Latest results from the NA64 experiment

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on behalf of the NA64 collaboration

SUSY 2024, Madrid
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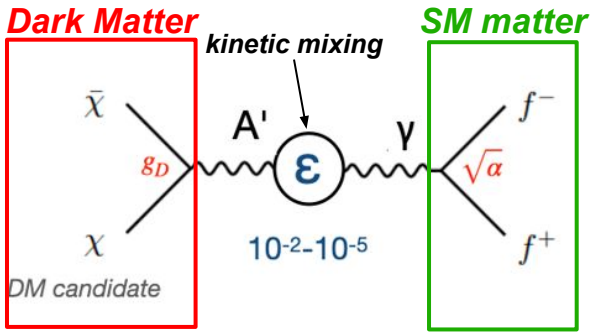
IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA

NA64 target: Light Dark Matter (LDM)

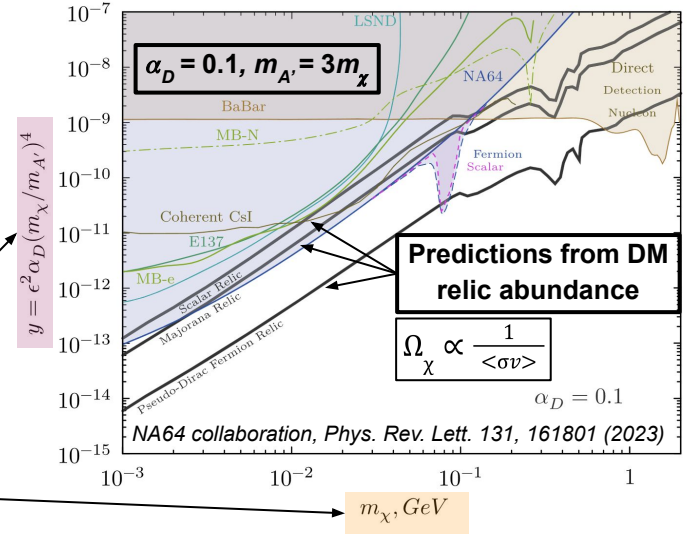
- Aside from gravity, an **additional** force between dark matter (DM) and visible/SM particles may exist
- **Mediator of force**: particles at sub-GeV mass scale, which could decay into dark matter
- Interact **feebly** with SM particles through various mechanisms

example: A' model (dark photon) from new U(1)' symmetry



$$\langle \sigma v(\bar{\chi}\chi(\rightarrow A' *\rightarrow) \bar{f}f) \rangle \propto \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4} = y/m_\chi^2$$

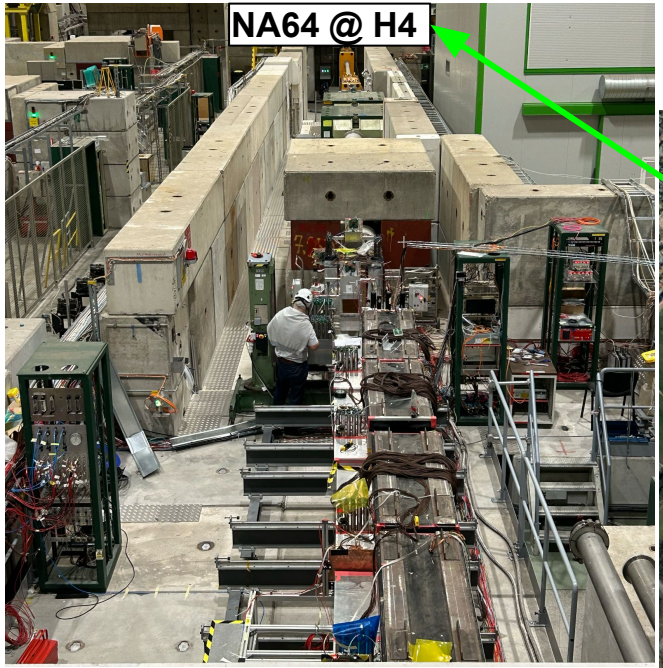
(annihilation rate)

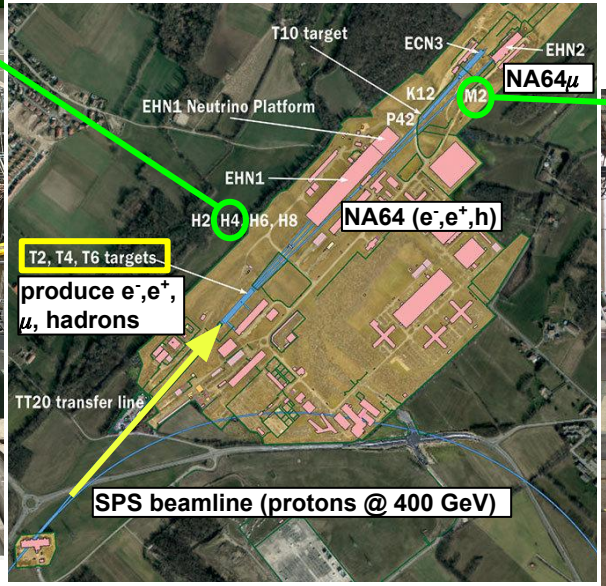


Probe the parameter space (m_χ, y) of LDM models that predict the observed relic DM density!

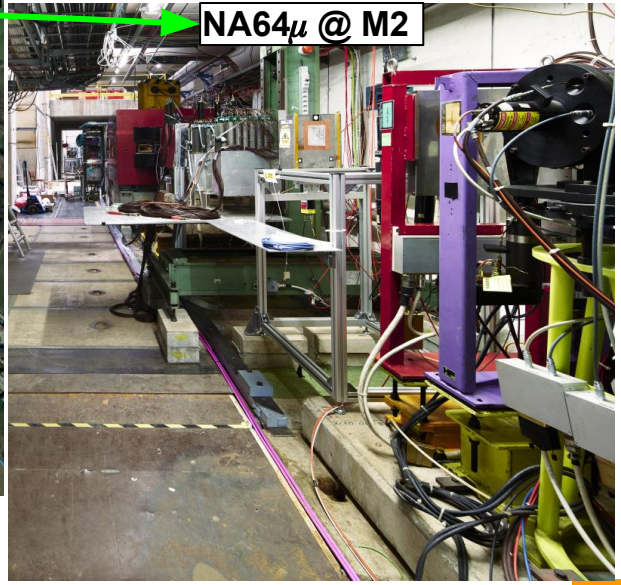
NA64 @ CERN SPS

NA64: a ***fixed target*** experiment at the CERN SPS, probing **LDM candidates** and other **New Physics** (NP) extensions using **electron** (e^-), **positron** (e^+), **muon** (μ) and **hadron** (h) beams.

