Highlights from the NA64 experiment

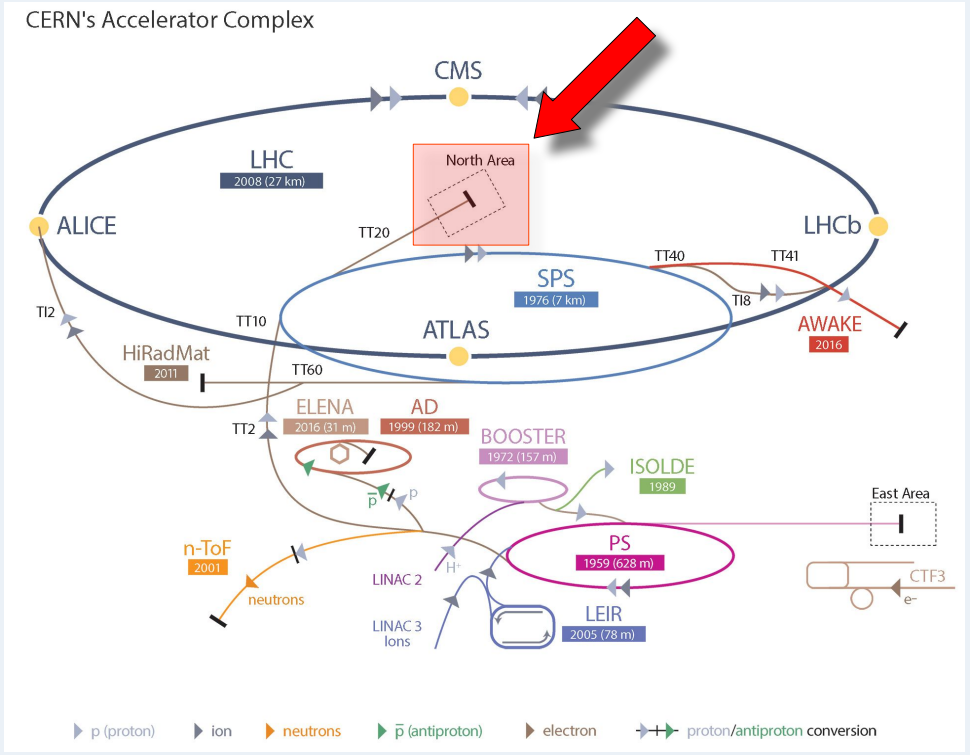
Benjamin Banto Oberhauser on behalf of the NA64 collaboration
Group Crivelli, ETH Zürich
DISCRETE 2024, December 3rd, 2024

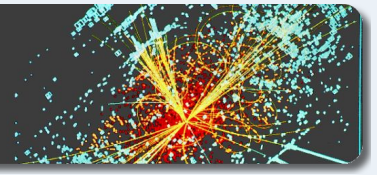
The NA64 experiment

- **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

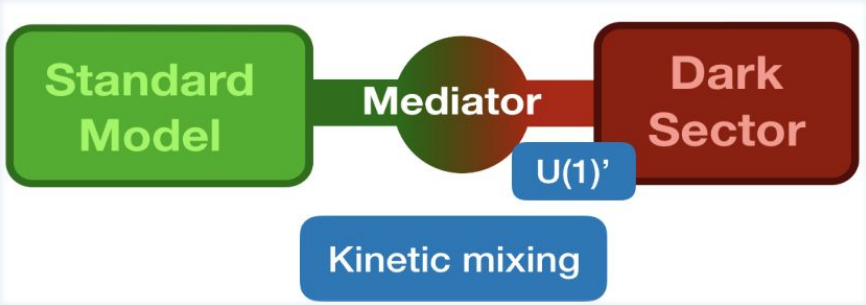
- Pioneering **active dump** and **missing energy** technique exploiting the unique, high-purity beams at CERN SPS:
  - ***NA64e***, ***NA64e⁺***
    - Search for LDM using electrons/positrons at H4
  - ***NA64μ***:
    - Phase 1: L_μ-L_τ Z' as a solution to the $(g-2)_\mu$ anomaly and LDM
    - Phase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



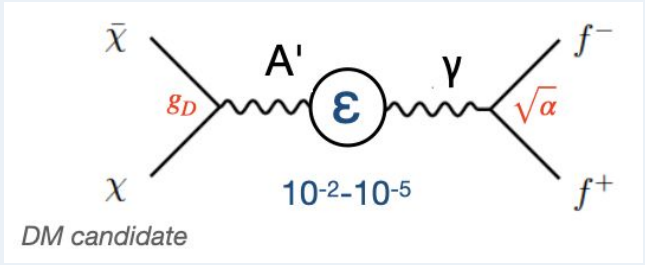


NA64 target: DS and Light Dark Matter

Dark Sector feebly interacting with SM



Dark Photon A'



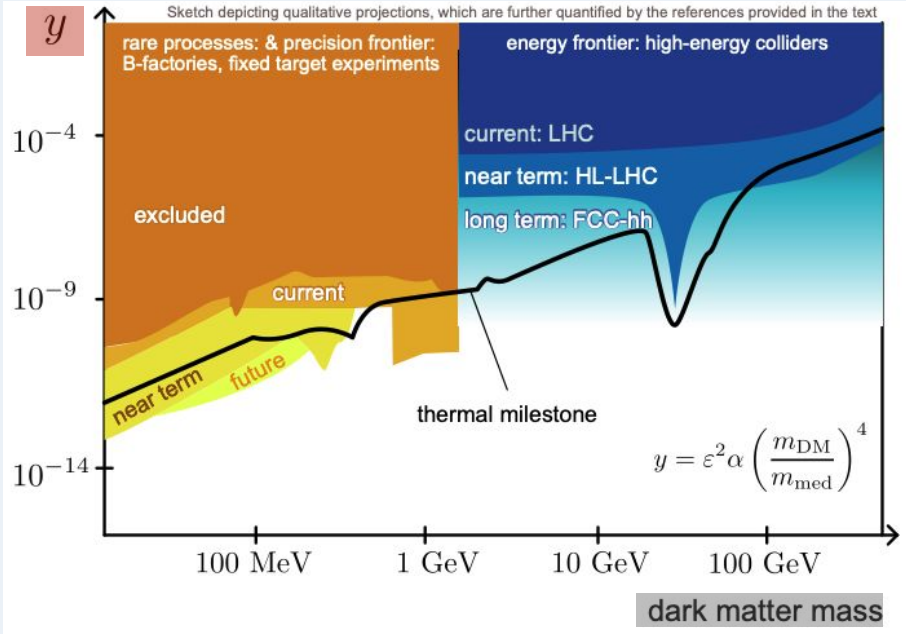
DM relic density

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$

$$\sigma v(\chi\chi \to A' \to ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

J.Feng, J. Kumar
Phys. Rev. Lett.101231301

Target in LDM parameter space



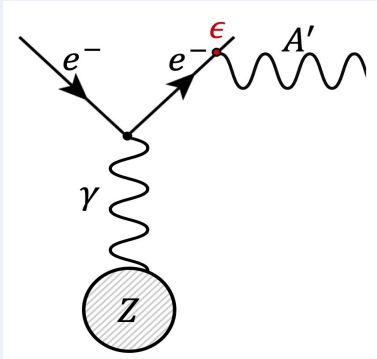
The NA64 technique

Active Dump + Fully hermetic detector

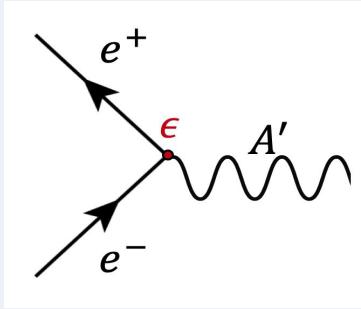
Initial well-defined beam

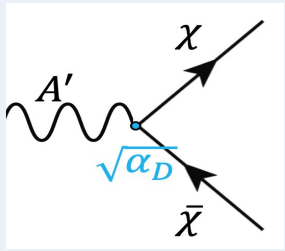
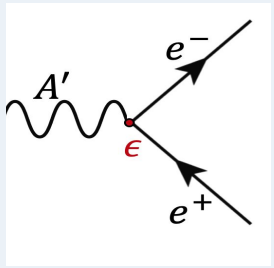
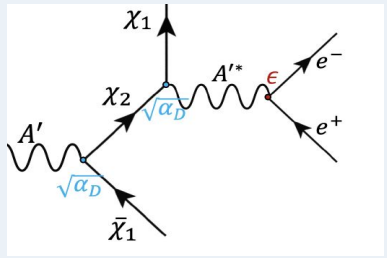
e^-, e^+, (μ, π)

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

Crucial milestones reached!

