Status and plans for the NA64 experiment

Benjamin Banto Oberhauser on behalf of the NA64 collaboration

154th SPSC meeting, September 3rd, 2024

The NA64 experiment

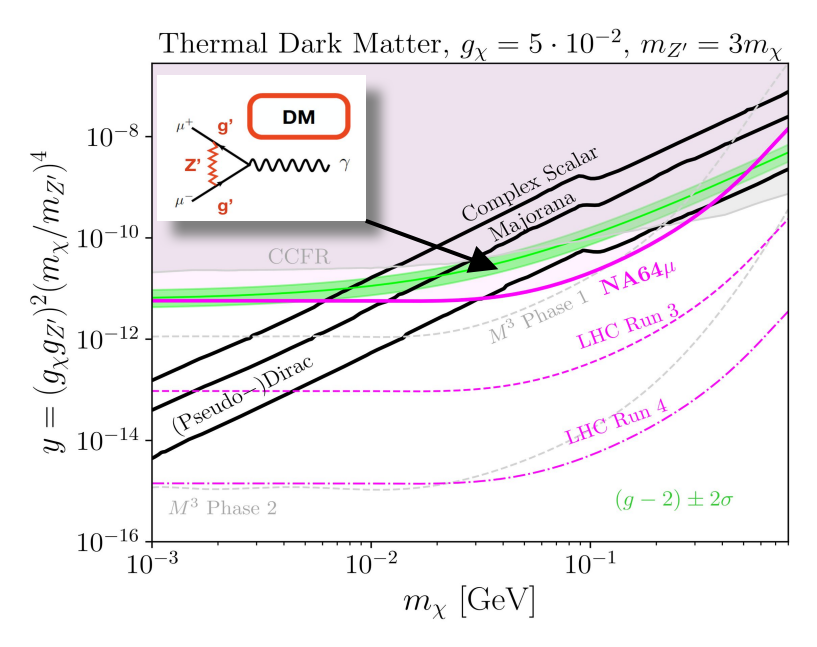
- **Fixed-target** experiment at the **intensity/precision frontier** searching for Dark Sector physics below the electroweak scale

  → Targeting **light thermal dark matter** in the MeV-GeV mass range
- Pioneering **active dump** and **missing energy** technique exploiting the unique, high-purity beams at CERN SPS:
  - ***NA64e***, ***NA64e⁺***
    - Search for LDM using electrons/positrons at H4
  - ***NA64μ***:
    - Phase 1: L_μ-L_τ Z' as a solution to the $(g-2)_\mu$ anomaly and LDM
    - Phase 2: Complementary LDM searches
  - ***NA64h***
    - Search for leptophobic DS coupled to light SM quarks

Crucial milestones reached!

NA64μ

First results with muon beam!



Yu. M. Andreev et al. (NA64 Collaboration), Phys. Rev. Lett. 132, 211803 (2024)

	2022	2023	2024	TOTAL
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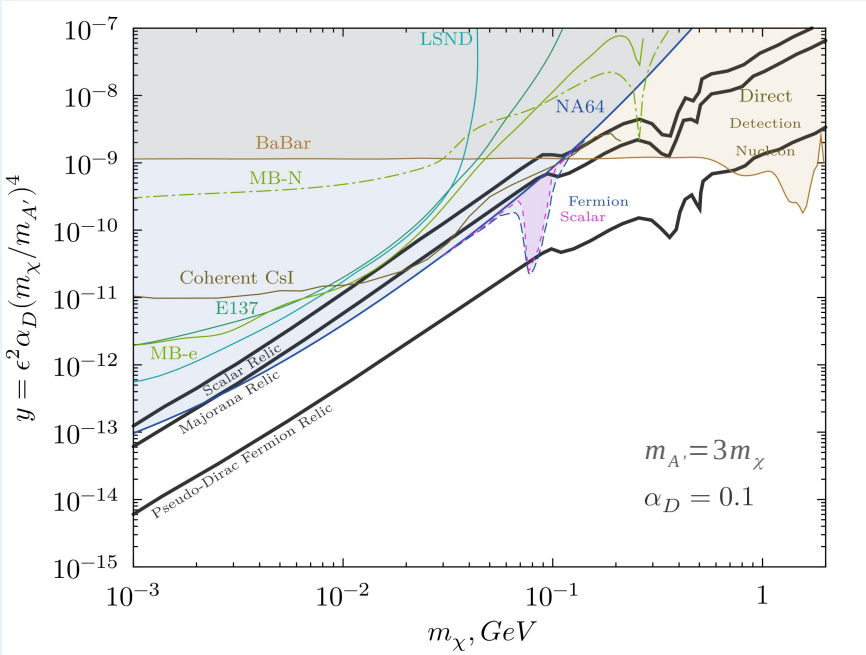
NA64e

Probing benchmark LDM scenarios!



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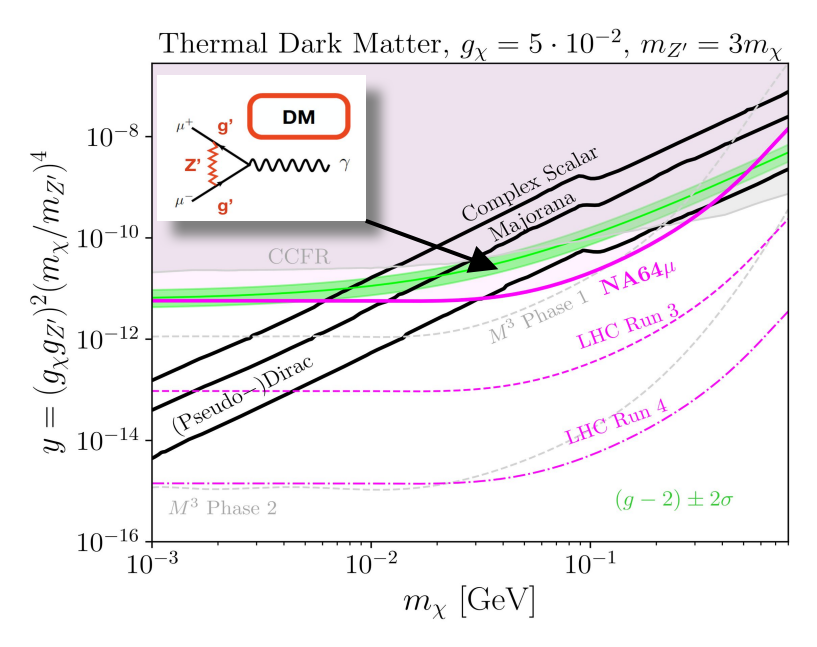

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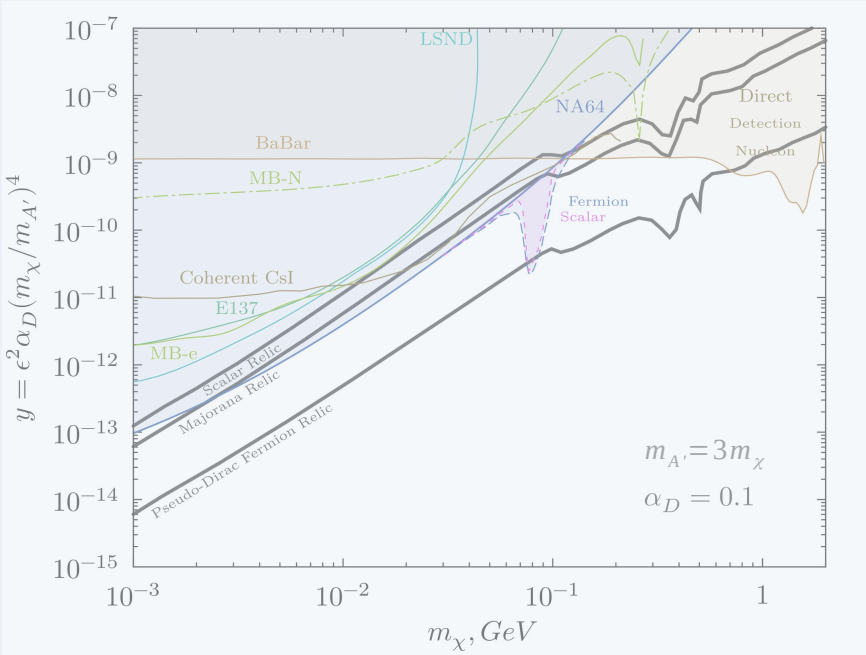

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NA64μ: First results with a muon beam!

Featured in Physics | Open Access

First Results in the Search for Dark Sectors at NA64 with the CERN SPS High Energy Muon Beam

Yu. M. Andreev *et al.*
Phys. Rev. Lett. **132**, 211803 – Published 21 May 2024

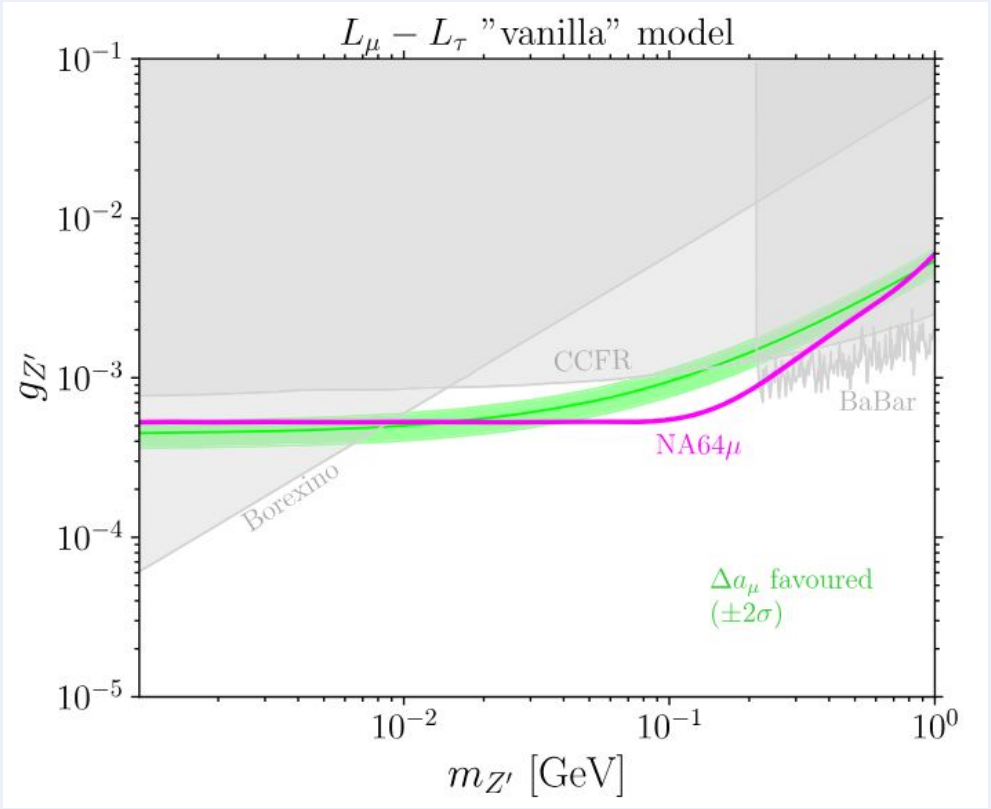
Physics See synopsis: Careful Accounting Could Reveal the Dark Sector

