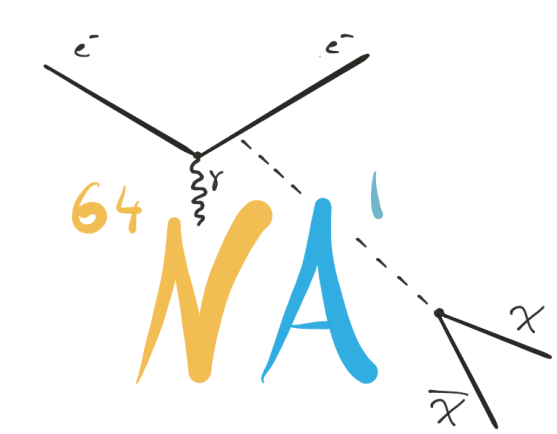


NA64 programme post LS3 - PBC Workshop - CERN 26.03.2024

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics on behalf of NA64 collaboration

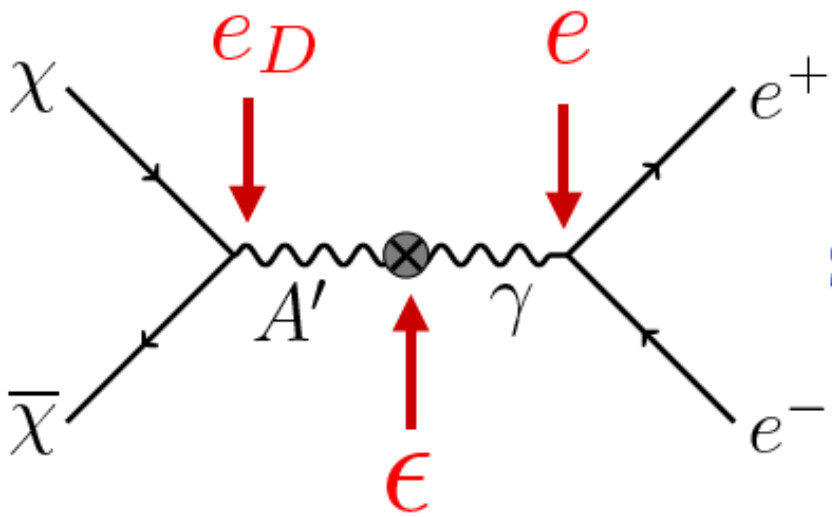
NA64 research program - input to EPPS 2018-2020

Process	New Physics	Comments, Projections for limits
e^- **beam**		Required number of EOT: 5×10^{12}
$A' \to e^+e^-$, and	Dark photon	$10^{-5} < \epsilon < 10^{-2}$, $1 \lesssim m_{A'} \lesssim 100$ MeV
$A' \to invisible$		$2 \times 10^{-6} < \epsilon < 10^{-3}$, $10^{-3} \lesssim m_{A'} \lesssim 1$ GeV
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)	Scalar, Majorana, pseudo-Dirac DM
		$\alpha_D^{S,M} \lesssim 1$, $\alpha_D^{p-D} \lesssim 0.1$, for $m_\chi \lesssim 100$ MeV
$X \to e^+e^-$	new gauge X- boson	^{8}Be* anomaly, $\epsilon_e^{up} < 10^{-5}; \epsilon_e^{low} > 2 \times 10^{-3}$
milliQ particles	Dark Sector, charge quantisation	$10^{-4} < mQ < 0.1$ e, $10^{-3} < m_{mQ} < 1$ GeV
$a \to \gamma\gamma, invisible$	Axion-like particles	$g_{a\gamma\gamma}^{inv} \lesssim 2 \times 10^{-5}$, $m_a \lesssim 200$ MeV
μ^- **beam**		Required number of MOT: $10^{11} - 5 \times 10^{13}$
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$	$(g\text{-}2)_\mu$ anomaly; $g_\mu^V \lesssim 10^{-4}$, with $\lesssim 10^{11}$ MOT
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)	$y \lesssim 10^{-12}$ for $m_\chi \lesssim 300$ MeV with $\simeq 10^{12}$ MOT
milliQ	Dark Sector, charge quantisation	$10^{-4} < mQ < 0.1$ e, $10^{-3} < m_{mQ} < 2.5$ GeV
$a_\mu \to invisible$	non-universal ALP coupling	$g_Y \lesssim 10^{-2}$, $m_{a_\mu} \lesssim 1$ GeV
$\mu - \tau$ conversion	Lepton Flavour Violation	$\sigma(\mu - \tau)/\sigma(\mu \to all) \lesssim 10^{-11}$
π^-, K^- **beams**	Current limits, PDG'2018	Required number of POT(KOT):$5 \times 10^{12}(5 \times 10^{11})$
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$	$Br(\pi^0 \to invisible) \lesssim 10^{-9}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-8}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-7}$
$K_S^0 \to invisible$	no limits	$Br(K_S^0 \to invisible) \lesssim 10^{-9}$
$K_L^0 \to invisible$	no limits	$Br(K_L^0 \to invisible) \lesssim 10^{-7}$
		complementary to $K^- \to \pi\nu\nu$

