Exploring dark sectors at the NA64 experiment

Workshop on Multi-front Exotic phenomena in Particle and Astrophysics

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on behalf of the NA64 Collaboration

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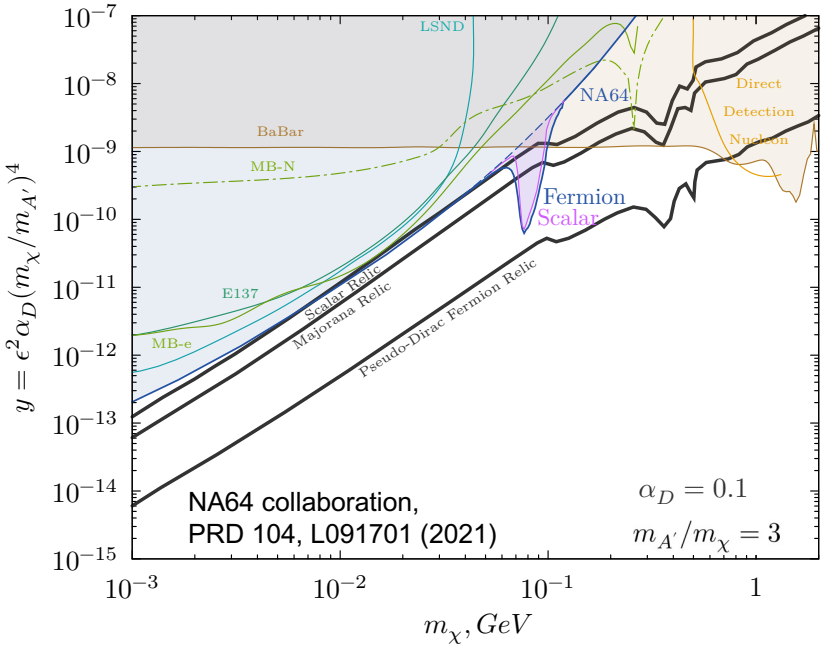
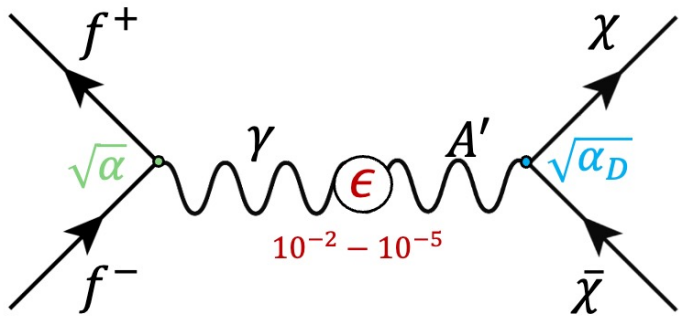
LIGHT THERMAL DARK MATTER

Renormalizable portals to dark sectors:

- Vector portal → dark photon
- Scalar portal → dark Higgs
- Fermion portal → heavy neutral leptons

NA64 main motivation: sub-GeV thermal dark matter





$$\mathcal{L}_{DP} = \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu \left(g_D \mathcal{J}^\mu_{DS} - e\varepsilon \mathcal{J}^\mu_{EM} \right)$$

DM abundance

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \approx 0.24$$

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

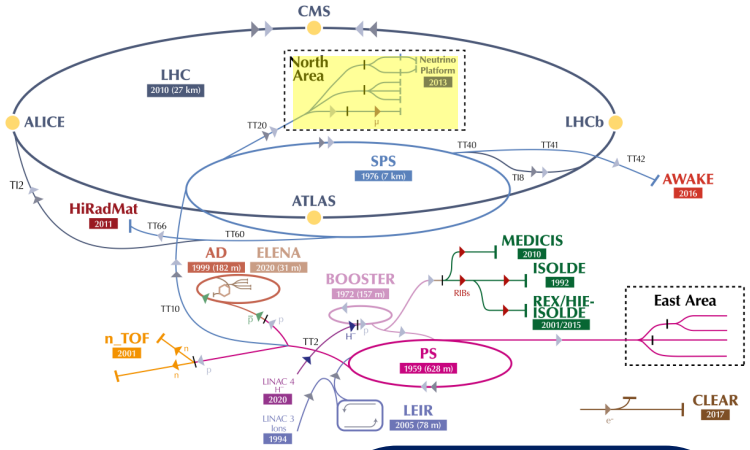
Free parameters:

$$m_{A'}, m_\chi, \epsilon, \alpha_D = {e_D^2}/{4\pi}$$

THE NA64 PHYSICS PROGRAM

The NA64 experiment:

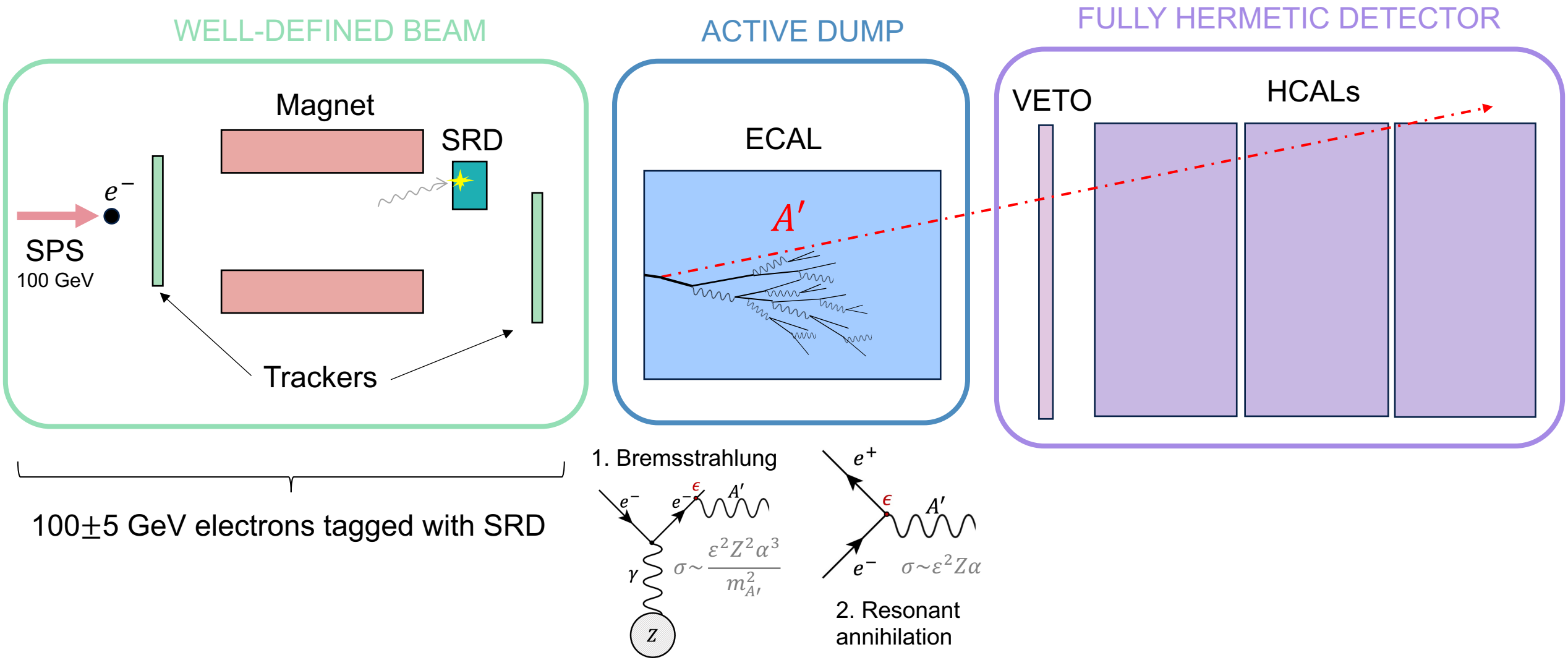
- **Fixed-target** experiment at CERN SPS (intensity frontier)
- Explores **LDM** candidates and **new physics** in the **MeV-GeV** scale
- **Active beam-dump** technique + **missing energy** search