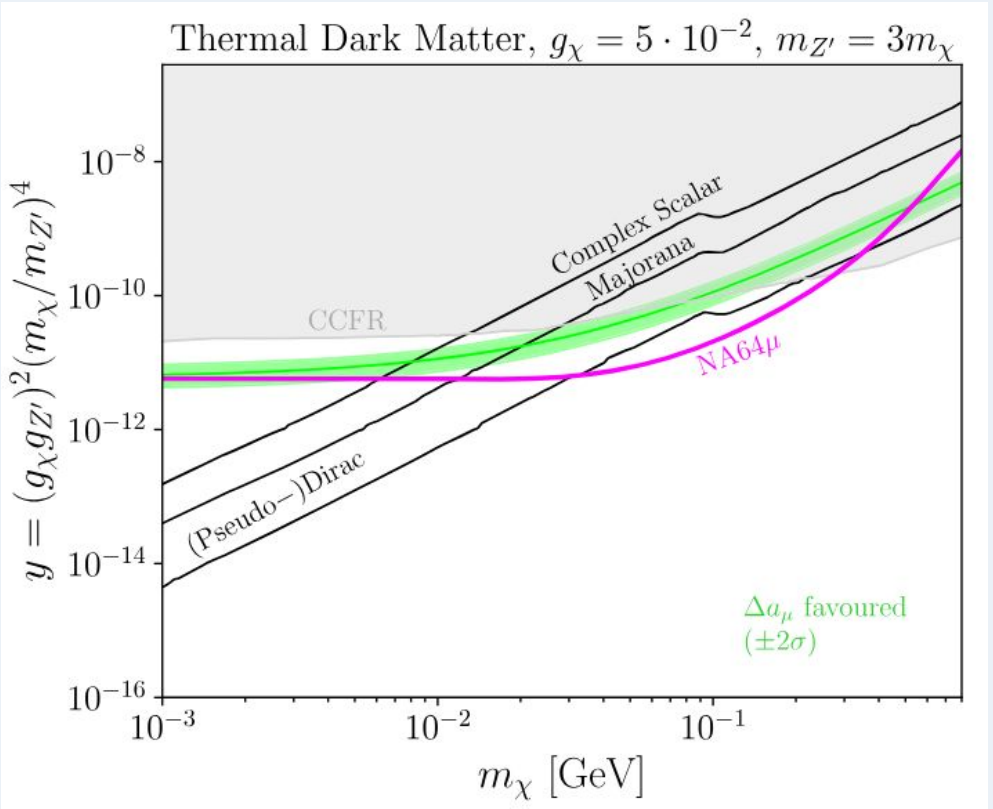
Careful Accounting Could Reveal the Dark Sector

HIGHLIGHTED IN PHYSICS

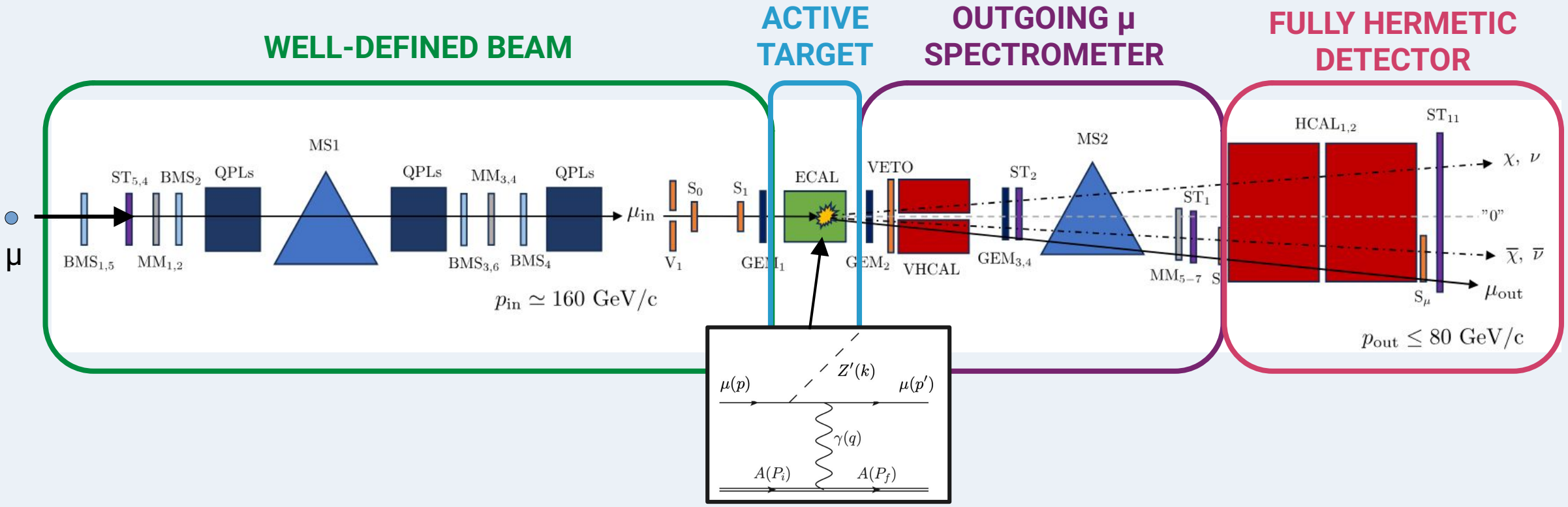
May 21, 2024 • *Physics* 17, s54

An experiment at CERN seeks signs of dark matter by looking for missing energy and momentum in the debris of particle collisions.





NA64μ: Dark Sector exploration with μ

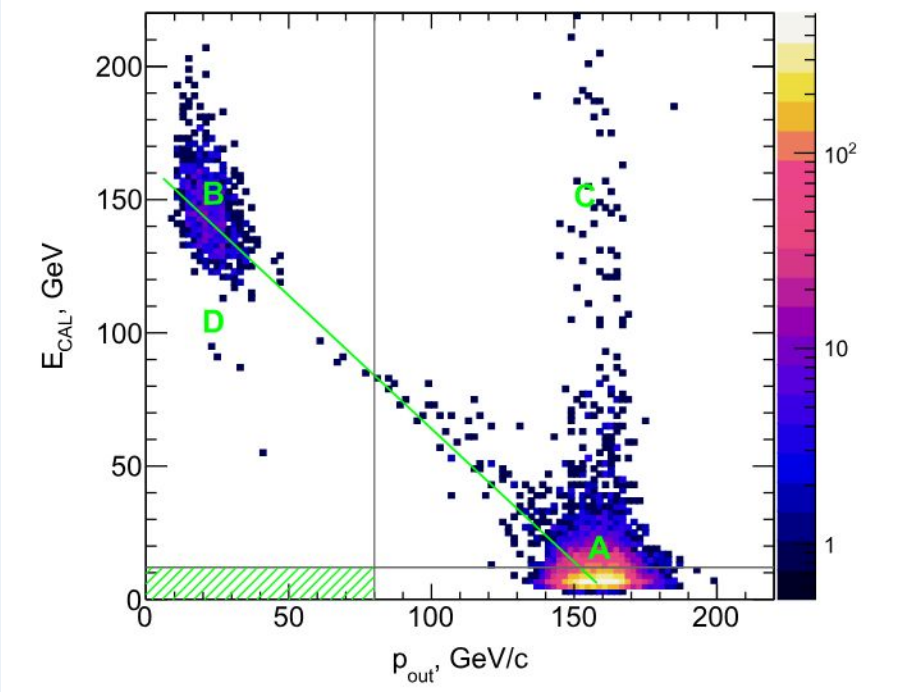


Signature: Incoming momentum > Measured energy + Outgoing momentum

160±20 GeV — MIP in ECAL and HCALs — < 80 GeV

NA64μ: Lessons learned

No signal events observed in 2x10[10] MOT!



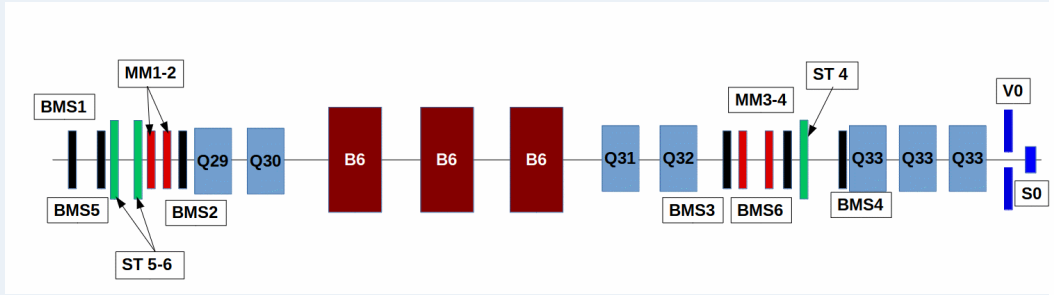
Background source	Background, n_b
(I) Momentum misreconstruction	0.05 ± 0.03
(II) $K \to \mu + \nu, \ldots$ in-flight decays	0.010 ± 0.001
(III) Calorimeter non-Hermiticity	< 0.01
Total nb (conservatively)	0.07 ± 0.03

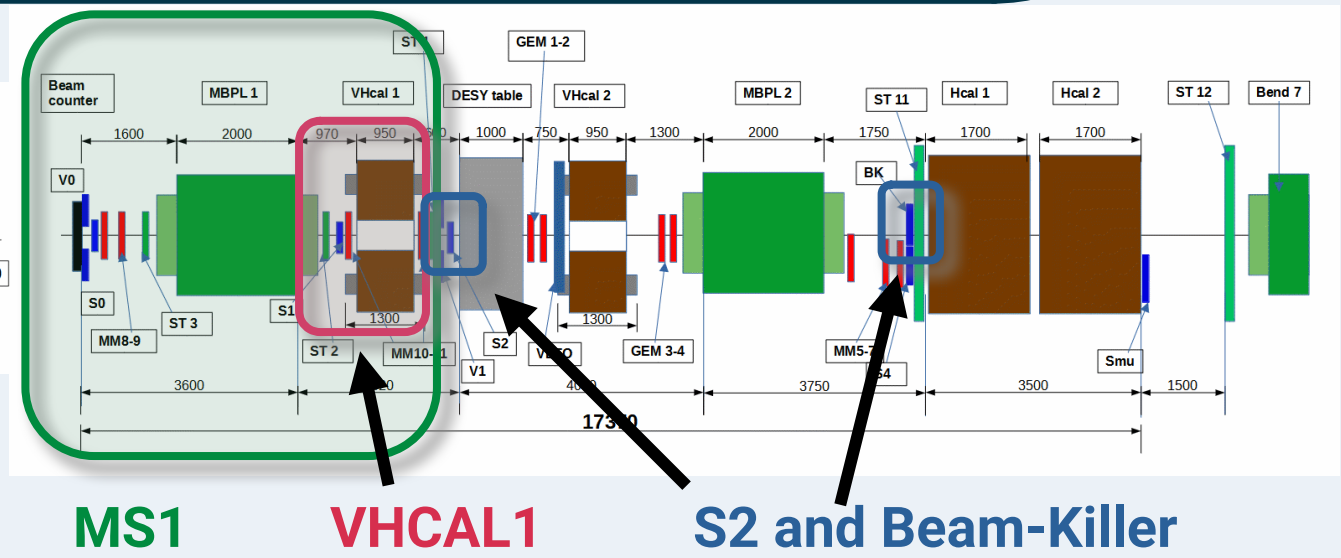
The results from 2022 demonstrate the technique and drive the upgrades for the next phase

Main challenges:

- Minimize initial and final μ momentum mis-reconstruction
- Fully hermetic detector

NA64μ: Setup improvements in 2023/24





Significant upgrades in 2023/2024:

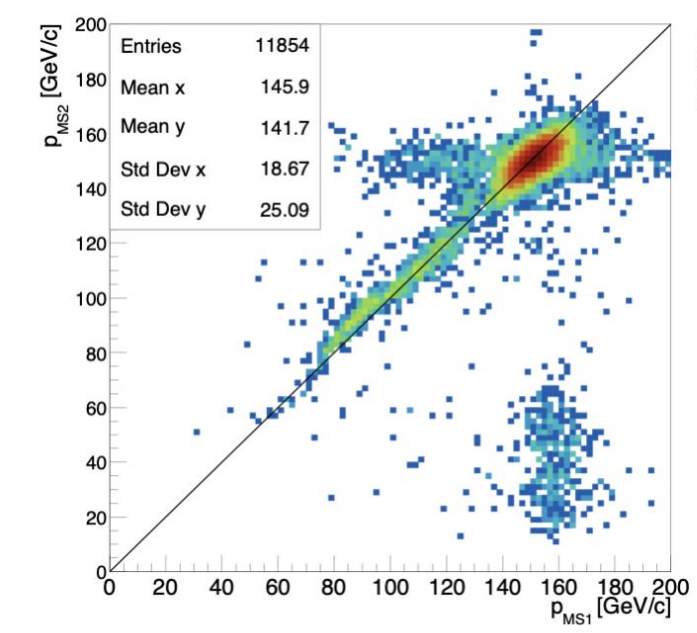
- Second magnet spectrometer (**MS1**)
- 8 new trackers
- Improved hermeticity with veto hadronic calorimeter prototype (**VHCAL1**)
- Additional trigger scintillators (**S2** and **BK**)

NA64μ: Analysis of the 2023 run

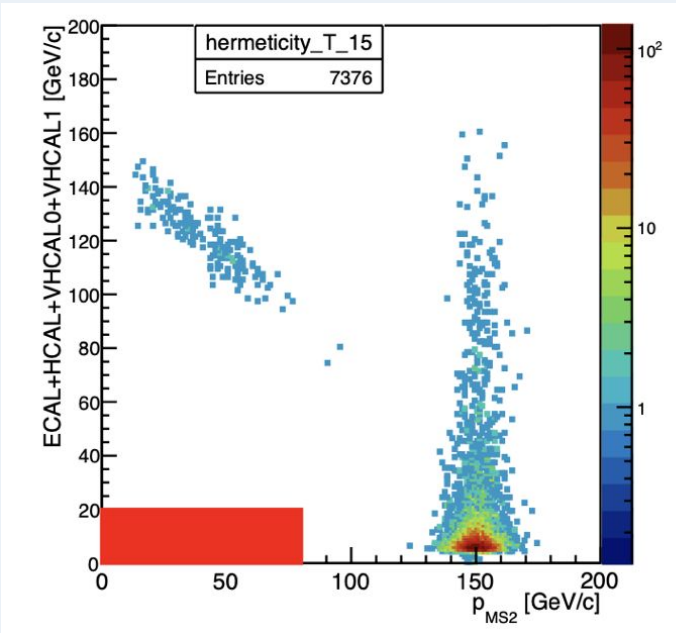
- 1.5×10^{11} MOT collected with improved setup
- Preliminary analysis with 1.3×10^{9} MOT (10% of data without ECAL) highlights the key role of MS1

  → **Improving momentum reconstruction** and **background suppression**

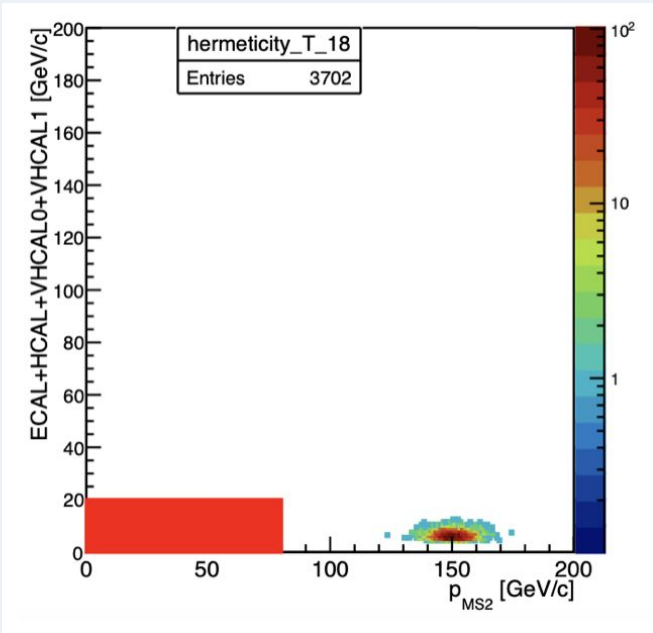
Initial distribution



Events after MS1



Events after all cuts

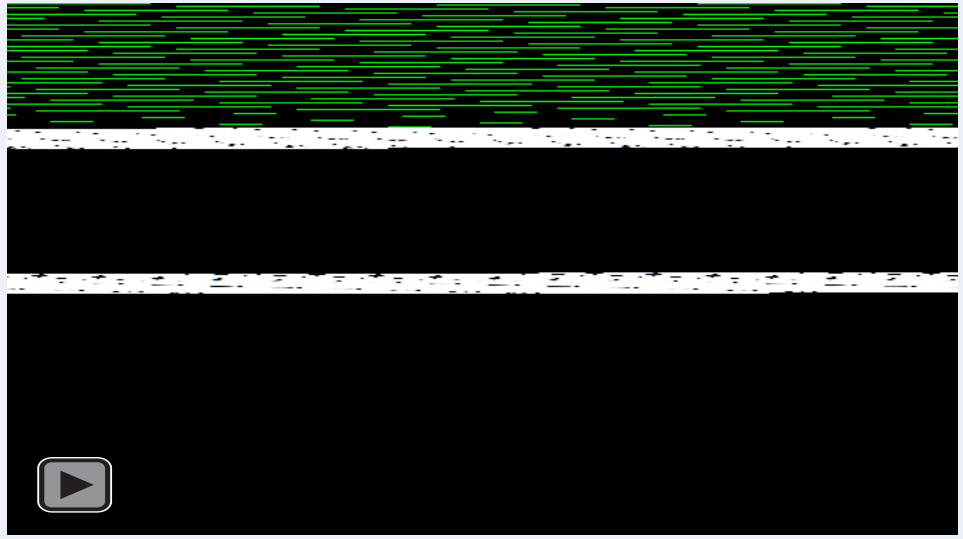


Results from physics trigger runs without ECAL in 2023

NA64μ status and beyond LS3

Status in 2023/2024:

- Collected a total of 3×10^{11} MOT
- Complementary measurements done:
  - Hadron contamination in the beam with 3-9 absorbers
  - Empty-target with hadrons and muons

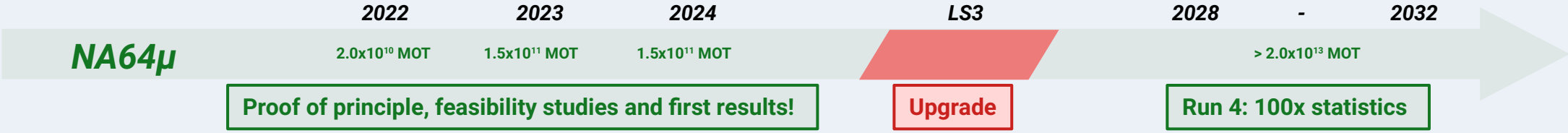


Plans beyond LS3:

- Collect two orders of magnitude more MOT

To successfully accomplish this target

- Suppress background to the level of 10^{-13}
- High intensity upgrade to fully exploit the M2 beam-line capabilities
- Need for permanent location in M2. We thank the BE-EA group for the encouraging discussions!



Crucial milestones reached!

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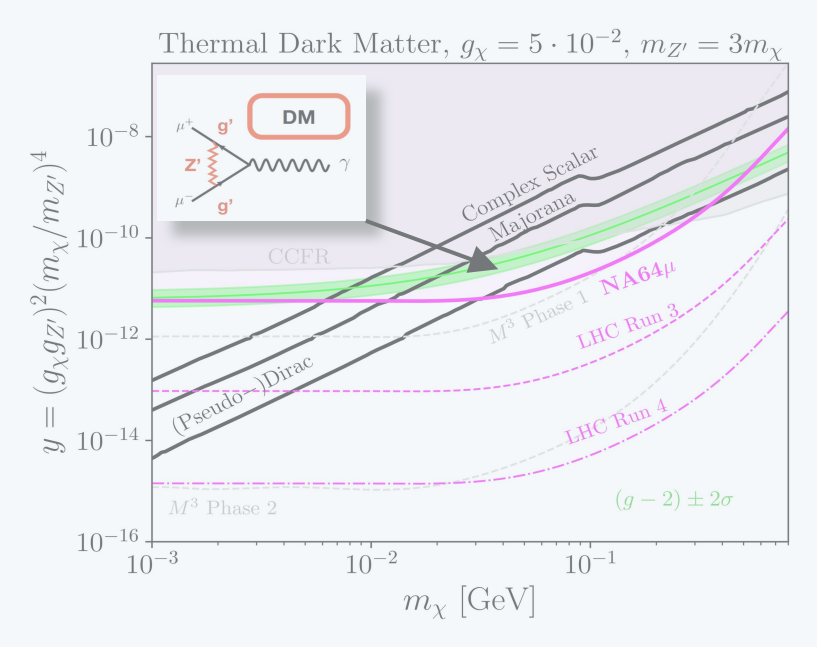

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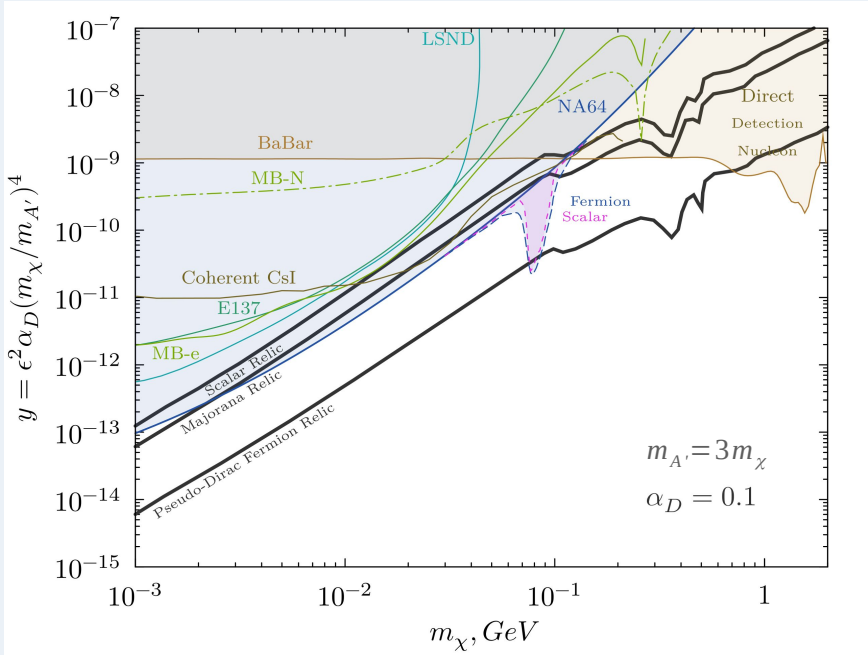