Latest results

- ***NA64e***

  World-leading sensitivity for Light Dark Matter (LDM) using 100 GeV e^-: *Phys. Rev. Lett. 131, 161801 (2023)*

- ***NA64e⁺***

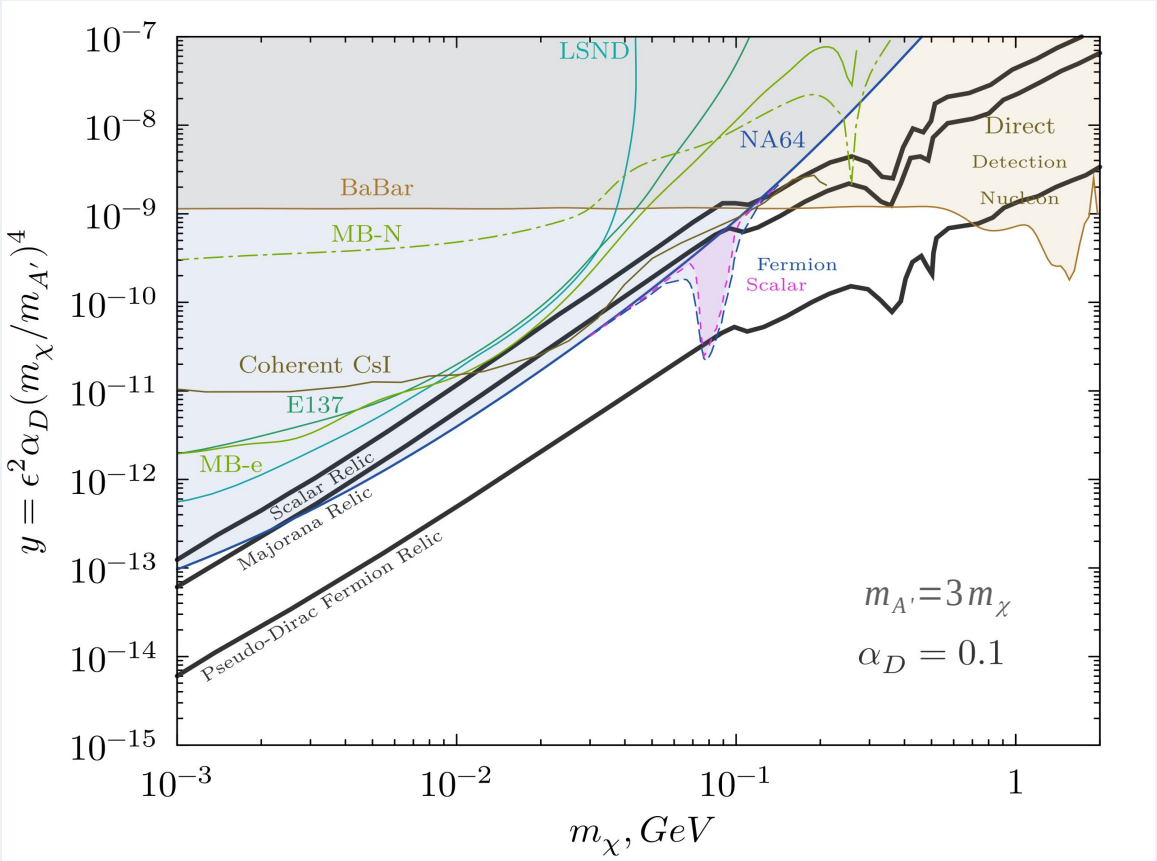
  First LDM results using a e^+ beam: *Phys.Rev. D 109, L031103 (2024)*

- ***NA64μ***

  First DS exploration using a μ^- beam: *Phys. Rev. Lett. 132, 211803 (2024)*

- ***NA64h***

  Proof of principle using charge-exchange reactions of a hadron beam: *Phys. Rev. Lett. 133, 121803 (2024)*



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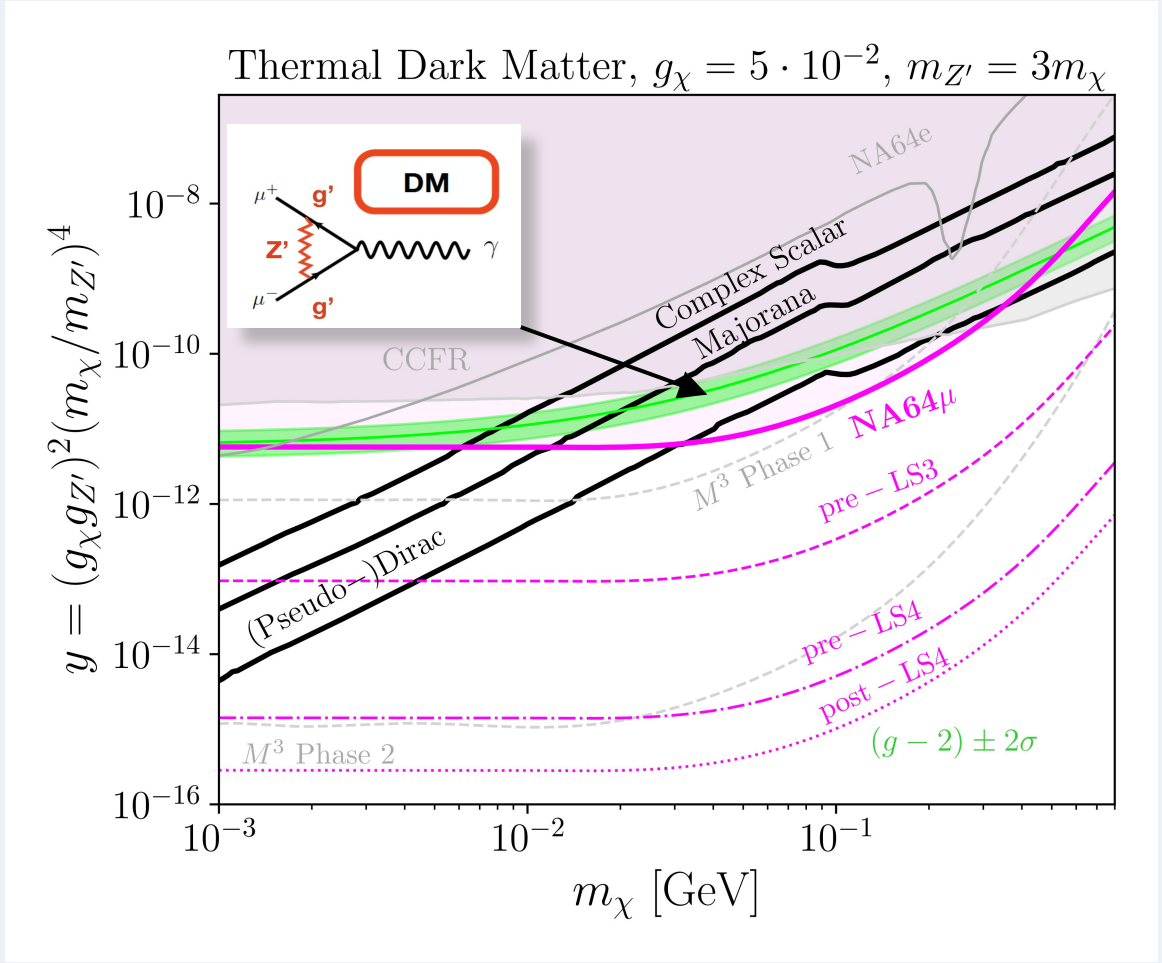
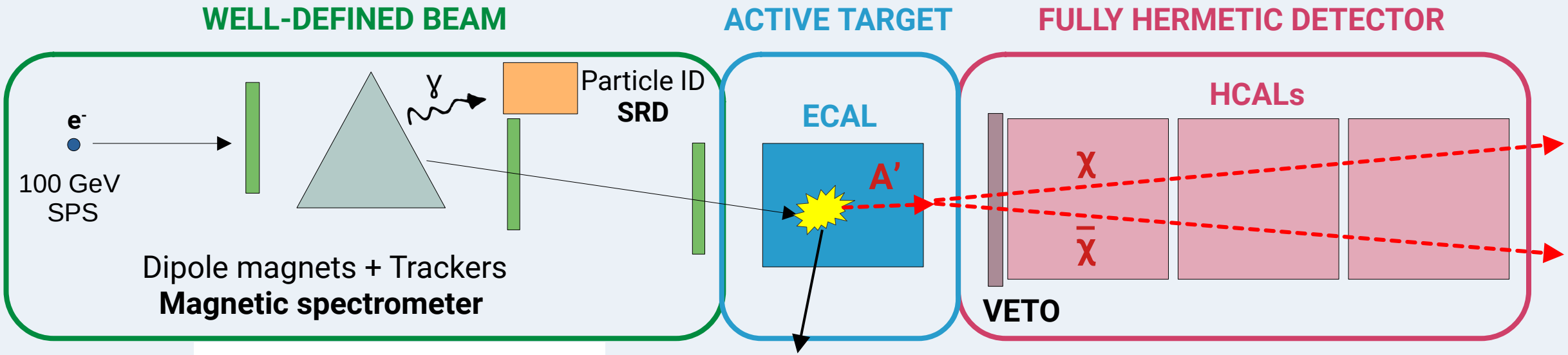
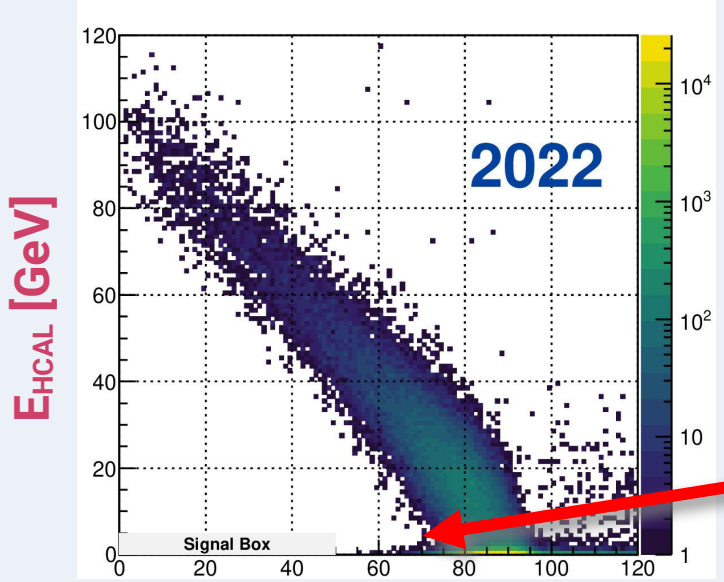
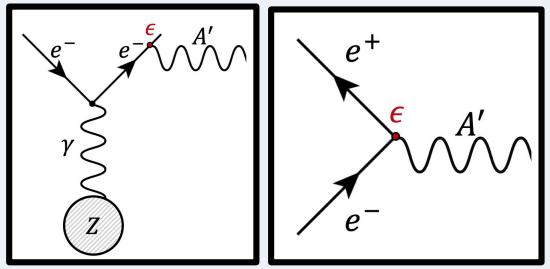


