ended in July):

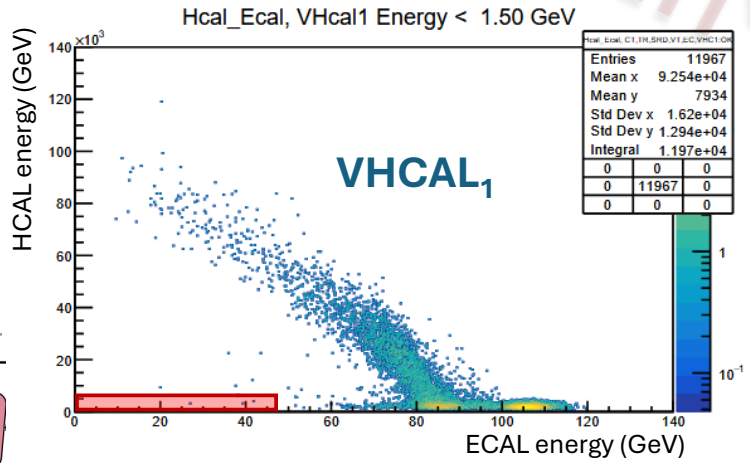
➡Asking for no energy deposition in two-VHCALs reduces background as expected!

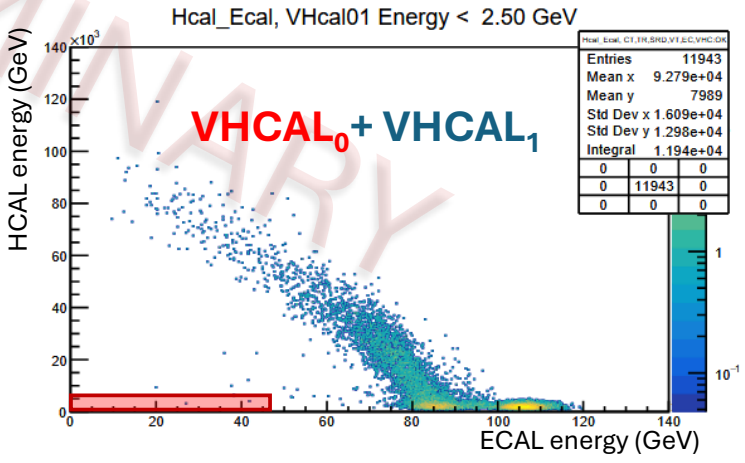


Preliminary test on limited 2025 data sample - No information from trackers used

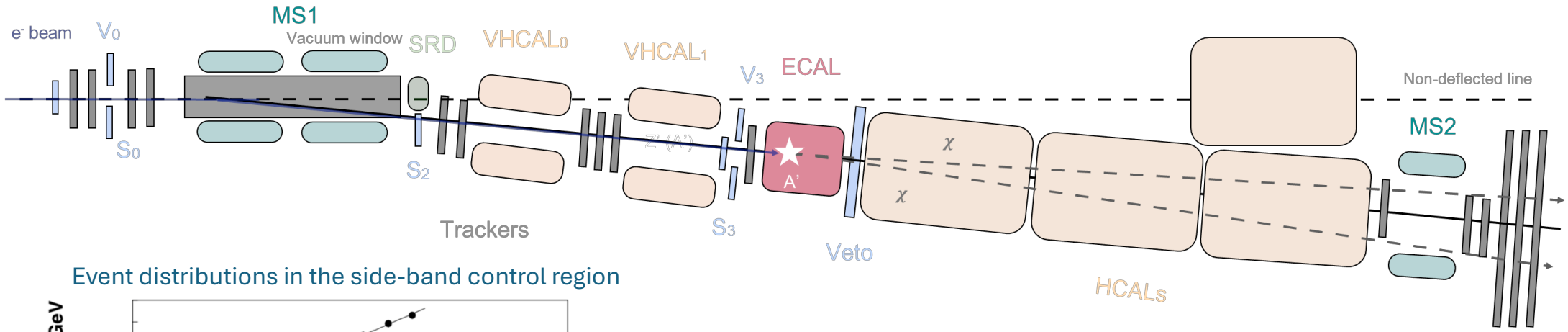




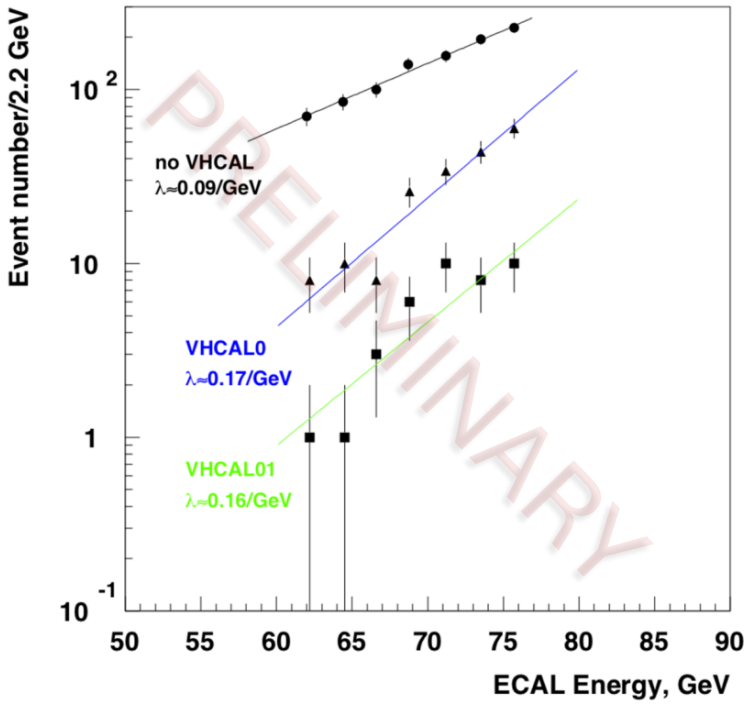




First look at the 2025 data



Event distributions in the side-band control region



- Possible further steps to mitigate the background level after LS3:
  - Remove as much material as possible upstream of VHCAL0; optimize the positions of all detectors
  - Improve detection efficiency of VHCAL (new PMT readout)
  - Upgrade the setup with larger-acceptance HCAL modules from the M2 line (need of a new support structure)