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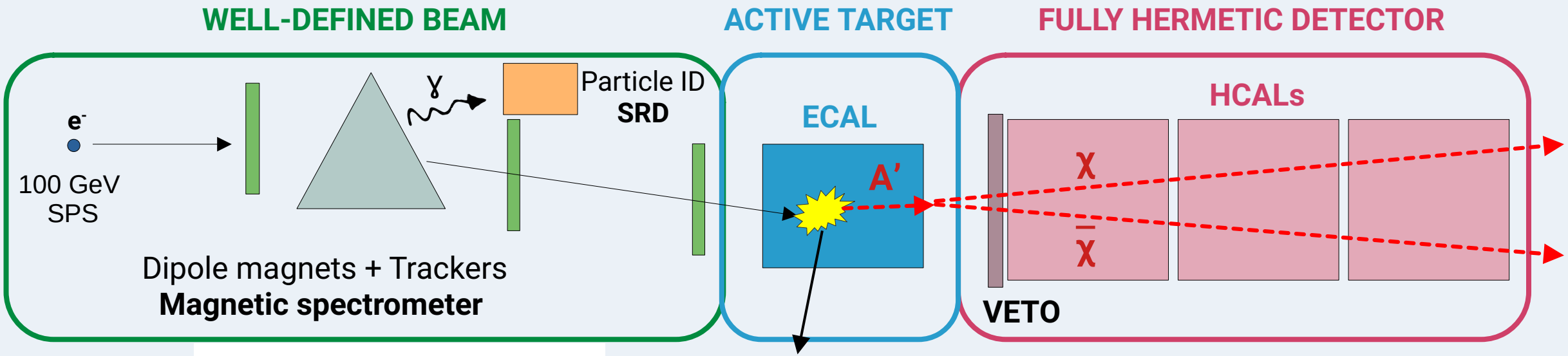
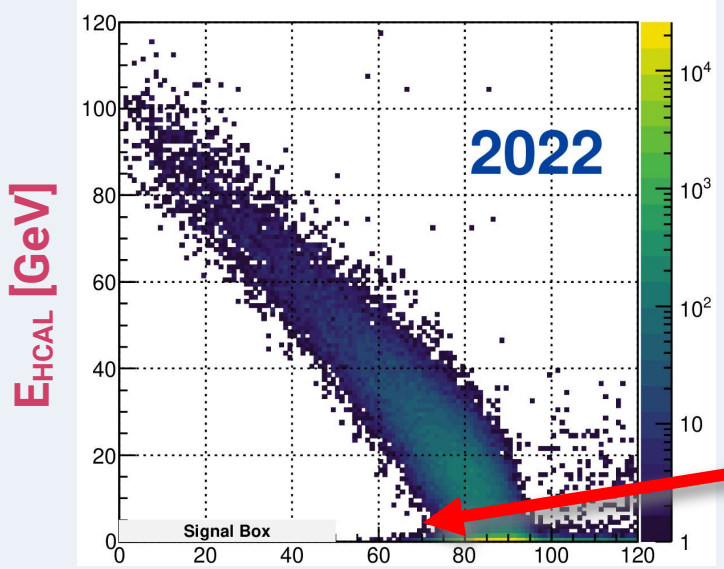
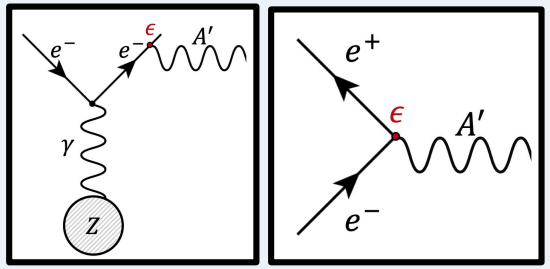
NA64e: Setup in 2022



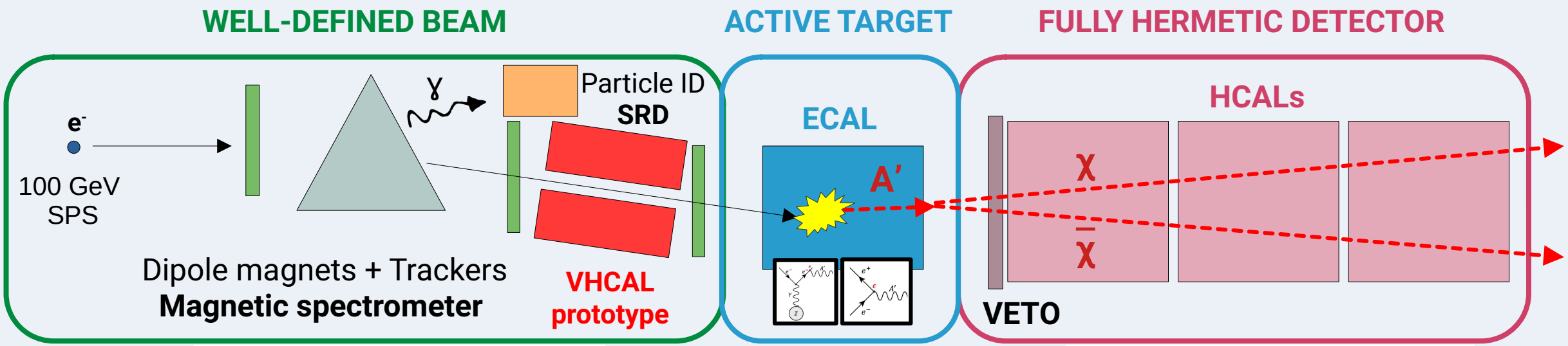


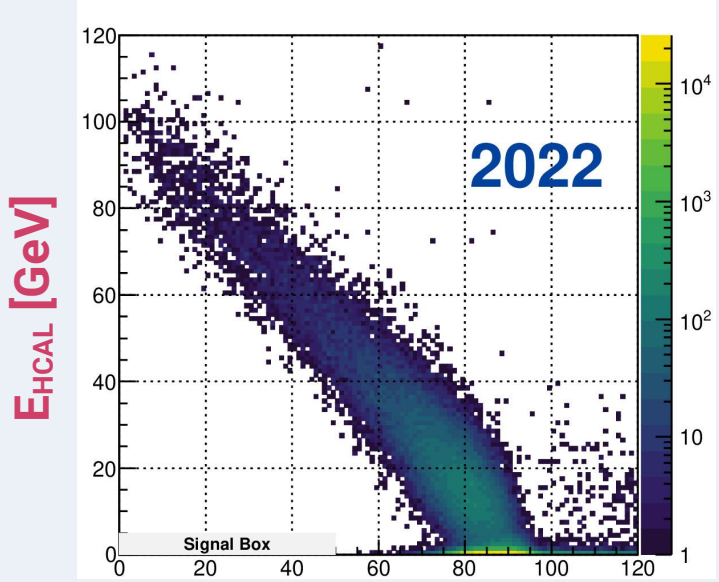


Dark Photon A'

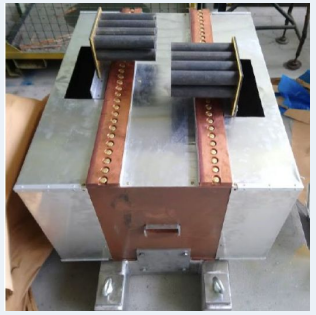
Main background from high-p_t hadronic secondaries from beam interactions before ECAL.

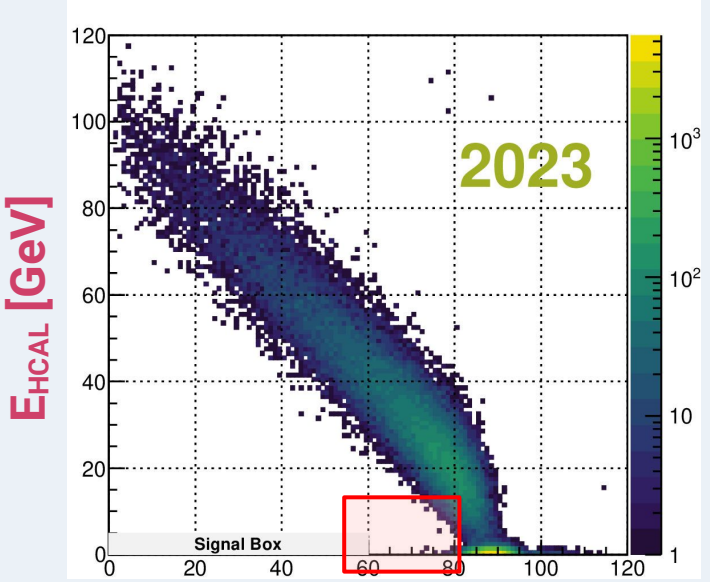
NA64e: Setup improvements in 2023/24





Encouraging results with
4.4×10^{11} EOT (2023)
→ Development of full-scale, **optimized VHCAL** after LS3



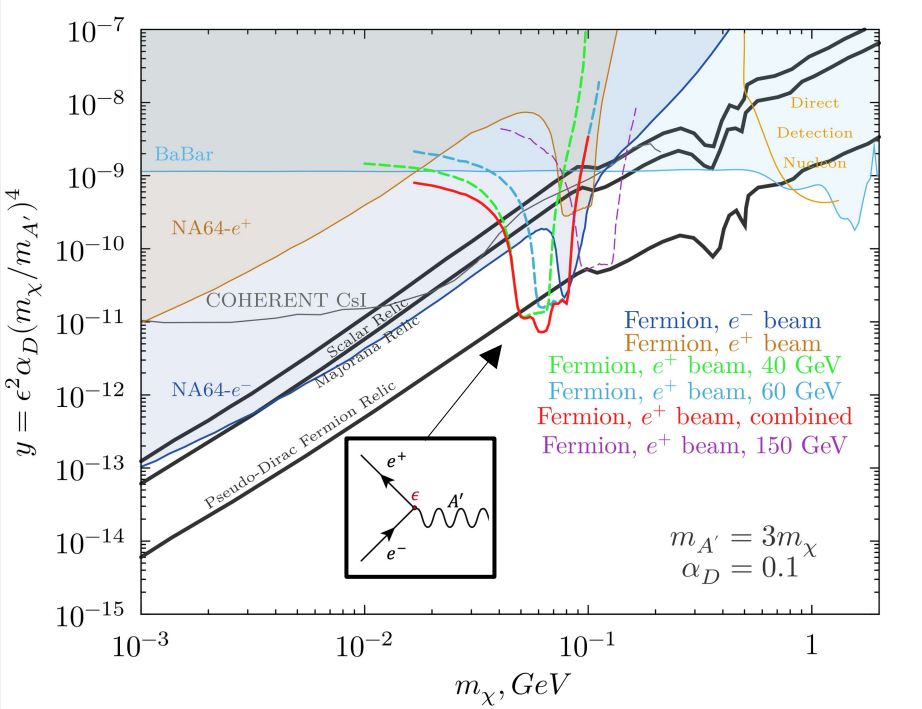


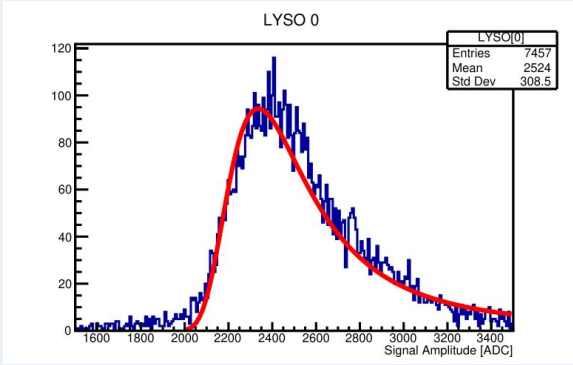
NA64e⁺

Exploiting the e⁺e⁻ resonant annihilation production, enhanced with a positron beam

- First results published (Phys. Rev. D 109 (2024) L031103)
  - Despite x100 less statistics → similar sensitivity at $M_{A'}$≈250 MeV
  - Main challenge: **hadronic contamination in beam**

- Proposal addendum submitted (SPSC-P-348-ADD-4)
  - Scanning with beam energies to probe the mass range 140 MeV ≲ $m_{A'}$ ≲ 250 MeV
  - **Goal:** Run at 40 and 60 GeV while keeping the experiment background-free
  - **In 2024:** successful tests with LYSO-based SRD