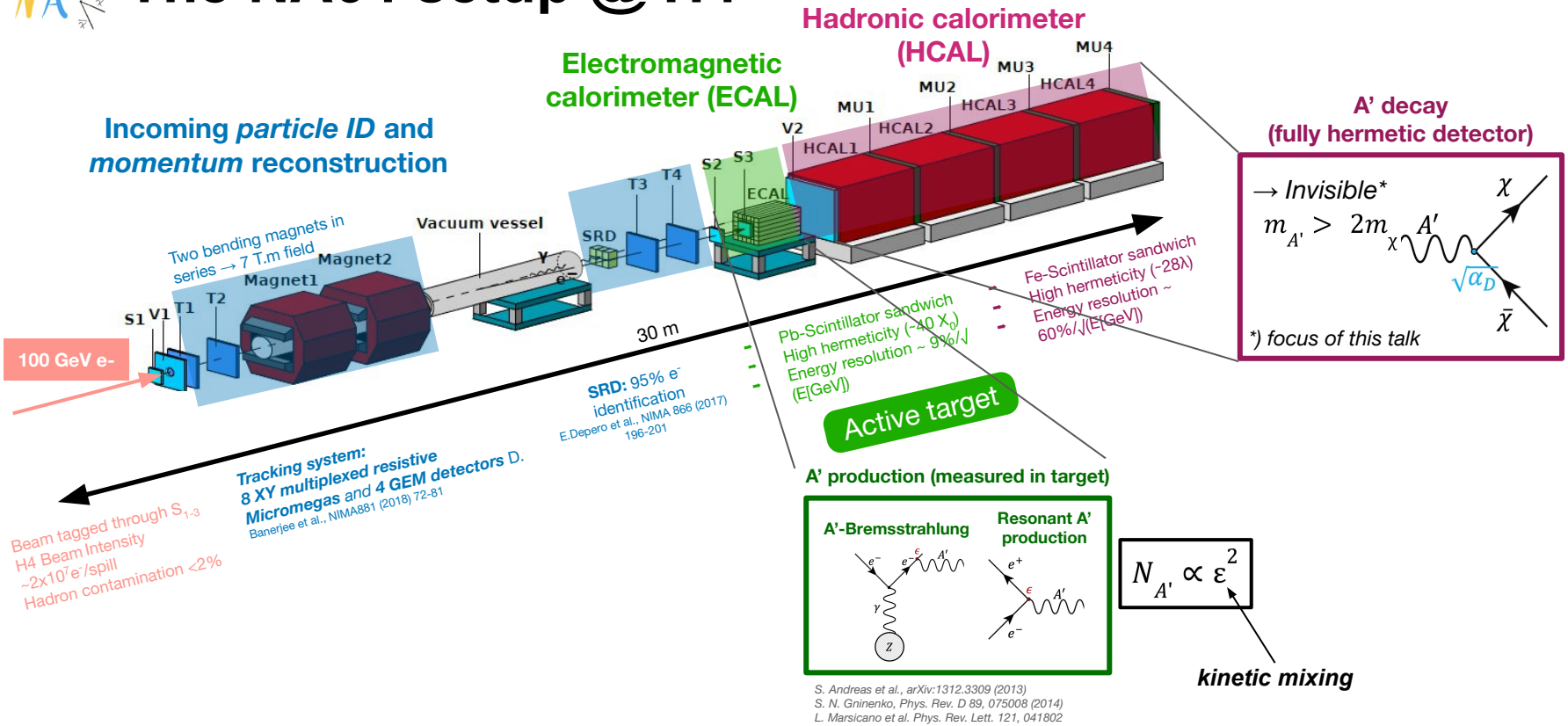




CERN Prévessin site (North Area)



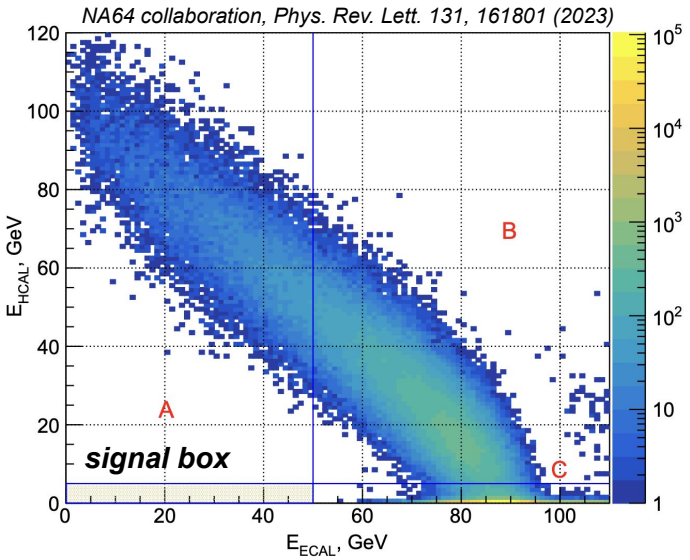
The NA64 setup @ H4



S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)
L. Marsicano et al. Phys. Rev. Lett. 121, 041802