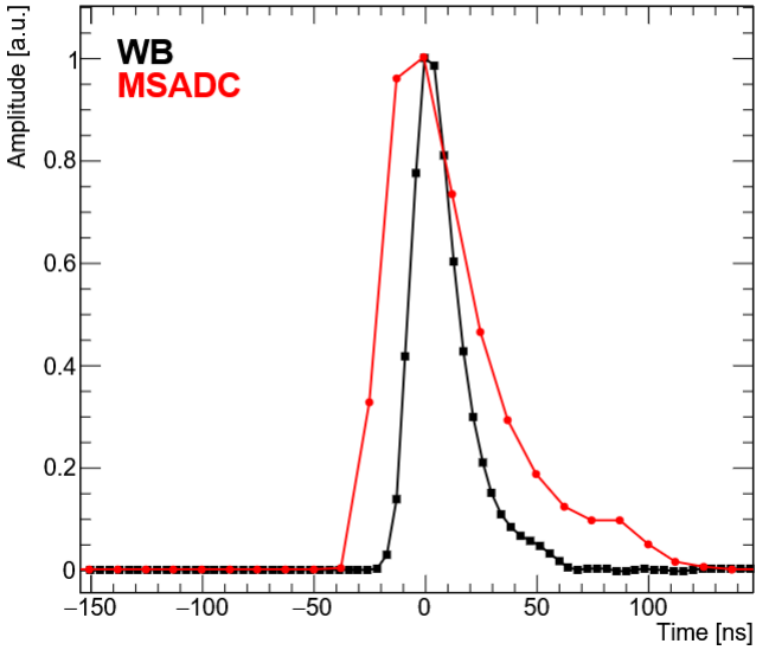
- Preliminary plan: collect further statistic during 2026 run to finalize background studies before LS3 (>10^{12} eOT combined with 2025)

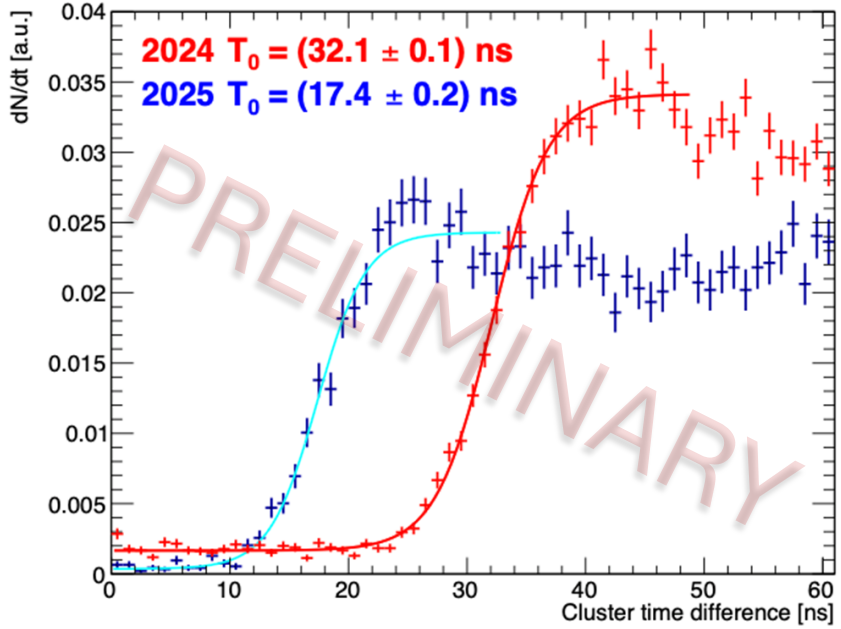
R&D towards higher intensities: fast readout

In view of post-LS3 high intensity running, new fast readout electronics, based on INFN «waveboard» digitizer was installed for 2025 run (PMT-based detectors)

- Factor 3 faster sampling rate (250 MHz) w.r.t. previous MSADC
- Dynamic range 2 V (14b)
- NA64 DAQ integration: fully synchronous system, fixed-latency, fixed-phase clock recovery from optical link (UCF protocol)

- Average intensity during 2025 run: 8×10^6 e^-/spill (20% higher than in previous year)
- Five days at 10^7 e^-/spill (highest possible intensities in the line with high quality beam).

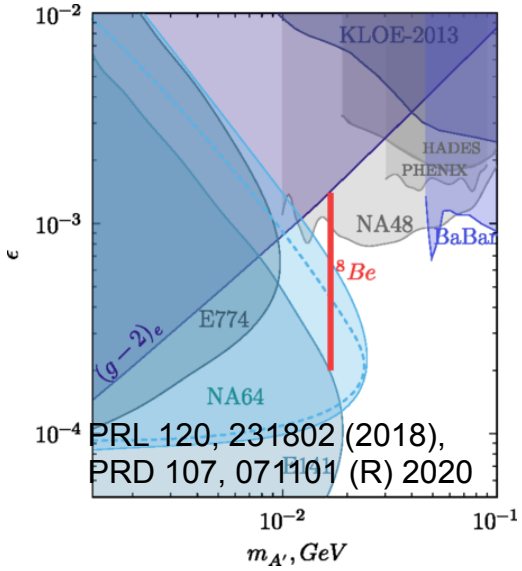




- New waveform fitting routine implemented for better pileup disentanglement
- Preliminary results are encouraging

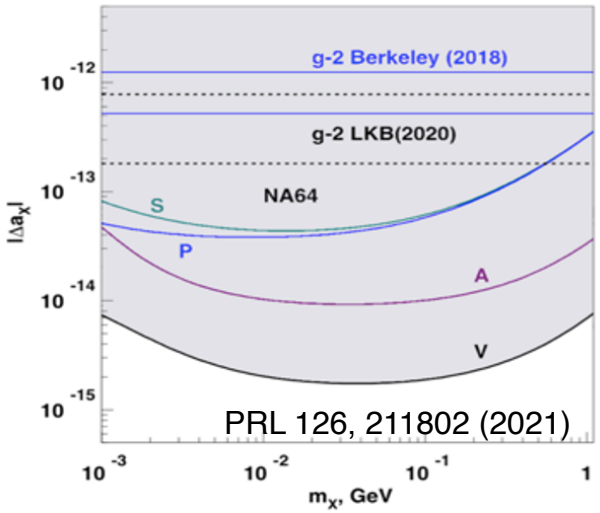
NA64 potential for additional new physics scenarios

