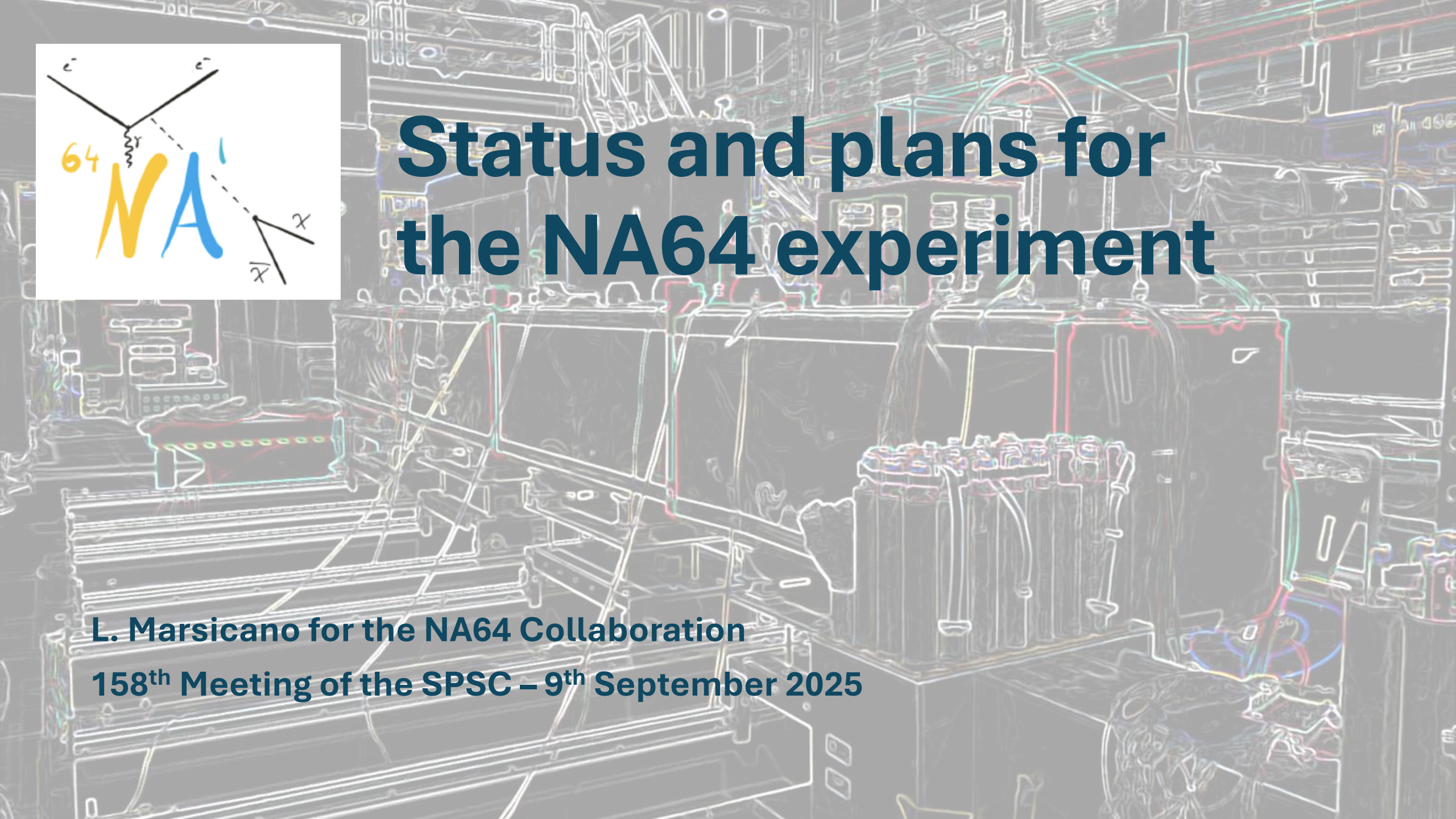


Status and plans for the NA64 experiment

L. Marsicano for the NA64 Collaboration

158th Meeting of the SPSC – 9th September 2025

NA64 physics case: the dark sector

Light Dark Matter hypothesis: DM is made of sub-GeV particles χ, part of a new "dark sector", feebly interacting with SM states through a new force in Nature

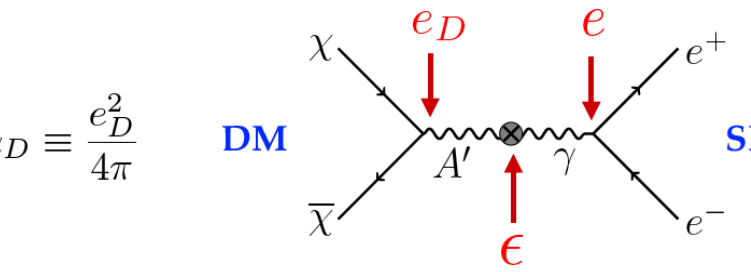
Representative case: *dark photon (A') model* -- new force is mediated by a new massive U(1) gauge boson; coupling to SM electric charge εe, with ε<<1

Cosmological prior
DM-SM thermal equilibrium in early Universe. Currently observed DM relic density is connected to χ+χ→SM+SM annihilation cross section (*"freeze-out"* mechanism).

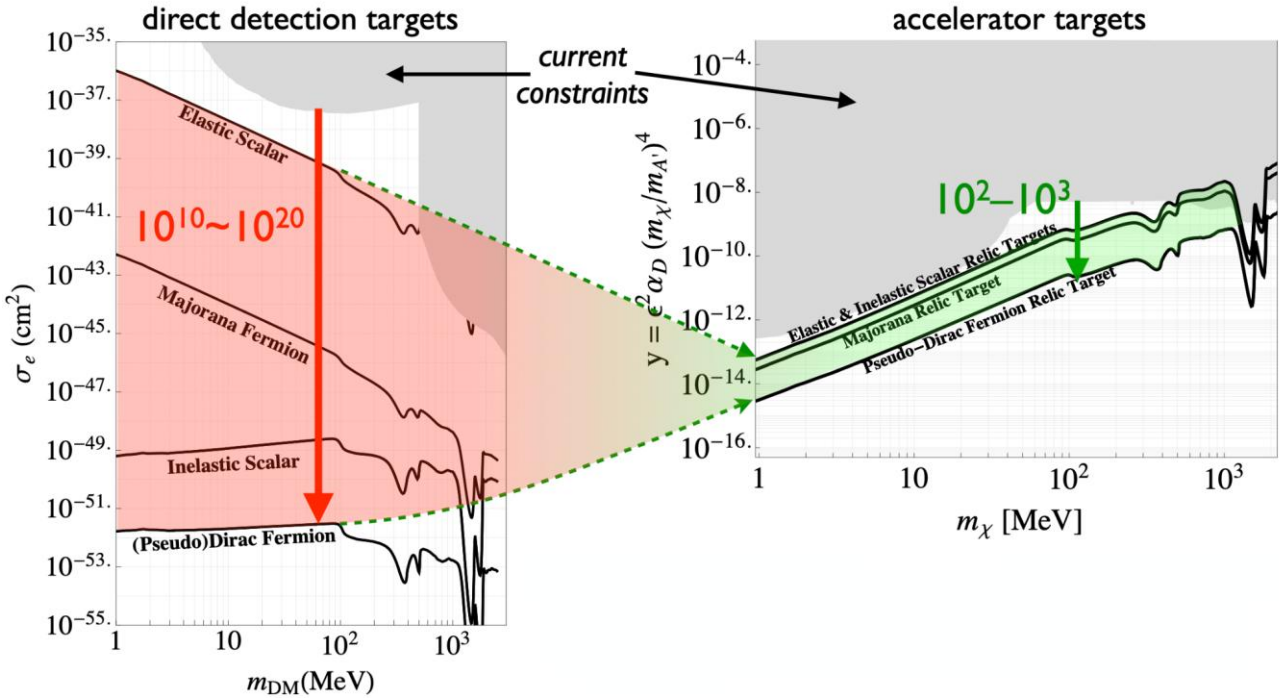
Key observation: the DM relic density inferred from astrophysical/gravitational measurements provides a target in the LDM parameters space.

LDM searches at accelerators → large energy / q^2 regime: experiments are (almost) insensitive to DM spin and mass matrix