https://indico.cern.ch/event/765096/contributions/

NA64 TARGET: THE VECTOR PORTAL & Light Dark Matter (LDM)

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



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

In this framework DM can be produced thermally in the early Universe

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_X \propto \frac{1}{<v\sigma>} \sim \frac{m_X^2}{y}$$

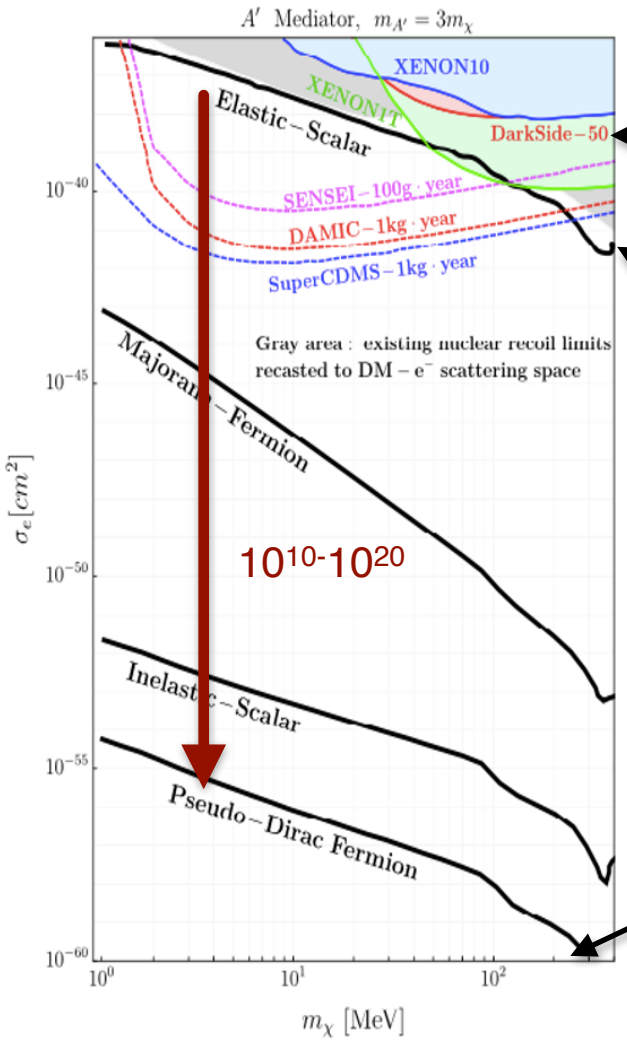
WHERE $$y = \epsilon^2 \alpha_D \left(\frac{m_X}{m_{A'}}\right)^4$$