A' -> visible and X17



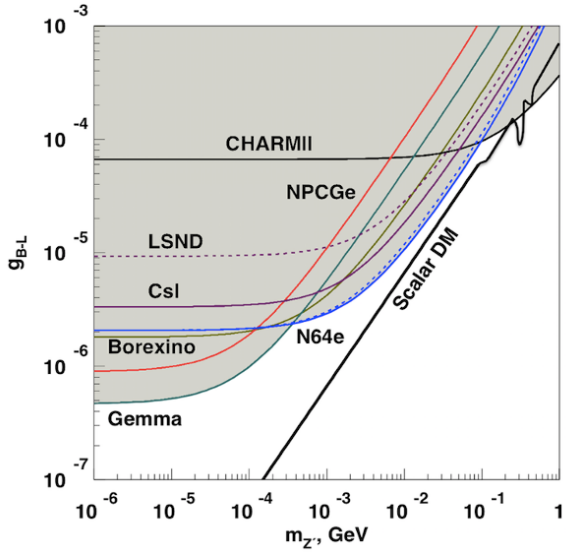
PRL 120, 231802 (2018),
PRD 107, 071101 (R) 2020

$e^-Z \to e^-ZX; X \to$ invisible



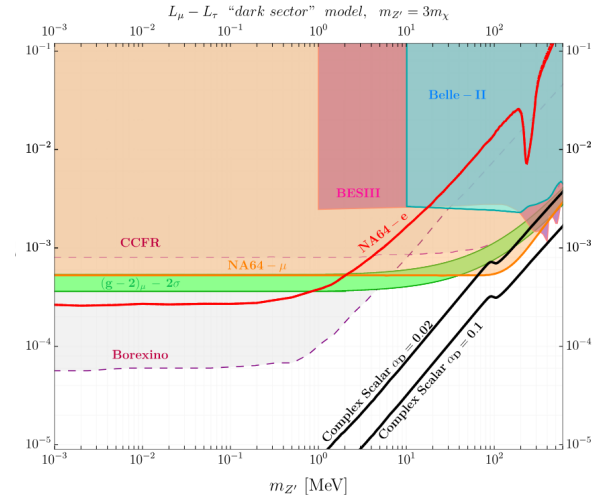
PRL 126, 211802 (2021)

B-L Z´vs neutrino scattering



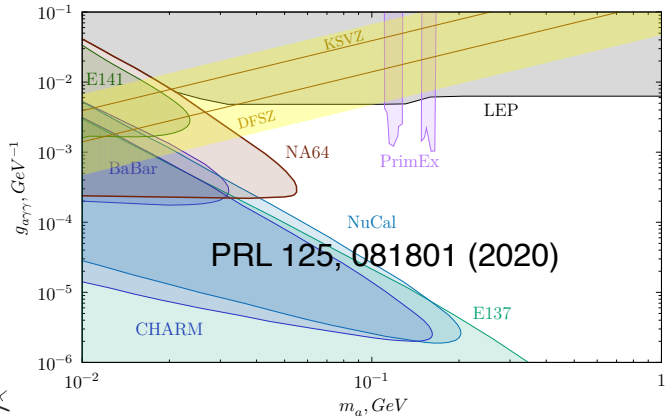
PRL 129, 161801 (2022)

Lmu-Ltau Z'



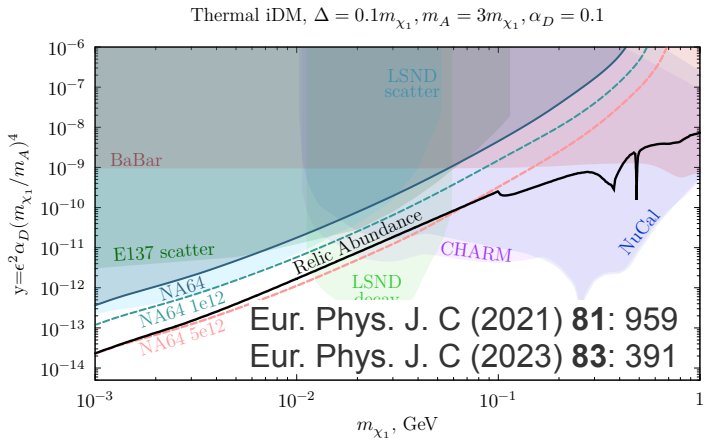
Y. M. Andreev et al. JHEP 07, 212 (2024)

QCD axion and ALPs



PRL 125, 081801 (2020)