NA64e: Setup in 2022



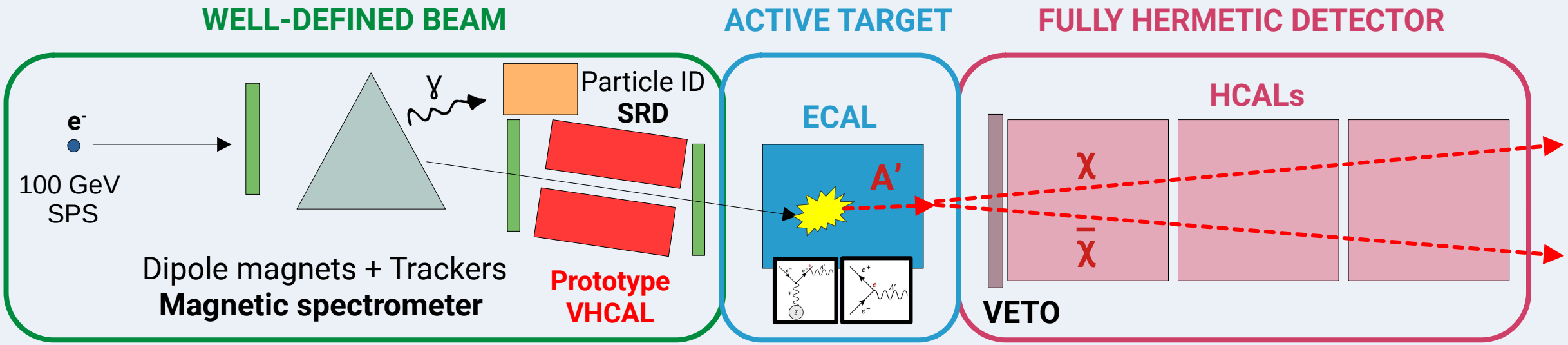


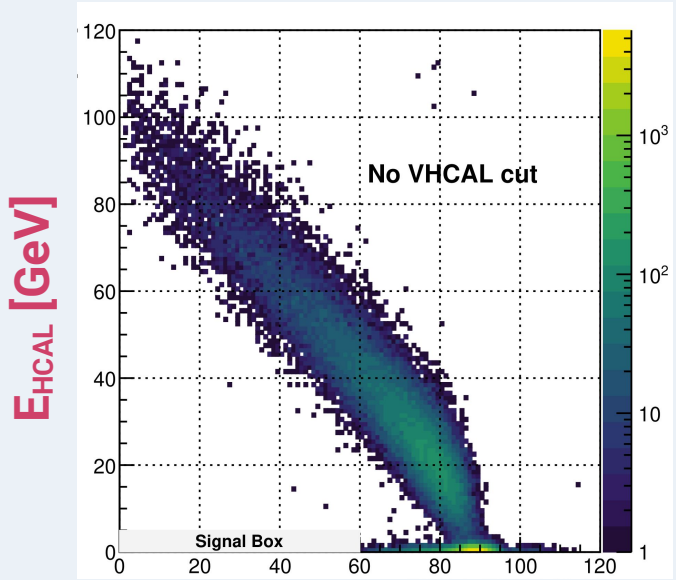


Dark Photon A'

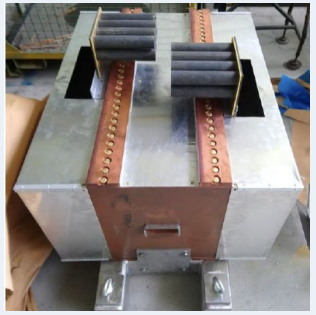
Main background from high-p_t hadronic secondaries from beam interactions before ECAL.

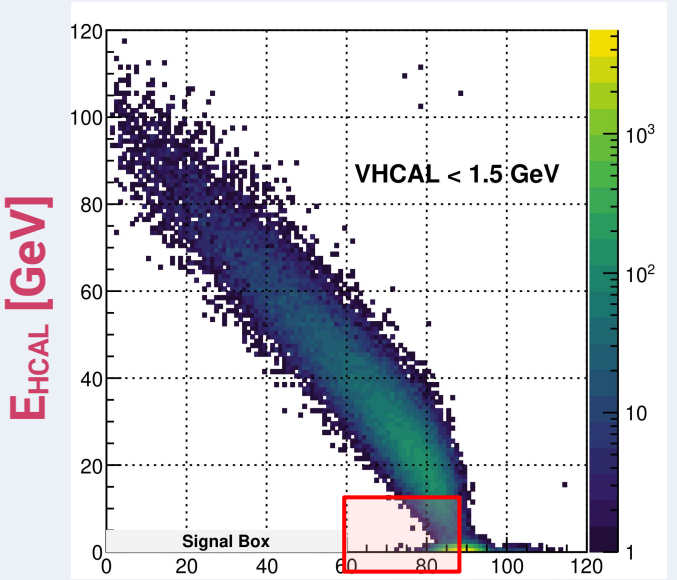
NA64e: Setup improvements in 2023/24





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





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

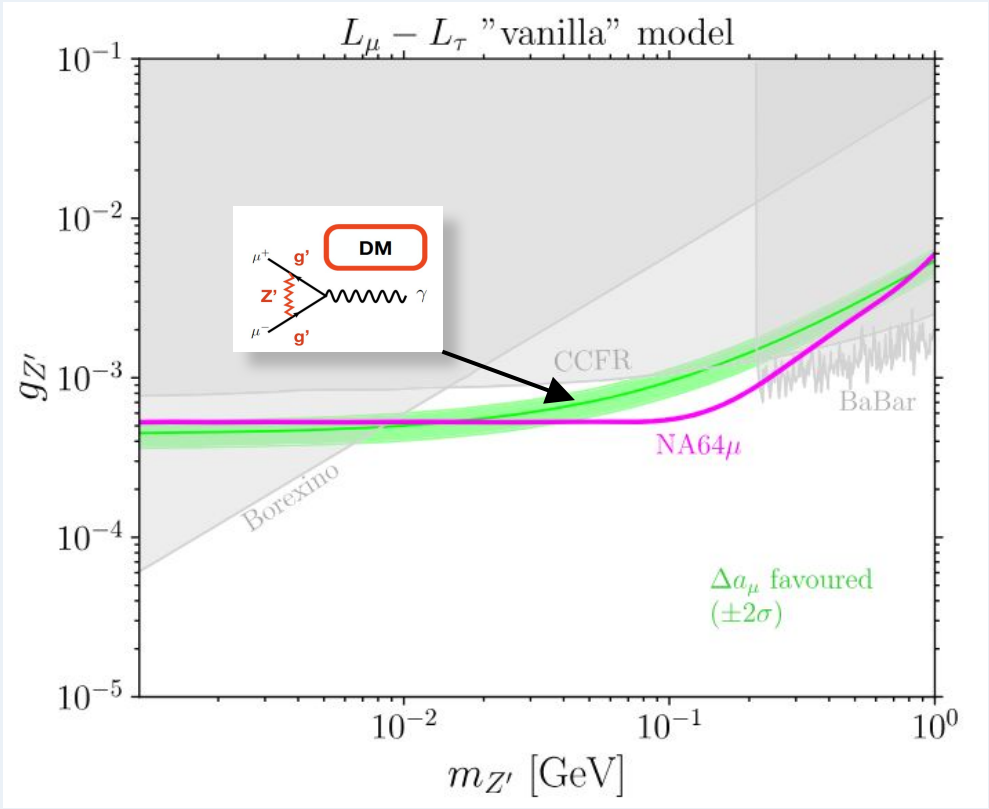
Physics See synopsis: Careful Accounting Could Reveal the Dark Sector

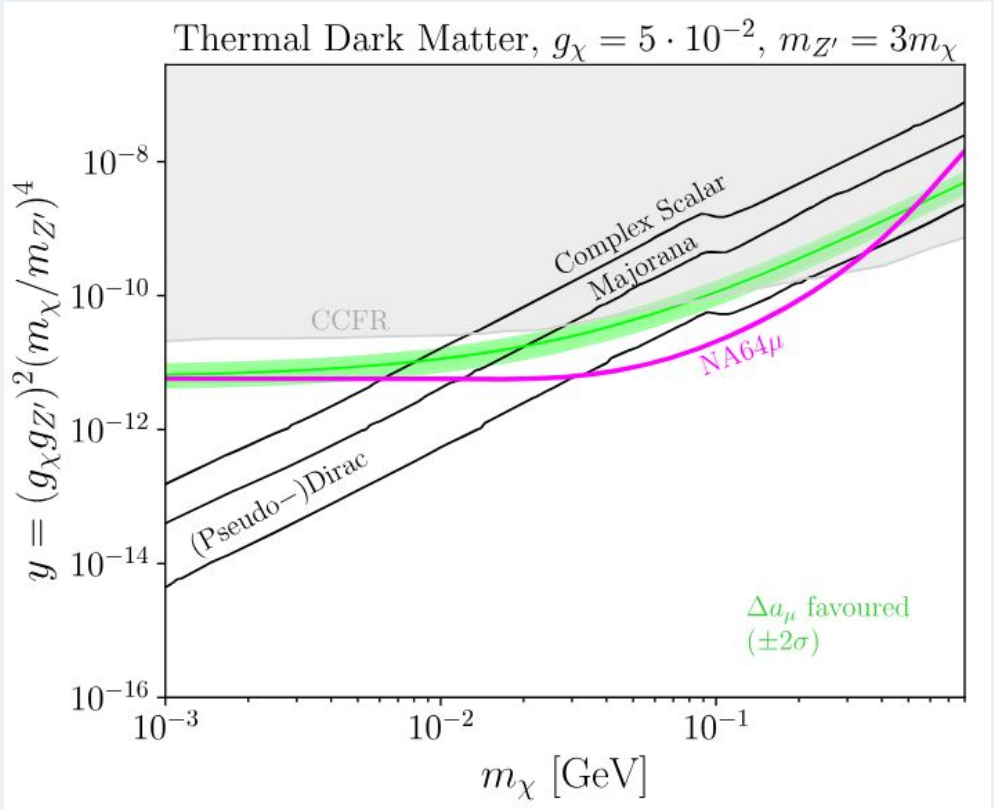
Careful Accounting Could Reveal the Dark Sector