J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008

Complementarity of direct detection and accelerators experiments

R. Essig, J. Mardon, and T. Volansky, PRD85, 076007 (2012), 1108.5383.

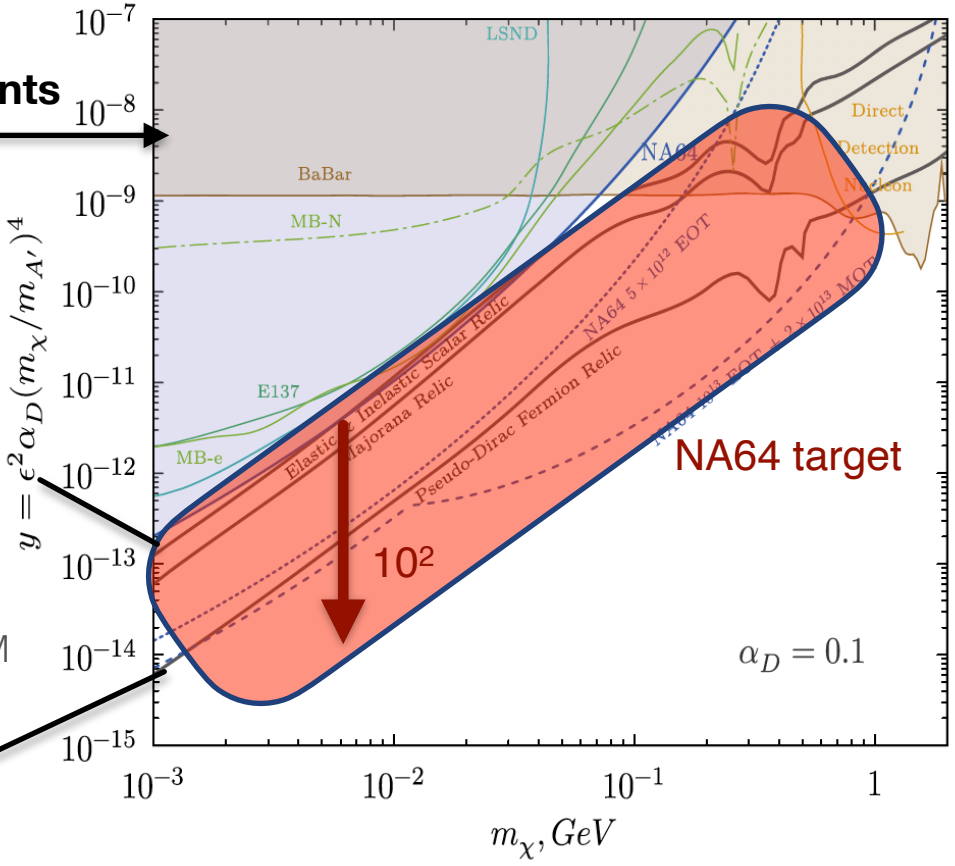
Direct Detection Targets



Current constraints

Solid lines predictions from DM relic abundance

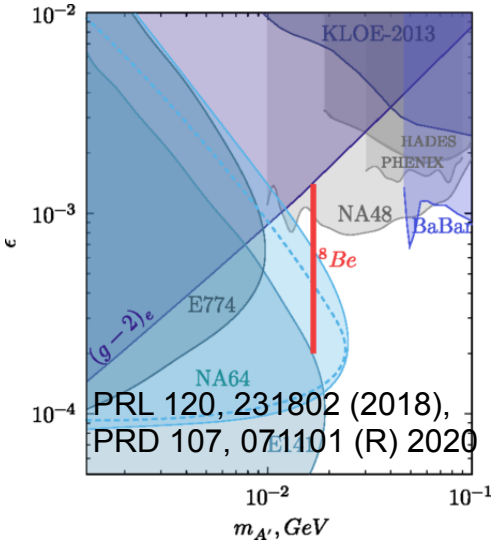
Accelerator Targets



NA64 collaboration, PRL 123, 121801 (2019)