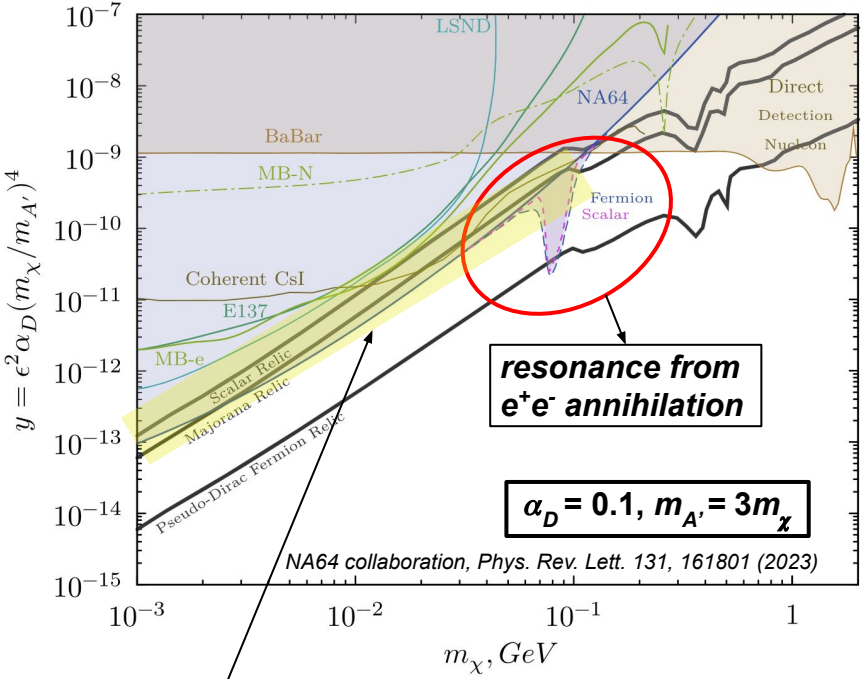
Signal: *Missing energy/momentum*

Current status: NA64e$^-$ @ 100 GeV



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

No signal in 9.37x10^{11} EOT observed



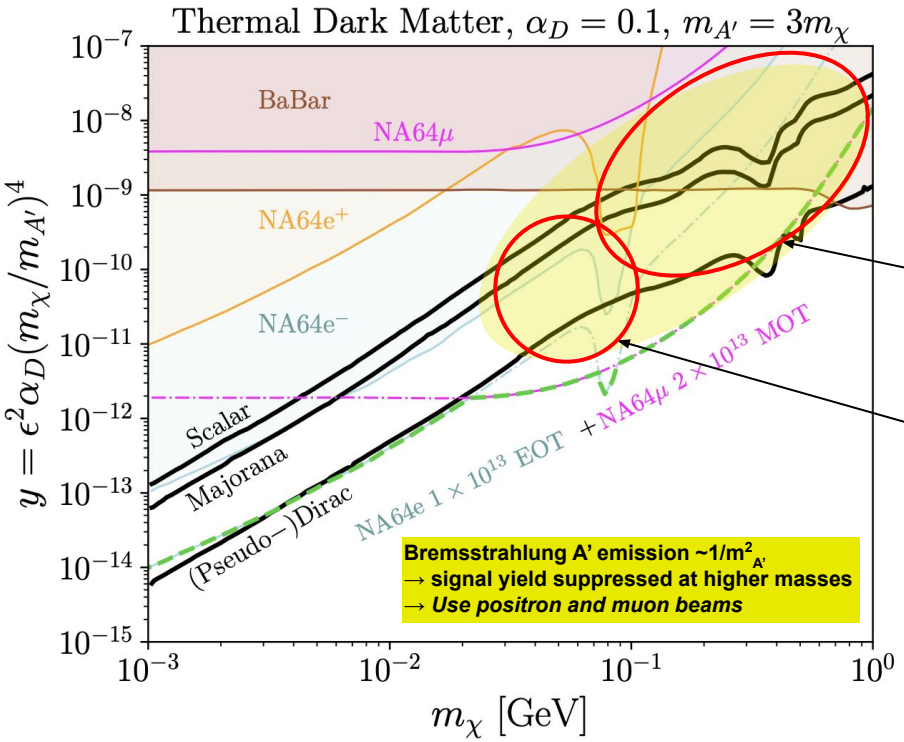
resonance from e$^+$e$^-$ annihilation

$\alpha_D = 0.1$, $m_{A'} = 3m_\chi$

Excludes Majorana and scalar thermal targets for $m_{A'} < 0.1$ GeV → Goal before LS3: collect 3x10^{12} EOT to fully cover these targets

Projected NA64 LDM sensitivity

How can we enlarge the sensitivity at higher masses?

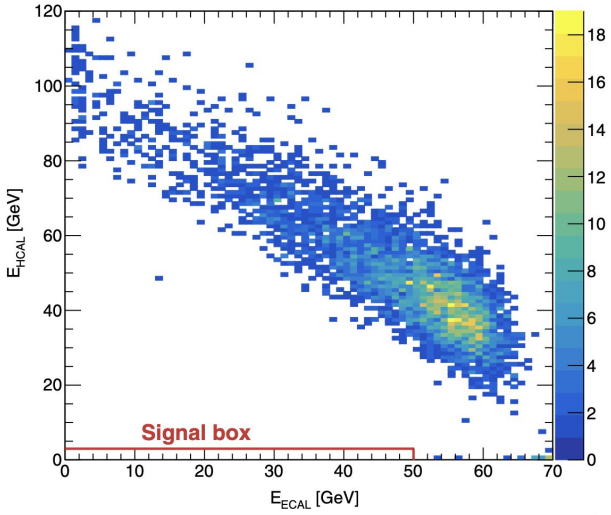


use a muon beam

Positron beam and A' resonant production

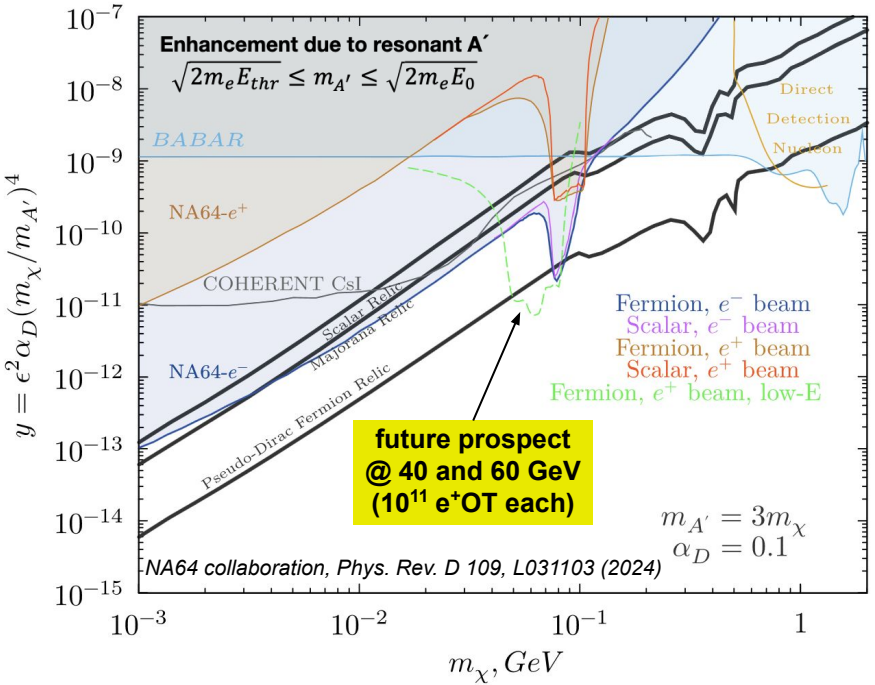
NA64e$^+$ (@ 100 GeV): A' resonance with e$^+$

NA64 collaboration, Phys. Rev. D 109, L031103 (2024)

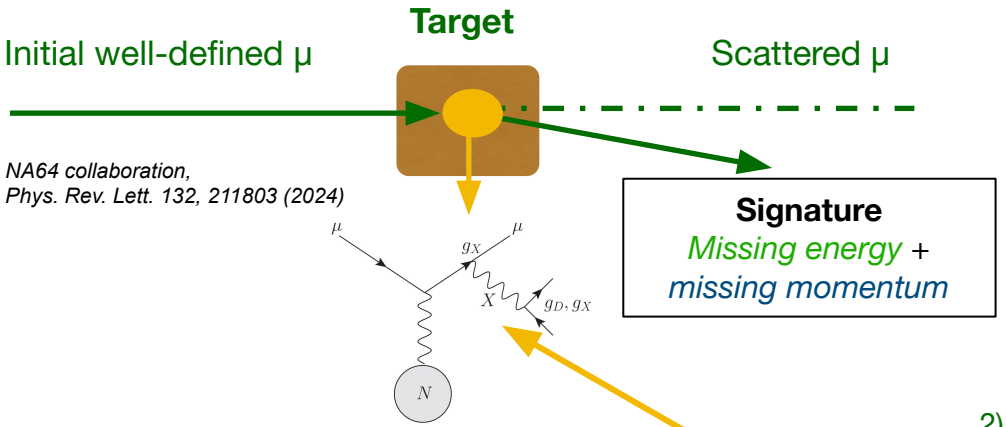


Background source	Background, n_b
(i) π, K decays	(0.06 ± 0.03)
(ii) e^+ hadronic interactions in the beam line	(0.011 ± 0.007)
(iii) dimuons	≤ 0.017
(iv) μ decays	$(1.2 \pm 0.2) \times 10^{-3}$
(v) e^+ hadronic interactions in the target	$\ll 10^{-3}$
(vi) hadrons interactions in the target	$\ll 10^{-3}$
Total n_b (conservatively)	(0.09 ± 0.03)