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



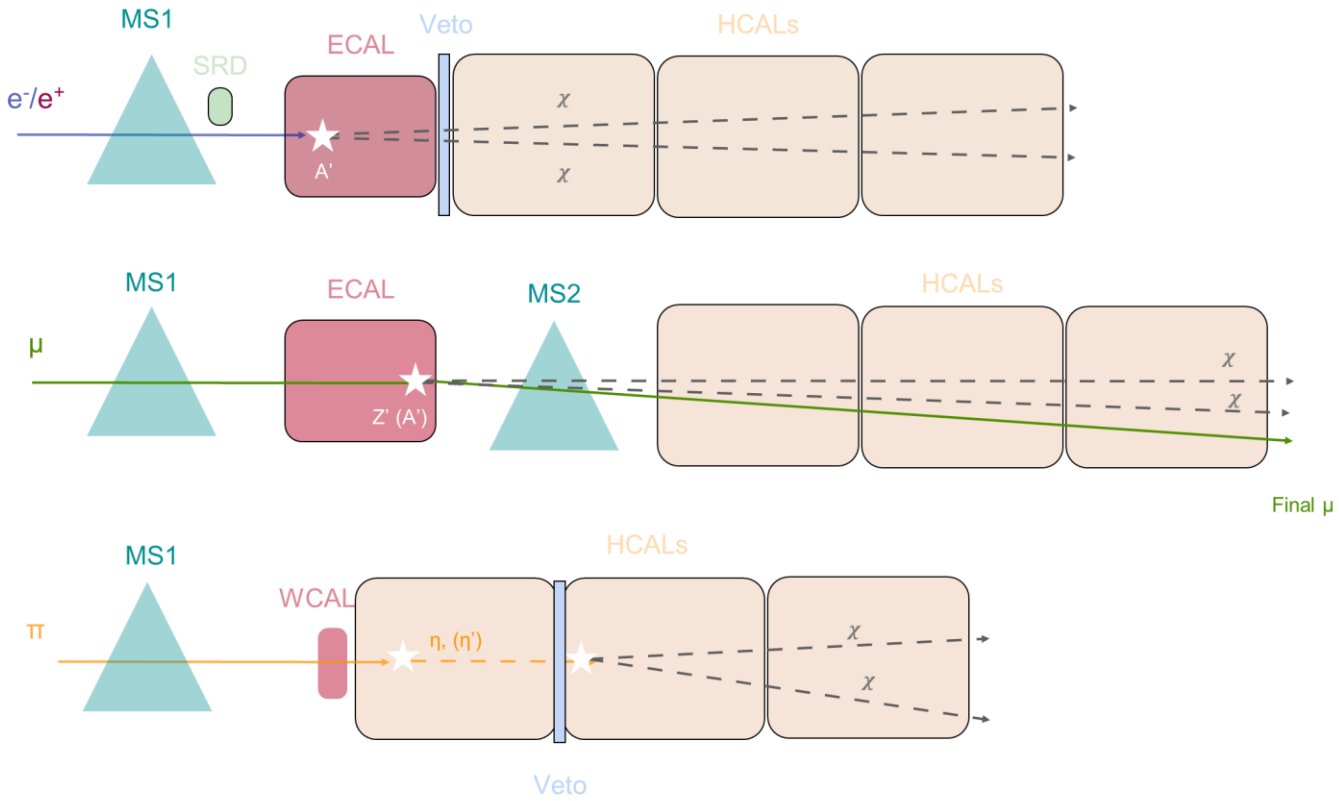
$\alpha \equiv \frac{e^2}{4\pi}$



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

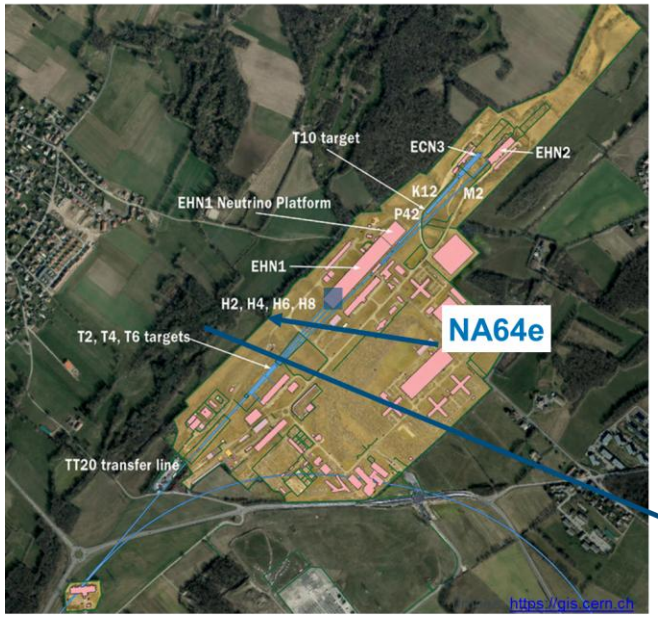


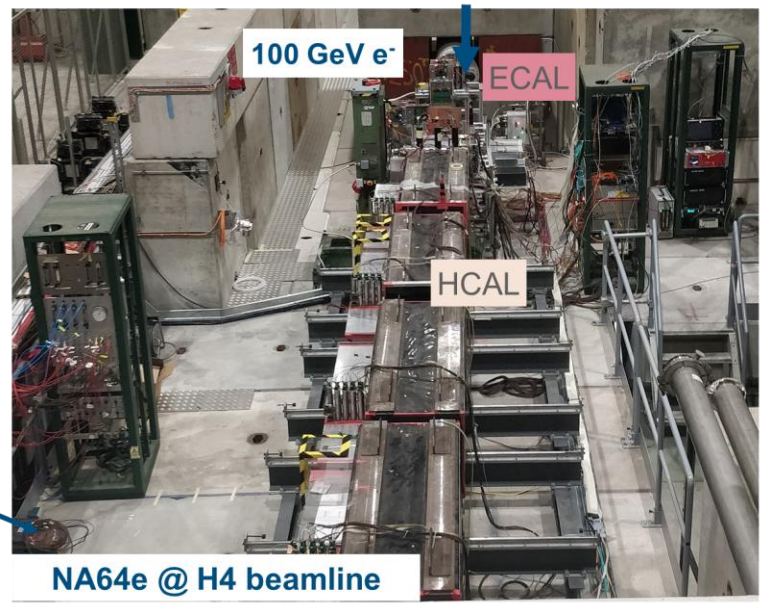
NA64 Program overview

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)

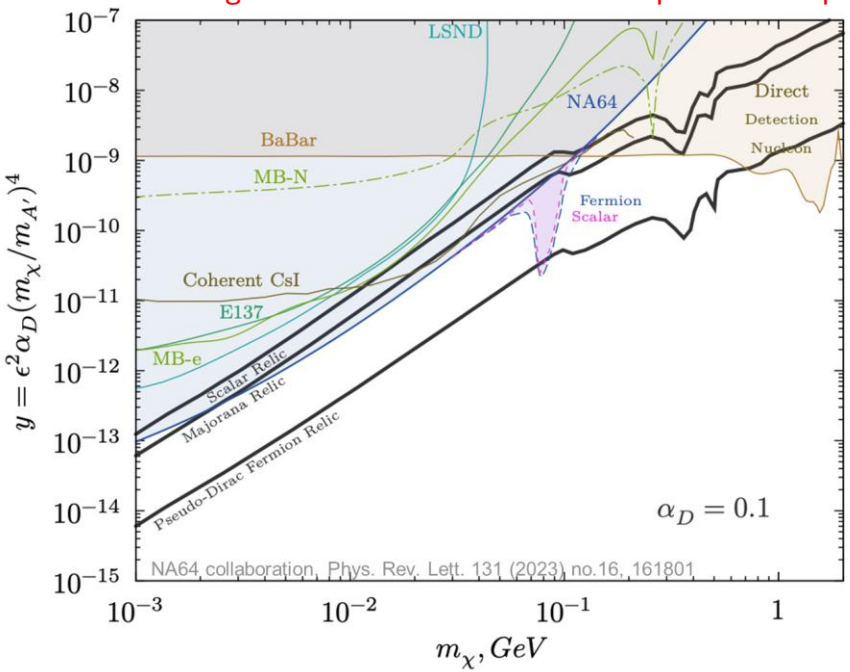
Status of NA64e/e+ @H4

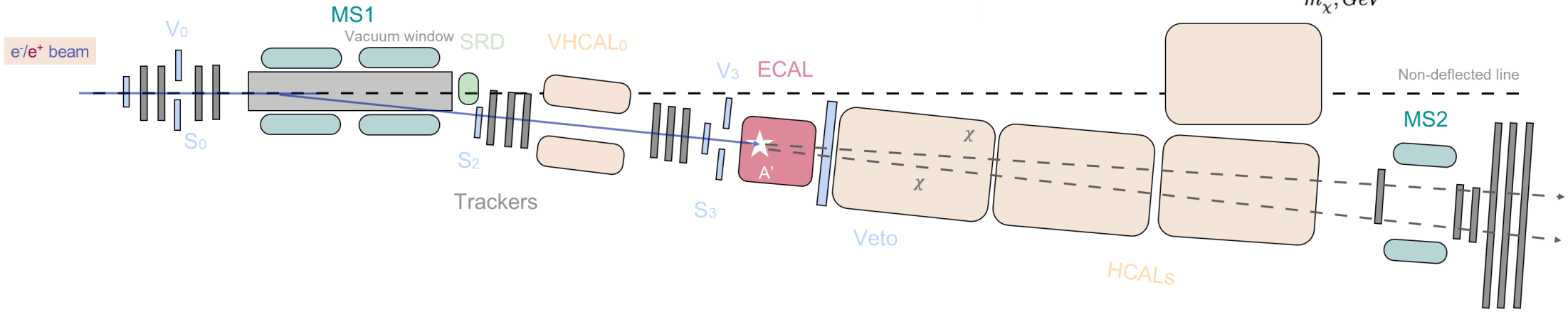




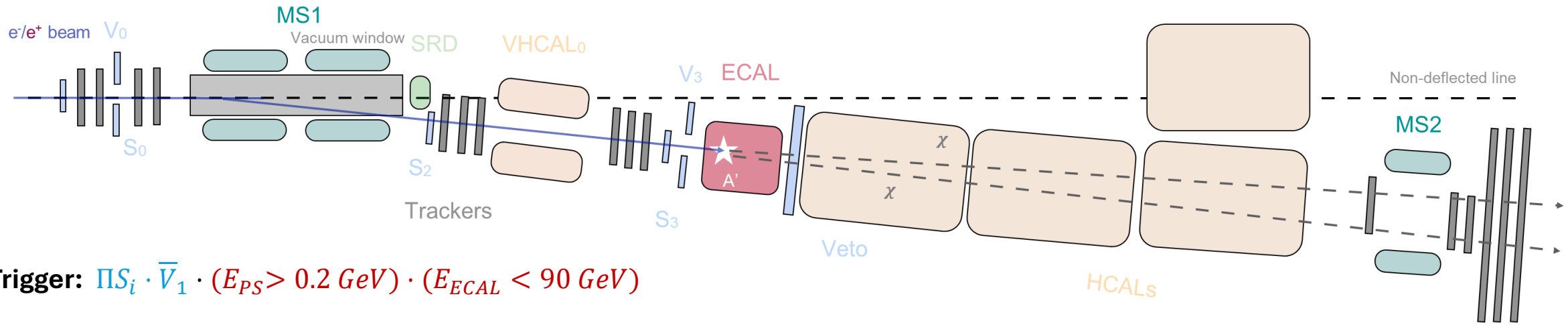
NA64e @ H4 beamline

World leading NA64 constraints on the LDM parameter space





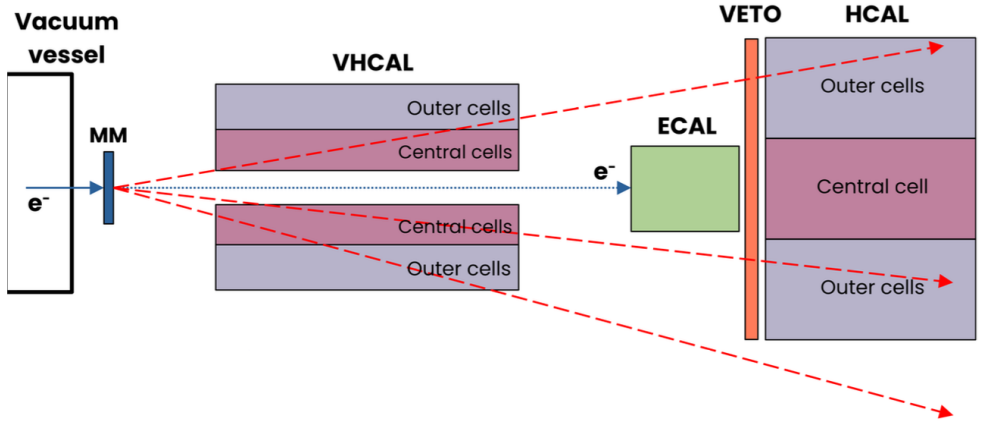
Status of NA64e @H4

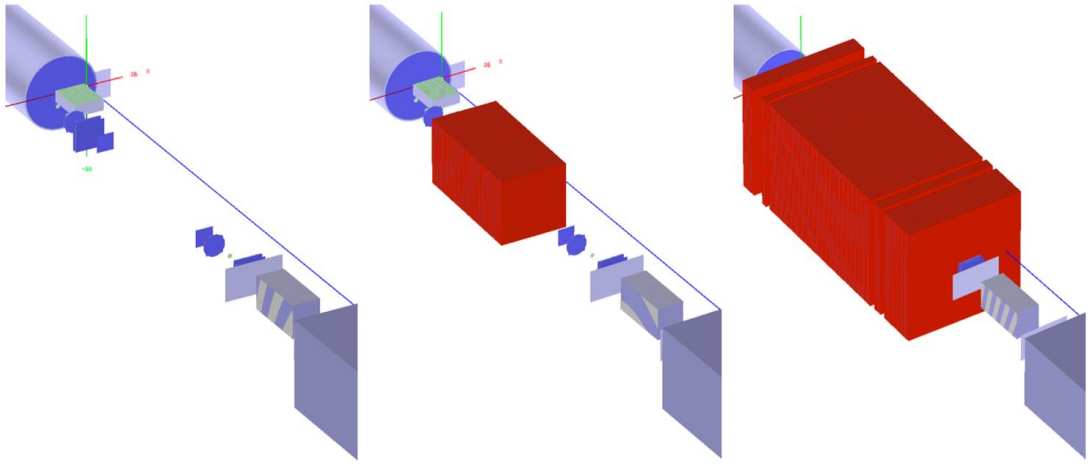


- **Trigger:** $\Pi S_i \cdot \overline{V}_1 \cdot (E_{PS} > 0.2\ GeV) \cdot (E_{ECAL} < 90\ GeV)$
- **Momentum reconstruction and PID**:
  - Magnetic spectrometer (MS1) + Synchrotron Radiation Detector (SRD)
- **Hermeticity**
  - Hadronic calorimeter (HCAL), veto hadron calorimeter (VHCAL) + Veto
-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