NA64 potential: additional new physics scenarios

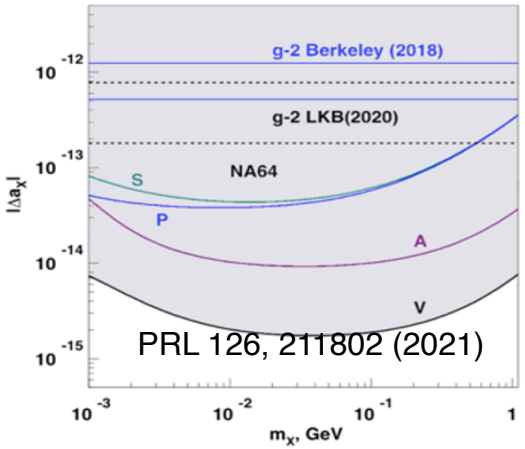
A' -> visible and X17



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

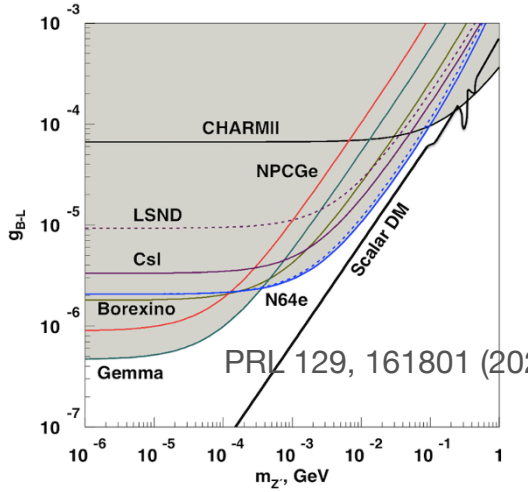
$e^-Z \to e^-ZX; X \to$ invisible

New Physics in $(g-2)_e$ vs $(g-2)_e$ from measurement of alpha

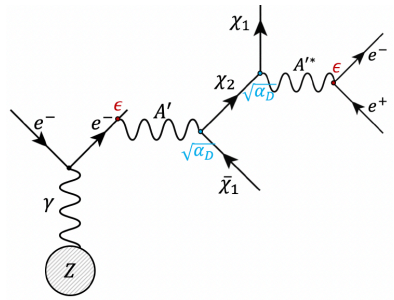


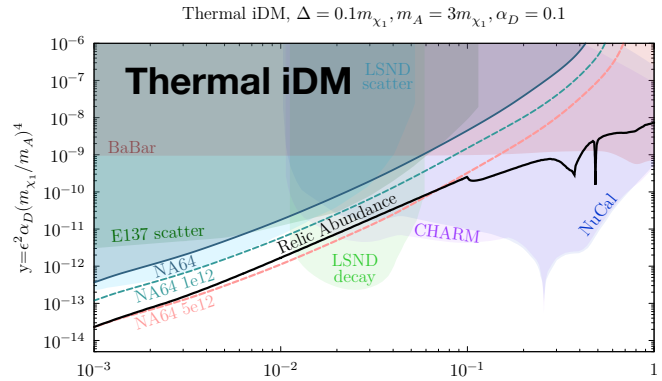
PRL 126, 211802 (2021)

B-L Z´ vs neutrino scattering



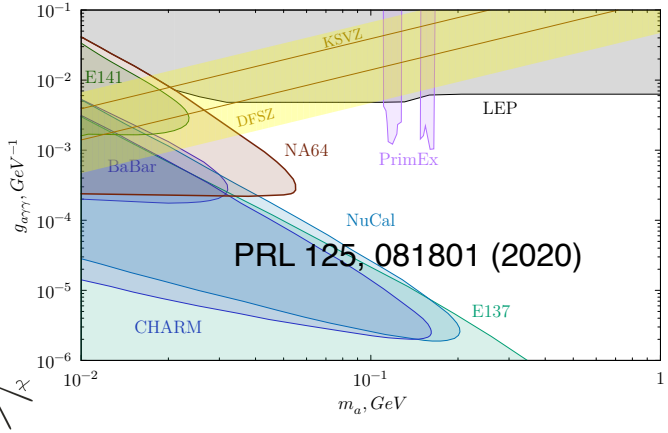
PRL 129, 161801 (2022)