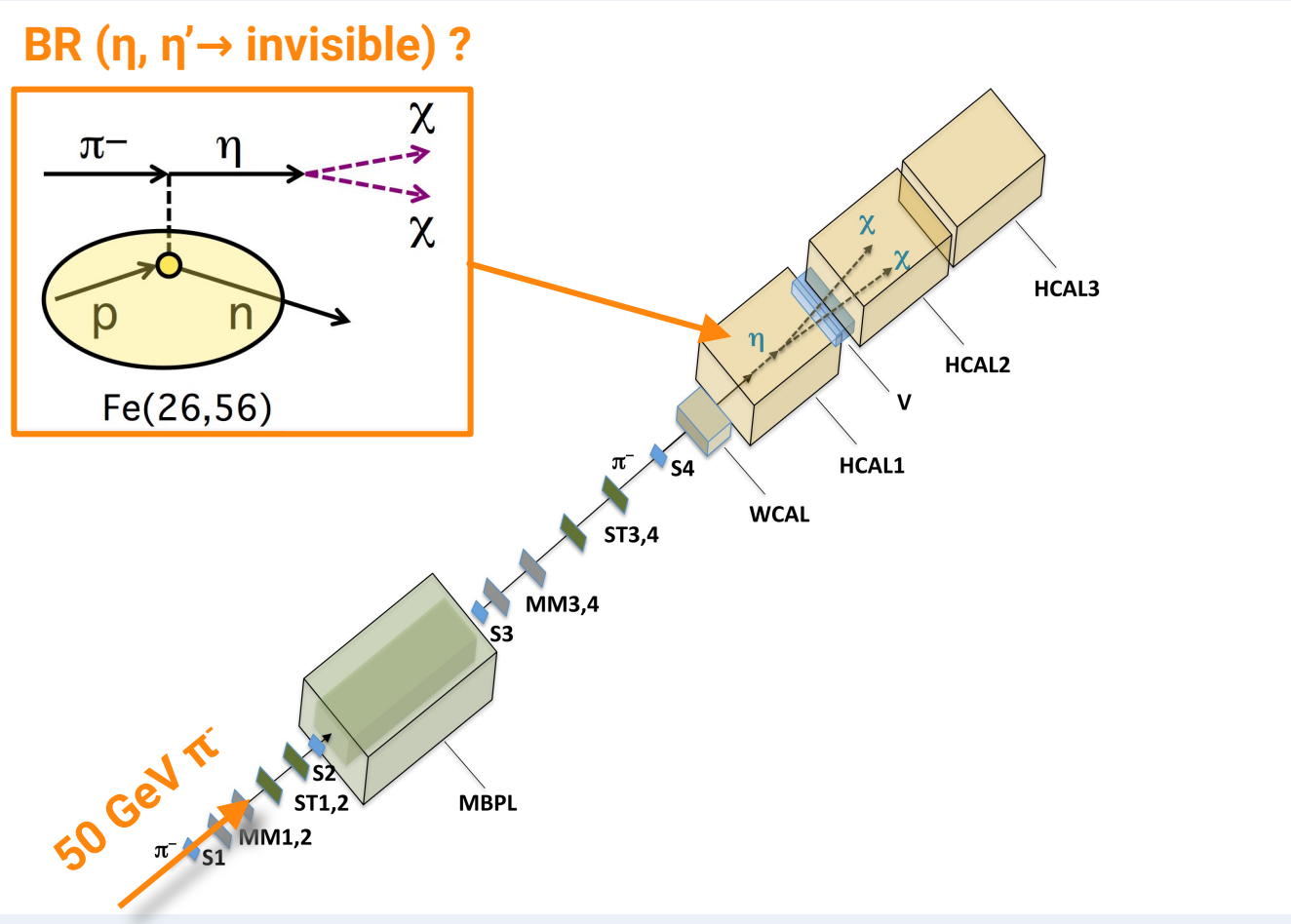


NA64h: Dark sectors coupled to quarks

In the SM: invisible decays from η, η', π^0, $K^0_{S,L}$ extremely small

Observation of such decays would be an indication of New Physics!

S. Gninenko, Phys. Rev. D91 (2015) 015004



Signature:

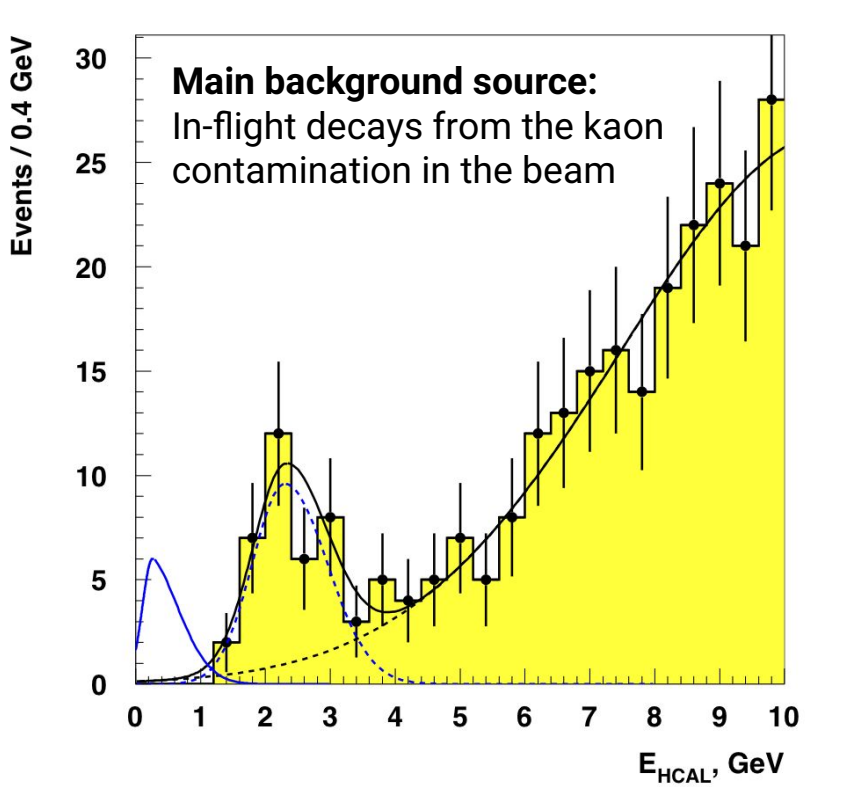
- Single 50 GeV track from incoming π
- MIP energy in WCAL
- No energy in HCAL

NA64h: First test runs in H4

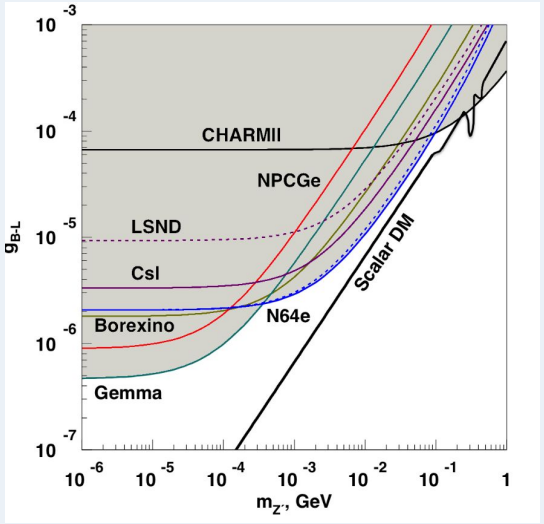
NA64h results 2.9 x 10^9 πOT (1 day in 2022)	**BESIII**
BR (η → *invisible*) < 1.1 x 10^{-4}	< 1 x 10^{-4}
BR (η' → *invisible*) < 2.1 x 10^{-4}	< 6 x 10^{-4}

Measurement by BESII: Physical Review D 87, 012009 (2013)

- Proof of principle demonstrated (ArXiv:2406.01990)
- Addendum for a dedicated NA64 program in preparation



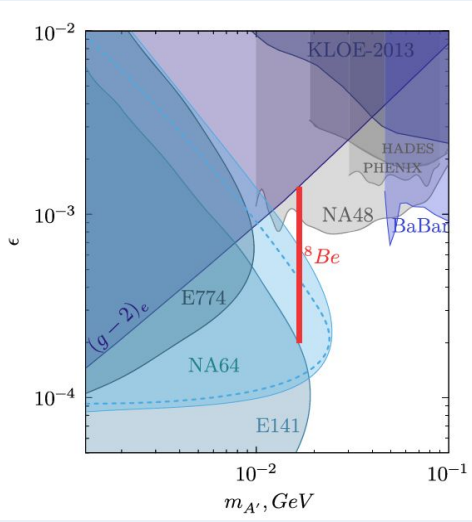
The extended NA64 physics program



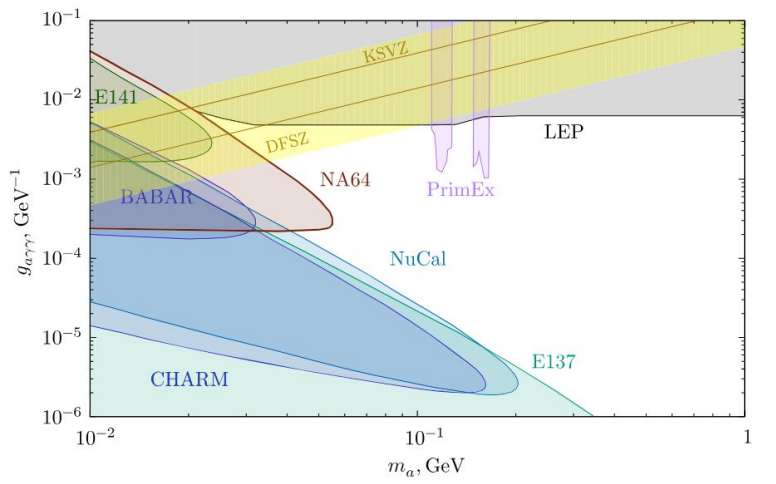
B-L model: PRL 129, 161801 (2022)

Comprehensive search for BSM physics

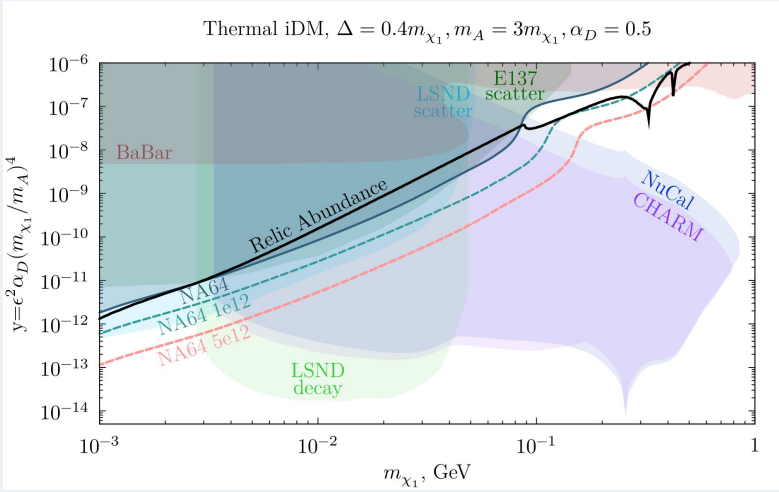
- ALP particles, light scalars
- B-L Z' models → Complementary to ν-scattering experiments
- Visible A' models → X17 anomaly from Atomki ^{8}Be measurement
- Inelastic LDM models with semi-visible signatures



X17 anomaly: PRD 107, 071101R (2020)