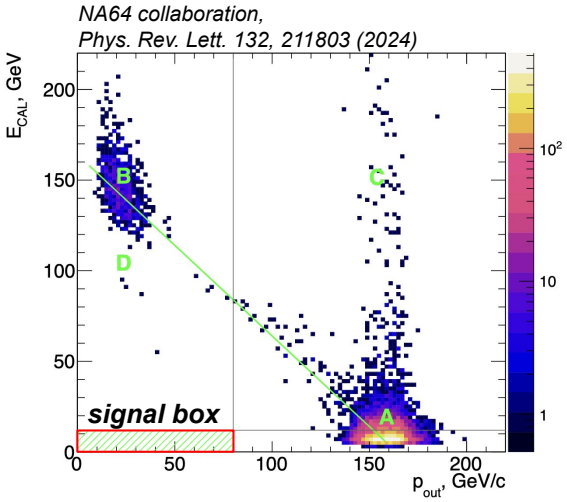
No signal in 1x10^{10} e$^+$OT observed



NA64μ: The signature

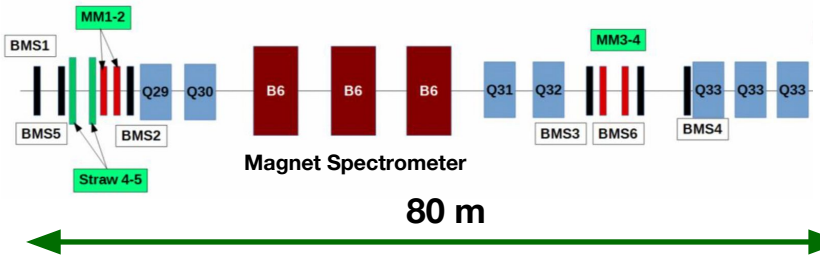


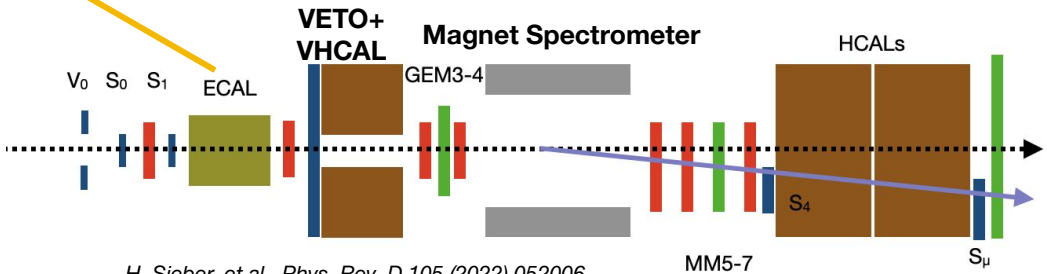
Signature
Missing energy +
missing momentum



2) -Scattered muon with momentum <80 GeV
-MIP energy in ECAL and HCAL
-No activity in VETO and VHCAL

1) Incoming muon momentum @160 GeV





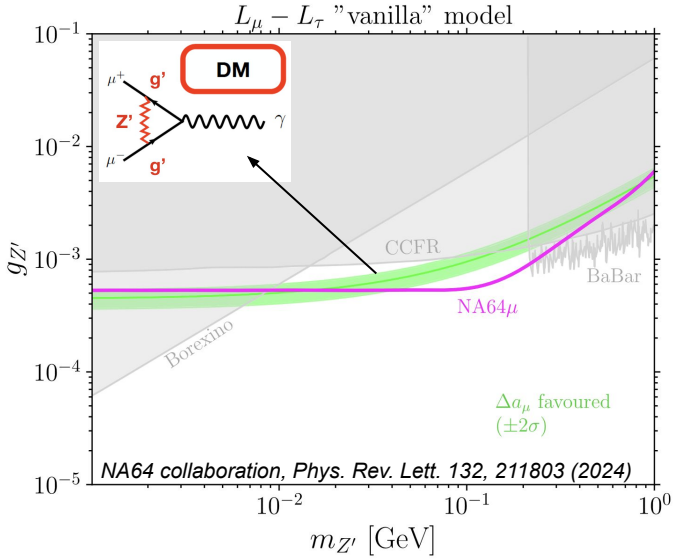
H. Sieber, et al., Phys. Rev. D 105 (2022) 052006
H. Sieber, et al., Phys. Rev. D 108 (2023) 056018

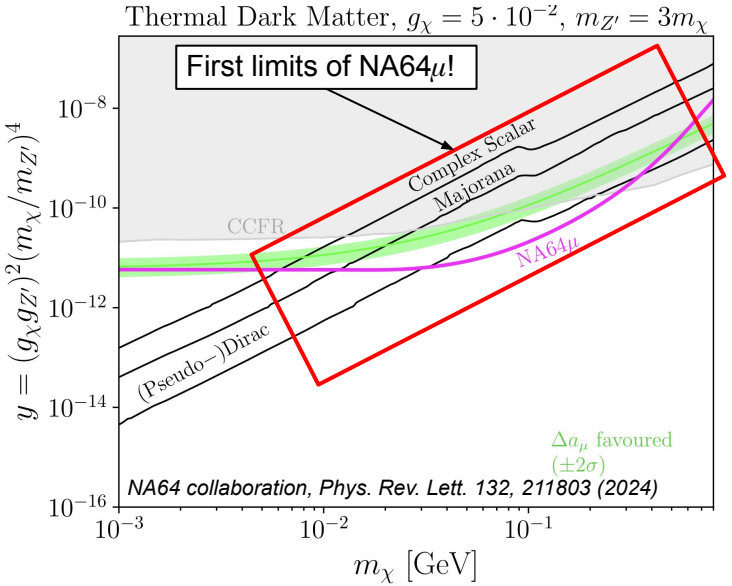
Current status: NA64μ @ 160 GeV

No signal in 1.98x10^{10} MOT observed

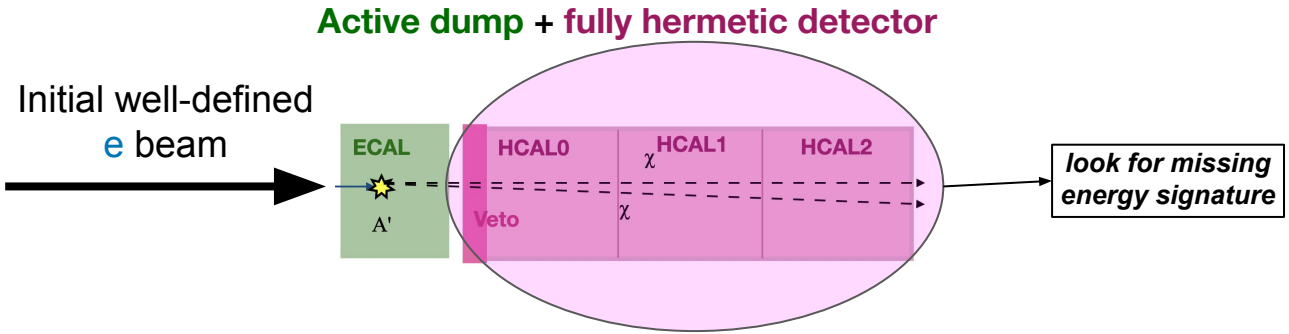
Background source	Background, n_b
(I) Momentum mis-reconstruction	0.05 ± 0.03
(II) $K \to \mu + \nu$, ... in-flight decays	0.010 ± 0.001
(III) Calorimeter non-hermeticity	< 0.01
Total n_b (conservatively)	0.07 ± 0.03

Benchmark model: $L_\mu - L_\tau$ Z'. Exclusion limits for other models to be published soon!