HIGHLIGHTED IN PHYSICS

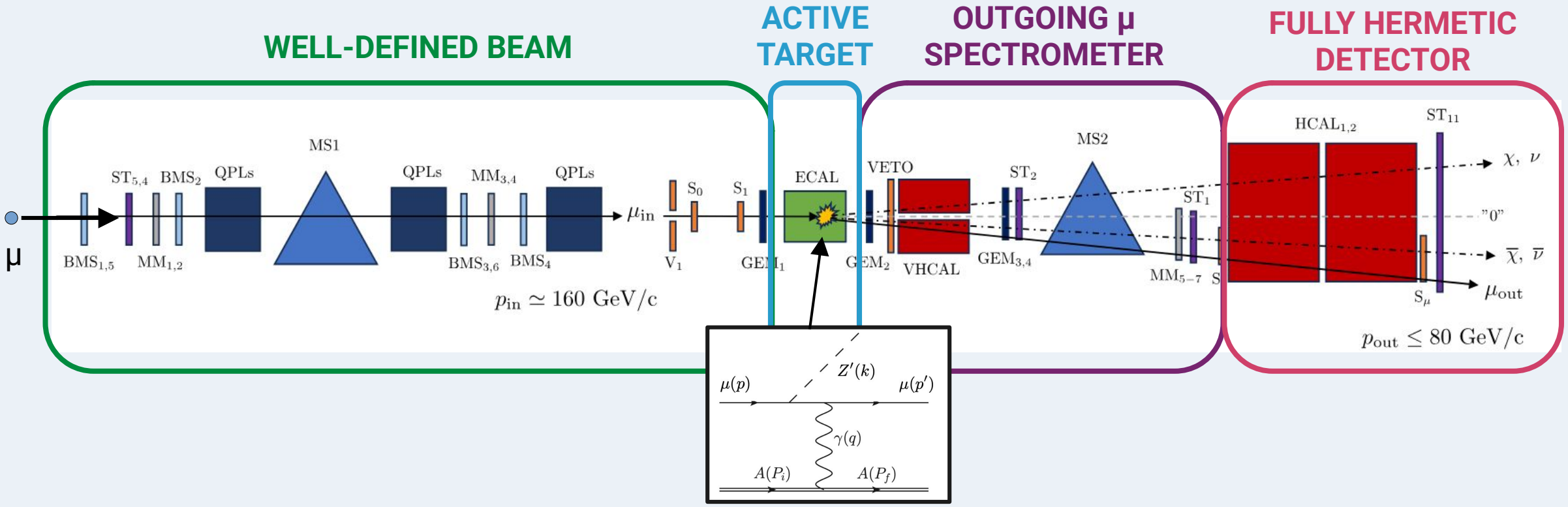
May 21, 2024 • *Physics* 17, s54

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

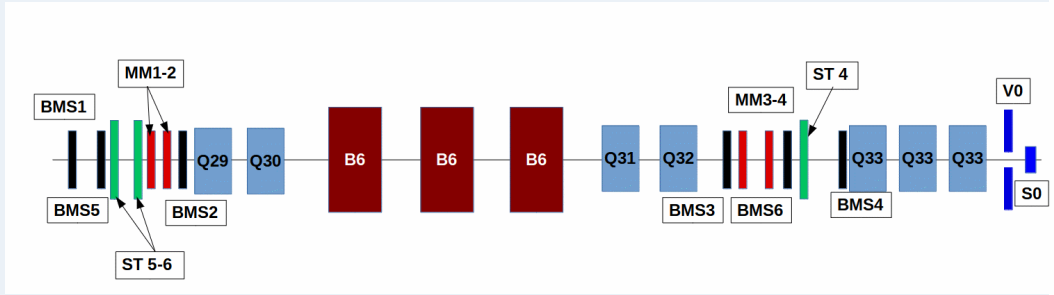


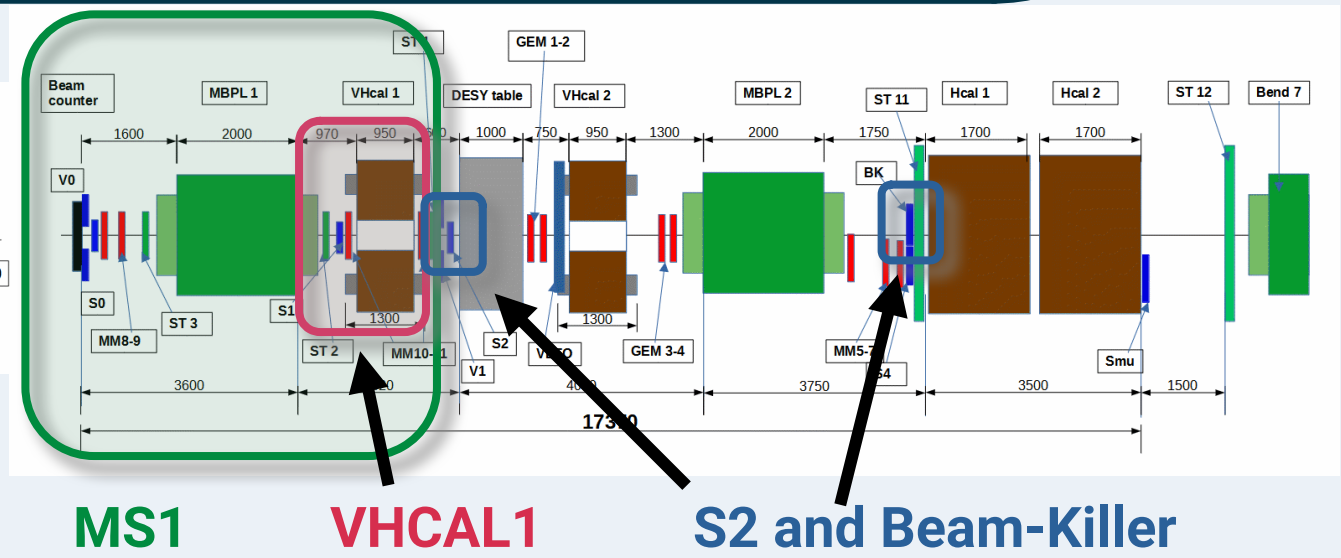
Signature: Incoming momentum > Measured energy + Outgoing momentum

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

arXiv:2409.10128

NA64μ: Setup improvements in 2023/24





Significant upgrades in 2023/2024:

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

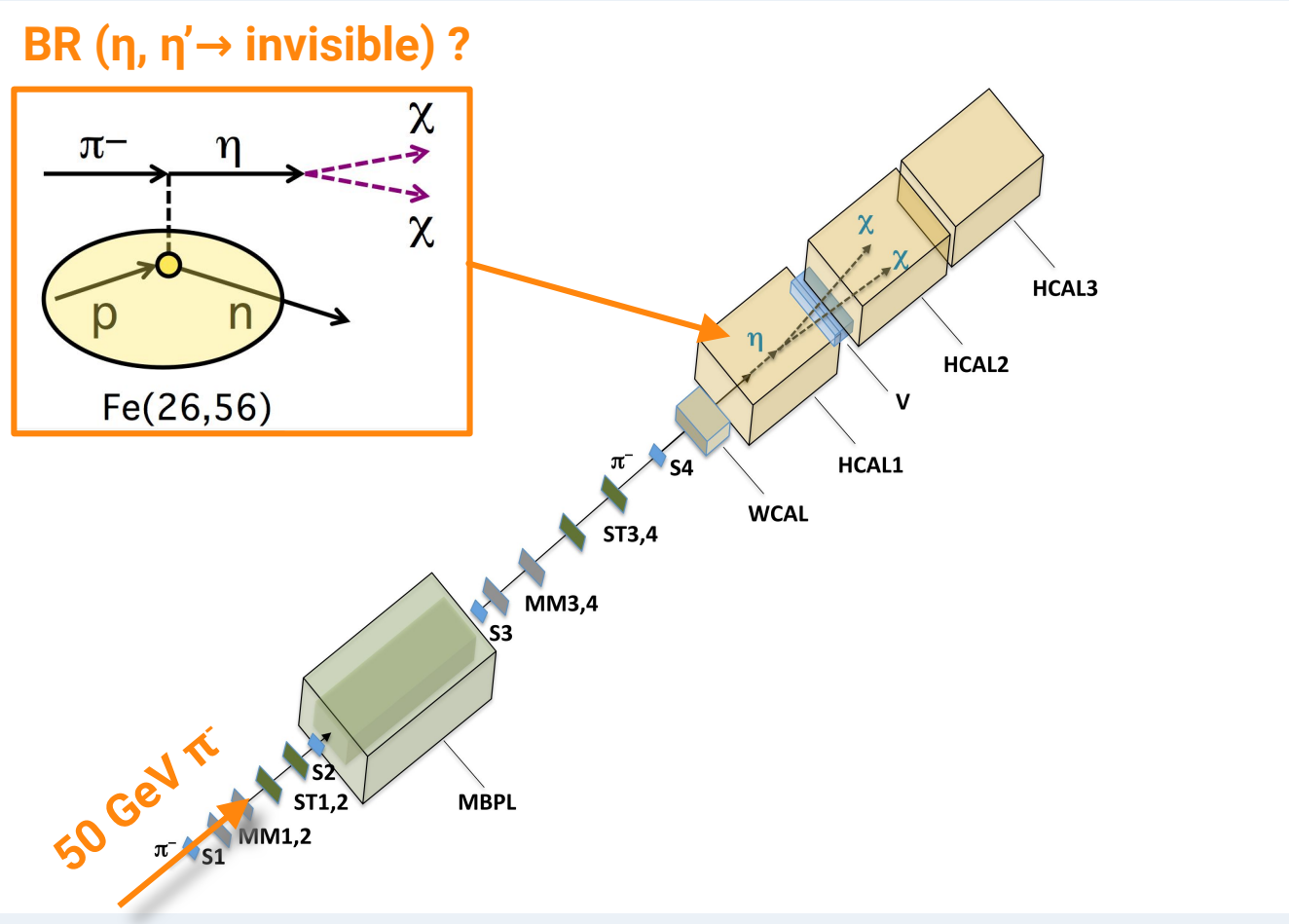
→ **Collected 15x more statistics 2021/2022**