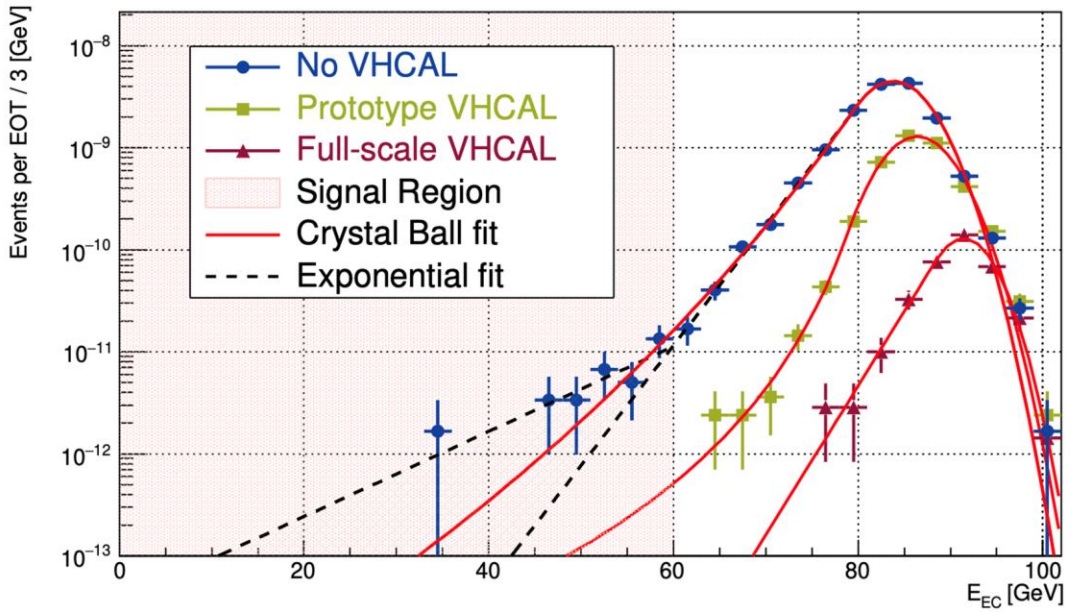
- ~1.6 10^{12} eOT collected in the same setup between 2023 and 2024
- Blinded data analysis ongoing
- Goal: LDM exploration and prove feasibility of post-LS3 program
- Plan: publish together 2023-2026 data

Understanding background from the hadron electroproduction in the beam line





- 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

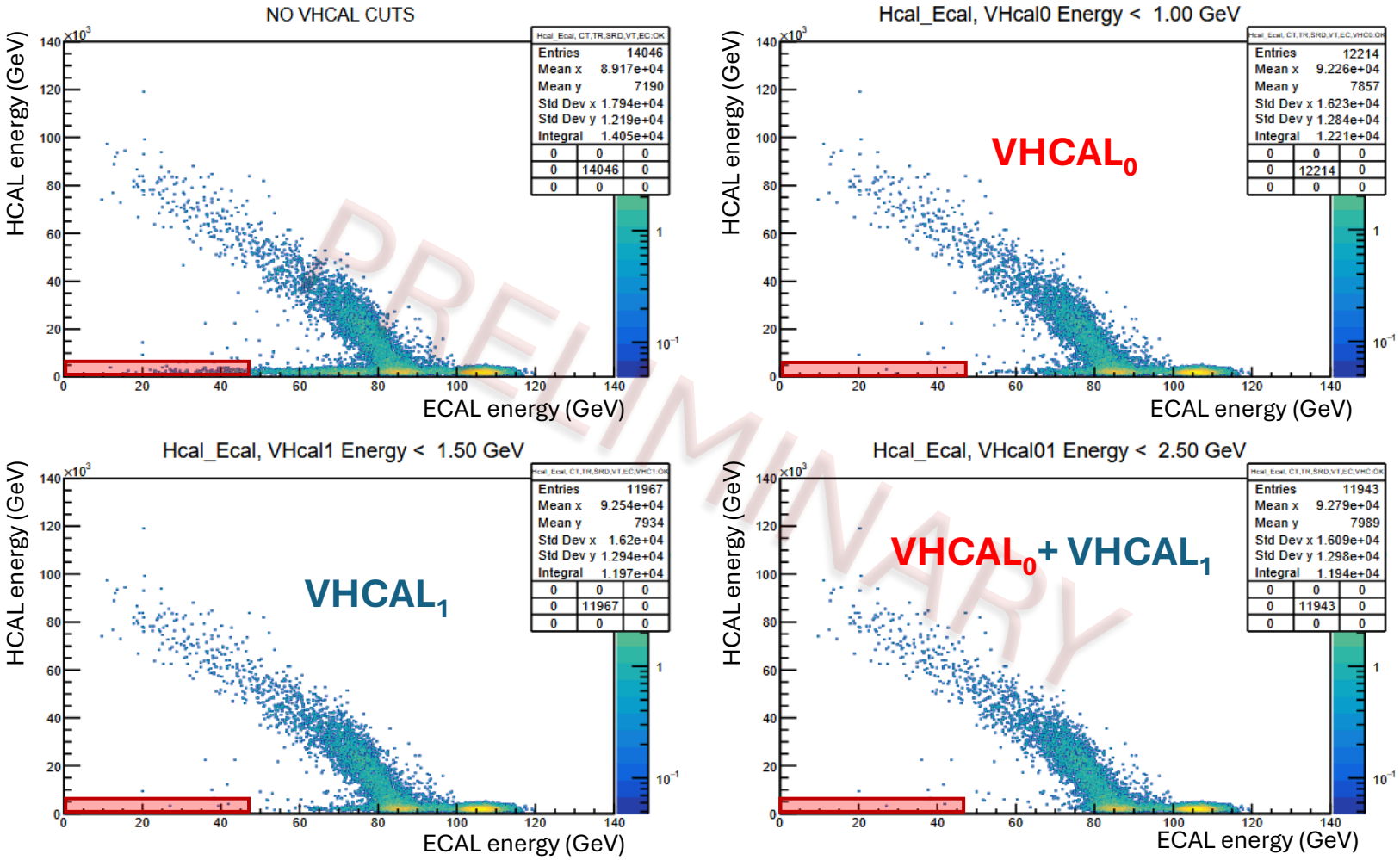


Quick look at 2025 electron data

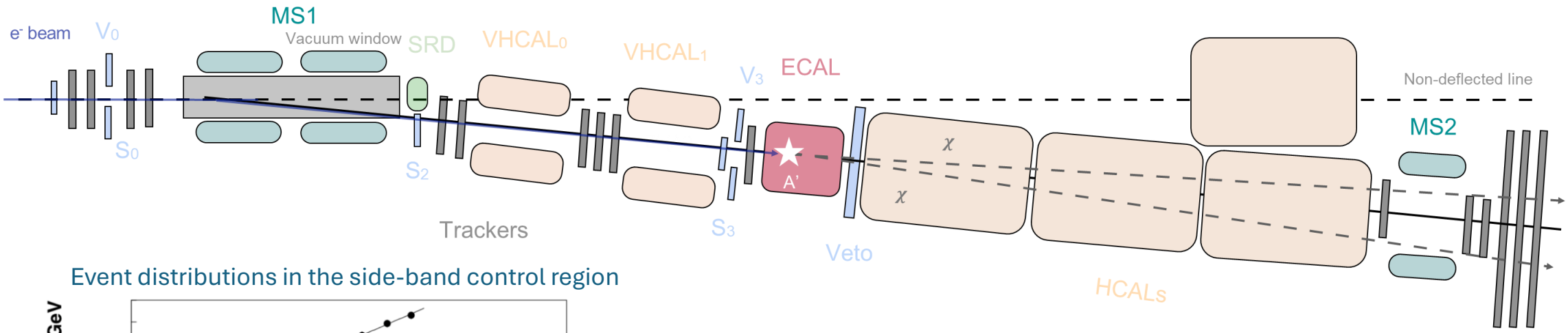
- ~5.9 × 10^{11} eOT collected during 2025 with improved setup (additional VHCAL module)
- Encouraging results from a "quick look" at data (the run ended in July):

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

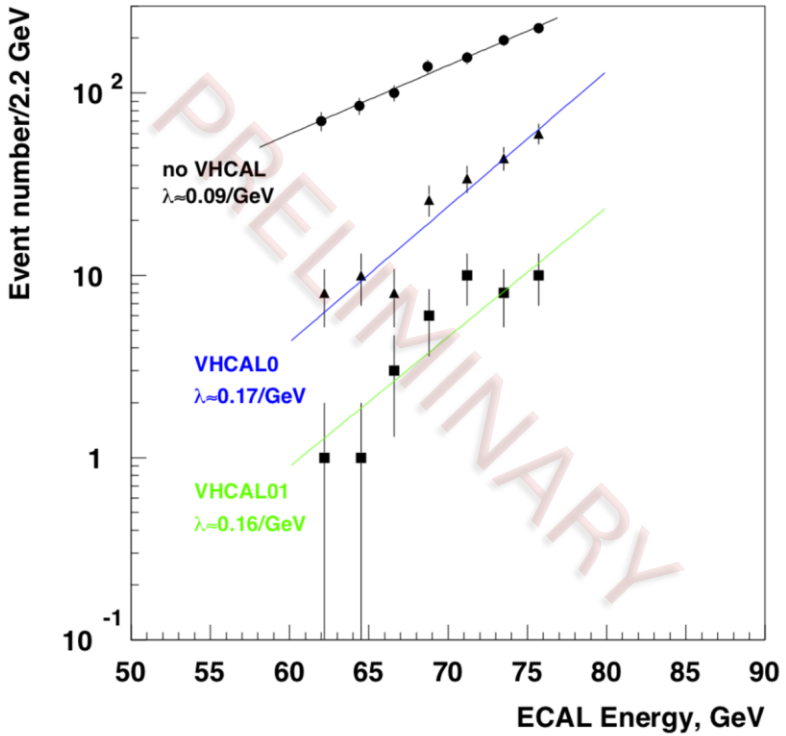
Preliminary test on limited 2025 data sample - No information from trackers used