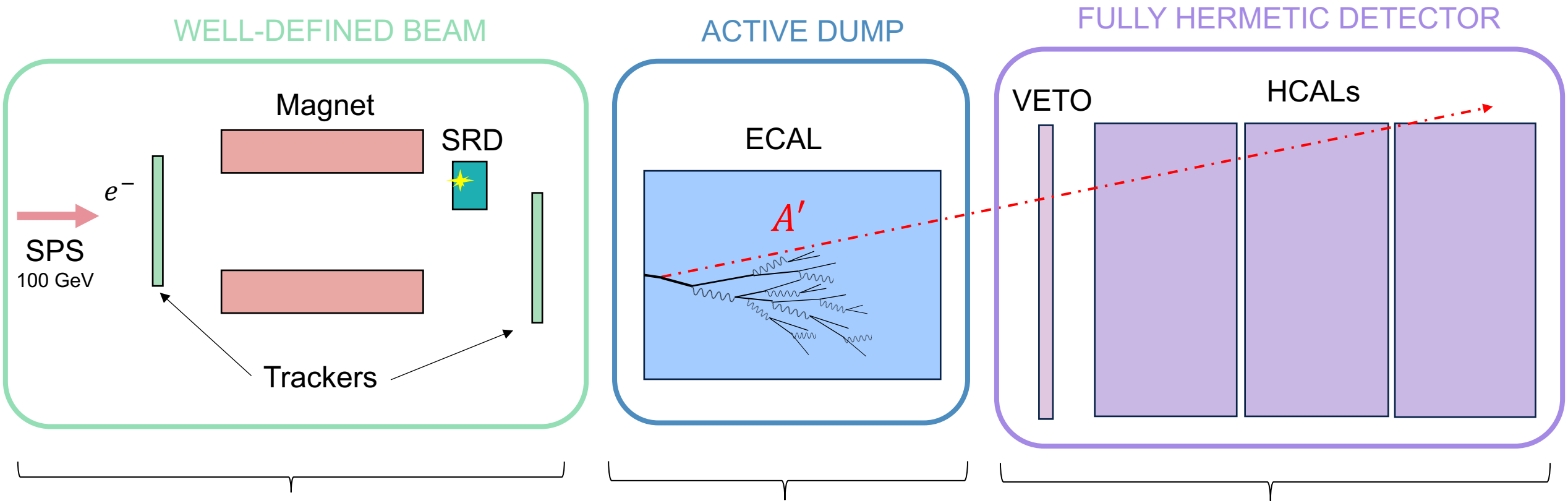
	2016-2018	2021	2022	2023	2024
NA64e invisible	$2.8 \cdot 10^{11}$ EOT	$6 \cdot 10^{10}$ EOT	$6 \cdot 10^{11}$ EOT	$5.1 \cdot 10^{11}$ EOT	$5.2 \cdot 10^{11}$ EOT
NA64e visible	$8.4 \cdot 10^{10}$ EOT				
NA64μ		$5 \cdot 10^{9}$ MOT	$2 \cdot 10^{10}$ MOT	$1.5 \cdot 10^{11}$ MOT	GOAL: $> 1.5 \cdot 10^{11}$ MOT
NA64e$^+$			$1 \cdot 10^{10}$ POT	$1.5 \cdot 10^{10}$ POT	$2.2 \cdot 10^{10}$ POT
NA64h			$2.9 \cdot 10^{9}$ πOT	$1.9 \cdot 10^{10}$ πOT	

TOTAL
~$2 \cdot 10^{12}$ EOT
~$1.8 \cdot 10^{11}$ MOT
~$4.7 \cdot 10^{10}$ POT
~$2 \cdot 10^{10}$ πOT

THE NA64 TECHNIQUE - e^- SETUP



THE NA64 TECHNIQUE - A' SIGNATURE



100±5 GeV electrons tagged with SRD

ECAL energy < 50 GeV

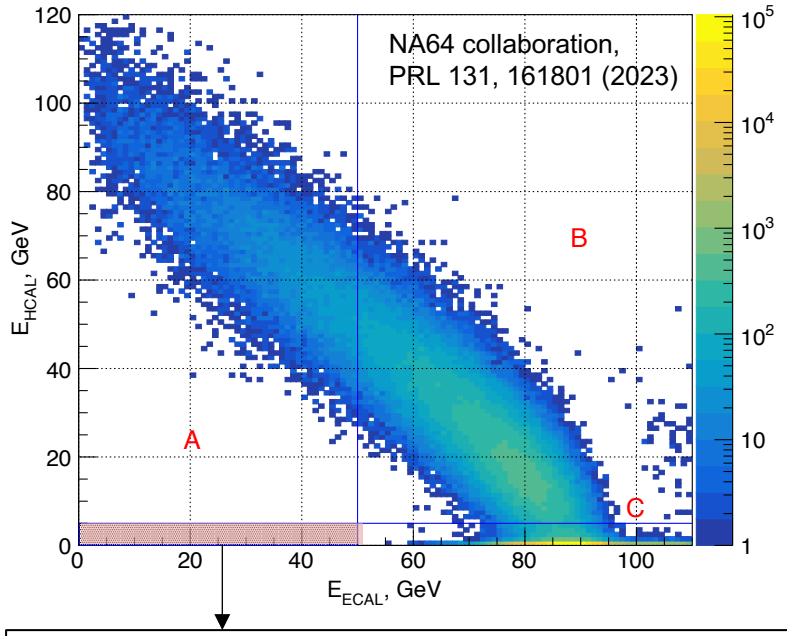
No activity in VETO and HCALs

Missing E → Dark photon candidate

→**Sensitivity** $\propto \varepsilon^2$
(beam dumps: $\varepsilon^4 \alpha_D$)

NA64e^- RESULTS

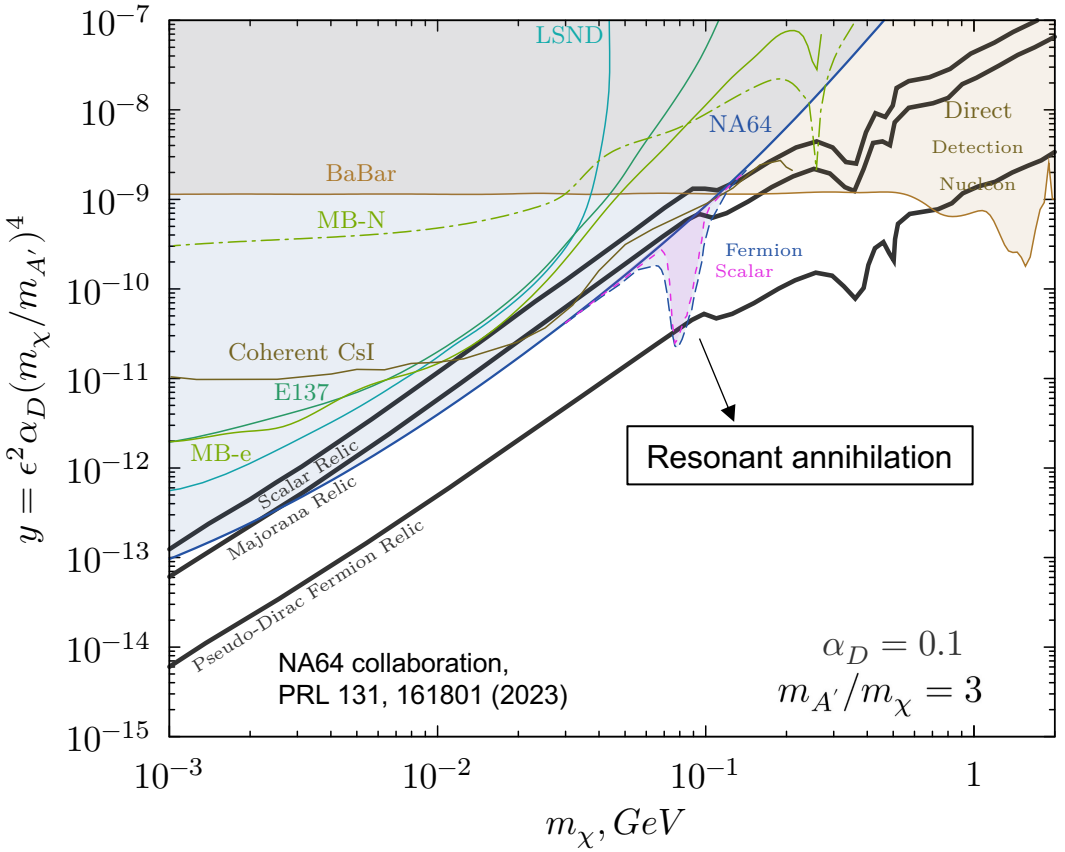
Combined statistics 2016-2022: **$9.4 \cdot 10^{11}$ EOT**
→ Unblinded data in E_{ECAL} vs E_{HCAL} plane:



Signal region: $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV

After unblinding:
no events in signal box

90% C.L. exclusions

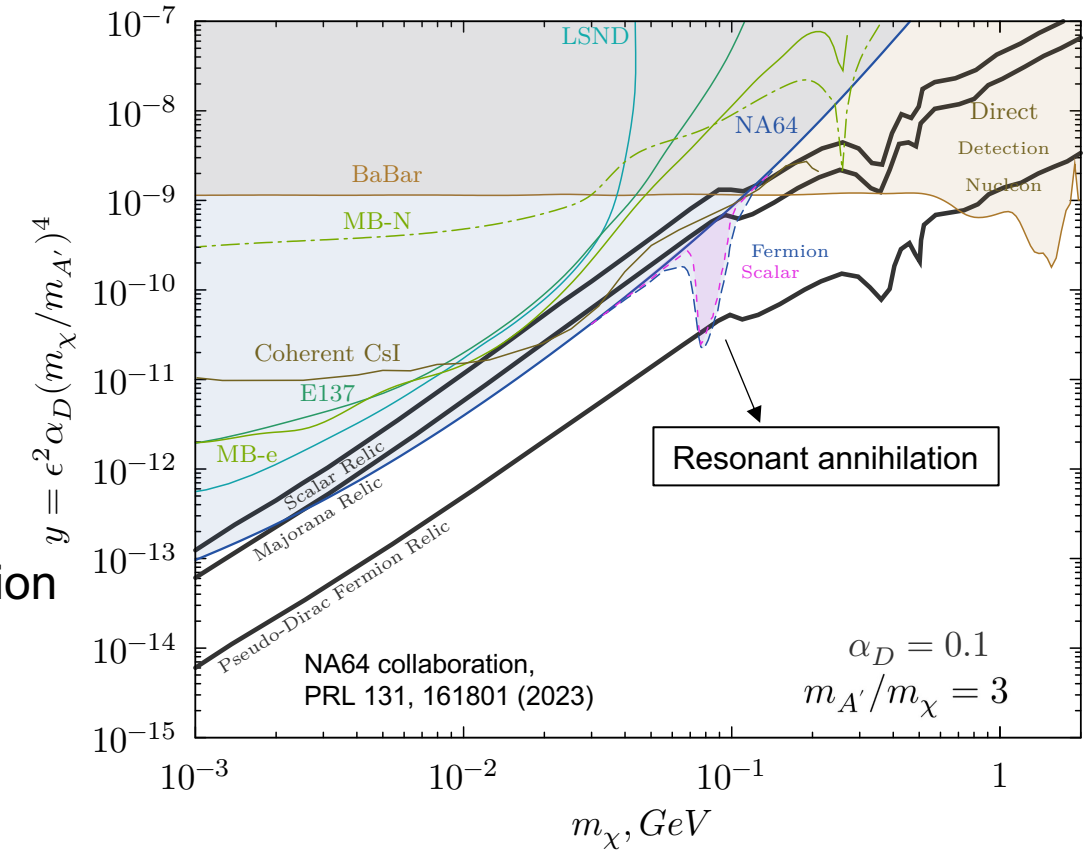


NA64 places the most stringent limits in the thermal LDM parameter space
→ Majorana and scalar scenarios excluded up to ~0.1 GeV

NA64e^- RESULTS

TABLE I. Expected background for 2021–2022 runs.

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



Setup improvements:

- **Veto Hadronic CALorimeter** (VHCAL) prototype addition
  → improve hermeticity
- **Lyso-based SRD** with lower SR threshold
  → reduce μ, π, K contaminants

New data collected during 2023+2024: $\mathbf{1.3 \cdot 10^{12}}$ **EOT → analysis ongoing**

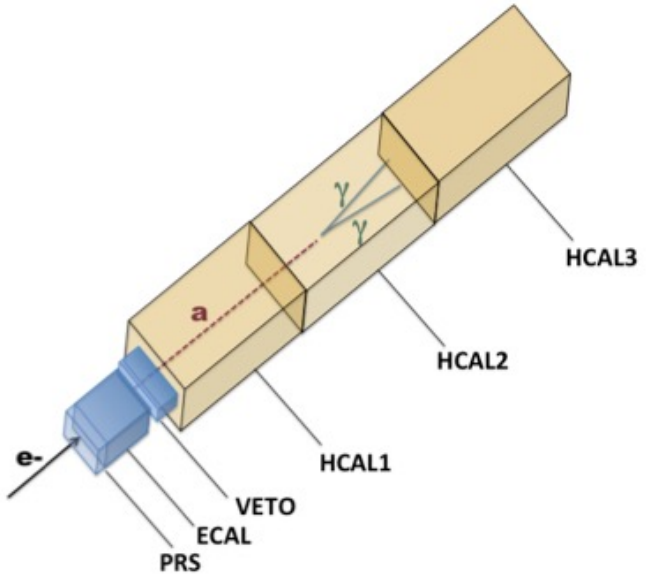
OTHER NEW PHYSICS SEARCHES

Result extension to other new physics cases, e.g.:

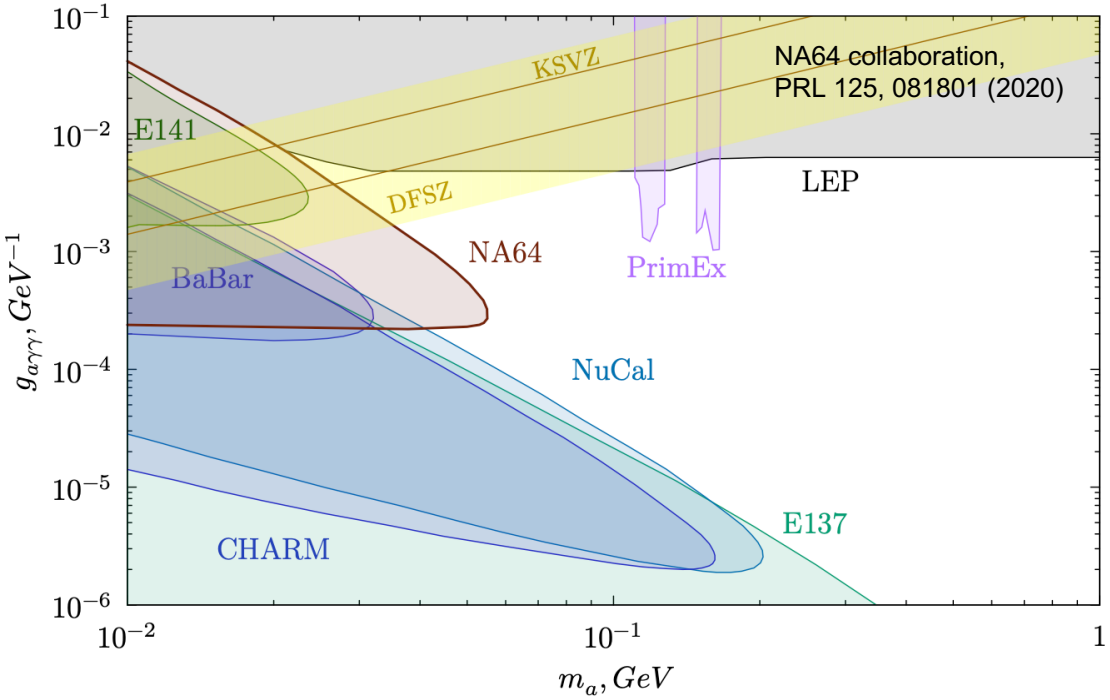
- **Axion-Like Particles (ALPs)**

Exploiting both *visible* & *invisible* signatures:

- $a \to \gamma\gamma$ decay beyond setup → **missing energy**
- $a \to \gamma\gamma$ decay in HCALs → **displaced vertex**



ALPs: $a \to \gamma\gamma$ search, *invisible* and *visible* events
(2016-2018 statistics: $2.84 \cdot 10^{11}$ EOT)

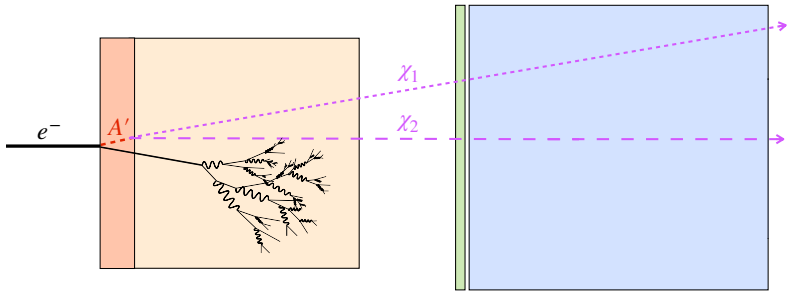


OTHER NEW PHYSICS SEARCHES

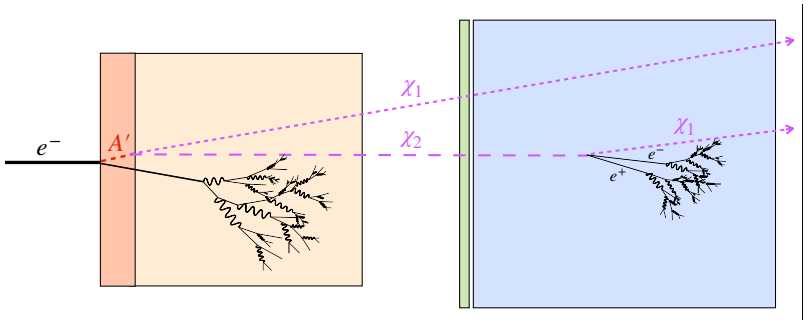
Result extension to other new physics cases, e.g.:

- Axion-Like Particles (ALPs)
- **Inelastic Dark Matter (iDM)**

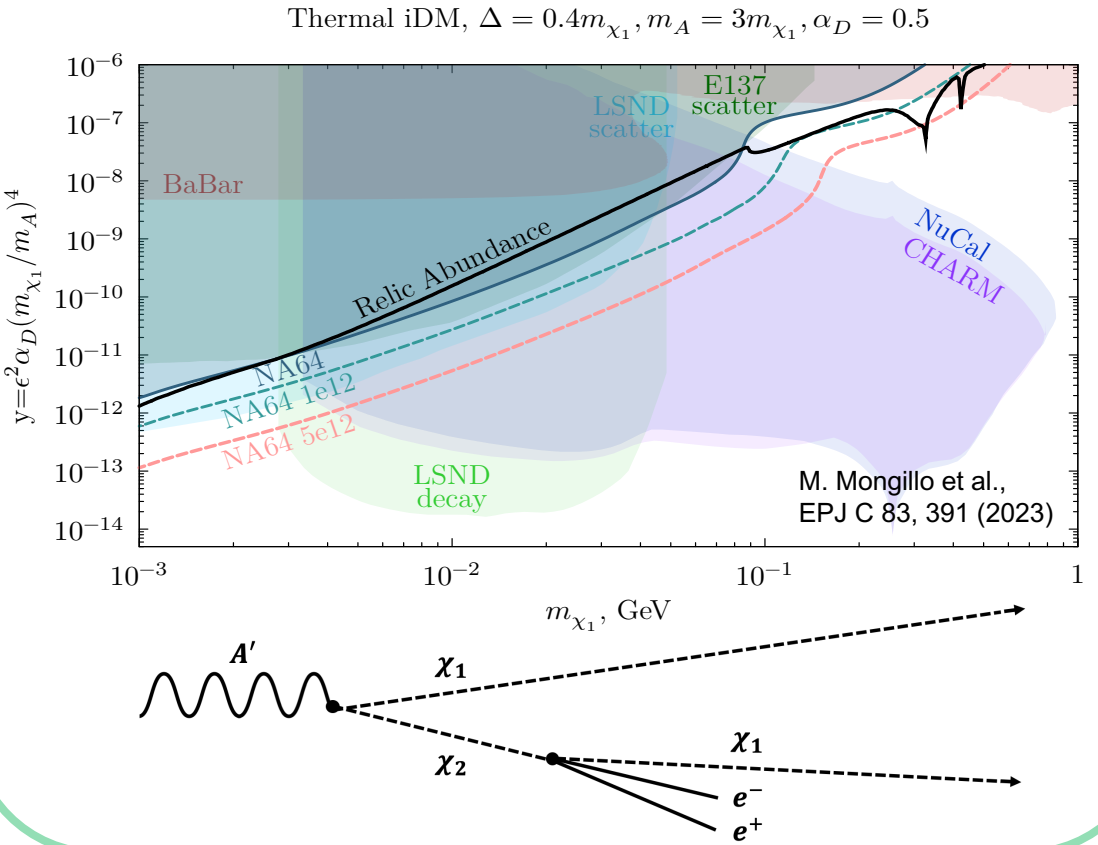
Exploiting only *invisible* signatures:



Analysis on *visible* signatures ongoing:



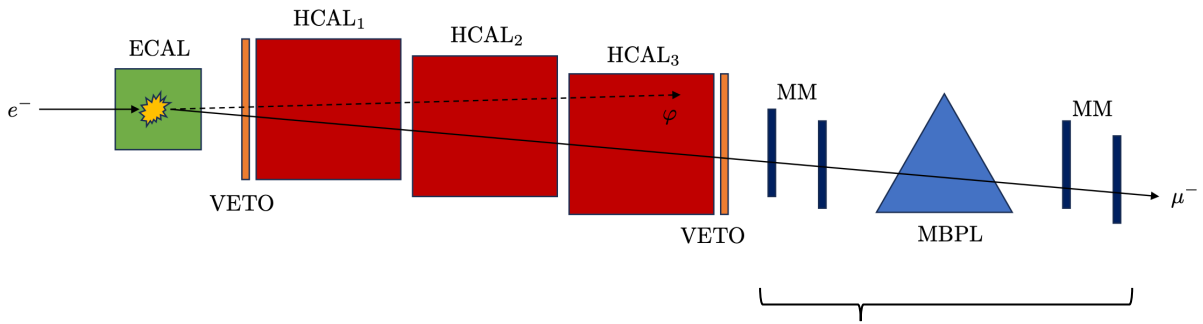
iDM: recast limits from *invisible A′* analysis
(2016-2018 statistics: $2.84 \cdot 10^{11}$ EOT)