Search for additional NP scenarios: An overview



Using sub-samples of the data collected in **NA64e**, constraints on a couple **New Physics** (NP) models were set, such as e.g.

- ALPs (2020, ***PRL*** *125, 081801*)
- B-L Z' (2022, ***PRL*** *129, 161801*)
- inelastic DM (iDM) (2023, *EPJC* ***83****, no.5, 391*)

→ more details about these three examples in backup

Summary and Outlook

NA64e

- Total **2016-2023** statistics: **1.5x10^{12} EOT**
  - Analysis of the 2016-2022 data (~10^{12} EOT) completed: LDM suggested parameter space probed **for the first time**. World-best sensitivity!
  - Analysis with latest data ongoing to probe:
    - uncovered area for classical axion models and ALPs
    - New hidden interactions in the neutrino sector, e.g. B-L Z'
    - inelastic DM model
- **2024 run finished this week (5.2x10^{11} EOT collected!) The plan is to collect 3x10^{12} EOT before LS3.**

NA64μ

- Total **2021-2023** statistics: **1.9x10^{11} MOT**
  - Analysis of the 2022 data (1.98x10^{10} MOT) completed: part of the g-2 and LDM parameter space excluded.
- **Goal to reach 3x10^{11} MOT before LS3**

NA64e$^+$

- Total **2022-2023** statistics: **1x10^{10} e$^+$OT (100 GeV) and 1.5x10^{10} e$^+$OT (70 GeV)**
  - Analysis of the 2022 data (~10^{10} e$^+$OT) completed: LDM using 100 GeV positrons demonstrating feasibility of the technique

NA64h

- **Proof of concept successful!** First results published in arXiv:2406.01990

NA64 is an ideal experiment to decisively discover or disprove very interesting predictive LDM models and greatly explore DS in the coming years

The high-sensitivity NA64 hunt for New Physics has just begun!

Thanks for your attention!

Acknowledgements

The NA64 collaboration, in particular L. Molina Bueno, H. Sieber, P.Crivelli and S.Gniennko

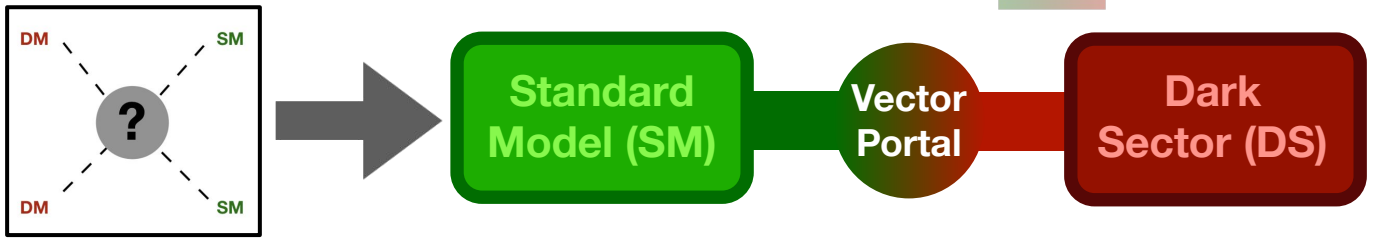
*Not all NA64 collaborators present

The NA64 collaboration in front of the M2 beamline experimental hall, where the NA64μ experiment is located

PID2021-123955NA-100

Outline

$$L_{tot} = L_{SM} + L_{DS} + L_{portal}$$



1) Light dark matter (LDM):

- ***invisible*** decays using 100 GeV electrons: 2016-2022 combined analysis **world-leading sensitivity!**
- **First LDM results using a e^+ beam**
- **First DS exploration using a μ beam**
- **Proof of principle NA64h**
- **Future prospects:**
  - **Collect more statistics to continue leading LDM searches in low mass region**

2) Search for additional new physics scenarios

- ALPs
- *B–L Z'*
- inelastic DM
- $L_\mu - L_\tau$ *Z'*

New analysis ongoing **with 5x (2016-2018 statistics)**

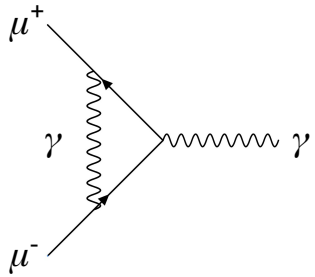
The NA64 physics program

	2016-2018	2021	2022	2023	2024	2025 + Long Shutdown 3 (**LS3**)
NA64e	**invis. mode** 2.84x10^{11} EOT **vis. mode** 8.4x10^{10} EOT	**invis mode** 6x10^{10} EOT	**invis mode** 6.3x10^{11} EOT	**invis mode** 5.1x10^{11} EOT	**invis mode** ~4x10^{11} EOT	
NA64μ		**pilot run** 5x10^{9} MOT	**μ (160 GeV)** 4x10^{10} MOT	**μ (160 GeV)** 1.5x10^{11} MOT	**μ (160 GeV)** *(starts in July)*	
NA64e+			**e+ (100 GeV)** 1x10^{10} e$^+$OT	**e+ (70 GeV)** 1.5x10^{10} e$^+$OT	**e+ (70 GeV)** *(starts 15.06.)*	
NA64h			**had. (50 GeV)** 2.92x10^{9} πOT	**had. (40 GeV)** 1.9x10^{10} πOT	-	
					ongoing!	

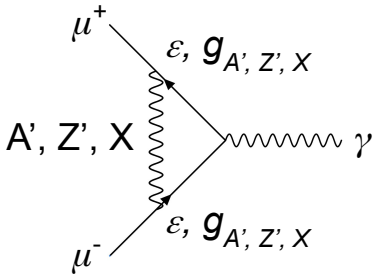
Motivation: Dark sectors (DS) to explain dark matter