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

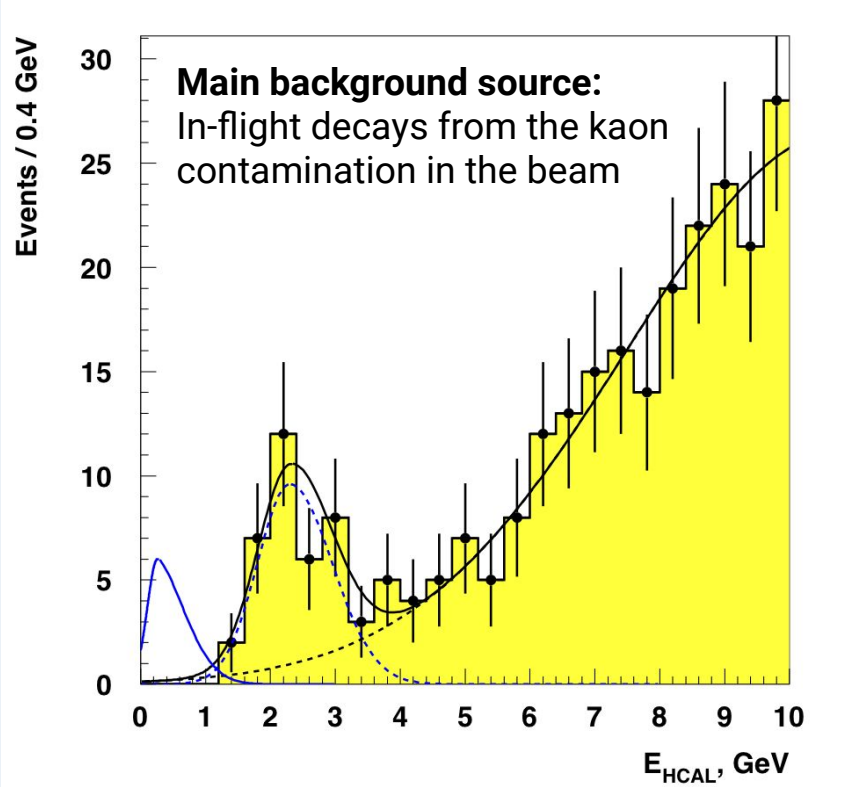
Main uncertainty from charge-exchange cross-sections errors at these energies (~30% at 50 GeV)

$$n_{signal} = n_{POT}\,\epsilon_{\pi}\,\epsilon_{S}\,\frac{\sigma_{\eta'}}{\sigma_{tot}}\,BR(\eta' \to invis)$$

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*) < 2.3 x 10^{-4} < 6 x 10^{-4}

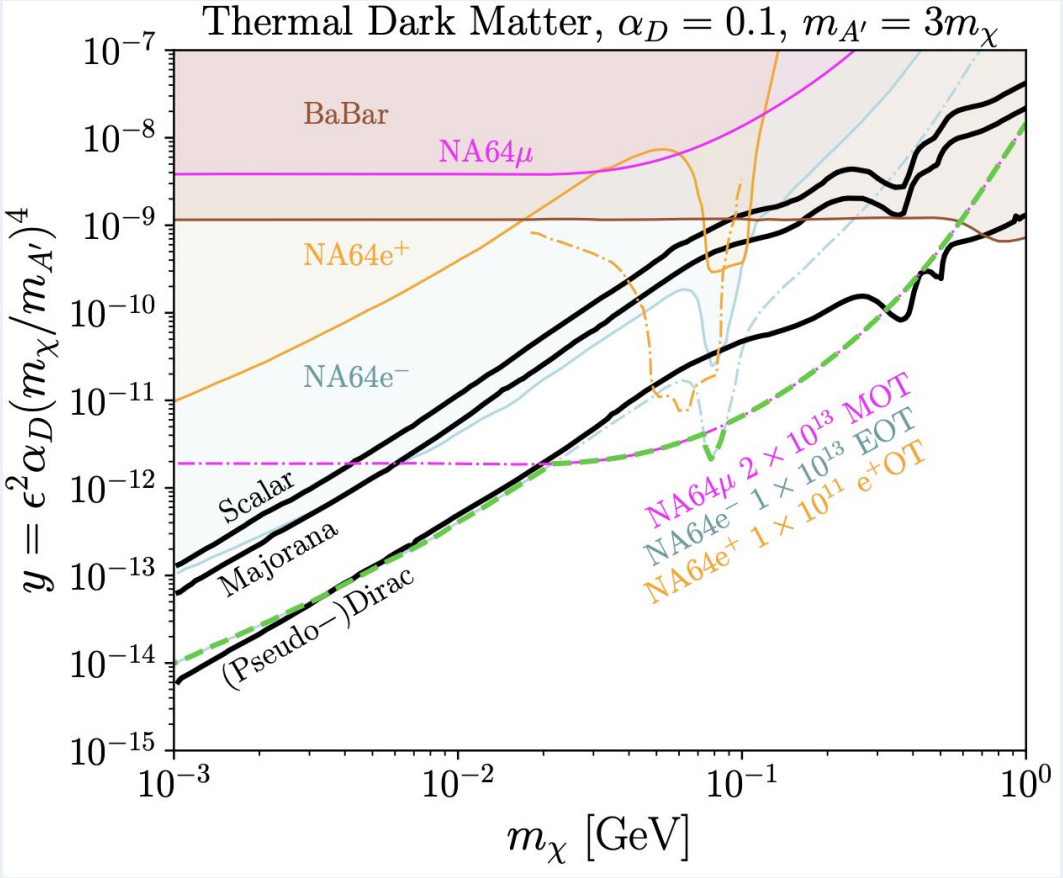
Measurement by BESIII: Physical Review D 87, 012009 (2013)



- Proof of principle demonstrated *Phys. Rev. Lett. 133, 121803 (2024)*
- Addendum for a dedicated NA64 program in preparation
- Two-week test beam requested at T9 in PS

Summary and outlook

	Goals	Current Total	Run 4 (statistics aim)
NA64e	Dark Sector Light Dark Matter ALPs, Z', ...	1.9x10^{12} EOT	~10^{13} EOT
NA64μ	Dark Sector, LDM (higher masses), Muon g-2 ALPs, Z', μ→ τ, ...	3.5x10^{11} MOT	~2x10^{13} MOT
NA64e$^+$	LDM (higher masses)	4.3x10^{10} e+OT	~1.3x10^{12} e+OT
NA64h	Invisible decays from η, η', π^0, $K^0_{L,S}$	2.9x10^9 πOT	Proposal to be submitted in 2025



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

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.