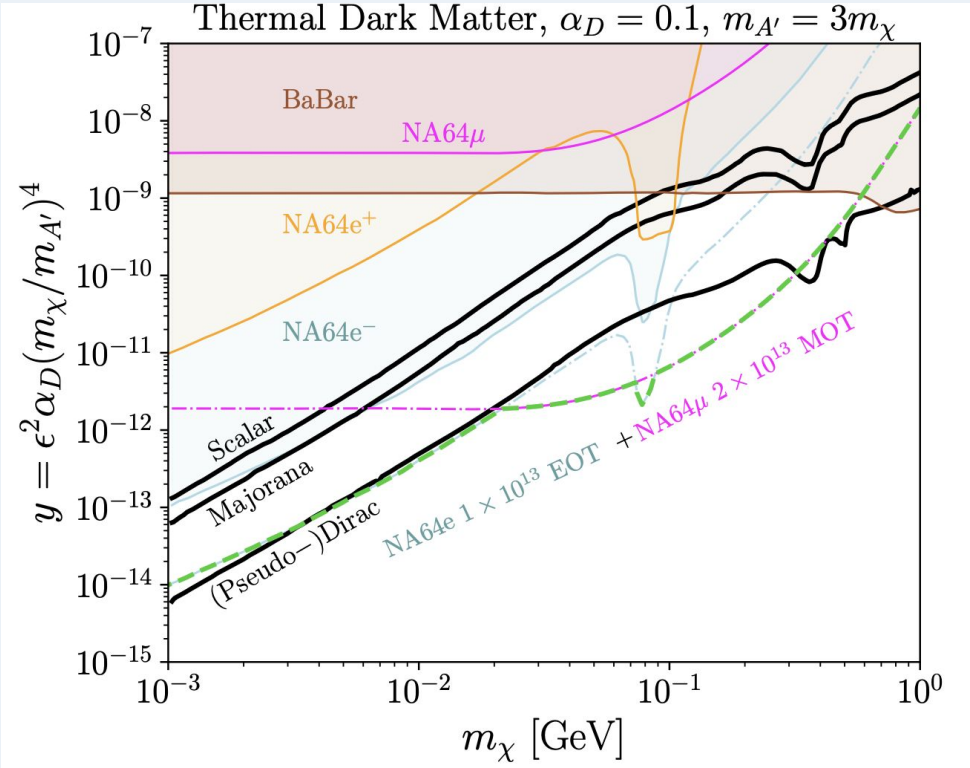
ALPs: PRL 125, 081801 (2020)



Inelastic DM: EPJC 83, 391 (2023)

Summary and outlook

Successful runs in 2023 and 2024 confirm the **robustness of the technique** and motivate the foreseen **upgrades after LS3**



In the coming years NA64 can decisively discover or disprove very interesting predictive LDM models and widely explore DS

Thanks!

We gratefully acknowledge all the CERN management and staff for their excellent support in preparing and running the NA64 experiment, in particular D. Banerjee, J. Bernhard, M. Brugger, N. Charitonidis, S. Girod and M. Lazzaroni from the BE-EA group and the PBC working groups.
Thanks Kristiane Bernhard-Novotny for the timelapse!

Backup slides

Plans before and after LS3

Run 4:
- High intensity detector and beam upgrade to run at 2×10^7 e/spill
- With 3500 spills/day and 8 week-run per year we would reach 1×10^{13} EOT

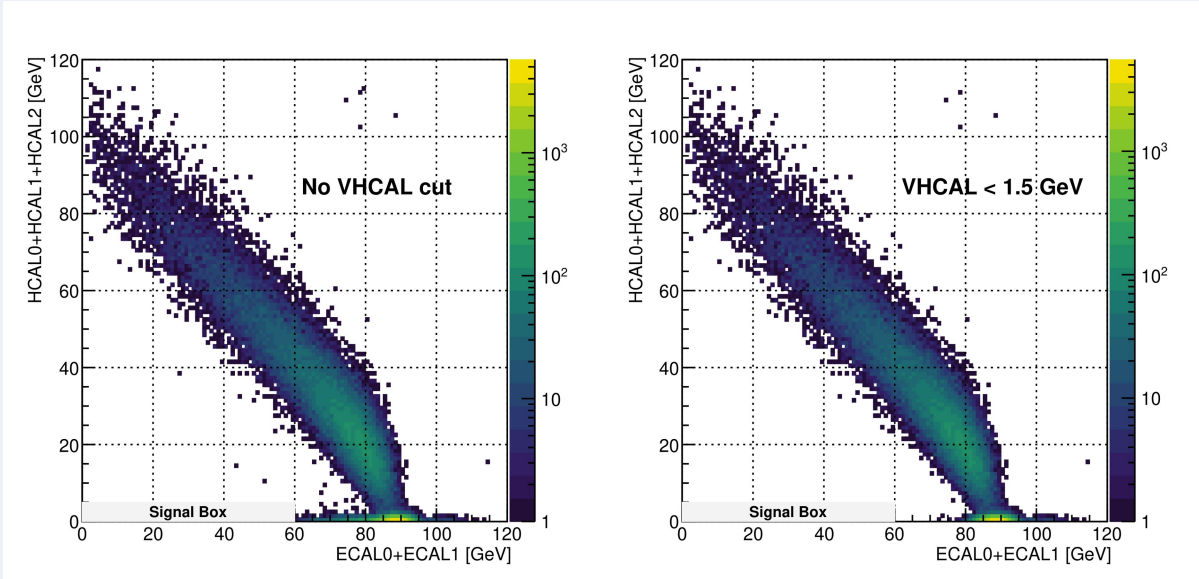
Run 4:
- High intensity upgrade to run at 5×10^7 μ/spill
- With 3500 spills/day and 4 week-run per year we would reach 2×10^{13} MOT

NA64e in 2023-2024

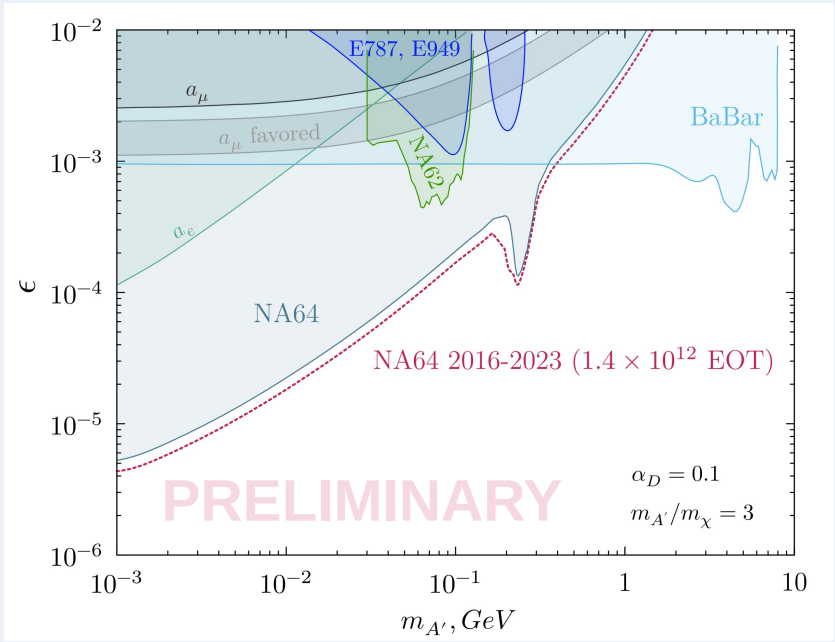
Preliminary results of analysis with 4.4×10^{11} EOT

→ Combined 2016-2023 = 1.4×10^{12} EOT

- Significant reduction of expected background
  → Enables us to extend signal region to [0 GeV, 60 GeV]
- Motivate the development of a full-scale, optimized VHCAL



✔ **Goal:** Keep experiment background-free up to 10^{13} EOT



NA64e⁺

Complementary strategy to explore the large-mass regime

- Breit-Wigner-like cross-section peaked at

$$m_{A'}^2 = 2 m_e E_e$$

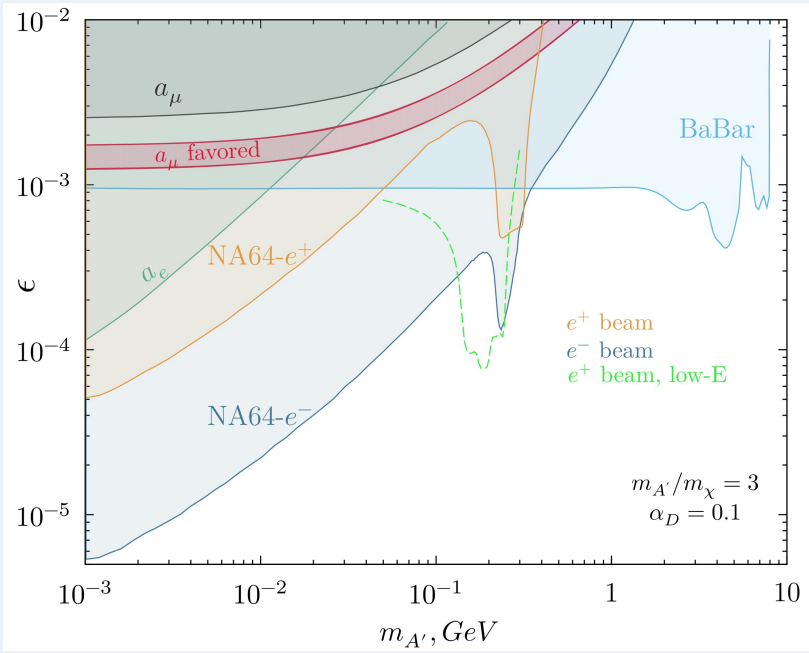
- Enhancement to the sensitivity limited by the missing-energy threshold E_{thr} and the beam energy E_0:

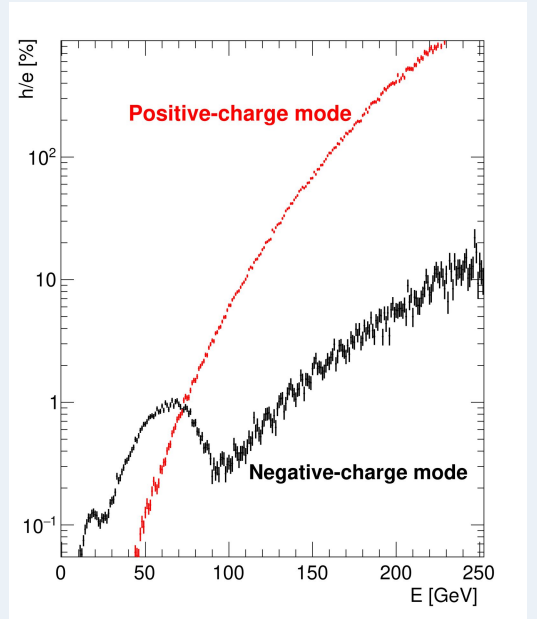
$$\sqrt{2 m_e E_{thr}} < m_{A'} < \sqrt{2 m_e E_0}$$

- Much higher (~4%) hadronic contamination at 100 GeV, mostly from the Λ → p π⁻ decay

Lower energy in SRD expected at low beam energies

→ Requires a new upgrade with higher light yield and better energy resolution → LYSO-based SRD