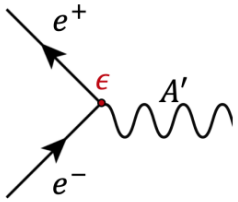
Thermal iDM



Eur. Phys. J. C (2021) **81**: 959
Eur. Phys. J. C (2023) **83**: 391

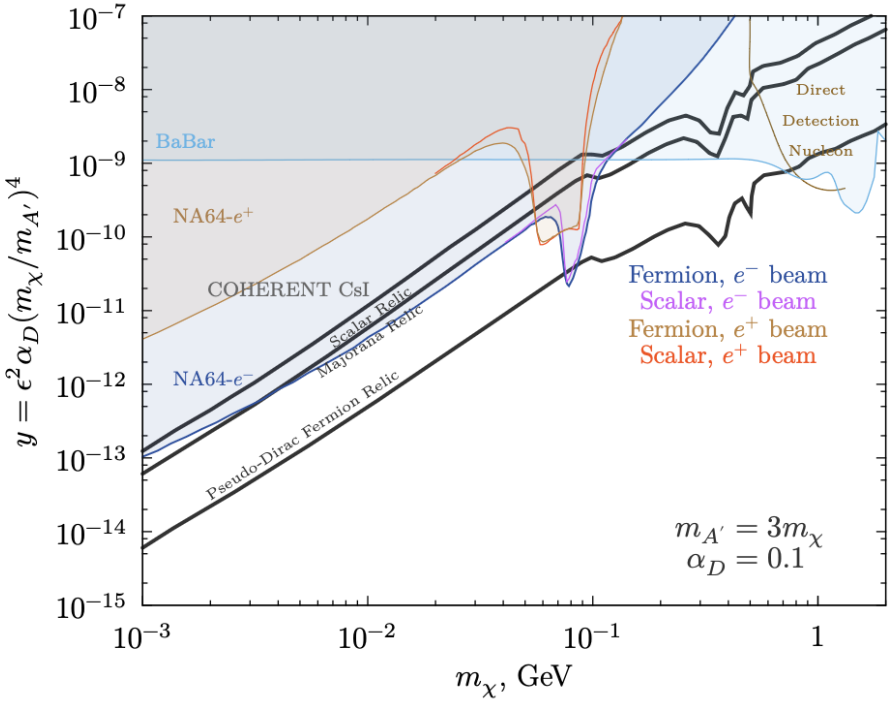
Results obtained with
3x10¹¹ EOT
(2016-2018 statistics)
Analysis in progress
10x more data on "tape"

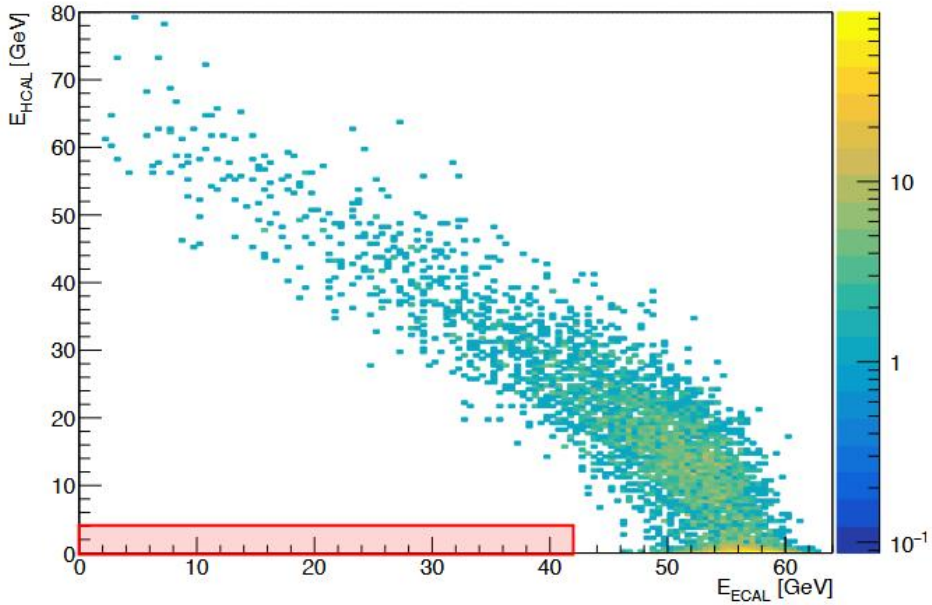
NA64e⁺ - Latest result with 70 GeV positron beam



NA64 positron program: exploit resonant e+e- annihilation for enhanced LDM production yield for > 100 MeV A' masses (CERN-SPSC-2024-003 ; SPSC-P-348-ADD-4)

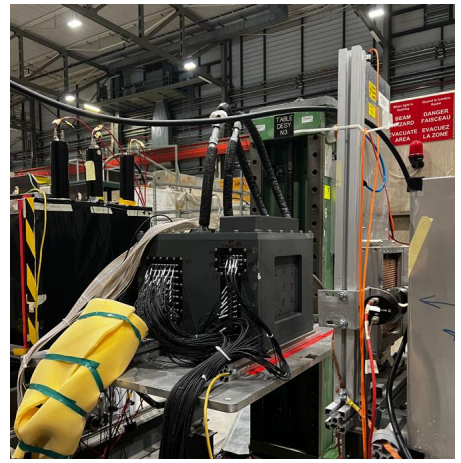
- First search using 100 GeV e+ published in Phys. Rev. D 109 (2024) no.3, L031103.
- Analysis of 1.6×10^{10} e+OT with 70 GeV beam energy collected in 2023 has been recently published in JHEP 06 (2025), 256:
  - Due to the low expected backgrounds, we could adopt an expanded signal window in ECAL, reaching up to 60% of the full beam energy
    - ➢ Improve NA64e limits in a narrow region, with a 2-orders of magnitude lower statistics w.r.t. electron data
    - ➢ Strengthening the case for the low-energy positron program at NA64 after LS3