Funded by SNSF Grants No. 197346 and 219485

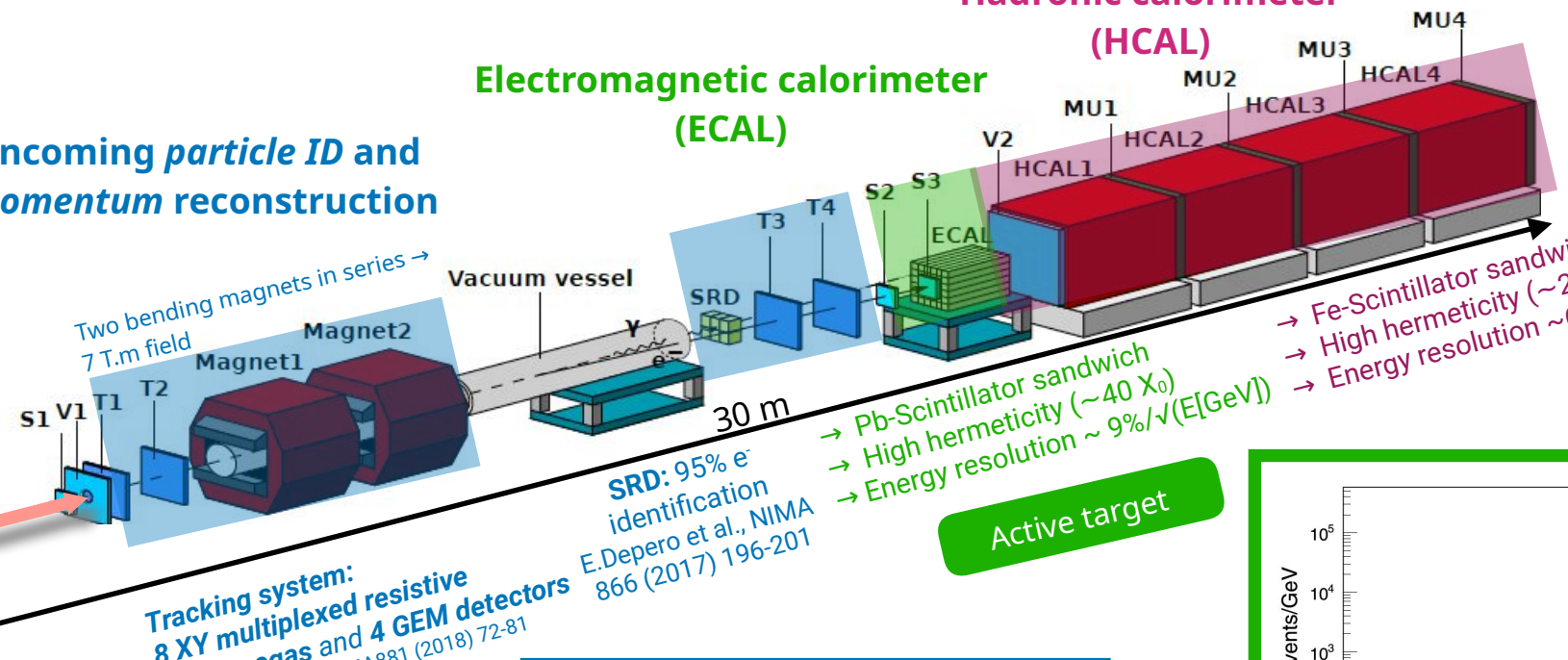
Backup slides

NA64 *invisible* mode: Experimental setup

Hadronic calorimeter (HCAL)

Electromagnetic calorimeter (ECAL)

Incoming *particle ID* and *momentum* reconstruction



H4 Beam
100 GeV e-

Beam tagged through $S_{1\text{-}3}$
H4 Beam Intensity ~2×10^7 e^-/spill
Hadron contamination <2%

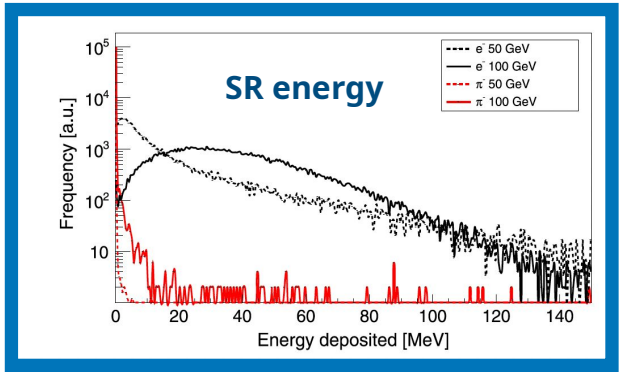
Tracking system:
8 XY multiplexed resistive Micromegas and 4 GEM detectors
D. Banerjee et al., NIMA881 (2018) 72-81

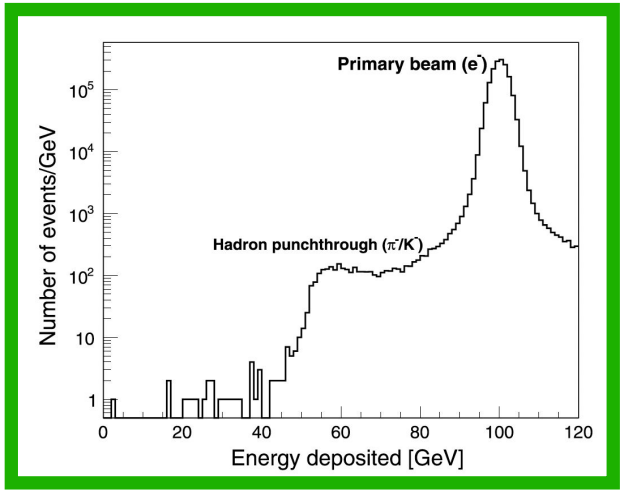
SRD: 95% e^- identification
E.Depero et al., NIMA 866 (2017) 196-201

→ Pb-Scintillator sandwich
→ High hermeticity (~40 X_0)
→ Energy resolution ~ 9%/√(E[GeV])

→ Fe-Scintillator sandwich
→ High hermeticity (~28λ)
→ Energy resolution ~60%/√(E[GeV])

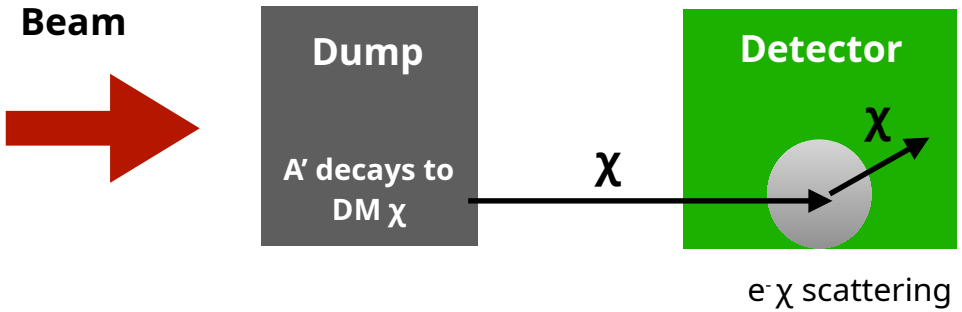
Active target





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

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

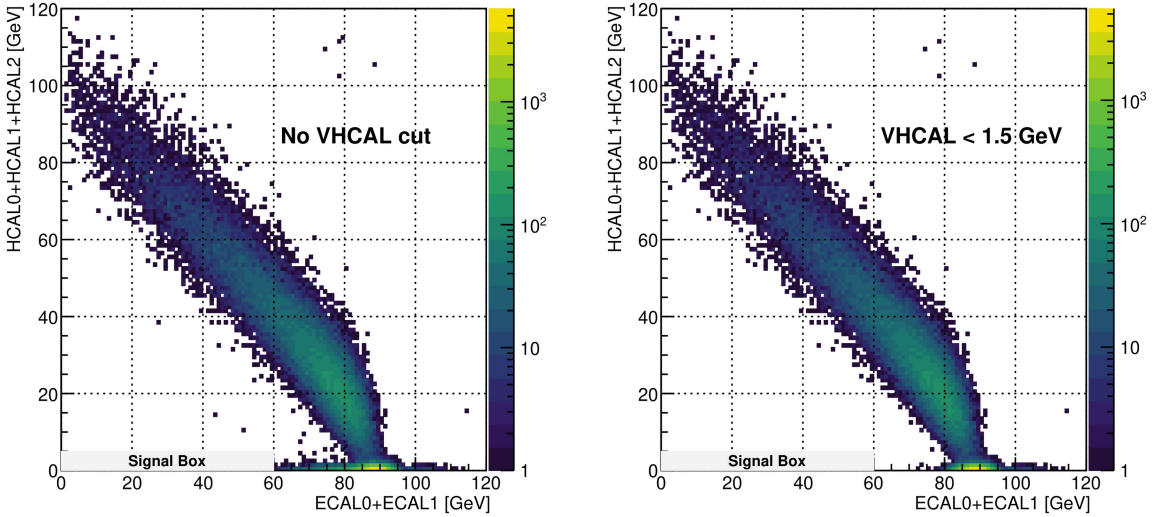
NA64e in 2023-2024

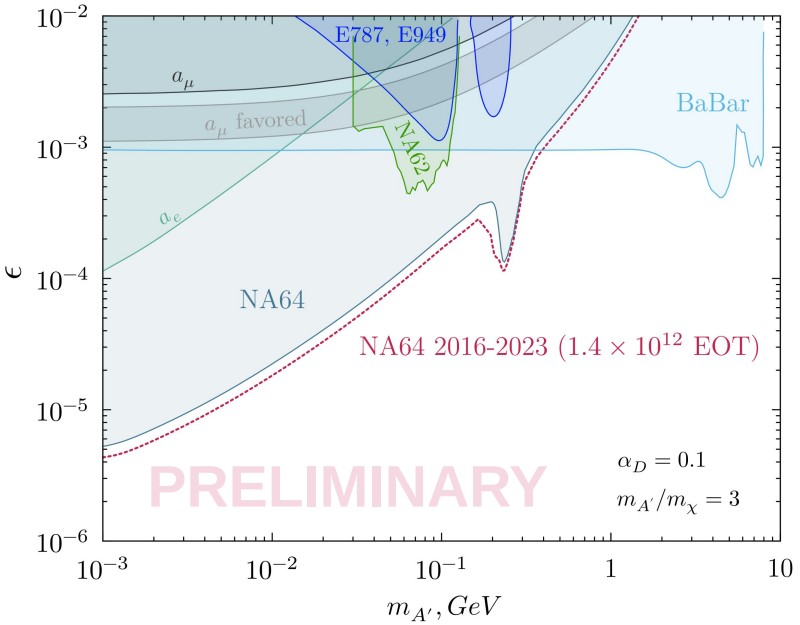
Preliminary results of analysis with 4.4×10^{11} EOT