Quick look at 2025 electron data



Event distributions in the side-band control region



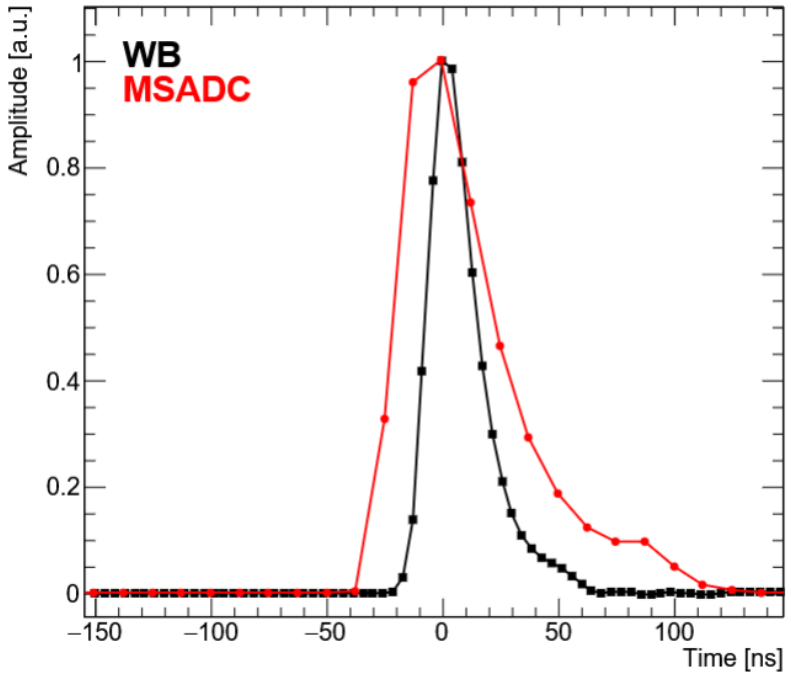
- Possible further steps to mitigate the background level after LS3:
  - Remove as much material as possible upstream of VHCAL0; optimize the positions of all detectors
  - Improve detection efficiency of VHCAL (new PMT readout)
  - Upgrade the setup with larger-acceptance HCAL modules from the M2 line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

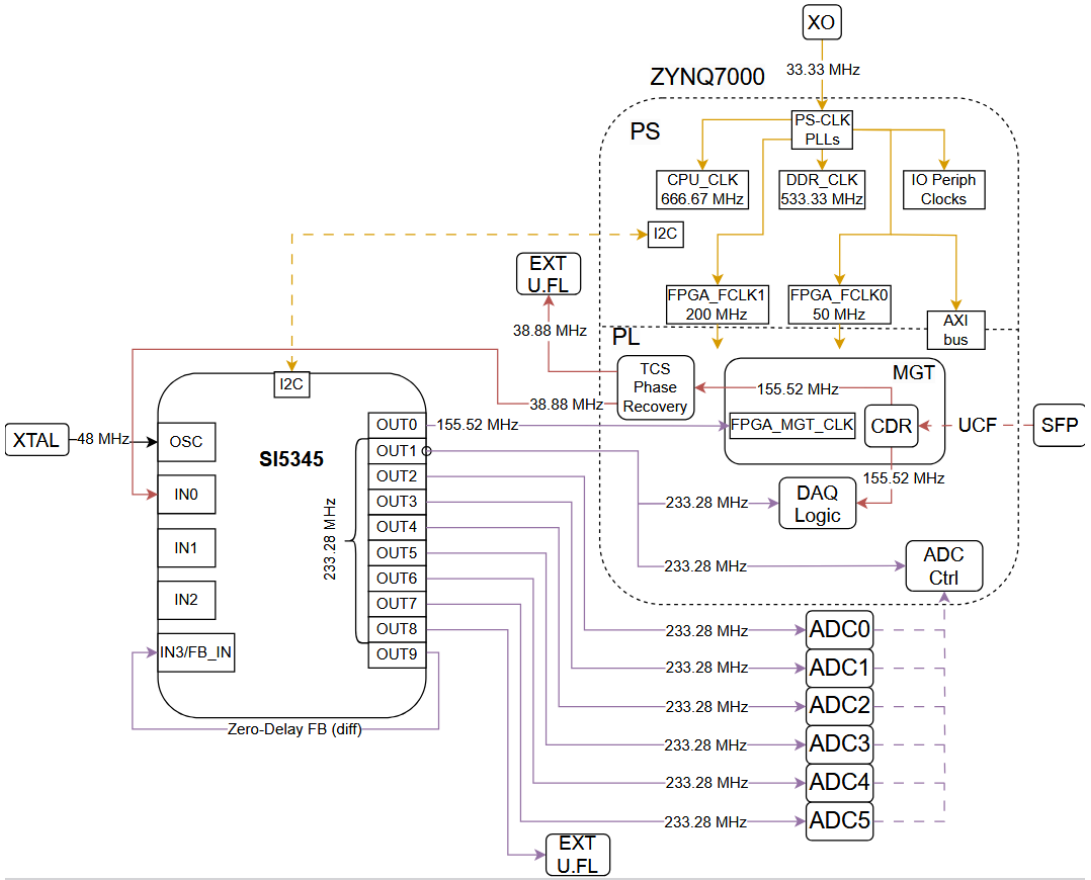
- Preliminary plan: collect further statistic during 2026 run to finalize background studies before LS3 (>10^{12} eOT combined with 2025)

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)

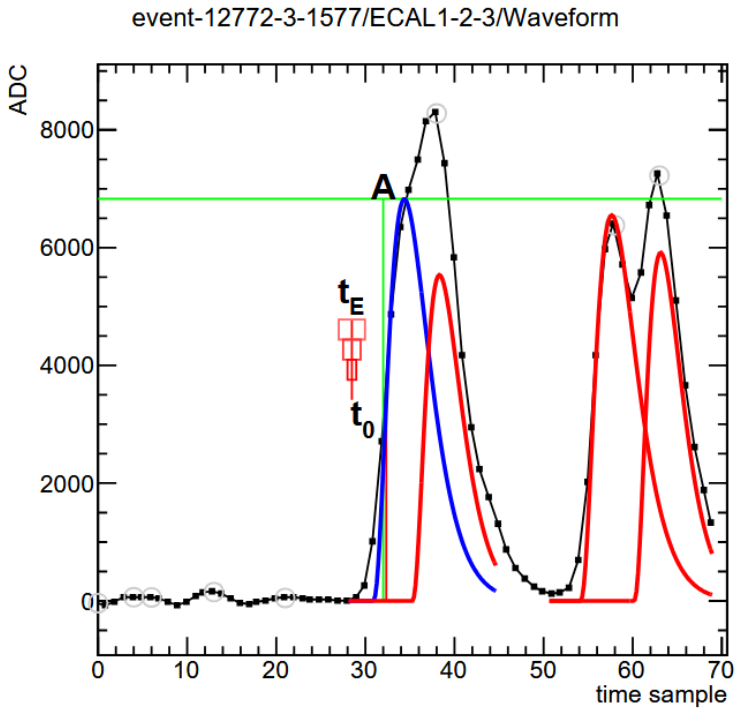


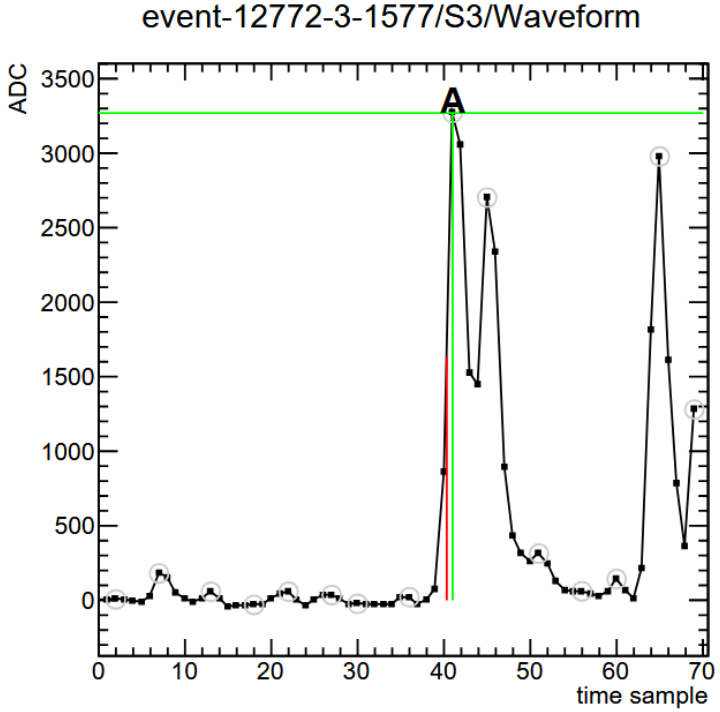


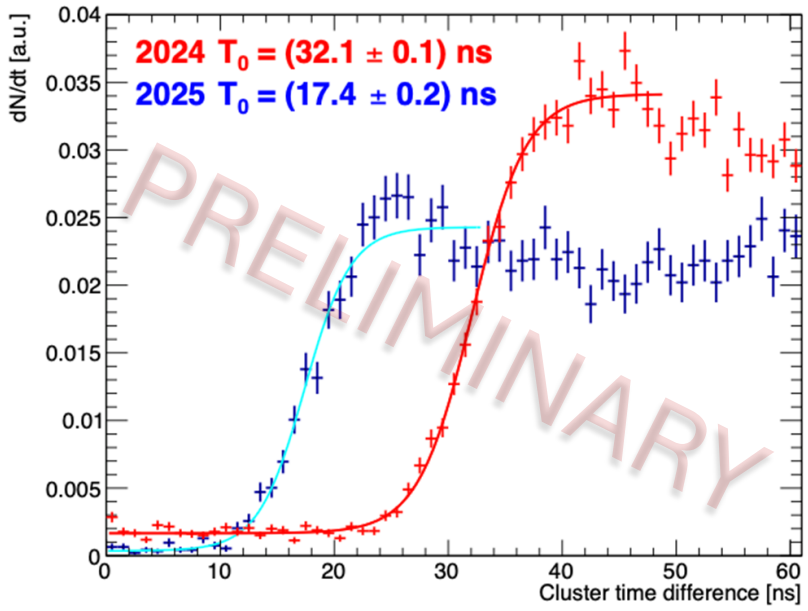
Software upgrades – waveform fitting routine

New readout electronics improve waveform reconstruction quality, allowing for better pile-up disentanglement in view of the high-intensity running

- New waveform-fitting routine implemented in reconstruction software, first step towards event clustering
- 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).
- Data analysis ongoing; preliminary results are encouraging



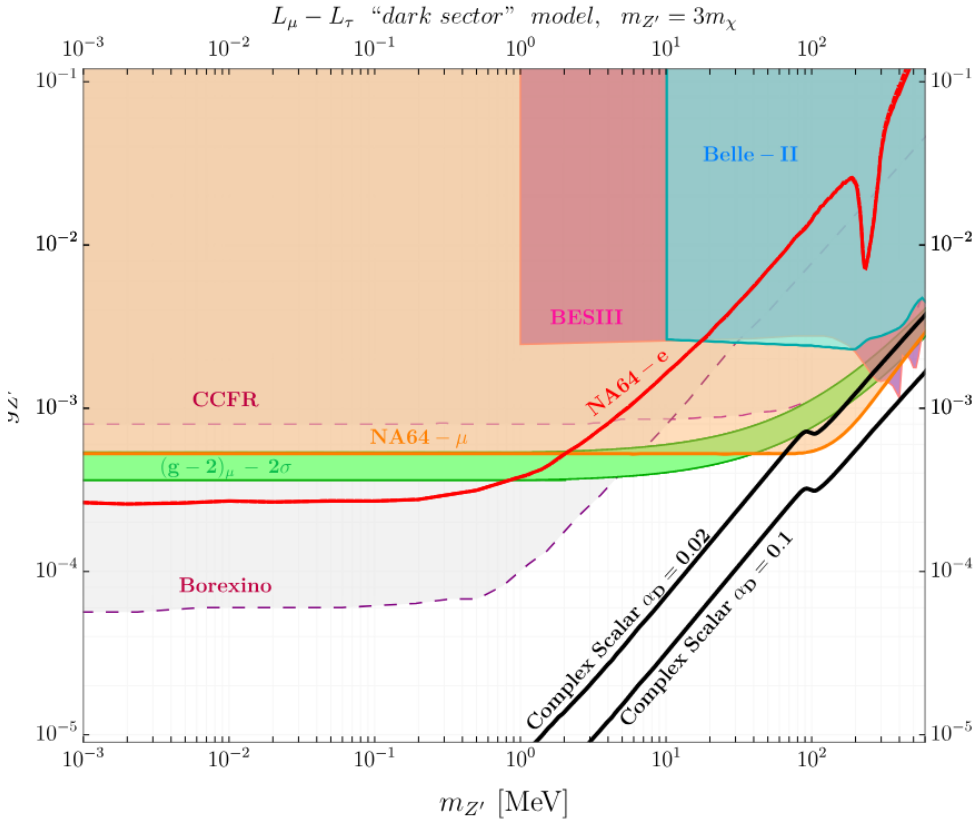




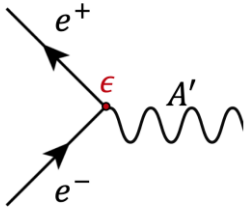
L_μ–L_τ Z' search at NA64e

Search for new, light Z' vector boson, with dominant coupling to μ and τ leptons at NA64e