NA64 collaboration,
Nucl.Instrum.Meth.A 1057 (2023) 168776

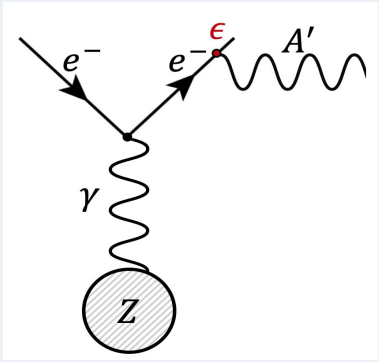
The NA64 technique

Active Dump + Fully hermetic detector

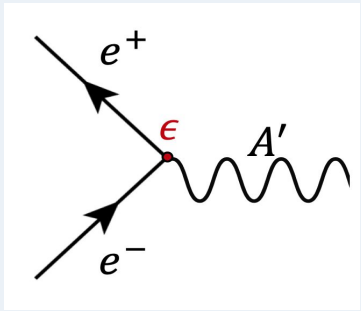
Initial well-defined beam

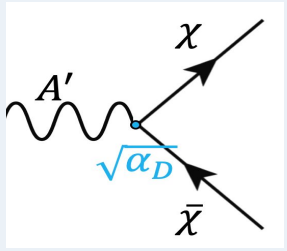
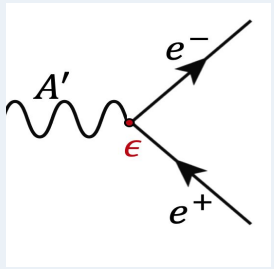
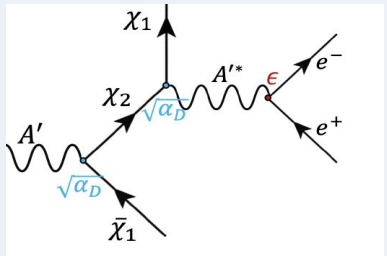
e^-, e^+, μ, π

A'-Bremsstrahlung

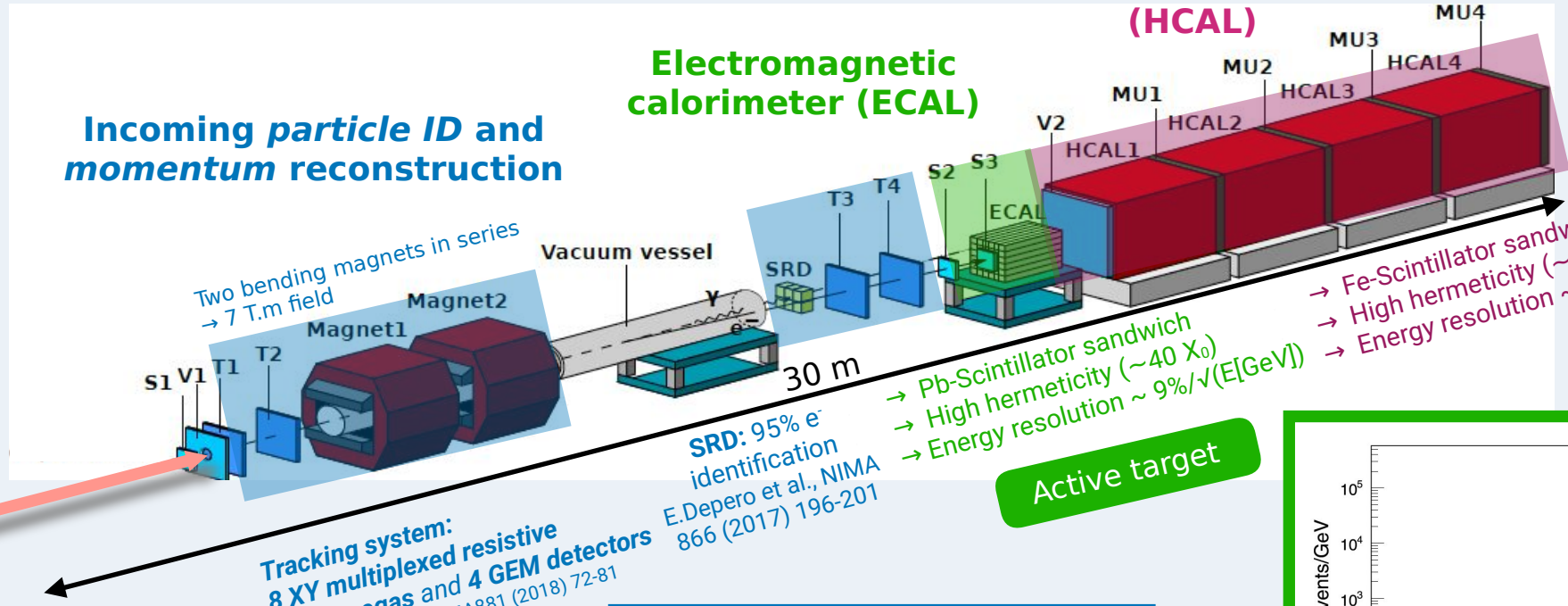


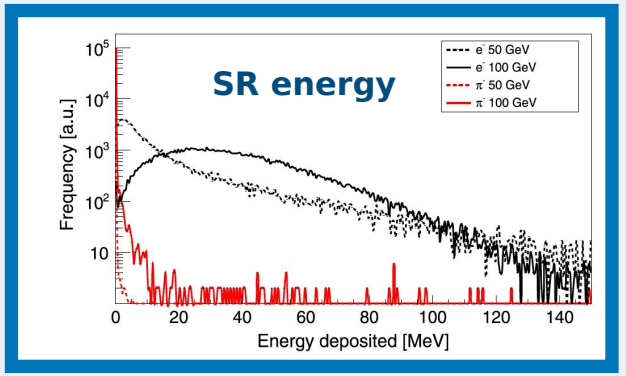
Resonant A' production

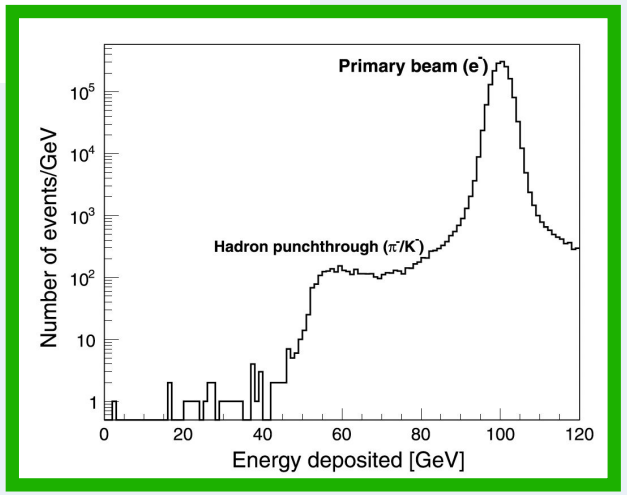


Decay		Signature
• *Invisible* $m_{A'} > 2m_\chi$		Missing energy
• *Visible* $m_{A'} < 2m_\chi$		SM pair particles
• *Semi-Visible* $m_{A'} > m_{\chi_1} >> m_e$		Missing energy + SM pair particles

NA64 *invisible* mode: Experimental setup

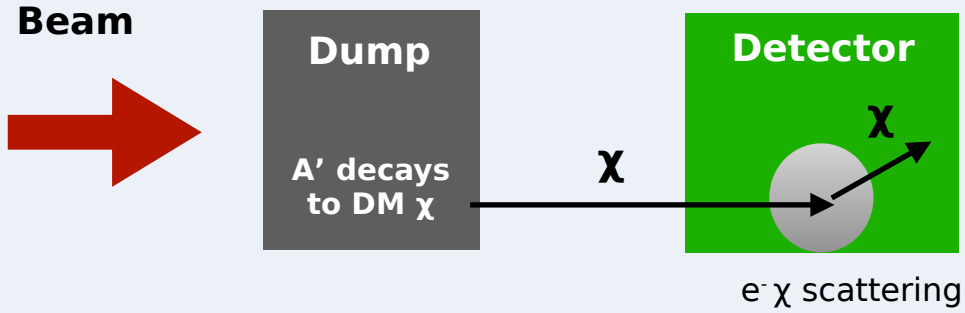






The NA64 technique

1) BEAM DUMP APPROACH
(MiniBooNE, LSND, NA62, SHIP, T2K, DUNE…)



Flux of X generated by decays of A's produced in the dump.

Signal: X scattering in far detector

$$\sigma \propto \epsilon^4 \alpha_D$$

2) NA64/LDMX APPROACH

Produced A's carry away energy from the active dump.

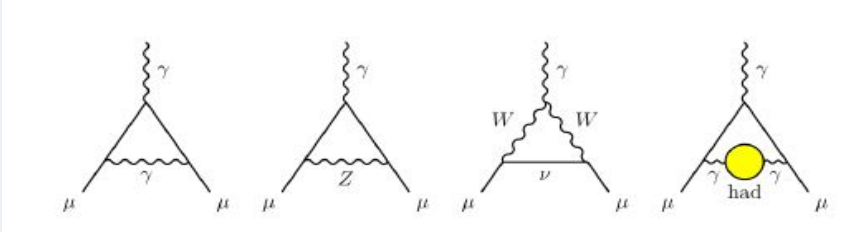
Signal: Missing energy/momentum

$$\sigma \propto \epsilon^2$$

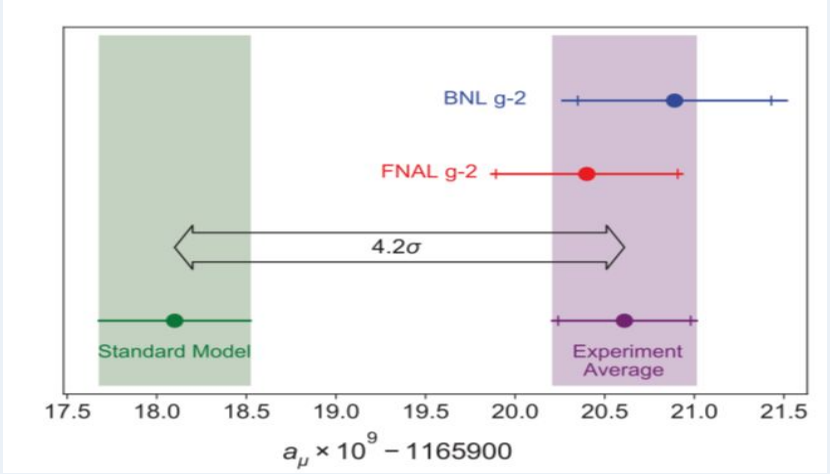
NA64μ: additional motivation, $(g-2)_\mu$

$$a_\mu = \frac{g_\mu - 2}{2}$$

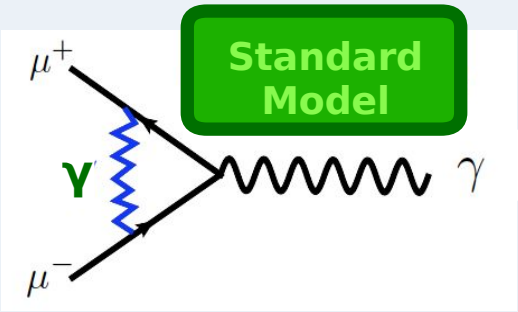
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$

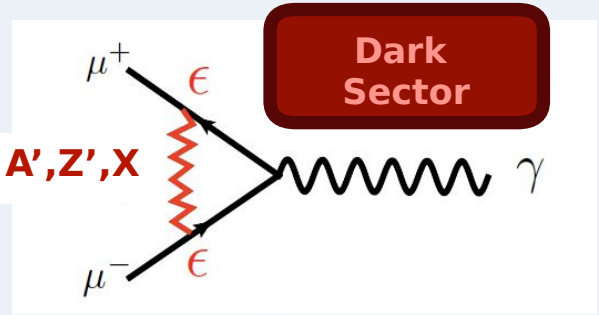


$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = (251 \pm 59) \cdot 10^{-11}$$



(Lattice QCD calculations are in better agreement)