OTHER NEW PHYSICS SEARCHES

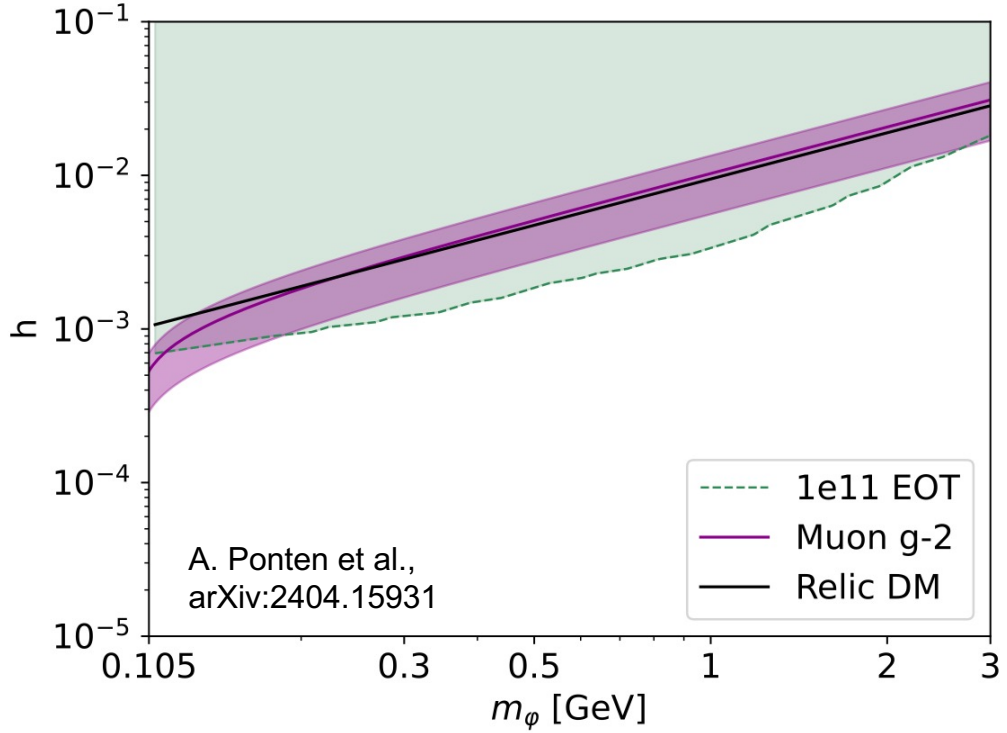
Result extension to other new physics cases, e.g.:

- Axion-Like Particles (ALPs)
- Inelastic Dark Matter (iDM)
- **Lepton Flavour-Changing scalar φ (LFC)**



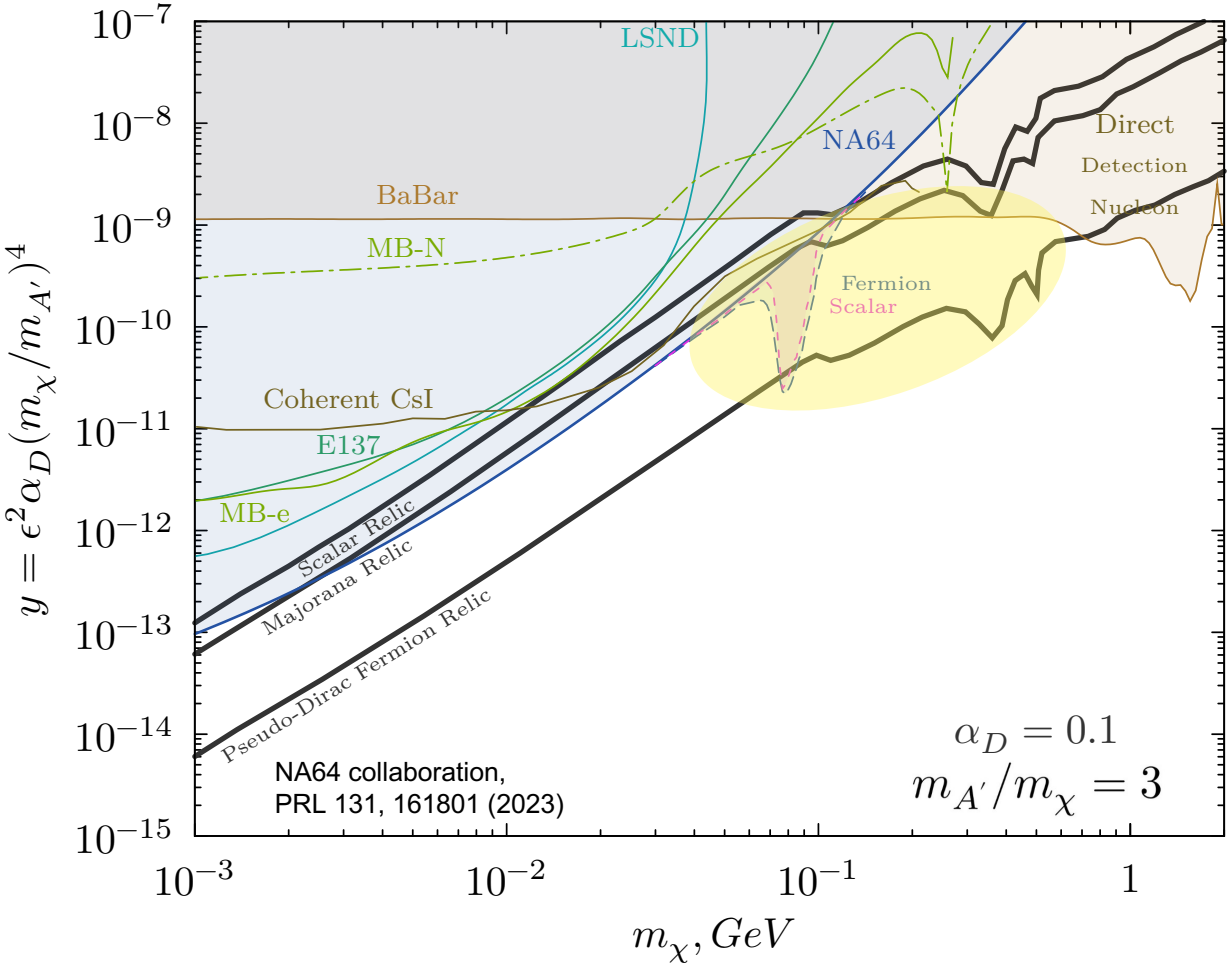
Additional spectrometer

LFC scalar: sensitivity study $eN \rightarrow \mu N\varphi$
(statistics: $1 \cdot 10^{11}$ EOT)



NA64 COMPLEMENTARY SEARCHES

NA64e^- results, 2016-2022 data, invisible A'



A'-bremsstrahlung production scales as $1/m_{A'}^2$

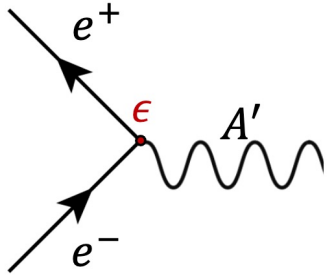
→ suppressed signal yield at higher A' masses

How to enhance the sensitivity at higher masses?

1. Using e^+ **beam** → resonant A' production
2. Using μ **beam** → radiative A' production

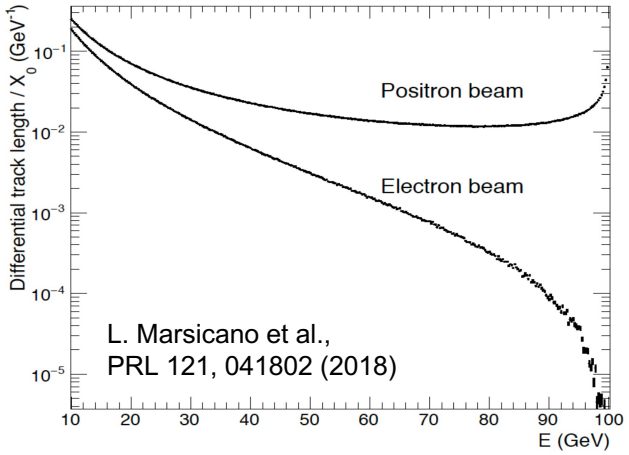
NA64 EXPLORATION WITH e^+ BEAM

Resonant e^+e^- annihilation in A':