- Completed re-analysis of the whole 2016-2022 NA64e dataset (Y. M. Andreev et al. JHEP 07, 212 (2024))
- Z' produced in the ECAL through loop-level coupling enabled by the mixing with the photon
- Same reconstruction algorithms and event selection criteria used for the A' search (analogous phenomenology)
- First exclusion of the g-2 compatible band, for $m_{Z'}$< 1 MeV, from an experiment at accelerators

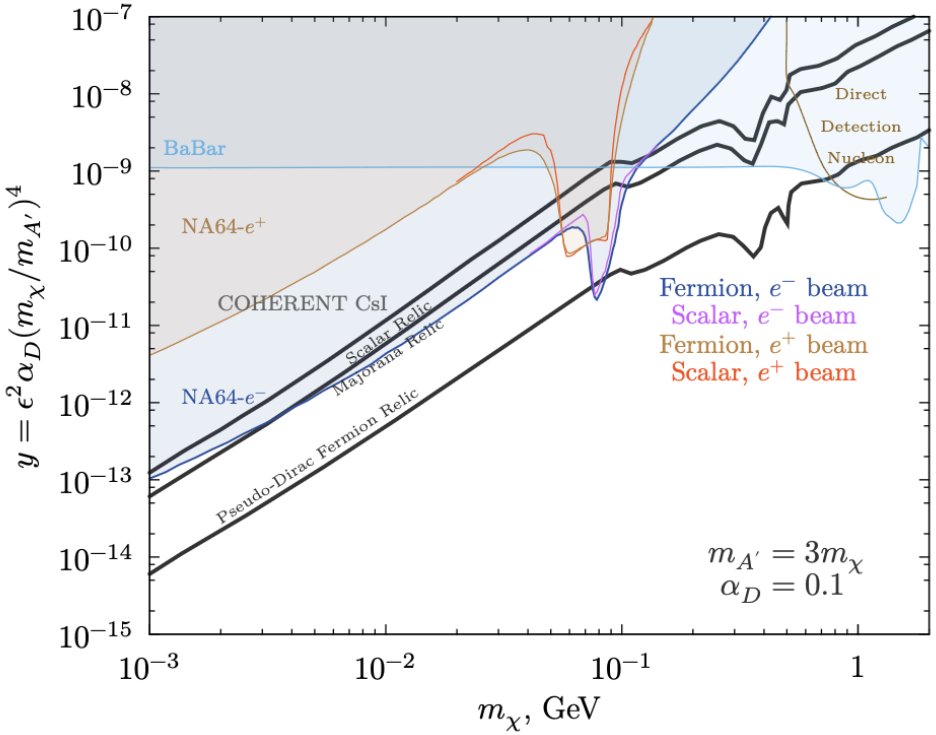


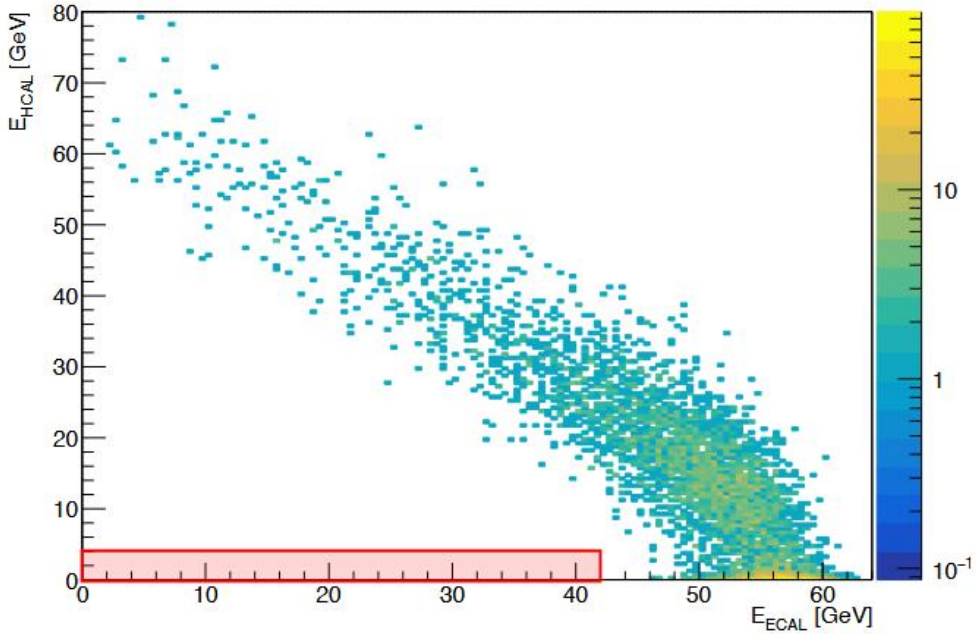
NA64e+ - Results of 2023 data analysis



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)

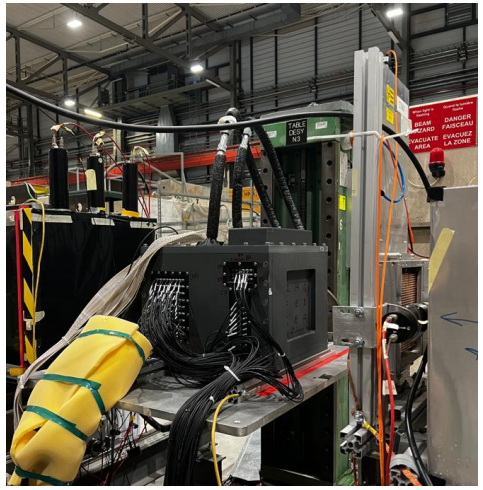
- First search using 100 GeV e+ published in Phys. Rev. D 109 (2024) no.3, L031103.
- Analysis of 1.6x10^{10} e+OT with 70 GeV beam energy collected in 2023 has been recently published in JHEP 06 (2025), 256:
  - Due to the low expected backgrounds, we could adopt an expanded signal window in ECAL, reaching 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





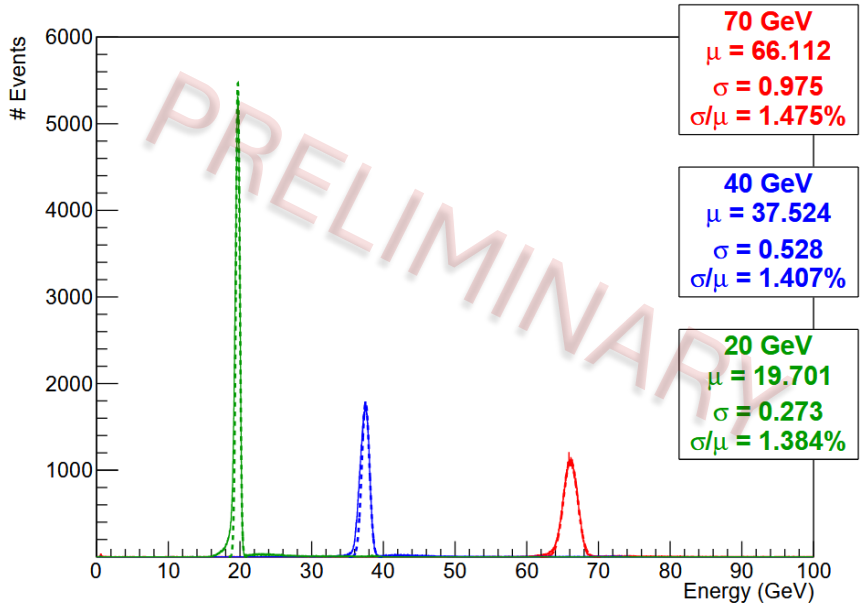
NA64e+ - 2025 data taking and prospects

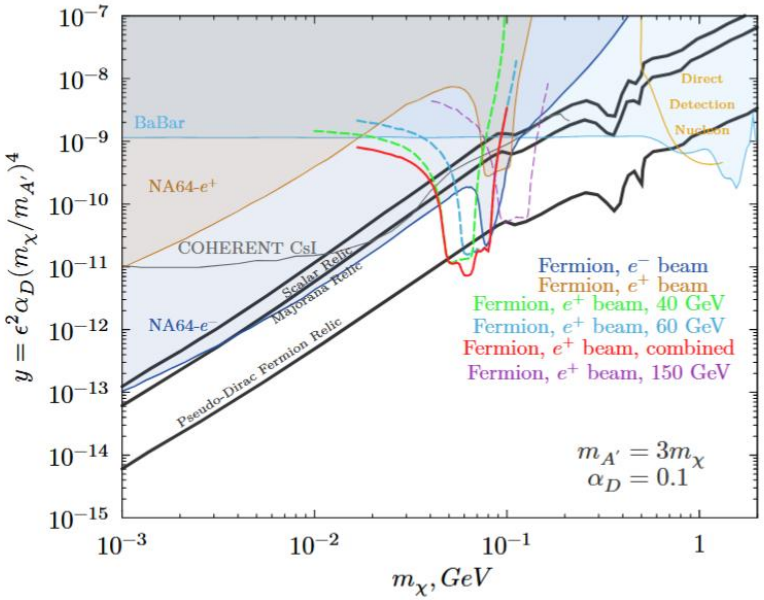
- 2025: collected data at 40 GeV and 45 GeV to demonstrate the feasibility of running at different initial energies to "scan" the A' space (~10^{10} e^+OT collected)
- New high resolution $PbWO_4$ "POKER" calorimeter used as an active target
- New LYSO-based synchrotron radiation detector for better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



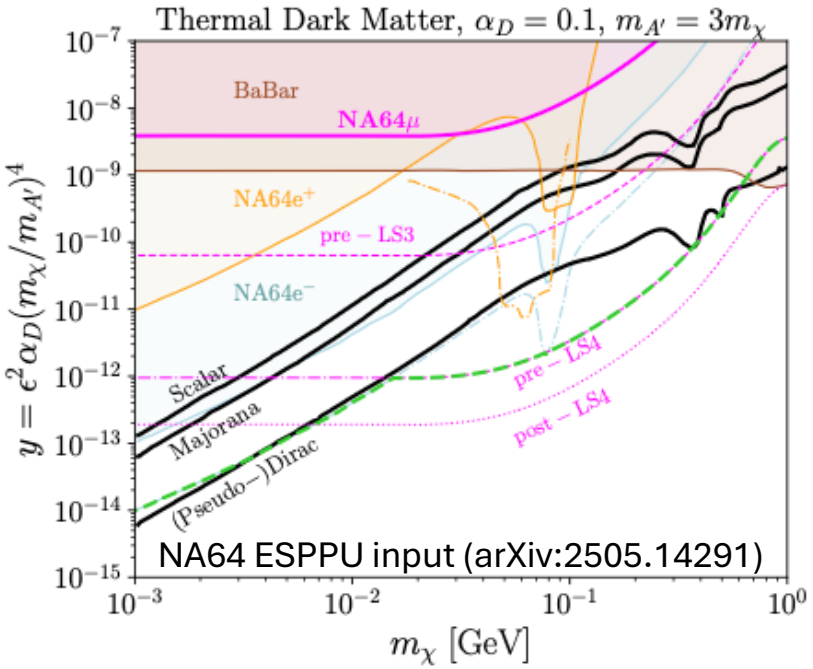
POKER calorimeter

- 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!