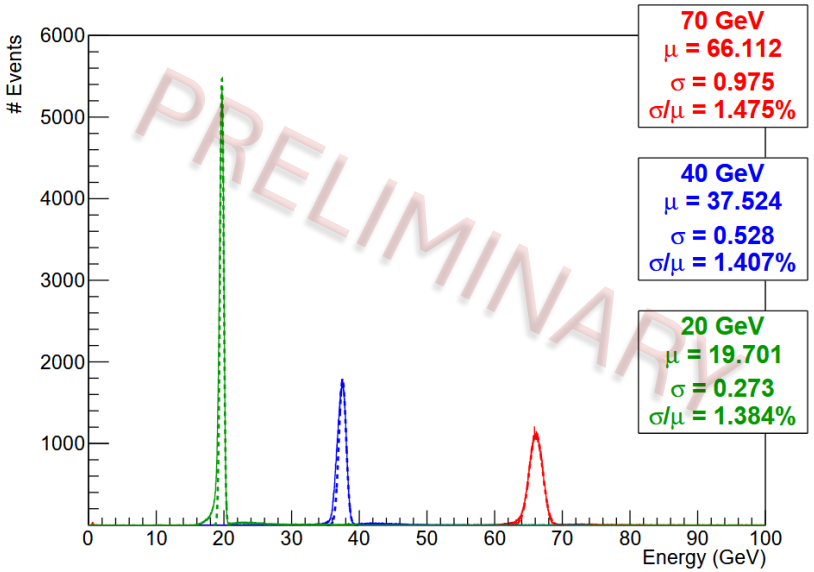
NA64e⁺ - 2025 run and future prospects

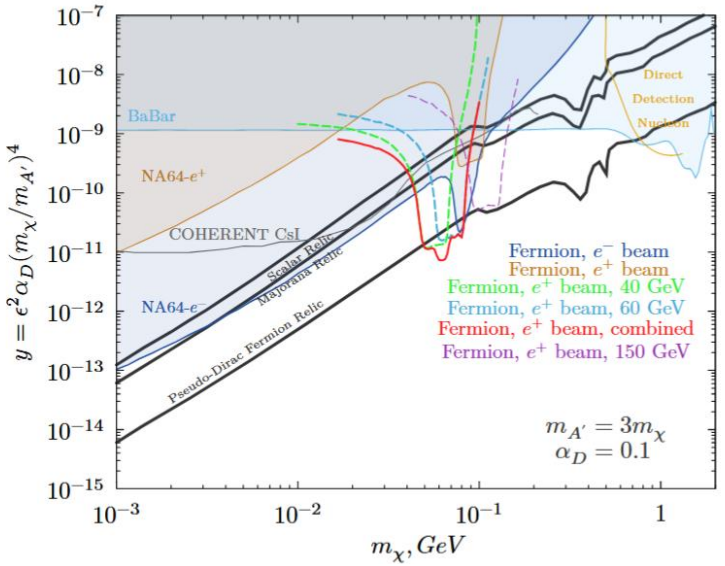
- 2025: collected data at 40 GeV and 45 GeV to demonstrate the feasibility of running at different initial energies to "scan" the A' space (~10^{10} e^+OT collected)
- New high resolution $PbWO_4$ "POKER" calorimeter used as an active target
- New LYSO-based synchrotron radiation detector for better incoming e^- /e^+ identification at low energy (first tested in 2024)



POKER calorimeter

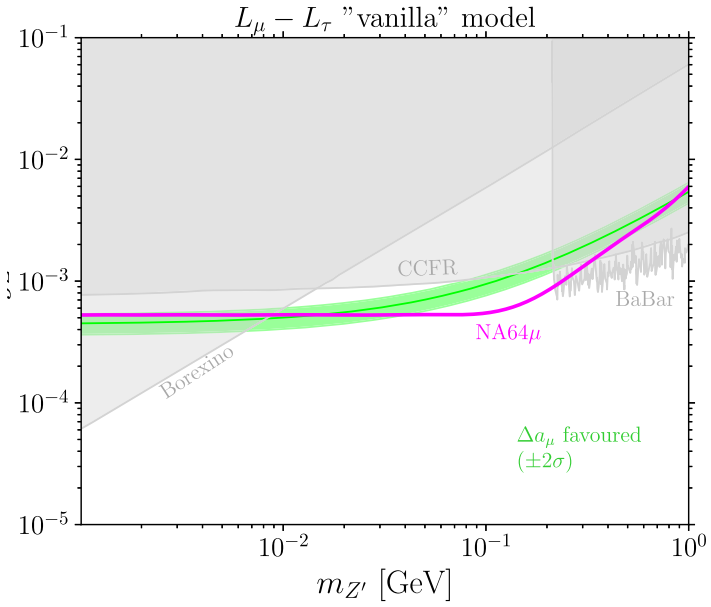
- High-resolution detector optimized to exploit the resonant annihilation missing energy signature
- 9×9 $PbWO_4$ crystal matrix + 2-layers pre-shower, SiPM readout
- Expected resolution:
  $\frac{\sigma_E}{E} \cong \frac{2.5\%}{\sqrt{E}} \oplus (0.5-1)\%$
  - Encouraging results from quick analisis!