→ 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

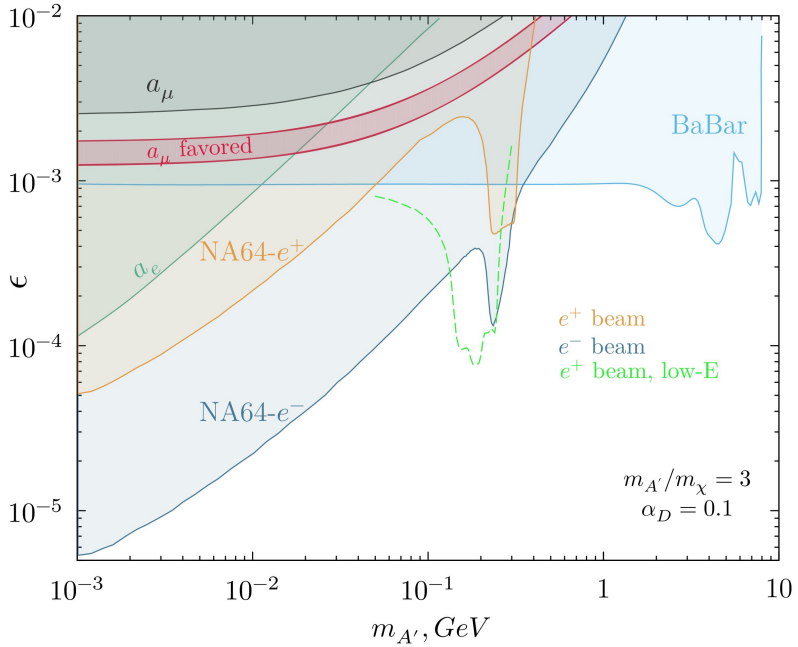
- Breit-Wigner-like cross-section peaked at

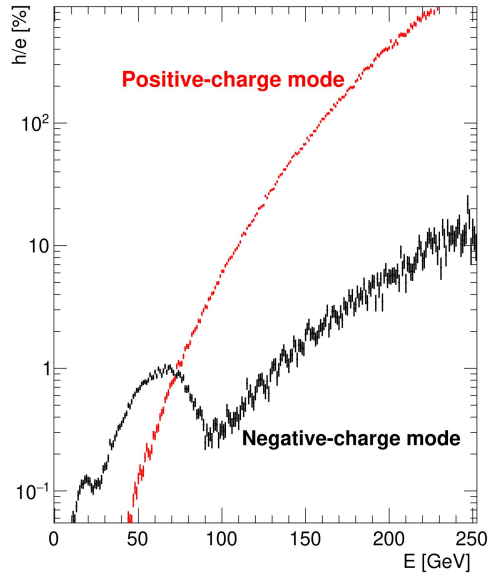
$$m_{A'}^2 = 2 m_e E_e$$

- 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 $\Lambda \rightarrow p\,\pi^-$ decay





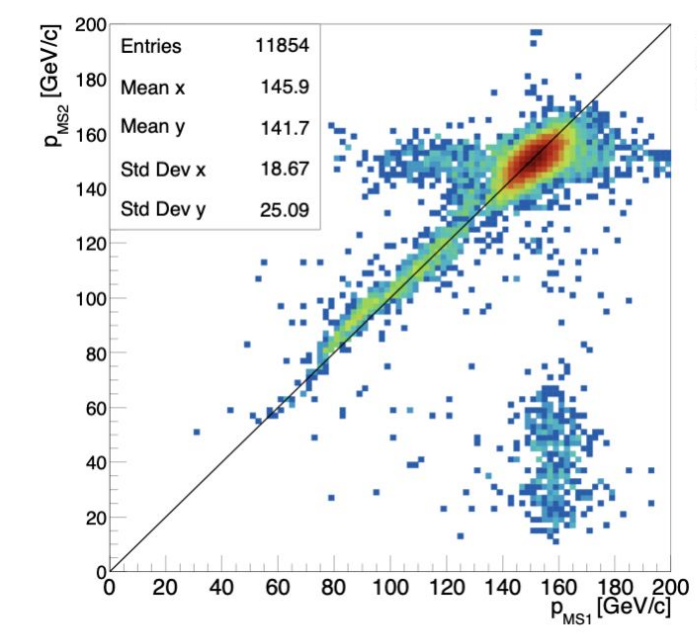
NA64 collaboration,
Nucl.Instrum.Meth.A 1057 (2023) 168776

NA64μ: Analysis of the 2023 run

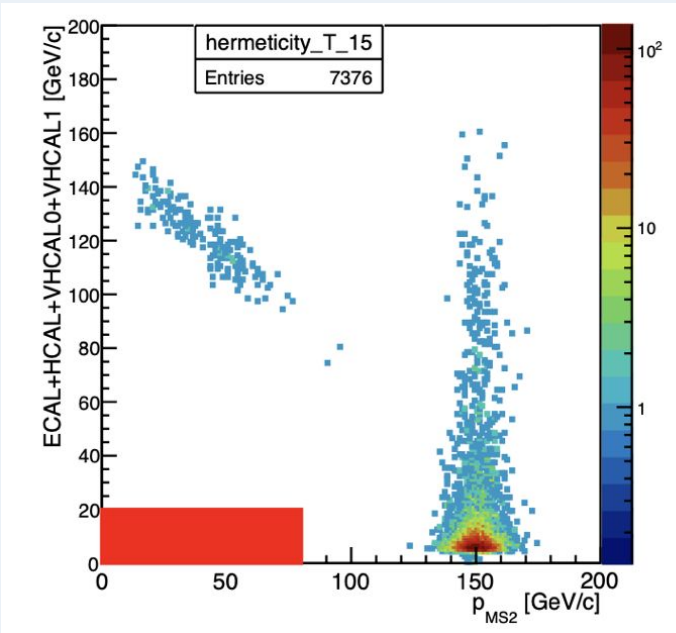
- 1.5×10^{11} MOT collected with improved setup
- Preliminary analysis with 1.3×10^{9} MOT (10% of data without ECAL) highlights the key role of MS1

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

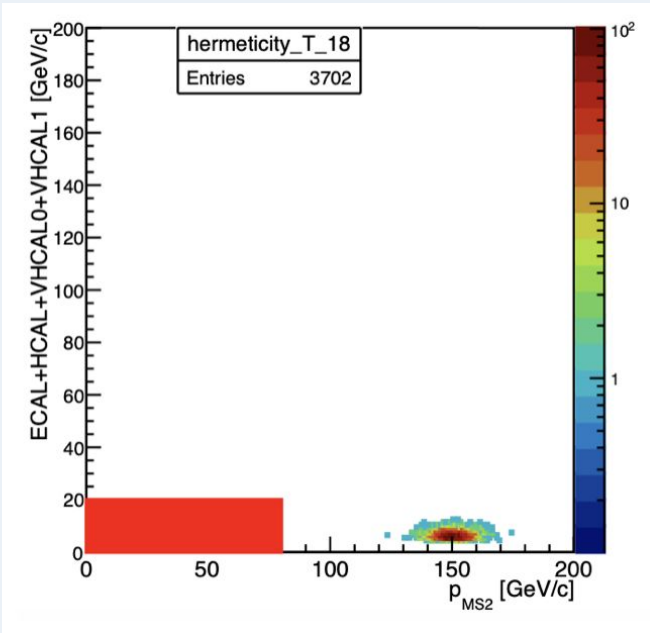
Initial distribution



Events after MS1



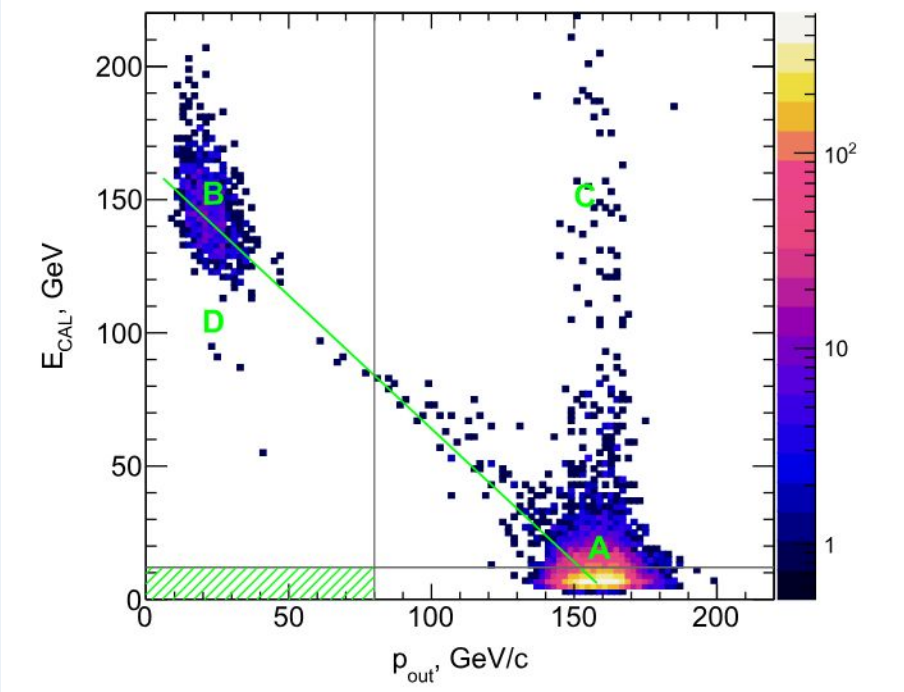
Events after all cuts



Results from physics trigger runs without ECAL in 2023

NA64μ: Lessons learned

No signal events observed in 2x10^{10} MOT!