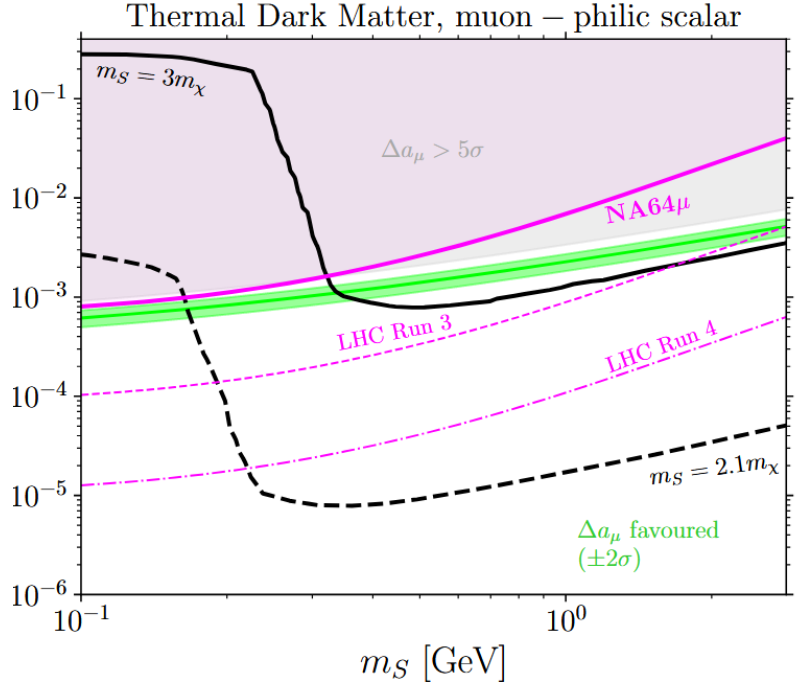


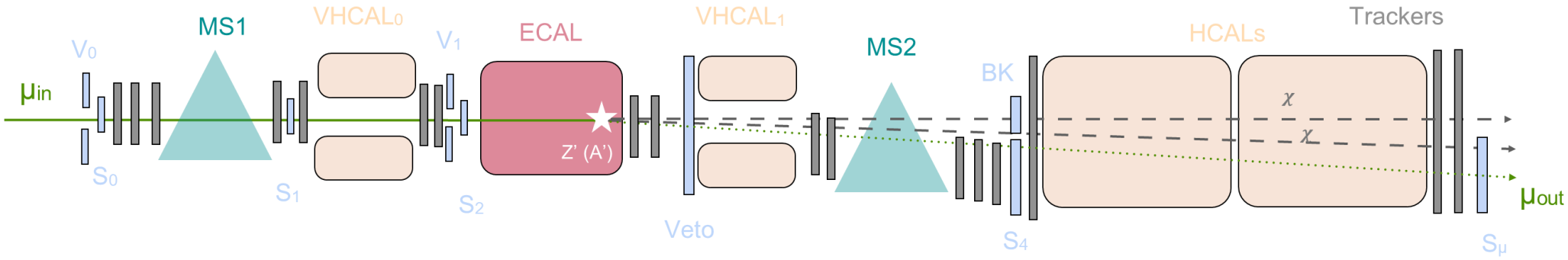


Status and latest results of NA64μ @M2

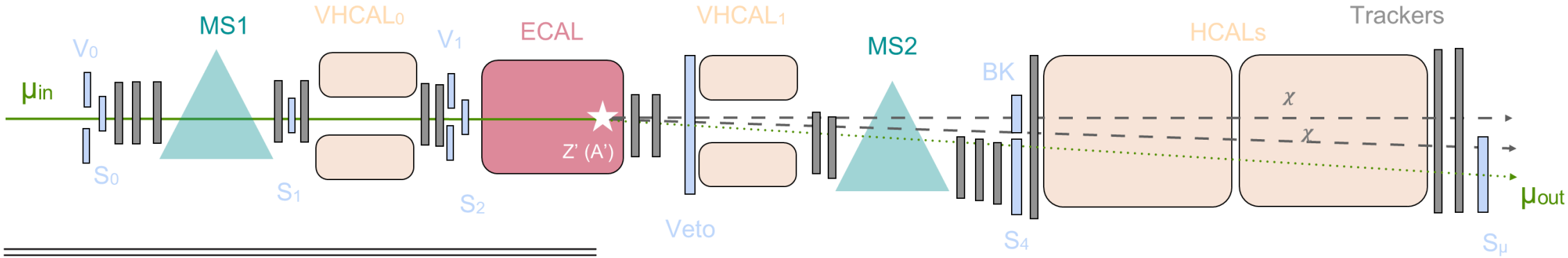


Y. M. Andreev et al. Phys. Rev. D 110, 112015 (2024)





NA64μ @M2 – 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

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:

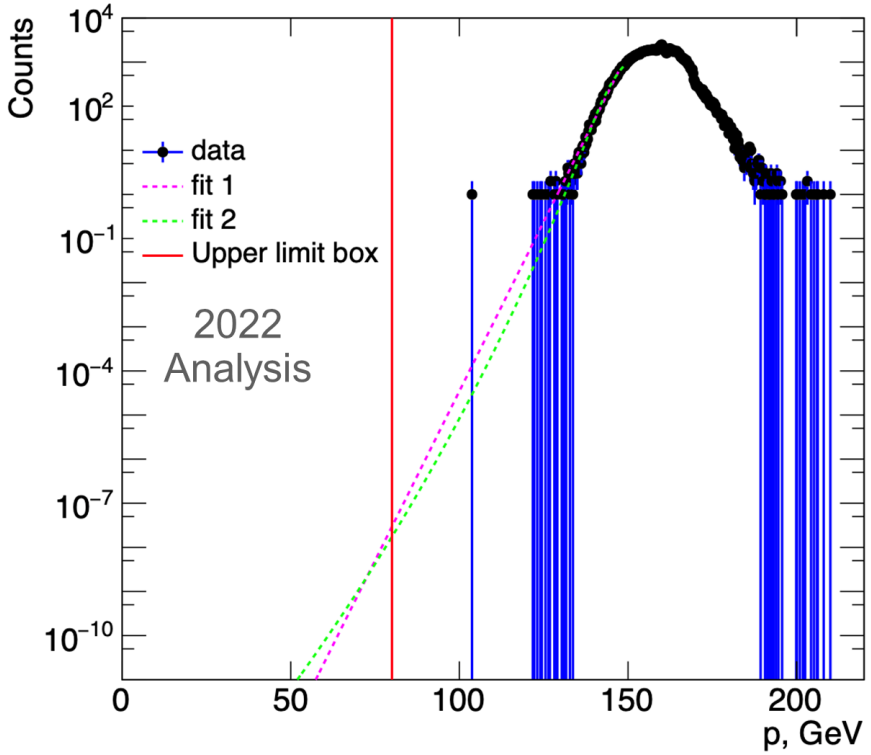
- Well-defined incoming muon track with 160 GeV
- No activity in the veto and VHCAL
- MIP in ECAL and HCAL
- Scattered muon E < 80 GeV

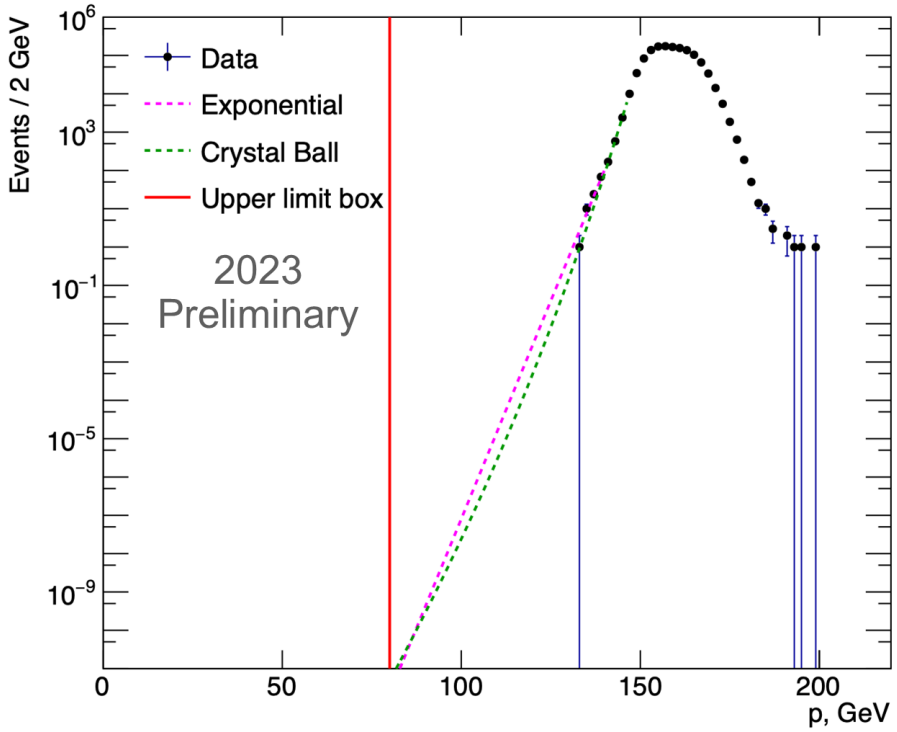
- Data collected up to 2022 published: Yu. M. Andreev et al. (NA64 Collaboration), Phys. Rev. Lett. 132, 211803 (2024), Y. M. Andreev et al. Phys. Rev. D 110, 112015 (2024).
- Setup optimized in 2023-2024 to reduce background and increase intensity
- Improved MS1 in 2024 (more efficient tackers)
- No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