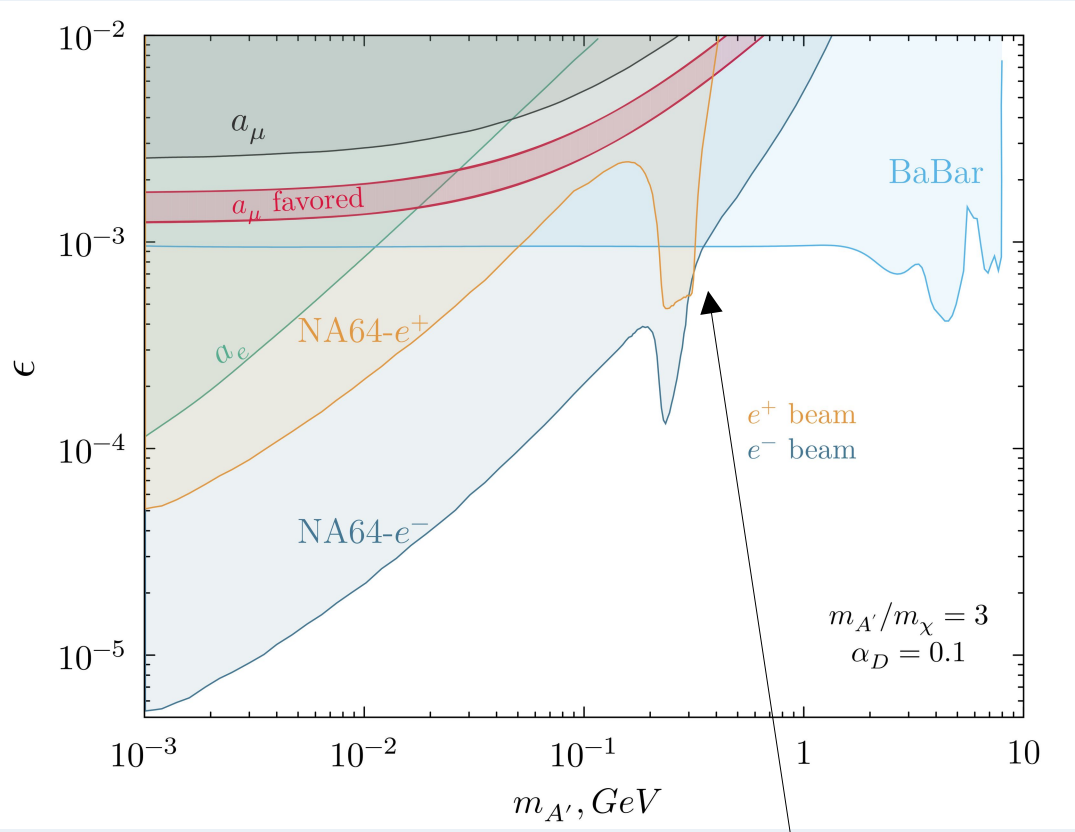


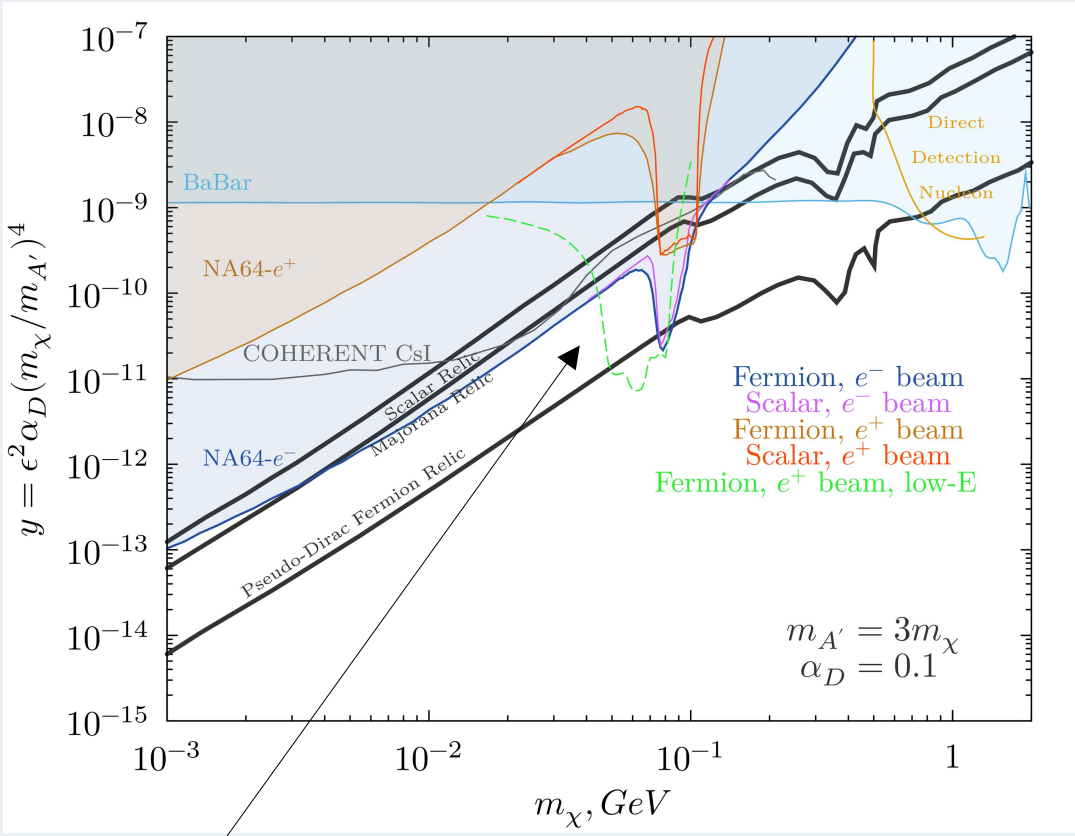


Specific target for NA64

New physics?
1-loop contributions from dark sector bosons such as A', Z' or a generic X

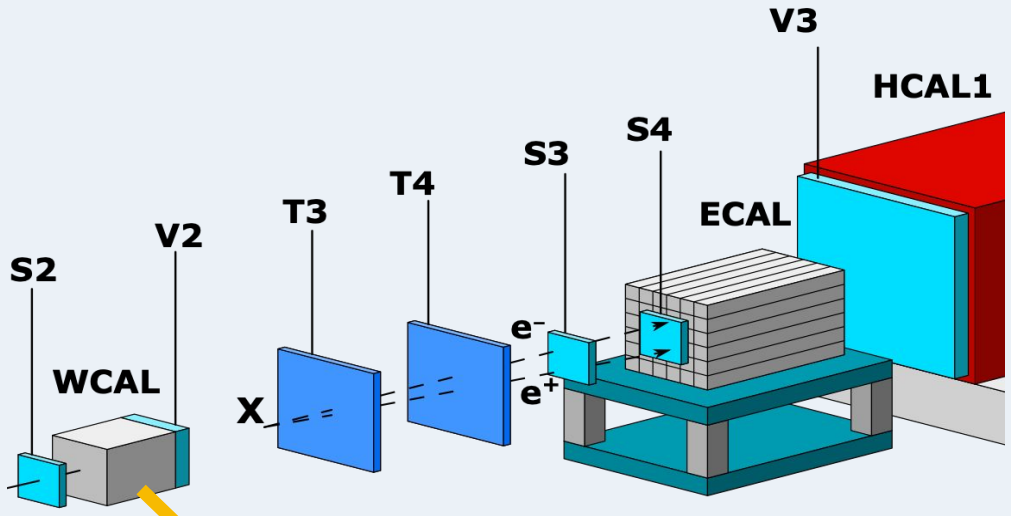
NA64e⁺: Latest results with 2022 run

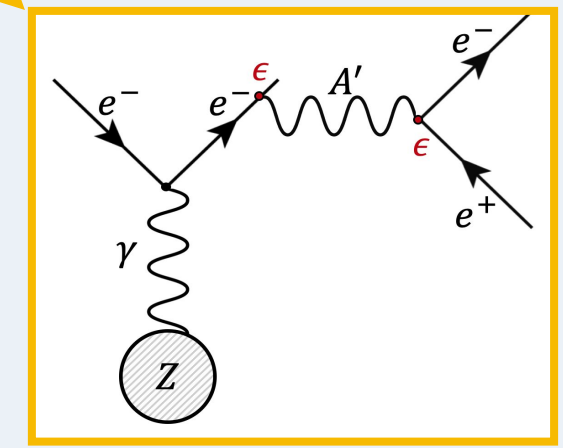




Enhanced sensitivity through resonant annihilation production

NA64 visible mode: 2017-2018 combined results

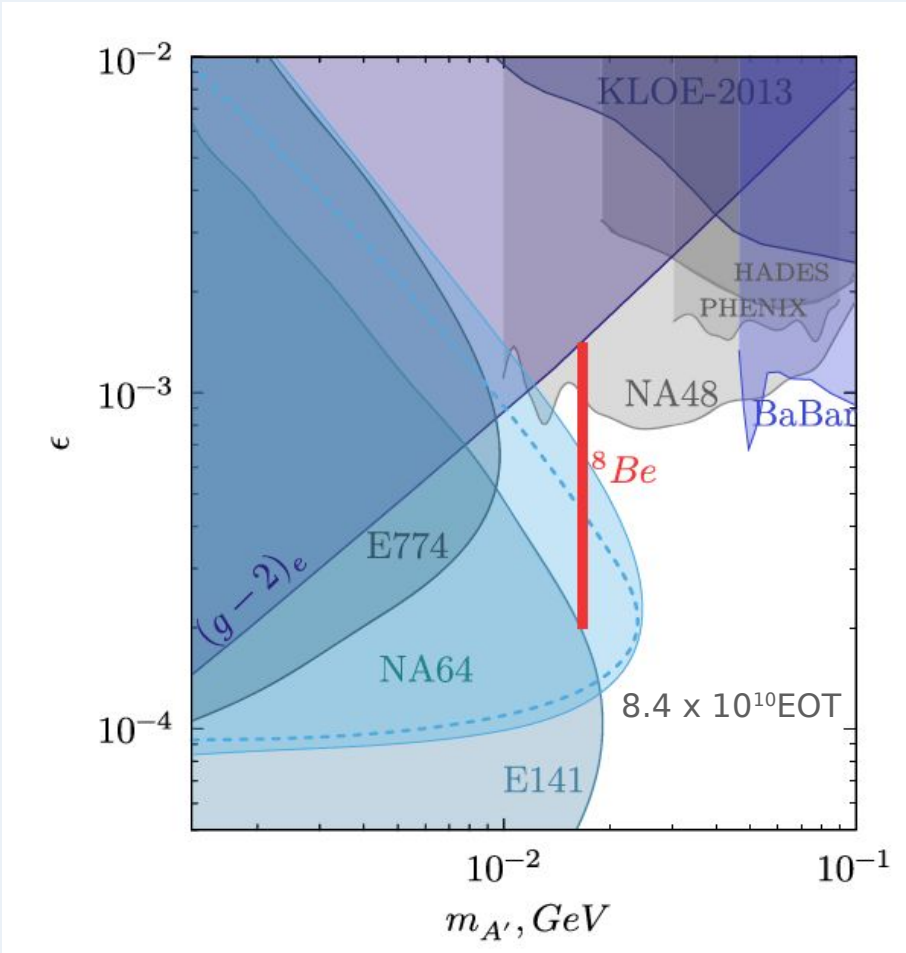




Compact Tungsten calorimeter

$$e^-Z \to e^-ZX_{17}(A');\ X_{17}(A') \to e^+e^-$$

Vector-like boson (benchmark model)



NA64 collaboration, PRL 120, 231802 (**2018**), PRD 107, 071101 (R) 2020