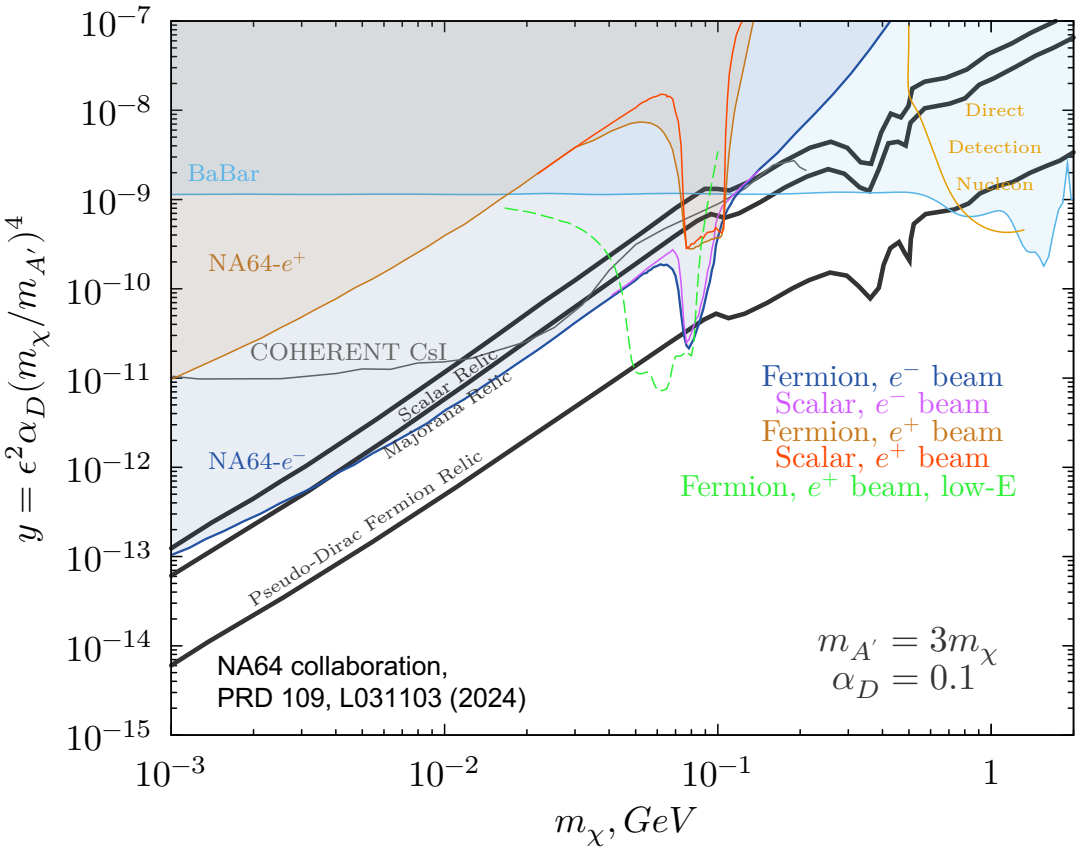


- Breit-Wigner-like $\sigma \sim \varepsilon^2 Z\alpha$ peaked at $m_{A'}^2 = 2m_e E_{e^+}$
- Signal enhancement in region:
$\sqrt{2m_e E_{thr}} < m_{A'} < \sqrt{2m_e E_0}$

e^+ beam: enhanced sensitivity in resonant region



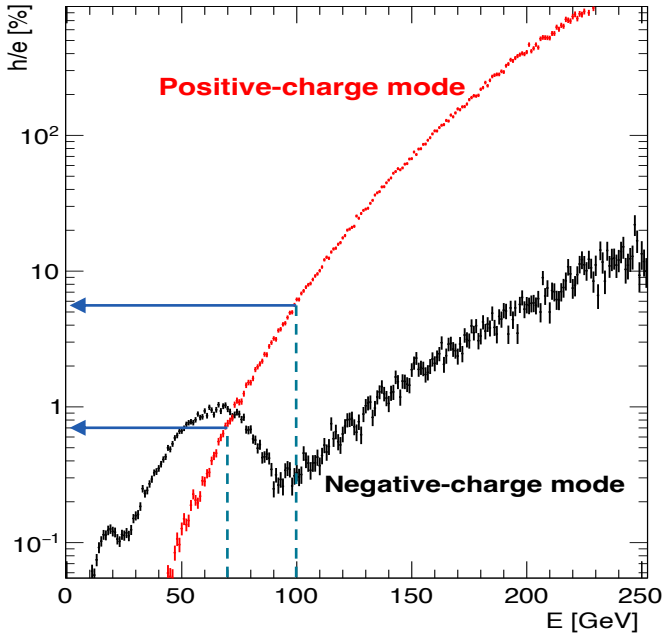
NA64e^+ results, 2022 pilot run
10^{10} POT, 100 GeV



NA64 EXPLORATION WITH e^+ BEAM

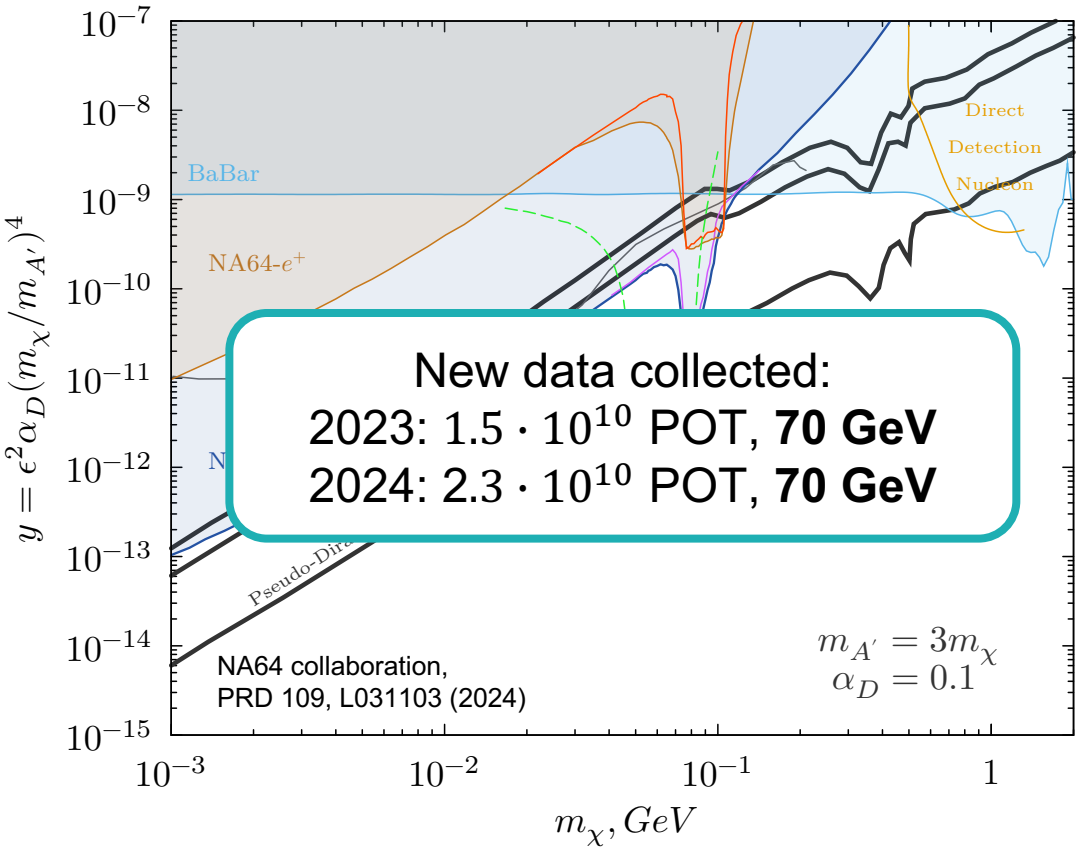
Main challenge at 100 GeV: higher hadronic background due to $\Lambda \to p\pi^-$