NA64μ - analysis in progress

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





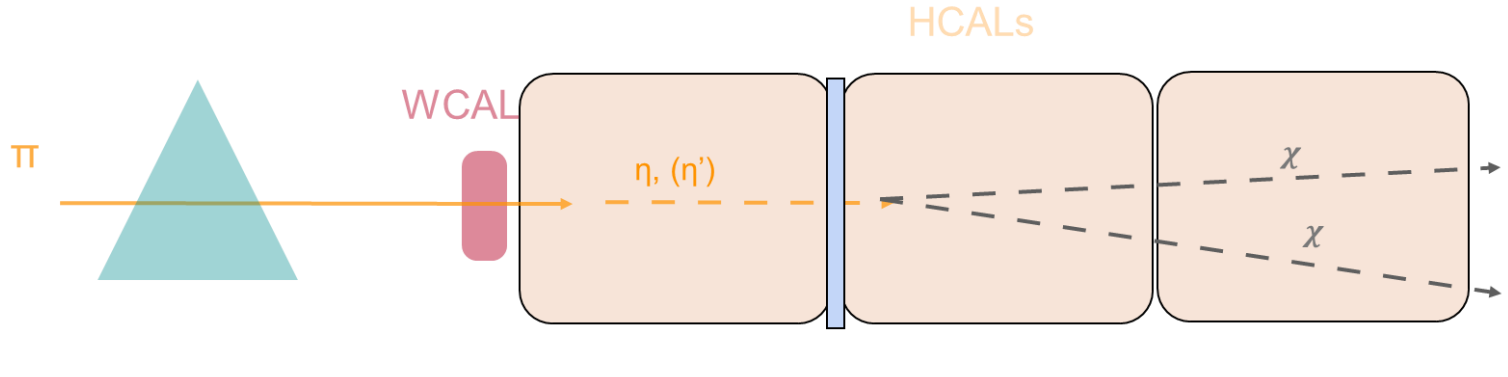
Run	2023	2024
p_{in} (MS1)	0.288	0.550
p_{out} (MS2)	0.415	0.519
Overall	0.263	0.451

Table 1. Preliminary track reconstruction efficiency in NA64μ

NA64h status

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
- 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

NA64 at CERN has unique sensitivity to Dark Sector physics. In the next years we expect either to unambiguously discover or reject nearly all benchmark thermal LDM models

NA64e

- Analysis of ~ 10^{12} eOT collected in 2018-2022 has been published: set world-leading limits in several LDM scenarios
- Analysis of data collected between 2023 and 2025 is ongoing
  - Starting from 2023, setup improved with first VHCAL prototype module
  - 2nd VHCAL module introduced in 2025, together with new fast readout electronics
- Immediate goal: finalize background and high-rate studies towards the high intensity run post LS3
- **Final goal: Collect ~10^{13} eOT after LS3 to explore all the thermal targets in the vector-mediated LDM and other BSM scenarios**

NA64e+

- Data collected at 100 GeV (2022) and 70 GeV (2023) beam energy have been published
  - Results prove the feasibility of multi-energy measurement campaigns with positrons
- New POKER calorimeter and LYSO-based SRD implemented (data analysis ongoing)
- **Proposal Addendum presented to SPSC for post-LS3 program at 60 GeV and 40 GeV**

NA64μ

- Analysis of data collected up to 2022 (~2 ×10^{10} μOT) has been published
- Setup optimized in 2023-2024 to minimize the main two background sources and increase intensity (3.5 ×10^{11} μOT collected)
- **Final goal: Collect 2 × 10^{13} μOT after LS3 to explore leptophilic DS coupled to muons and LDM complementary to e^+ and e^-**

NA64h

- First proof-of-concept results of the analysis of 2.9 x 10^9 πOT (1 day in 2022) published
  - set world-leading constraints on η, η' invisible decay
- Analysis of the 2025 data collected with an improved setup in progress
- Further tests at low energy foreseen at PS T9 in the next weeks
- **Proposal addendum for post-LS3 program is in preparation**

Thanks!

We gratefully acknowledge all the CERN management and staff for their excellent support in preparing and running the NA64 experiment, in particular CERN BE-EA department (N. Charitonidis, G. Dal Masso, D. Banerjee).

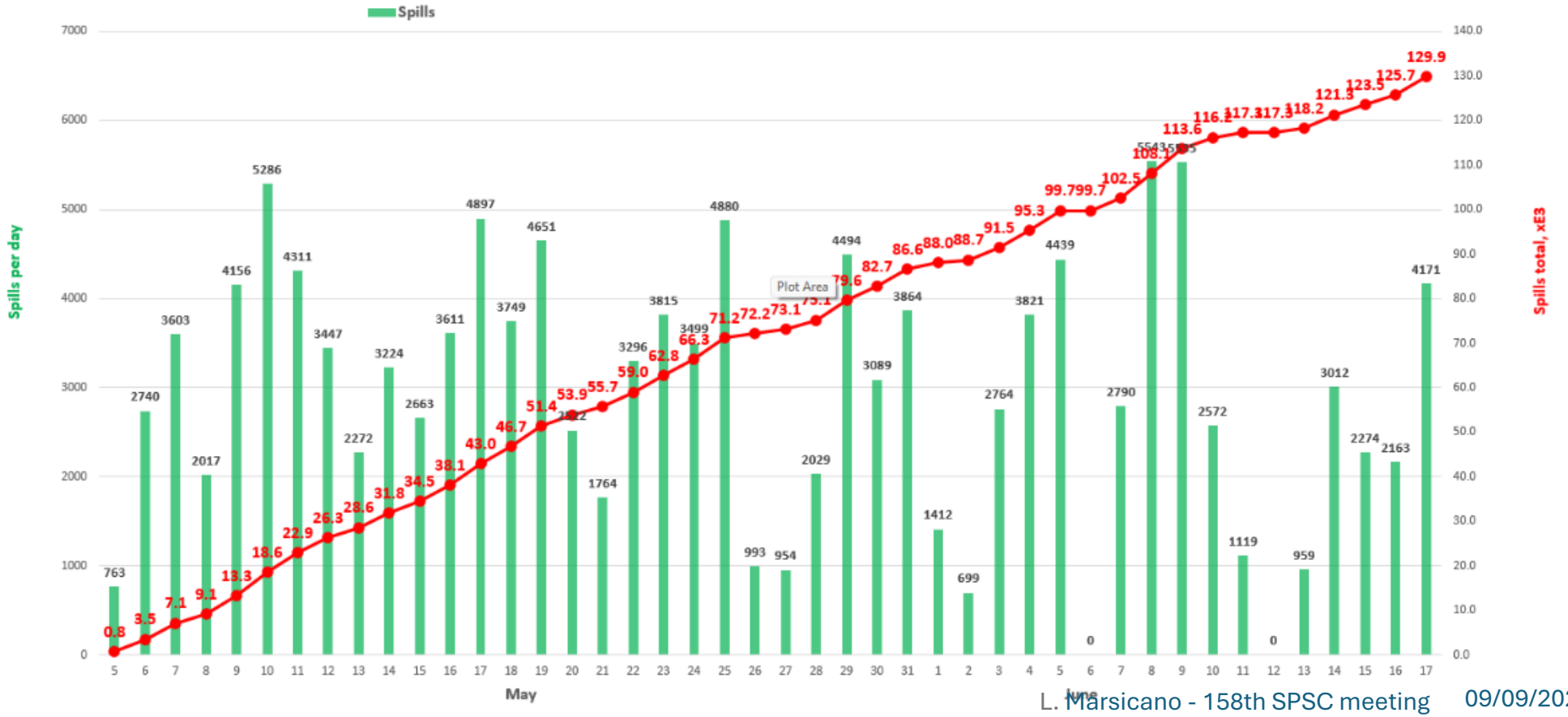
Backup

2025 Beam Stabilty

Beam optics significantly improved this year (thanks to G. Dal Masso and N. Charitonidis from CERN BE-EA!)

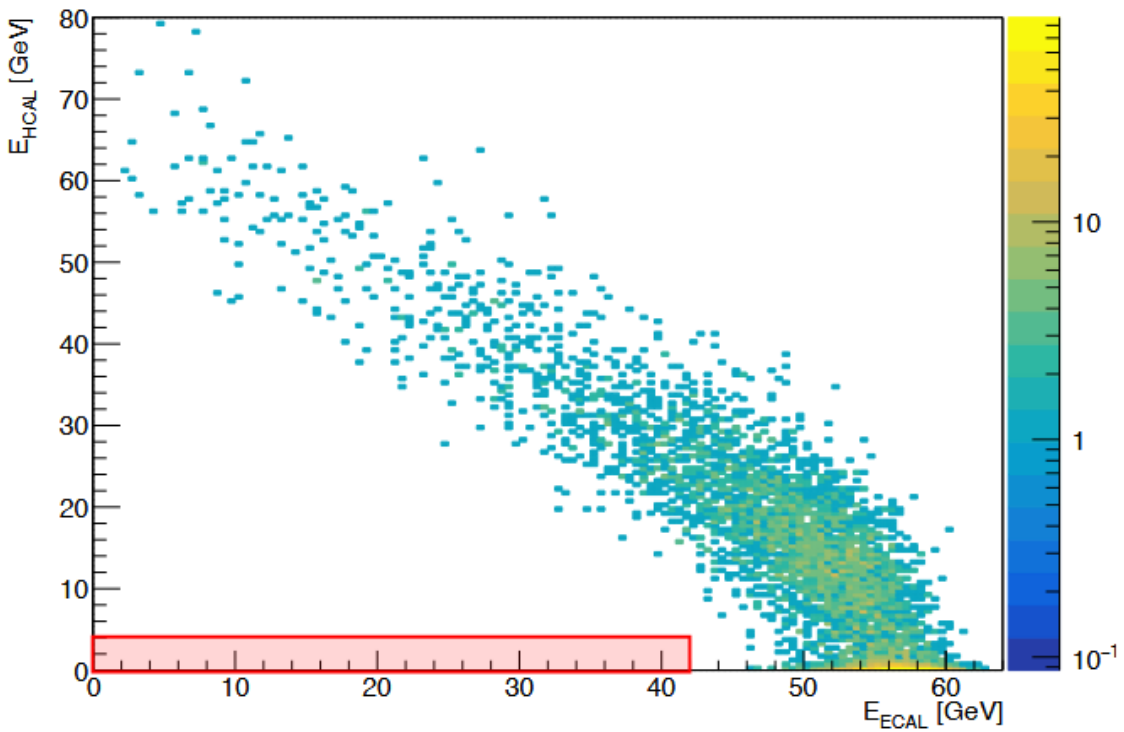
Results:

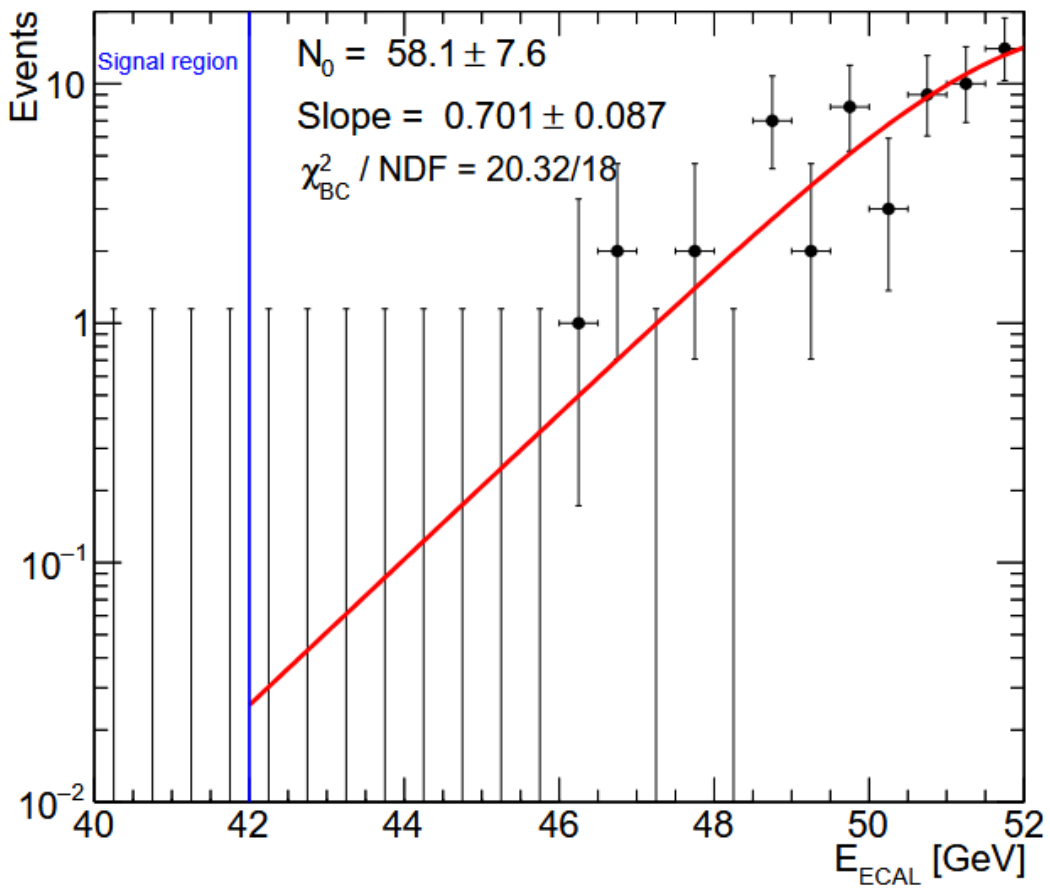
- 5% increase in our beam telescope efficiency with respect to previous years (73% coincidence of all scintillator counters)
- Reduction of halo rate from 5% to 1%