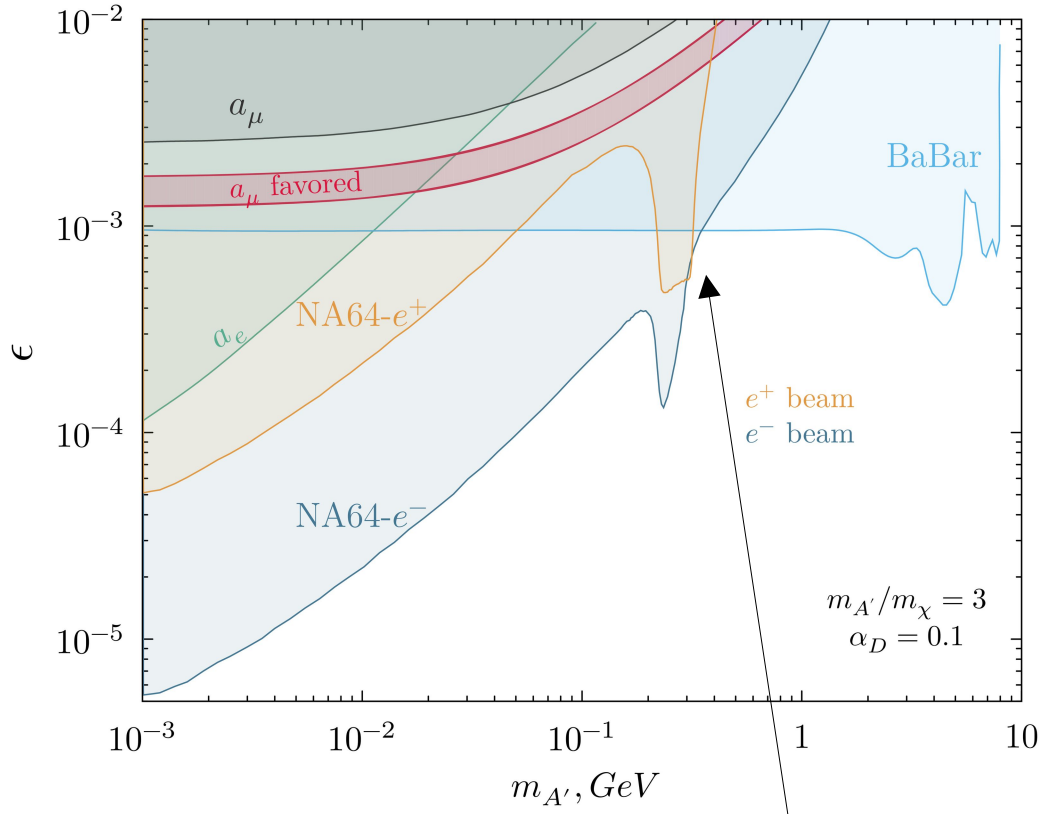
Background source	Background, n_b
(I) Momentum misreconstruction	0.05 ± 0.03
(II) $K \to \mu + \nu, \ldots$ in-flight decays	0.010 ± 0.001
(III) Calorimeter non-Hermiticity	< 0.01
Total nb (conservatively)	0.07 ± 0.03

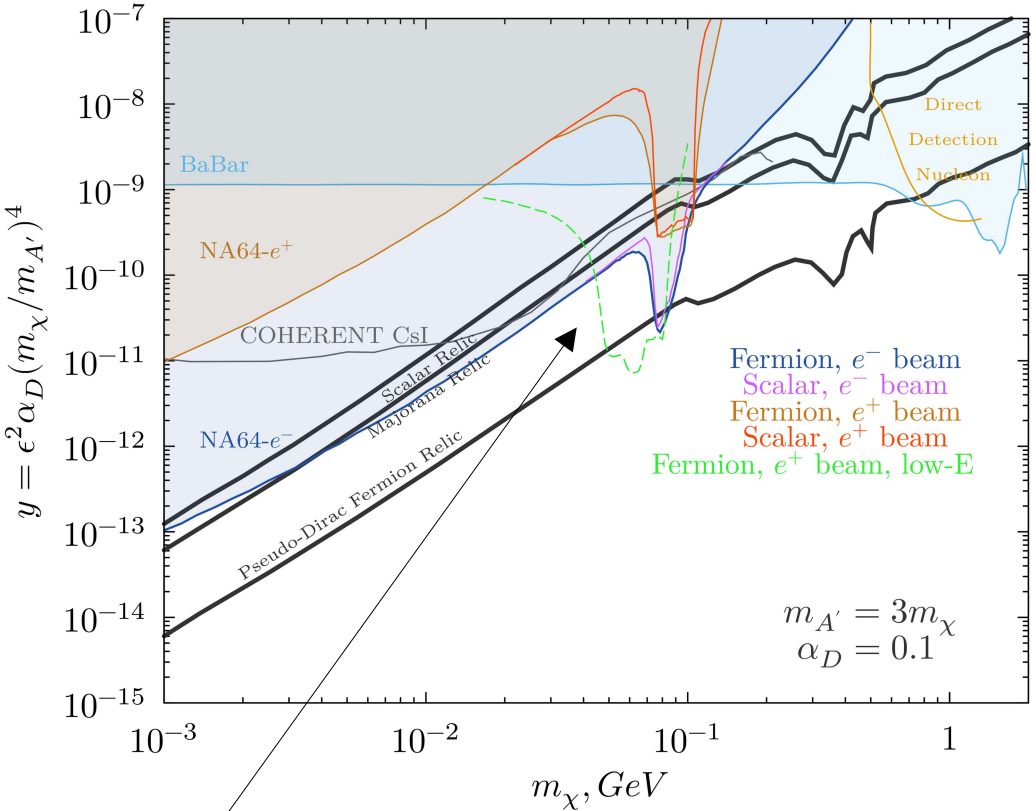
The results from 2022 demonstrate the technique and drive the upgrades for the next phase

Main challenges:

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

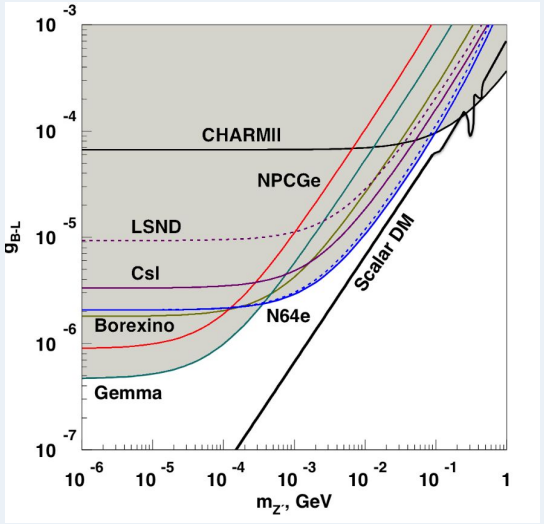
NA64e⁺: Latest results with 2022 run





Enhanced sensitivity through resonant annihilation production

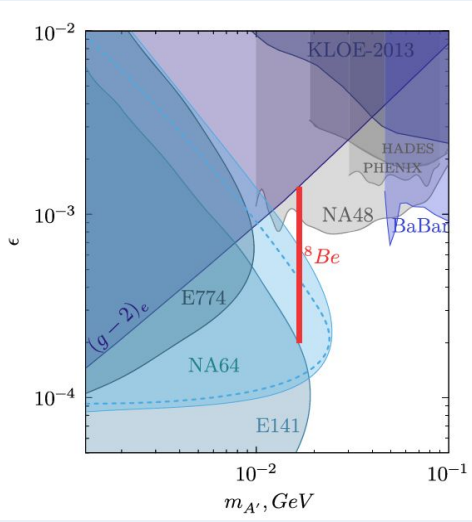
The extended NA64 physics program



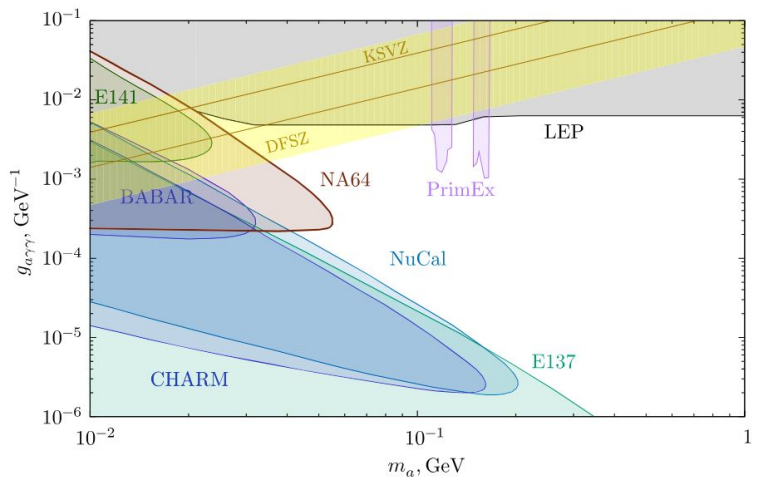
B-L model: PRL 129, 161801 (2022)

Comprehensive search for BSM physics

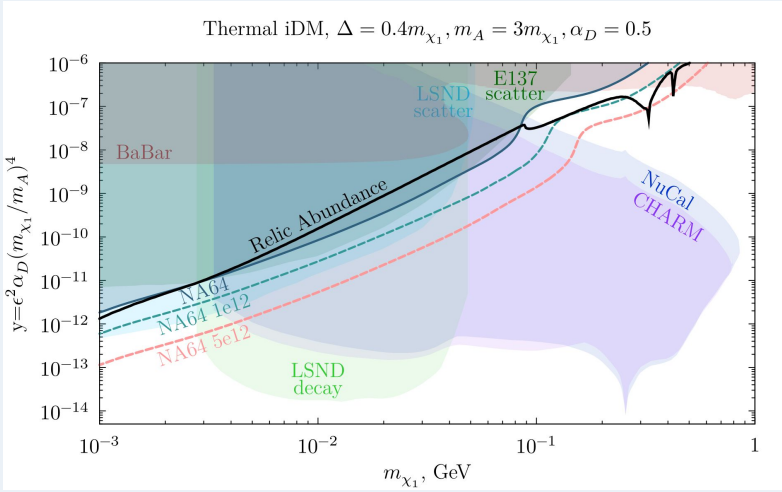
- ALP particles, light scalars
- B-L Z' models → Complementary to ν-scattering experiments
- Visible A' models → X17 anomaly from Atomki ^{8}Be measurement
- Inelastic LDM models with semi-visible signatures



X17 anomaly: PRD 107, 071101R (2020)



ALPs: PRL 125, 081801 (2020)



Inelastic DM: EPJC 83, 391 (2023)