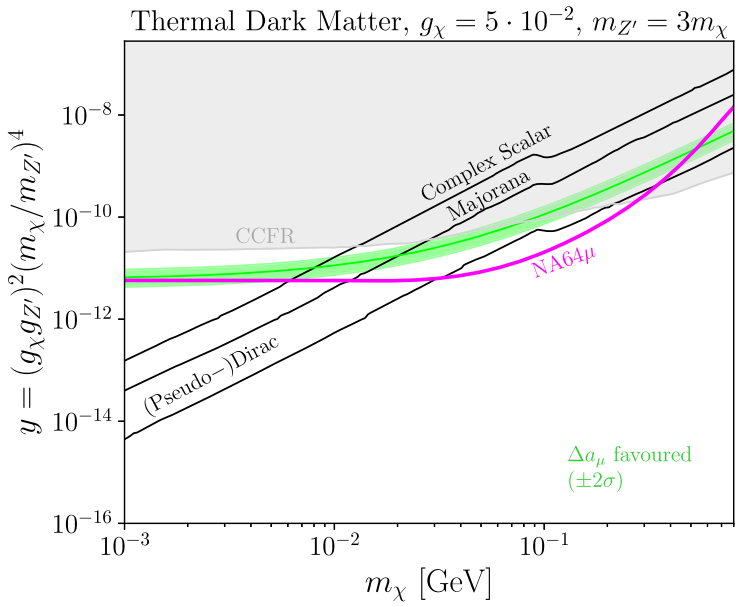


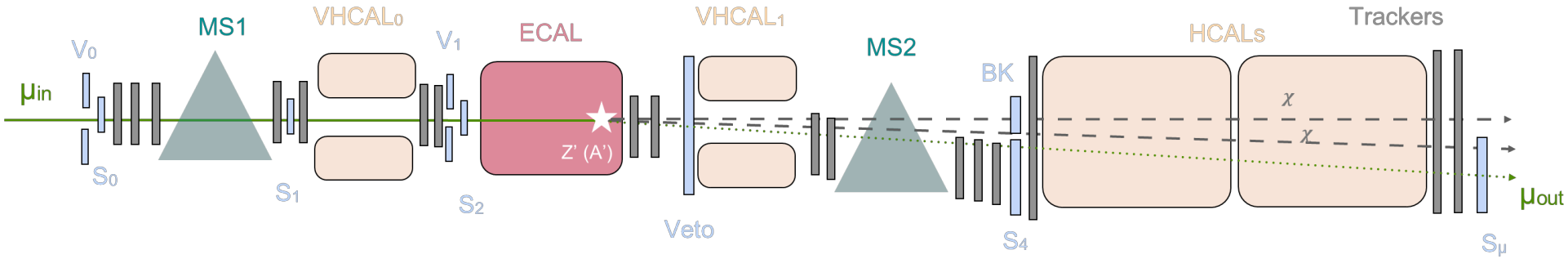


Status and results of NA64mu at M2 beamline

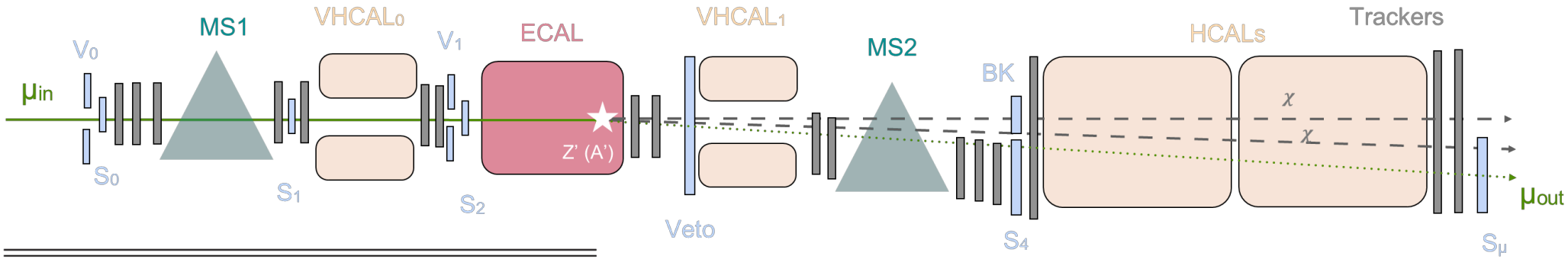
NA64, PRL132 (2024) 21, 211803, PRD 110, 112015 (2024)







NA64mu status



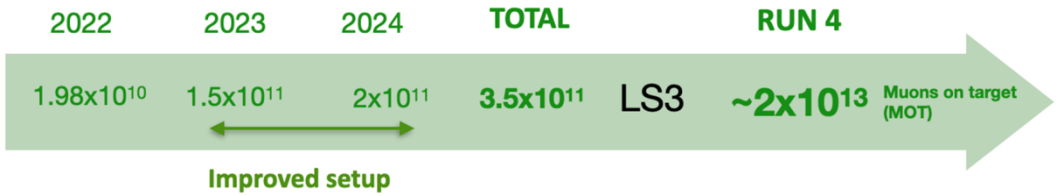
Background source	Background, n_b
(I) Momentum misreconstruction	0.05 ± 0.03
(II) $K \to \mu + \nu, \ldots$ in-flight decays	0.010 ± 0.001
(III) Calorimeter non-Hermiticity	< 0.01
Total nb (conservatively)	0.07 ± 0.03

- Data collected up to 2022 published: Yu. M. Andreev et al. (NA64 Collaboration), Phys. Rev. Lett. 132, 211803 (2024), Y. M. Andreev et al. Phys. Rev. D 110, 112015 (2024).
- Setup optimized in 2023-2024 to reduce background and increase intensity
- Improved MS1 in 2024 (more efficient tackers)
- No data taking in 2025 → longer run in 2024 to accommodate AMBER and MUoNE requirements
- Two independent blinded analysis ongoing (2023 and 2024 data samples)

Trigger: $S_0 \times \overline{V_0} \times S_1 \times S_2 \times S_3 \times \overline{V_1} \times S_4 \times \overline{BK} \times S_\mu$

Signal signature:

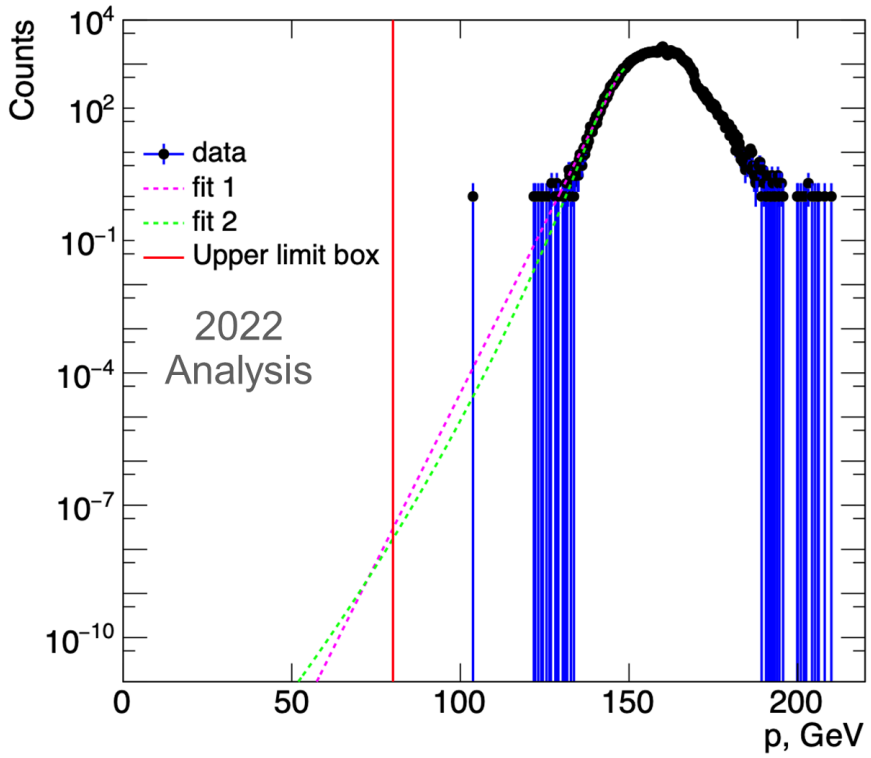
- Well-defined incoming muon track with 160 GeV
- No activity in the veto and VHCAL
- MIP in ECAL and HCAL
- Scattered muon E < 80 GeV