Additional motivation: $(g\text{-}2)_\mu$ anomaly

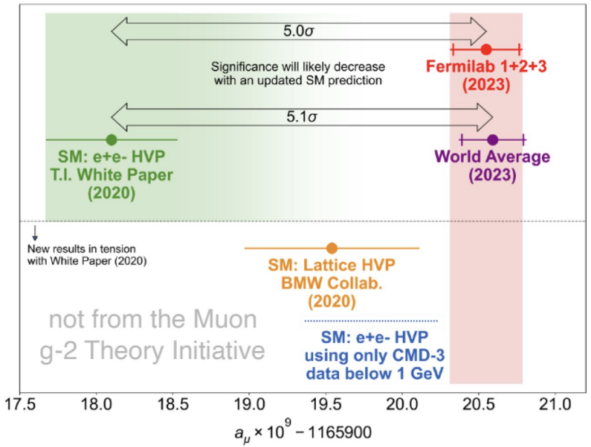
→ *we can check it "for free"*



standard model



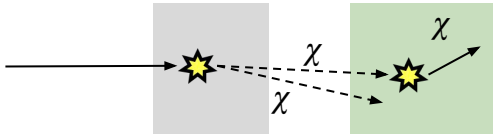
possible DS extension



B. Li, Proceedings of Science (HQL 2023) 009
DOI: http://doi.org/10.22323/1.462.0009

Detection technique: Beam dump vs active dump

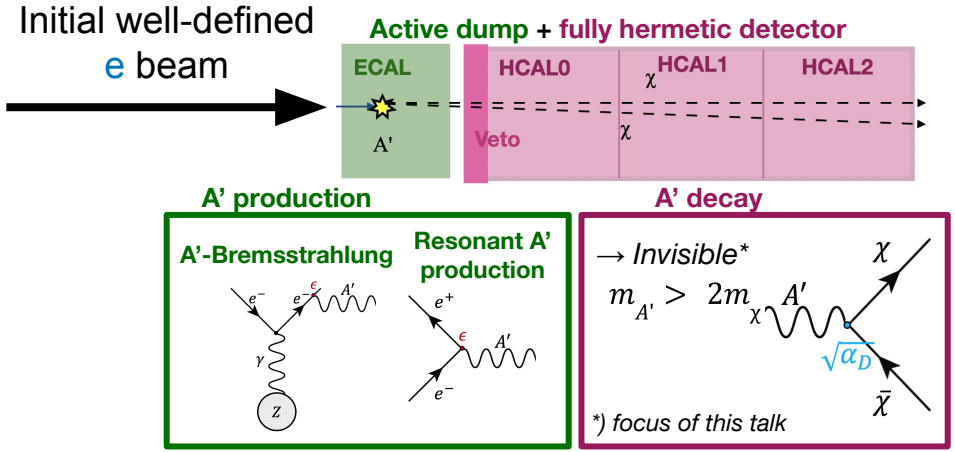
1) BEAM DUMP APPROACH
(MiniBooNE, LSND, NA62, SHIP, T2K, SBND, DUNE, …)



A' is produced in the dump and its posterior decay is measured in a detector downstream
Signal: χ scattering in far detector

$$N_{A'} \propto \varepsilon^4 \alpha_D$$

2) ACTIVE DUMP APPROACH
(NA64, LDMX)



A' production is measured in the target
Signal: Missing energy/momentum

$$N_{A'} \propto \varepsilon^2$$

S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)
L. Marsicano et al. Phys. Rev. Lett. 121, 041802

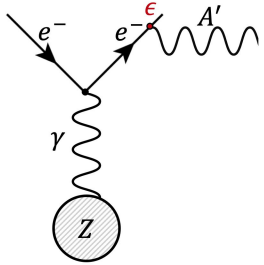
example: if $\varepsilon = 10^{-5}$, NA64 approach has an advantage of ~10 orders of magnitude compared to beam dump approach

The signature at NA64

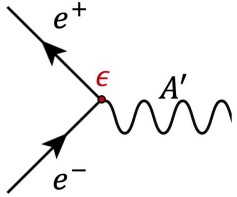
Initial well-defined
e-, e+, μ, h beam

Active Dump

A'-Bremsstrahlung

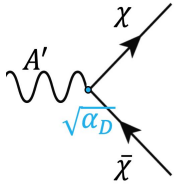
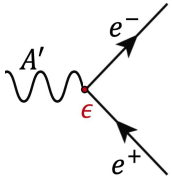
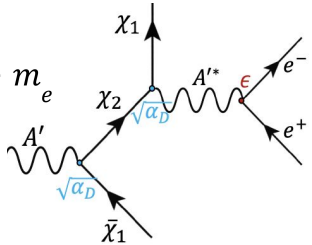


Resonant A' production



+

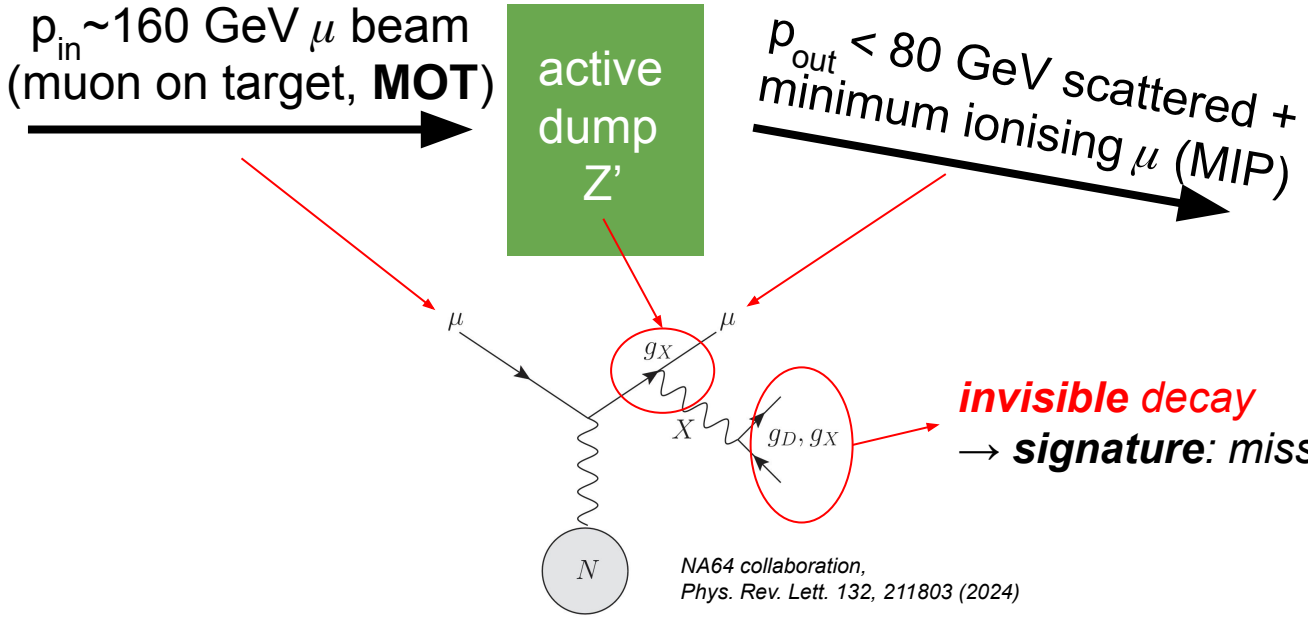
Fully hermetic detector

Decay		Signature
→ *Invisible* $m_{A'} > 2m_\chi$		Missing energy/momentum
→ *visible* $m_{A'} < 2m_\chi$		SM pair particles
→ *semi-visible* $m_{A'} > m_{\chi_1} \gg m_e$		Missing energy/momentum + SM pair particles

S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)
L. Marsicano et al. Phys. Rev. Lett. 121, 041802