2023 Positron analysis – background study

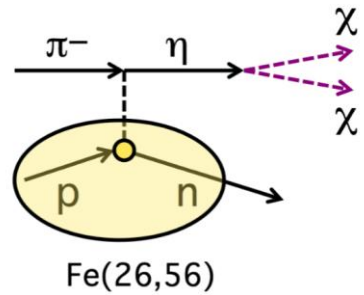
Extrapolation to signal box: 0-42 GeV



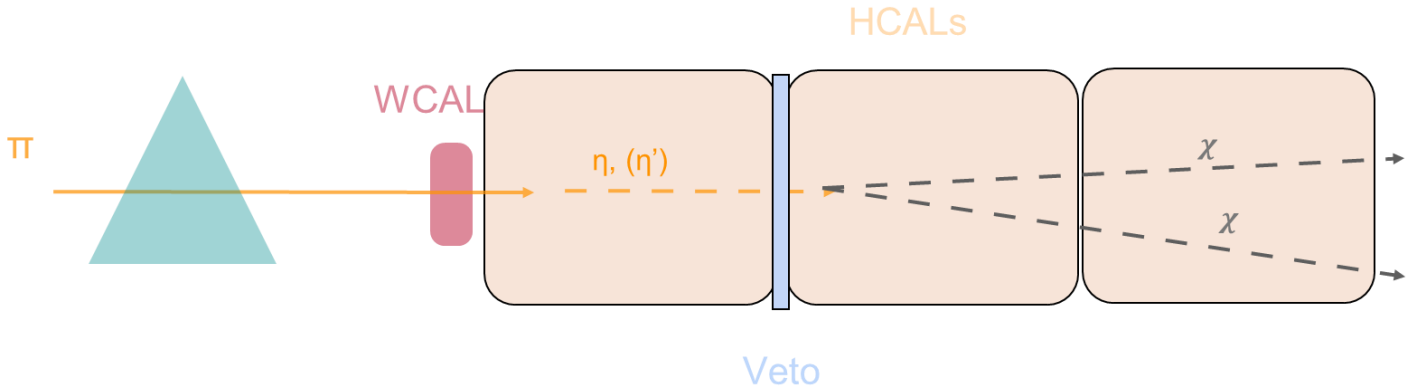


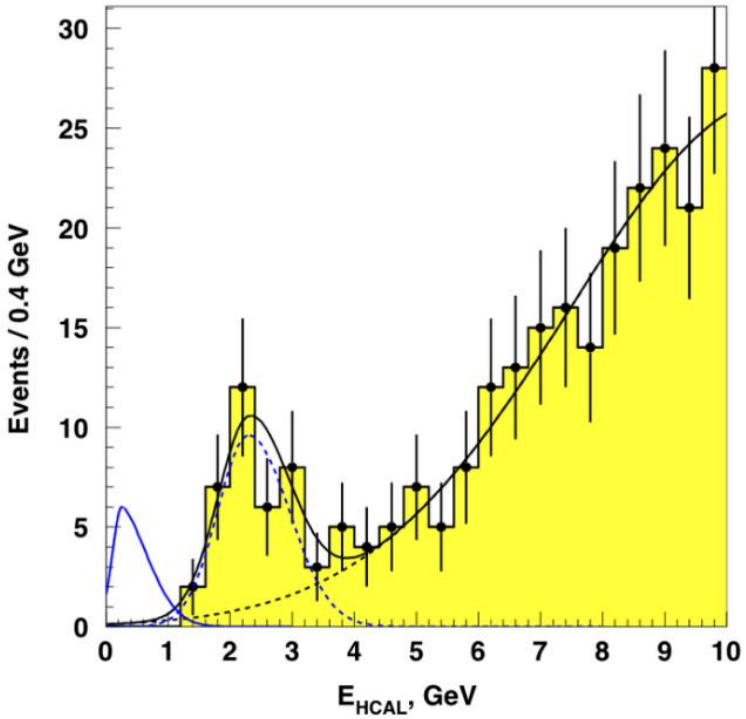
NA64h results

- Proof of principle demonstrated (Y. M. Andreev et al. Phys. Rev. Lett. 133, 121803 (2024))
- Addendum for a dedicated NA64h program in preparation



BR (η → invisible) < 1.1 x 10⁴
BR (η' → invisible) < 2.1 x 10⁴



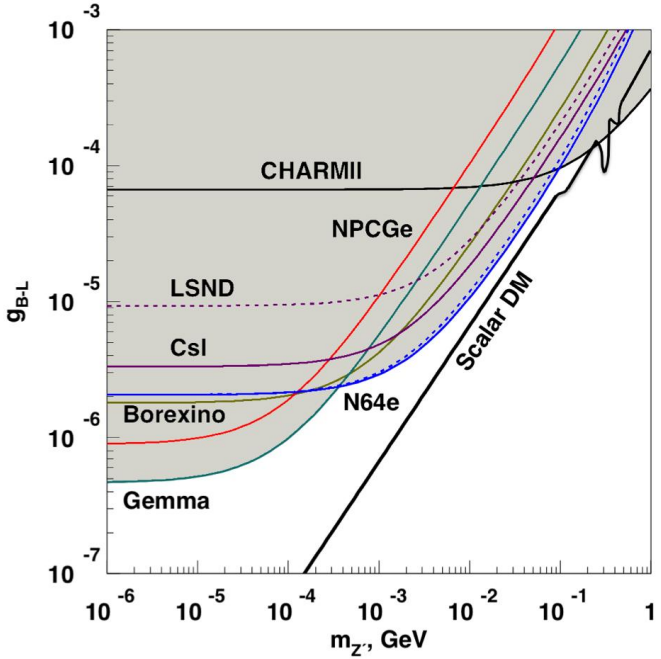


The NA64 extended physics program

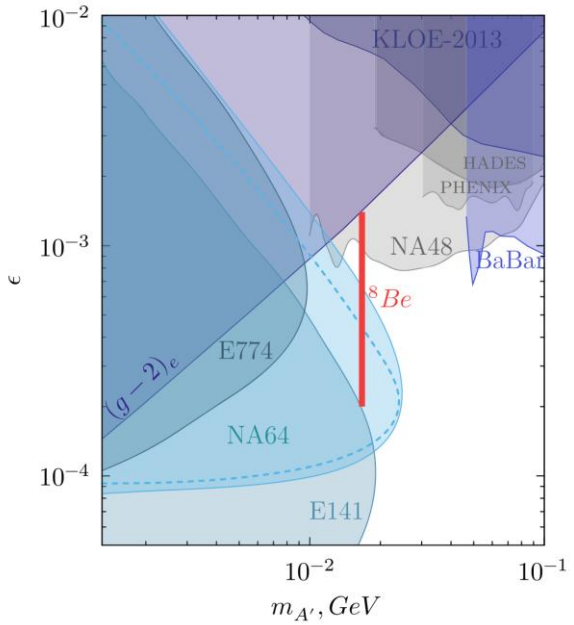
Comprehensive BSM searches:

- ALP particles, light scalars
- B-L Z' models Complementary to ν-scattering experiments
- Visible A' models (X17 anomaly from ATOMKI ^{8}Be measurement)
- Inelastic LDM models with semi-visible signatures

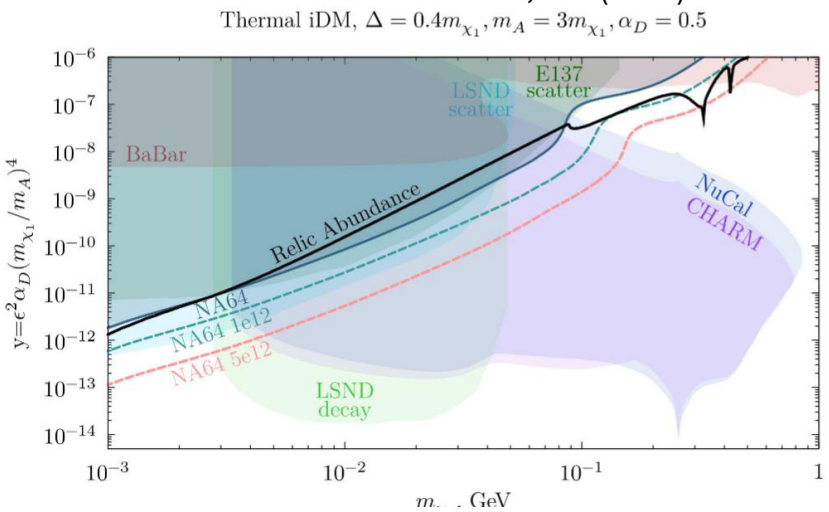
B-L model: PRL 129, 161801 (2022)

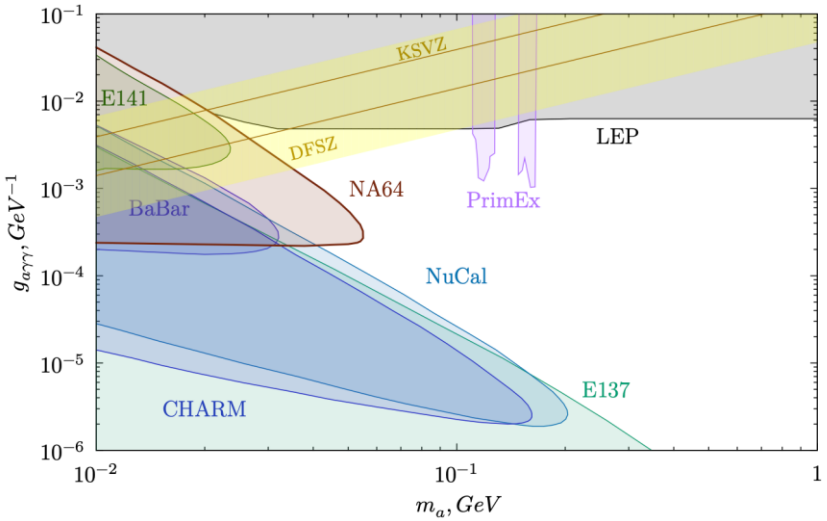


X17 anomaly: PRL 120, 231802 (2018)
PRD 107, 071101R (2020)



Inelastic DM: EPJC 83, 391 (2023)





ALPs: PRL 125, 081801 (2020)