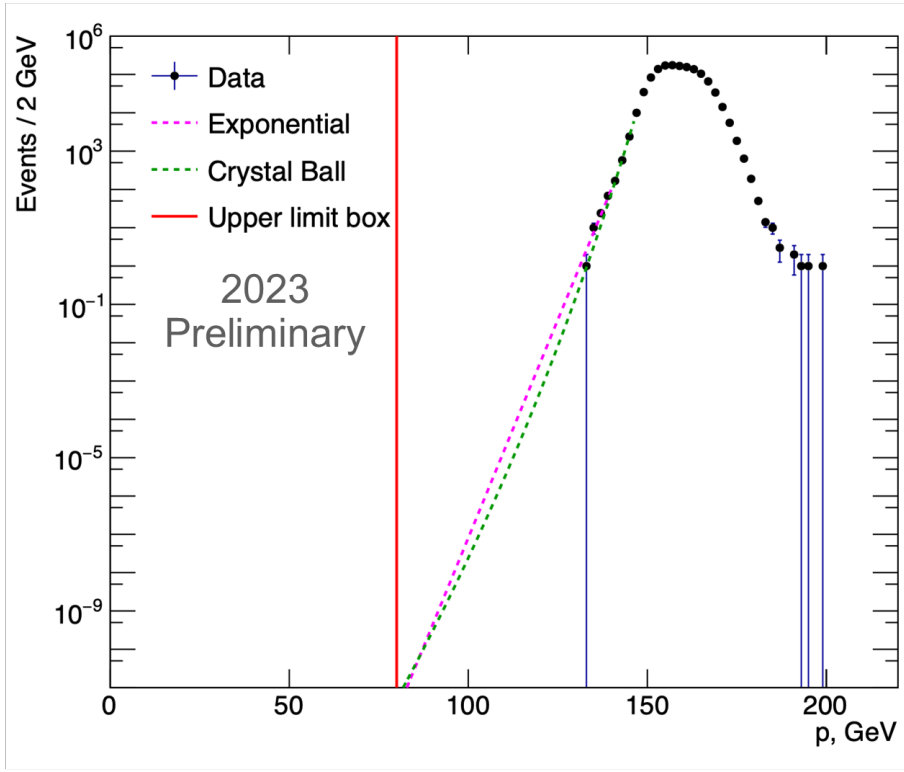


NA64mu ongoing analysis

Selection Criteria

- Time selection
- Well-reconstructed single muon track traversing the setup
- Single track in MS1 with p_{MS1} within 160 GeV/c ± 3 σ_{MS1}
- Single hit in the detectors and clean track after MS2
- No energy in VHCALs and VETO outer cells
- MIP-compatible energy in calorimeter, particle impinging on ECAL central cells





Run	2023	2024
p_{in} (MS1)	0.288	0.550
p_{out} (MS2)	0.415	0.519
Overall	0.263	0.451

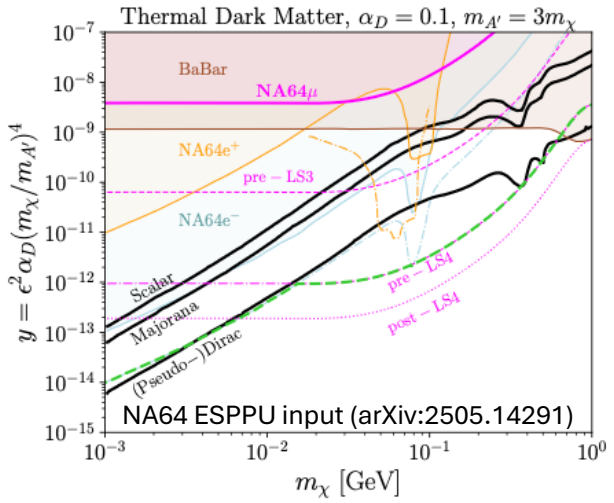
Table 1. Preliminary track reconstruction efficiency in NA64μ

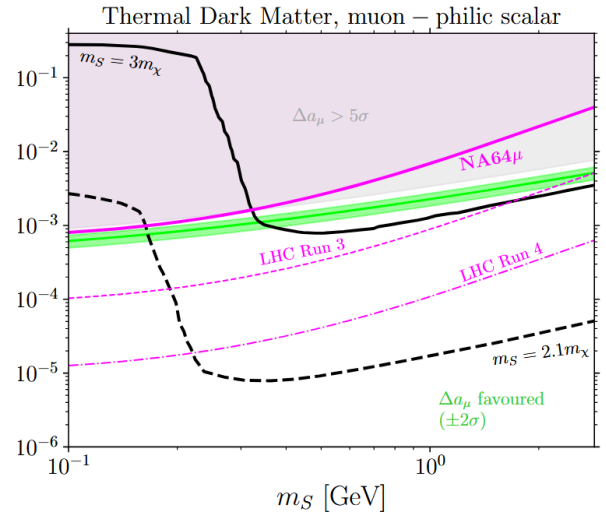
Post LS3 prospects for NA64μ

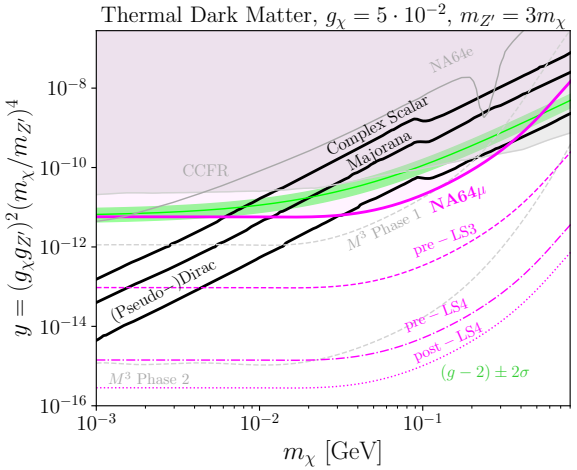
NA64, PRL132 (2024) 21, 211803, PRD 110, 112015 (2024)