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



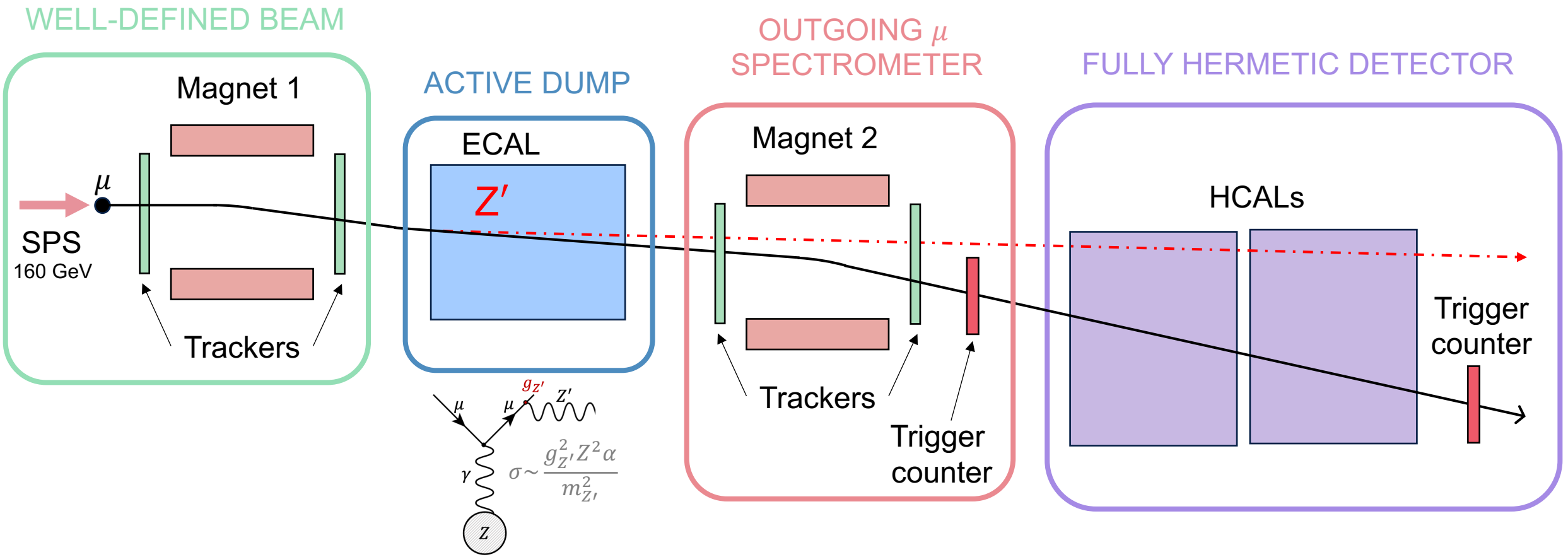
- New **lyso-SRD** prototype tested in 2024 run and added in trigger
- Collected data with **different beam energies** to scan the parameter space

NA64e^+ results, 2022 pilot run
10^{10} POT, 100 GeV



New data collected:
2023: $1.5 \cdot 10^{10}$ POT, **70 GeV**
2024: $2.3 \cdot 10^{10}$ POT, **70 GeV**

NA64 EXPLORATION WITH μ BEAM



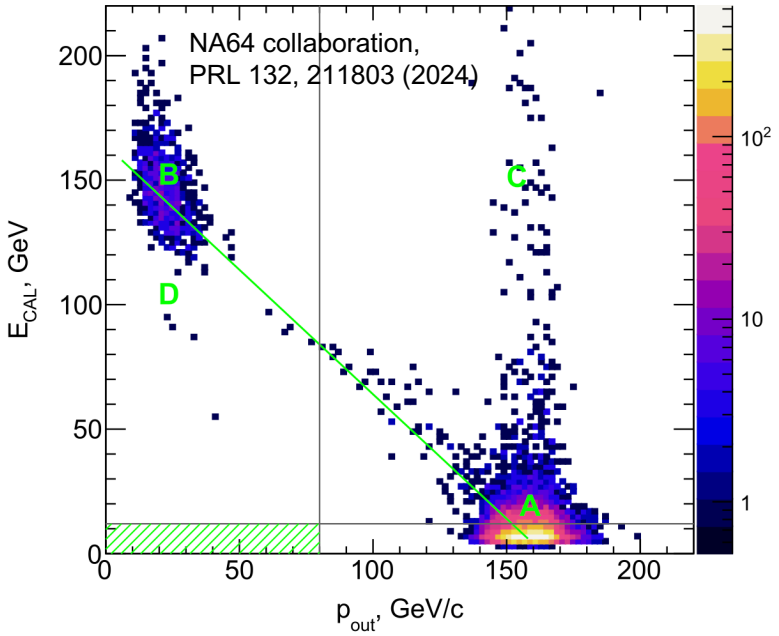
Incoming momentum:
160±20 GeV

Measured energy + momentum < 80 GeV
MIP in ECAL and HCALs

→ Dark Z event

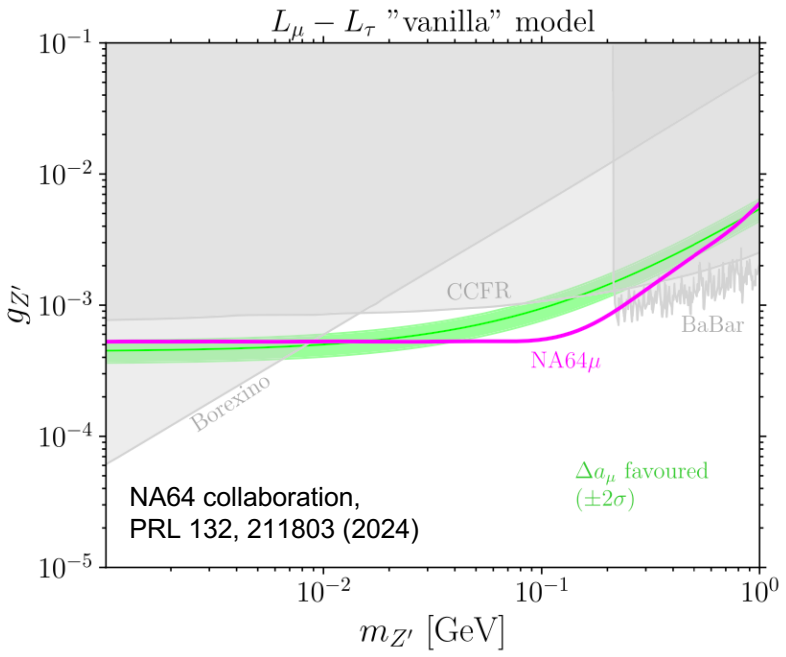
NA64 EXPLORATION WITH μ BEAM

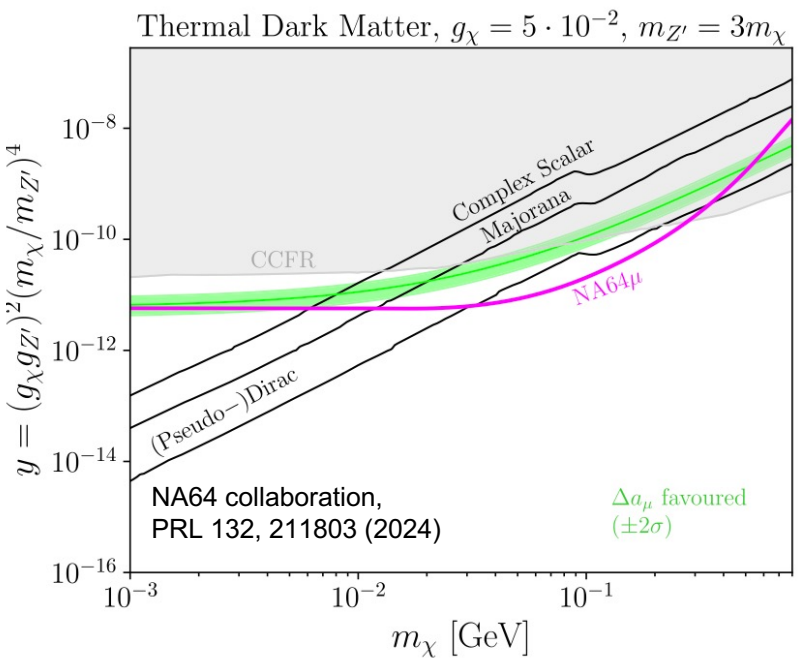
Statistics 2022 data: **$2 \cdot 10^{10}$ MOT**
→ Events in E_{CAL} vs outgoing momentum plane:



No signal event was observed yet!