The signature at NA64μ

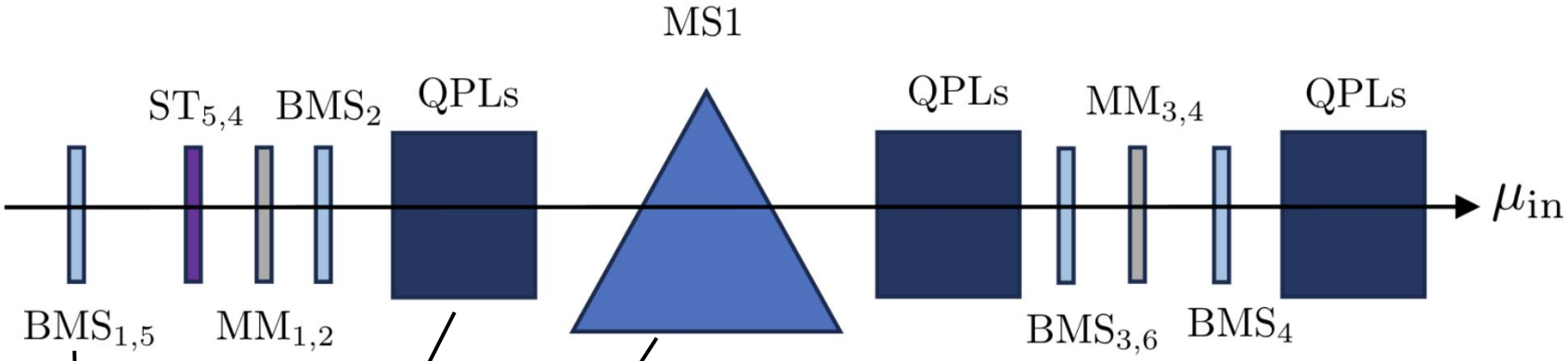
Missing momentum technique



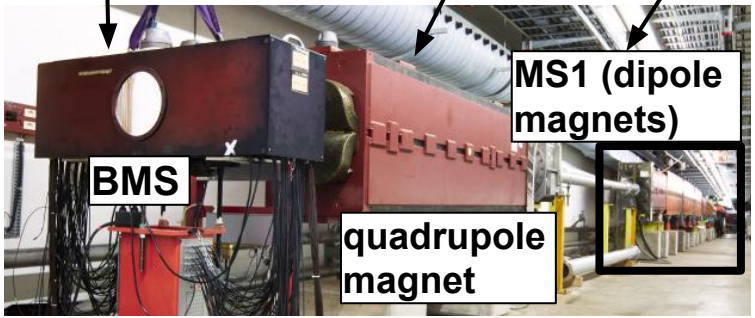
***invisible** decay*
→ ***signature**: missing momentum*

NA64 collaboration,
Phys. Rev. Lett. 132, 211803 (2024)

The NA64μ setup: M2 beamline



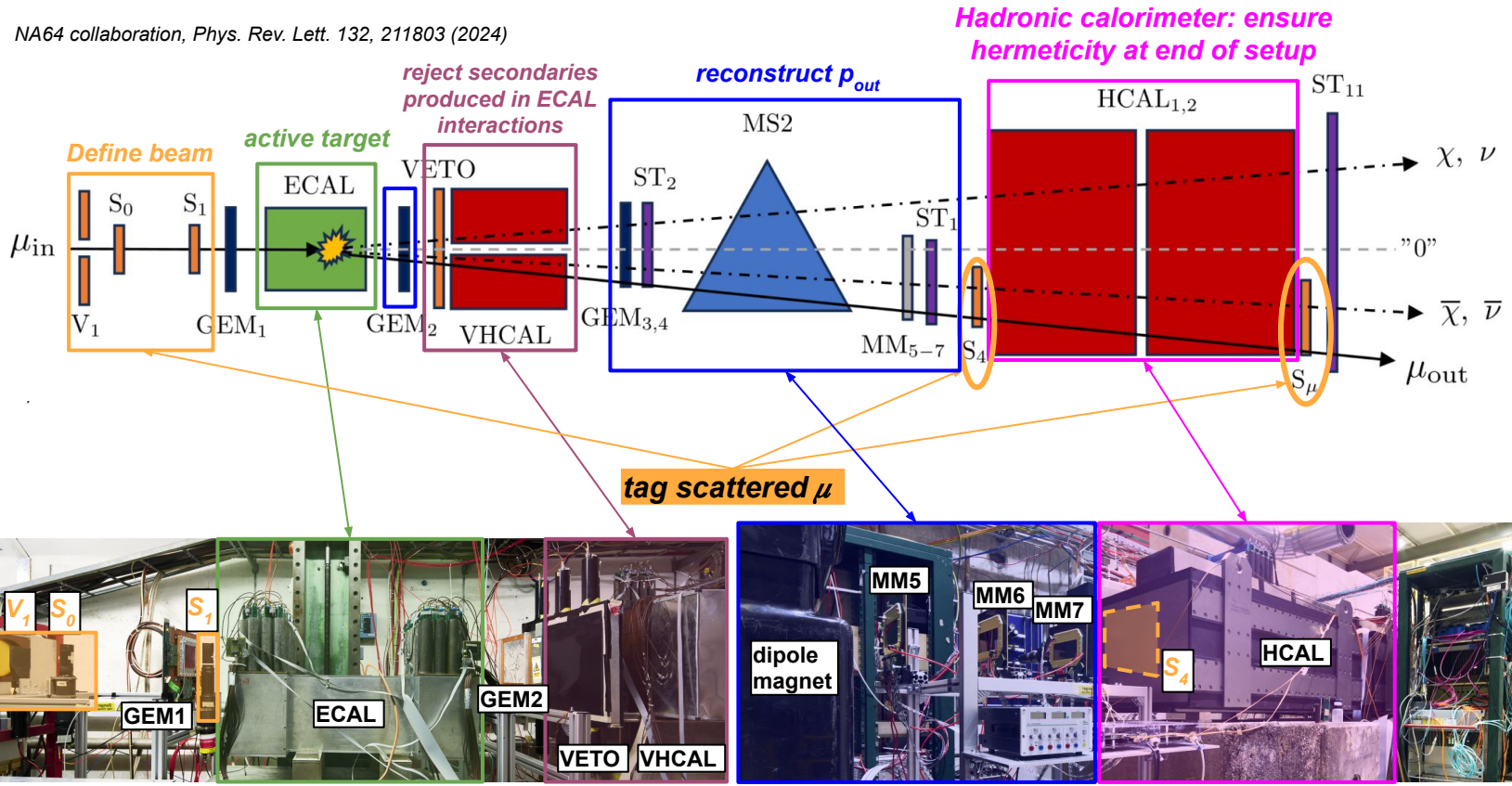
NA64 collaboration, Phys. Rev. Lett. 132, 211803 (2024)



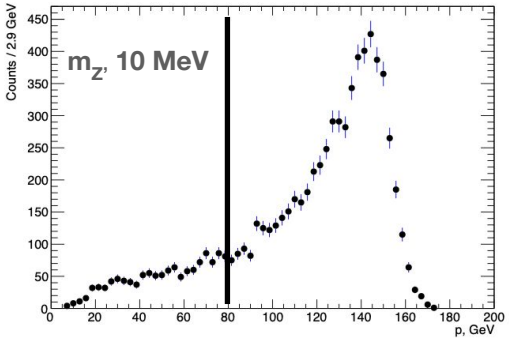
measure incoming momentum @ 160 GeV

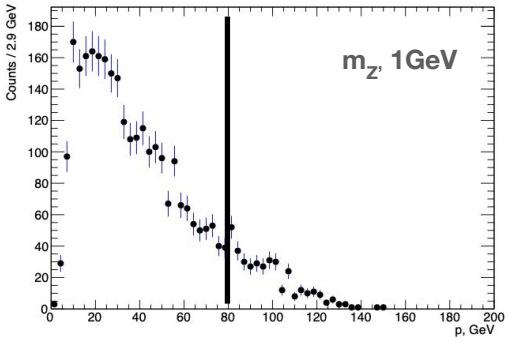
The NA64μ setup: main part

NA64 collaboration, Phys. Rev. Lett. 132, 211803 (2024)