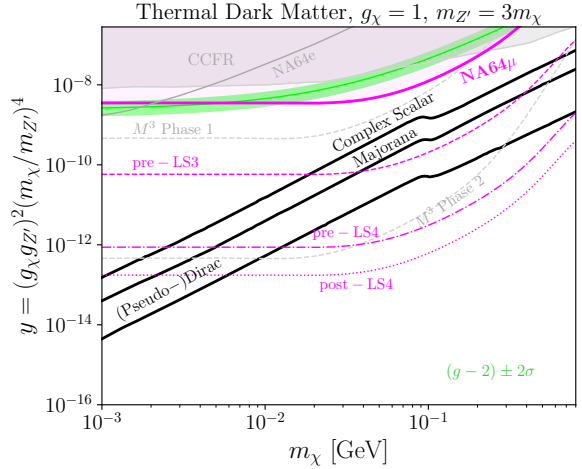
During LS3:
setup upgrade to run up to 5x10^7 muons/spill (the maximum the beam line can deliver are 4x10^8 muons/spill)

GOAL for LHC-RUN4 > 2× 10^{13} EOT









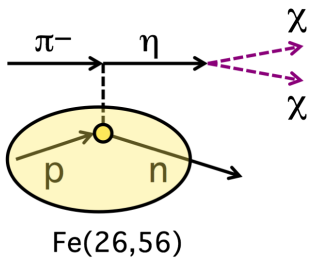
Planned upgrades include:
ECAL (readout)
HCAL (larger acceptance modules)
VHCAL (optimisation of prototype, 2 modules)
Second spectrometer with double magnet
Segmented trigger (hodoscope)
DAQ & readout

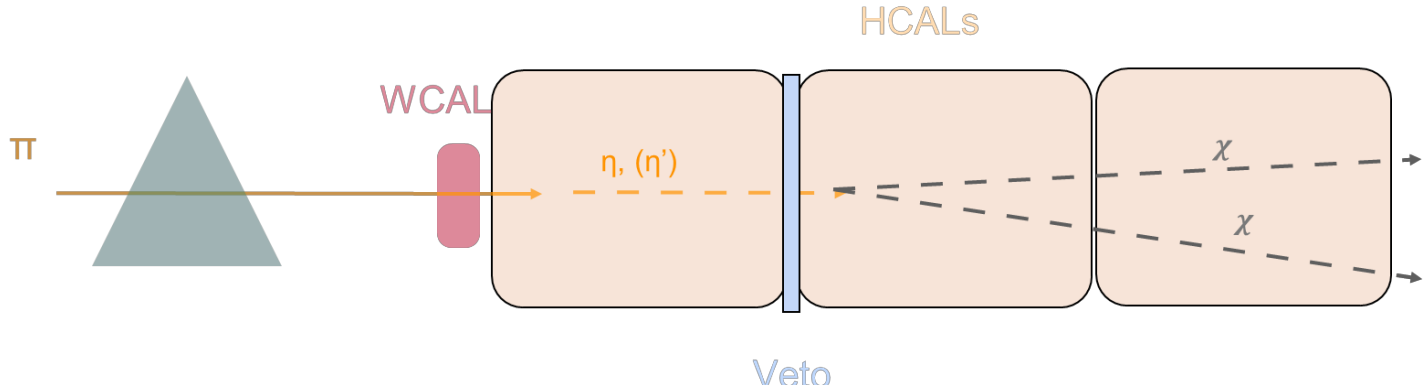
See next talk of Victor for additional BSM scenarios that can be tested with NA64mu or Eberhart et al., arXiv:2504.05873 (leptophilic ALPs), new ideas more than welcome!

NA64h - first results

NA64h: Search for Dark Sector predominantly coupled to quarks with pion, kaon, and proton beams at the CERN SPS

- Sensitive to several models via missing-energy technique (invisible decays of η, η', ω, ρ mesons, oscillations of neutral kaon into its "dark" partner, production of leptophobic LDM states)
- First proof-of-concept results from the the analysis of 2.9 x 10^9 πOT (1 day in 2022) with a simple setup:





- Results published in Y. M. Andreev et al. Phys. Rev. Lett. 133, 121803 (2024)
  - Set most stringent constraints on η, η' invisible decay

$$\mathrm{Br}(\eta \to \mathrm{invisible}) < 1.1 \times 10^{-4},$$

$$\mathrm{Br}(\eta' \to \mathrm{invisible}) < 2.1 \times 10^{-4},$$

- Additional data collected in 2025 with modified setup
- Possibility to run the experiment at the PS is under study
  - First tests at PS T9 are foreseen from the 24th of September until October 8th to understand the beam quality

An addendum to the SPSC with our future plans after LS3 is in preparation

Summary and Outlook

NA64e⁻

- **Tot.** collected statistics **~2 x 10^{12} EOT ->** probing **LDM benchmark model** and improve sensitivity **ALPs, L_μ-L_τ, and B-L Z', iDM,…**
  Plan: 1.5x statistics before and total of ~1. x 10^{13} EOT after LS3

NA64μ

- **2022:** 2x10^{10} MOT, **2023/4:** 3.5x10^{11} MOT(upgraded setup)->*$(g\text{-}2)_\mu$ and L_μ-L_τ Z'*
- **Plan post LS3: 2. x 10^{13} EOT after LS3**

NA64e⁺

- Pilot run 2022 (2 days) ~1x10^{10} E+OT, 2023 run at 70 GeV (1 day)
- **Plan: 40, 60 GeV ~2. x 10^{11} E+OT after LS3**

NA64h

- **2022** ~2x10^{9} pions (1 day) -> proof of principle (DS coupled to quarks), addendum in preparation to run after LS3

The **exploration of the NA64 physics potential has just begun**. Proposed searches with **leptonic and hadronic beams**: unique sensitivities **highly complementary to similar projects.**

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