→ 90% C.L. exclusion limits on benchmark model $L_\mu - L_\tau$:

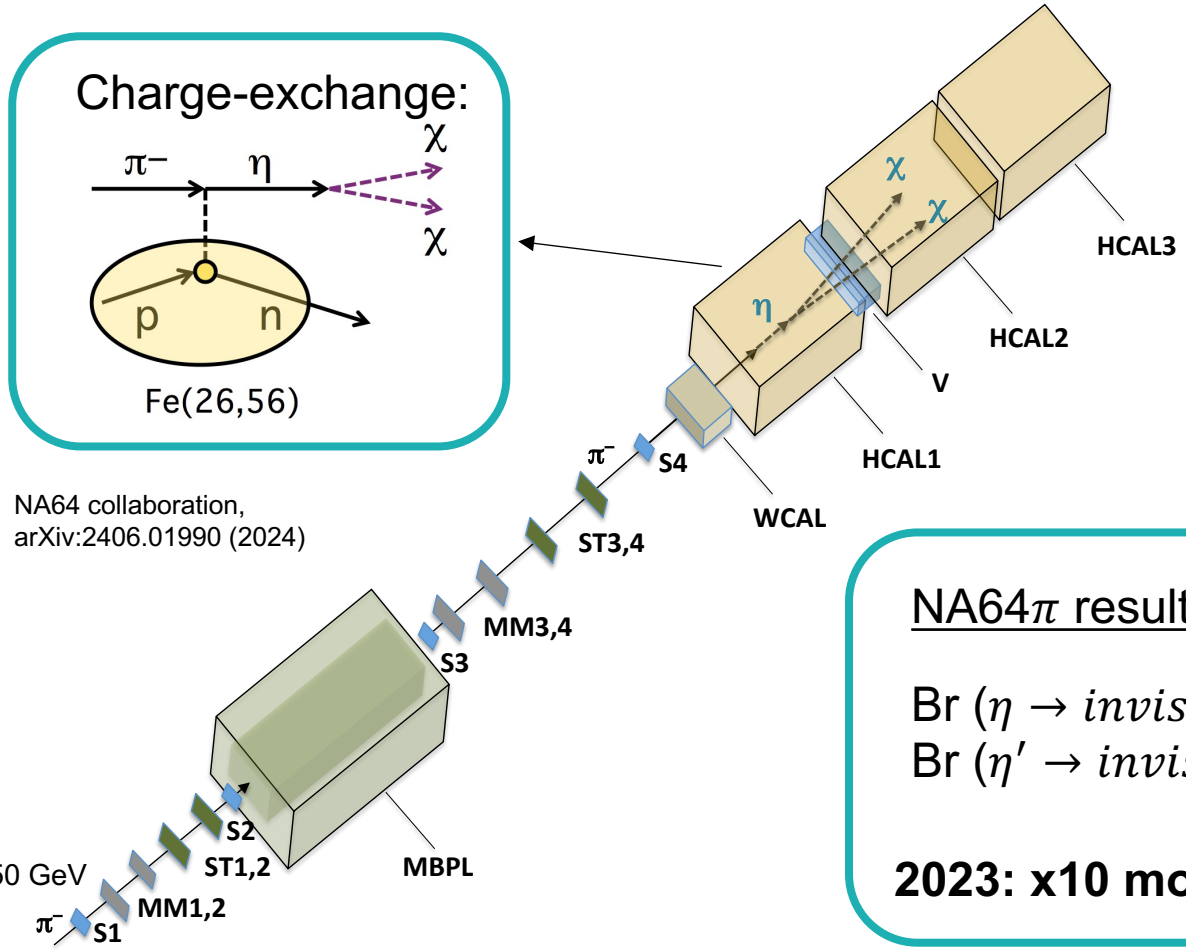




New data collected in 2023: **$1.5 \cdot 10^{11}$ MOT** (x10 more statistics)
→ 2024: additional **~50 days** of beam-time starting in 2 weeks

NA64 EXPLORATION WITH HADRON BEAM

Very small rate for $\pi^0, \eta, \eta', K_L, K_S, \rightarrow \nu\bar{\nu}$ decays in the **SM** → Observation of these invisible decays would hint at **New Physics**



NA64 collaboration, arXiv:2406.01990 (2024)

Signature:

- MIP in WCAL (from π^-)
- Missing energy in HCALs (C.E. and $\eta, \eta' \rightarrow$inv.)

Main background: decays from kaon contaminants in the pion beam ($K^- \rightarrow \mu^- \bar{\nu}_\mu$)

NA64π results, 2022 data, $2.9 \cdot 10^9$ 50 GeV πOT	BESIII
Br $(\eta \rightarrow invisible) < 1.1 \cdot 10^{-4}$	$< 1 \cdot 10^{-4}$
Br $(\eta' \rightarrow invisible) < 2.1 \cdot 10^{-4}$	$< 6 \cdot 10^{-4}$

2023: x10 more statistics collected (40 GeV) → analysis ongoing

OUTLINE AND FUTURE PROSPECTS

Programs: NA64 conducts **4 complementary programs** using different initial beams from SPS

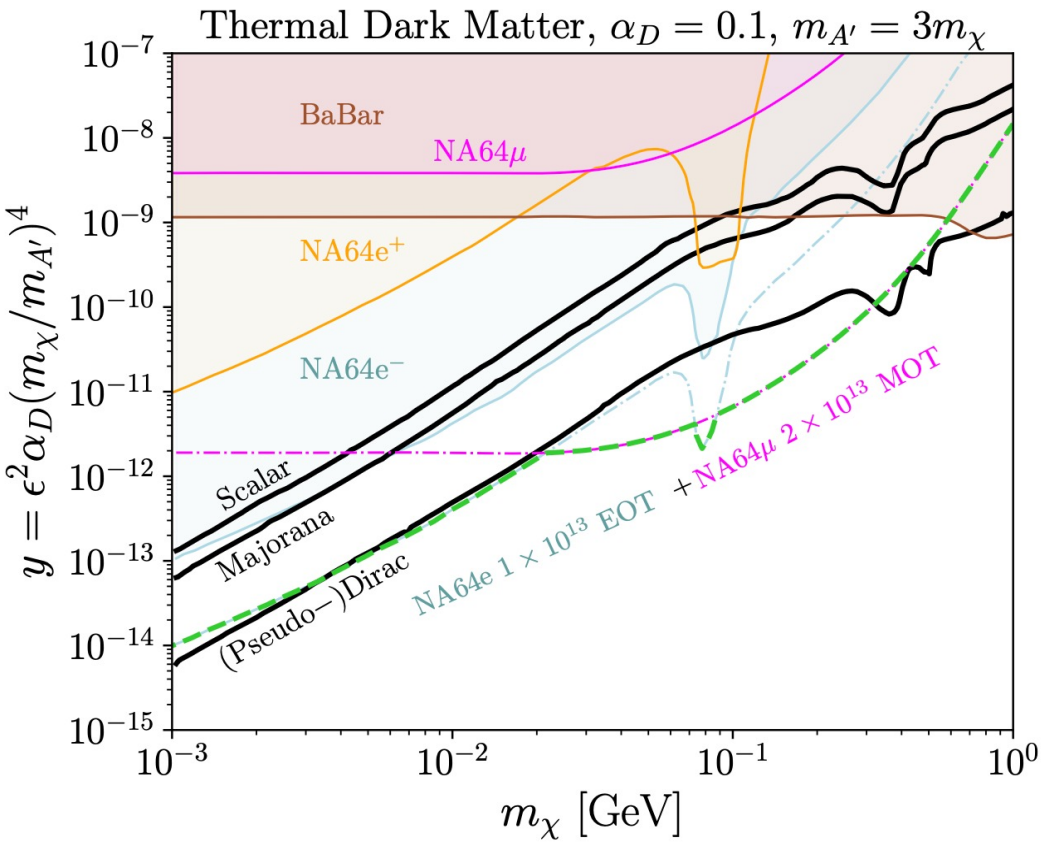
Status**:** Analyses ongoing with **improved setups** and **higher statistics**

Results: **Stringent limits** placed on LDM scenarios and other New Physics models

Planned upgrades during LS3:

- **Faster electronics** (DAQ and tracker readout) to increase beam intensity ($1.5 \cdot 10^7$ e^-/spill and $5 \cdot 10^7$ μ/spill)
- Improved detectors **hermeticity** and **performance**

Exploration goal after LS3



THANK YOU!

Acknowledgments

NA64 collaboration
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IFIC group: L. Molina Bueno, M. Tuzi

BACKUP SLIDES