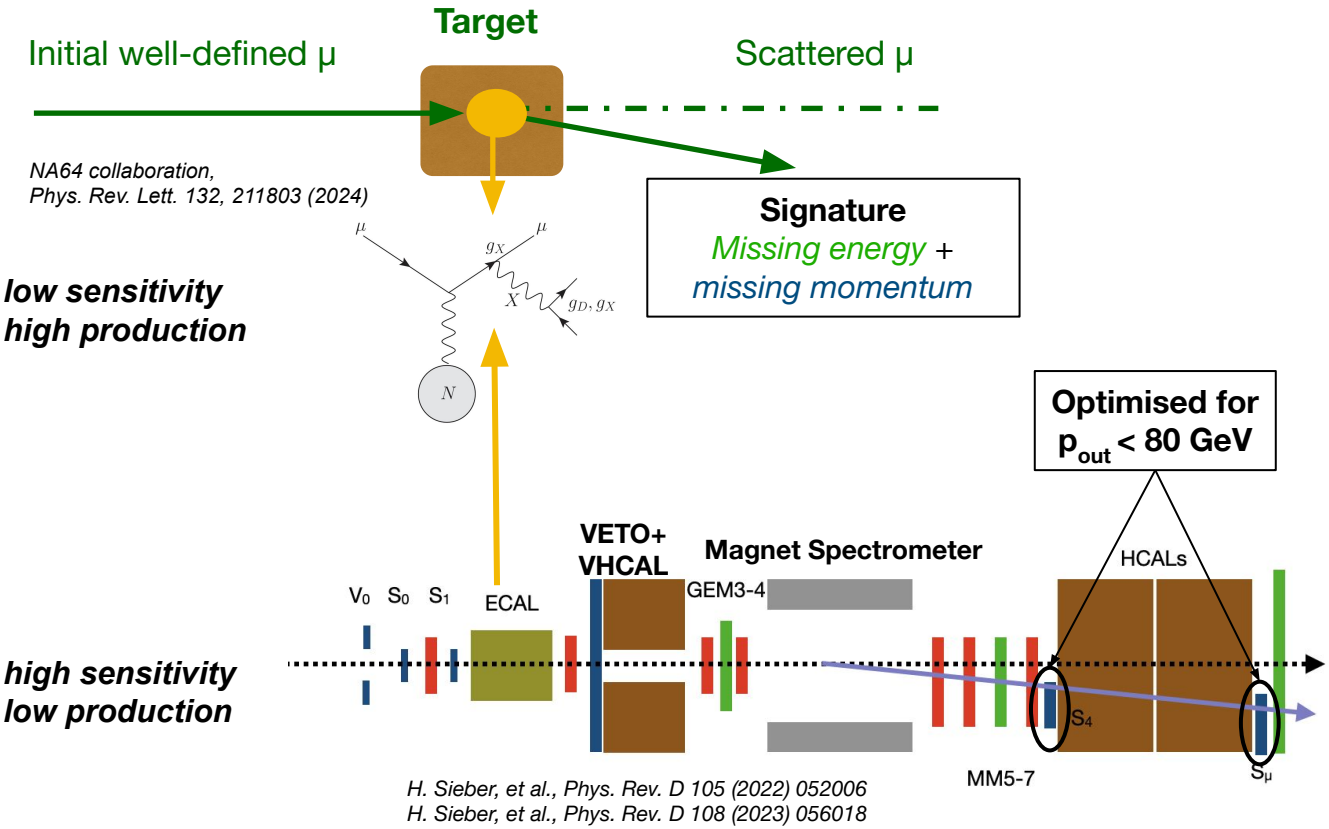
Trigger at NA64μ



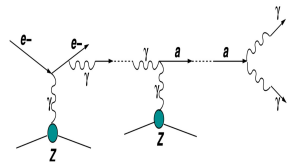


low sensitivity
high production

high sensitivity
low production

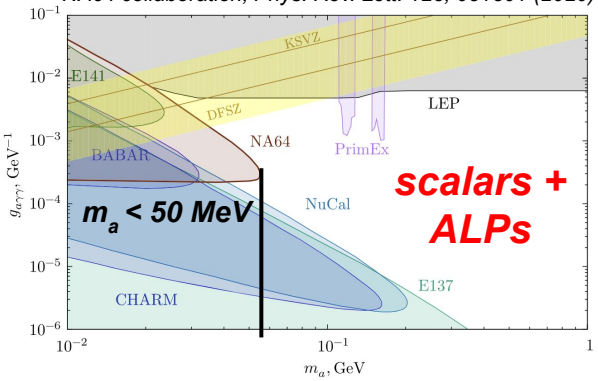


Search for additional NP scenarios: An overview

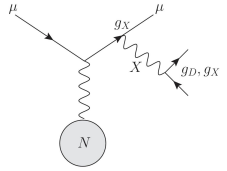


$e^-Z \to e^-Z\gamma$, $\gamma Z \to a^* \to \gamma\gamma$
(Primakov-effect → deposit only in last HCAL)

NA64 collaboration, Phys. Rev. Lett. 125, 081801 (2020)

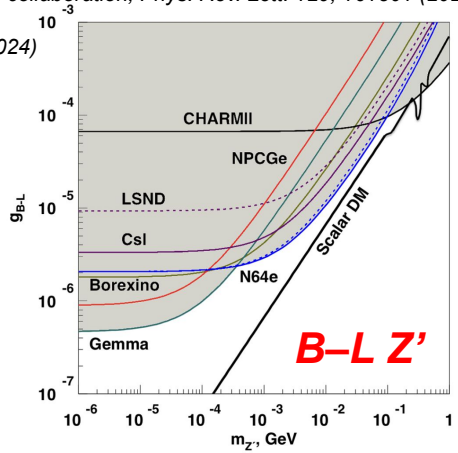


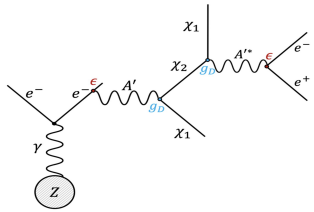
NA64 collaboration, Phys. Rev. Lett. 132, 211803 (2024)



$e^-Z \to e^-ZZ'$, $Z' \to \nu\nu$/invis
(dark Bremsstrahlung)

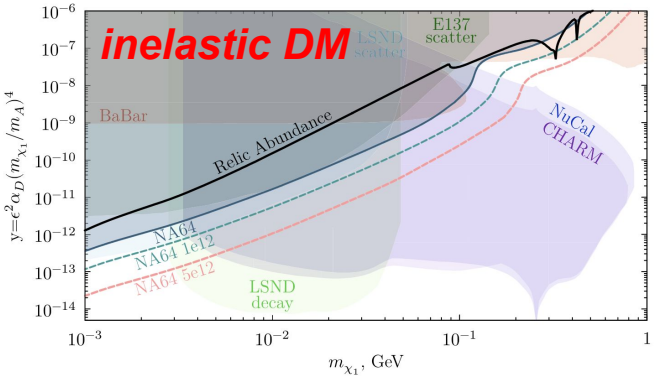
NA64 collaboration, Phys. Rev. Lett. 129, 161801 (2022)





$e^-Z \to \chi_1\chi_2, \chi_2 \to \chi_1 e^+e^-$
(semi-visible decay)

Thermal iDM, $\Delta = 0.4m_{\chi_1}, m_A = 3m_{\chi_1}, \alpha_D = 0.1$



M. Mongillo et. al, Eur. Phys. J. C (2023) 83:391