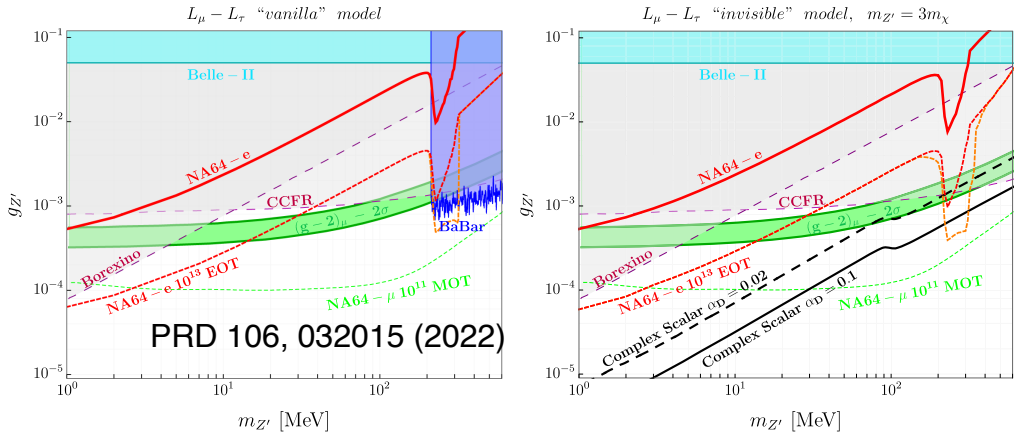
Eur. Phys. J. C (2021) **81**: 959
Eur. Phys. J. C (2023) **83**: 391

QCD axion and ALPs



PRL 125, 081801 (2020)

Lmu-Ltau Z' models

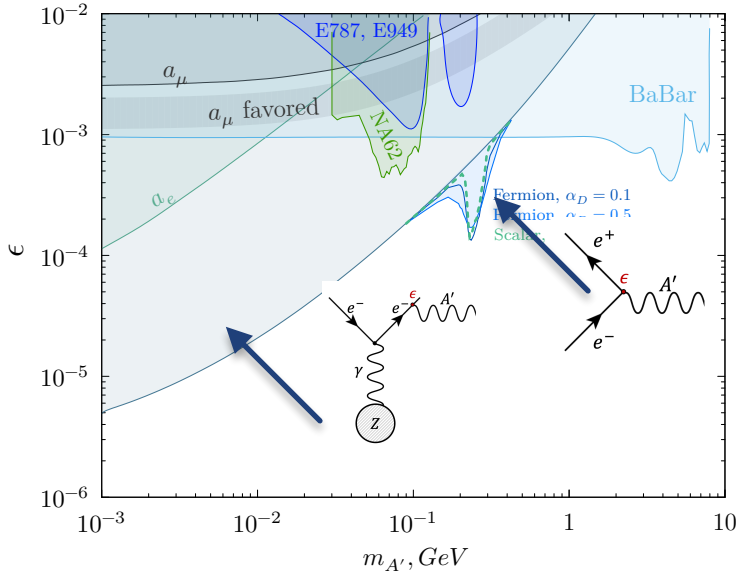


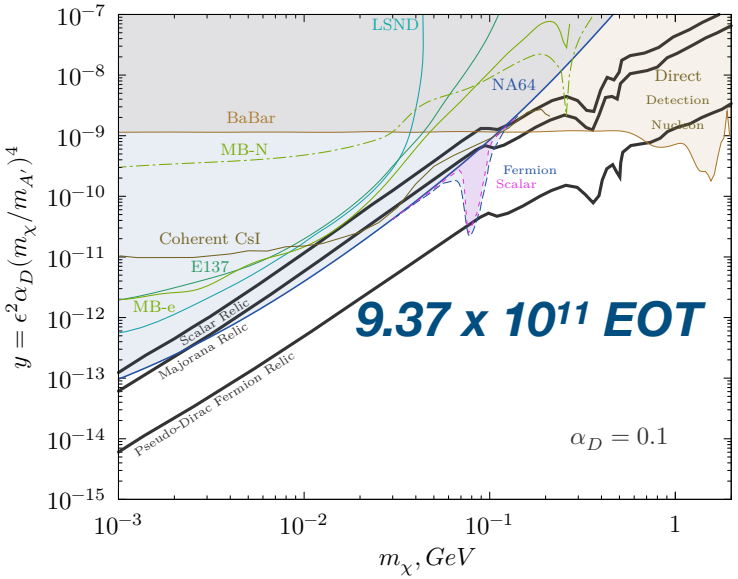
PRD 106, 032015 (2022)

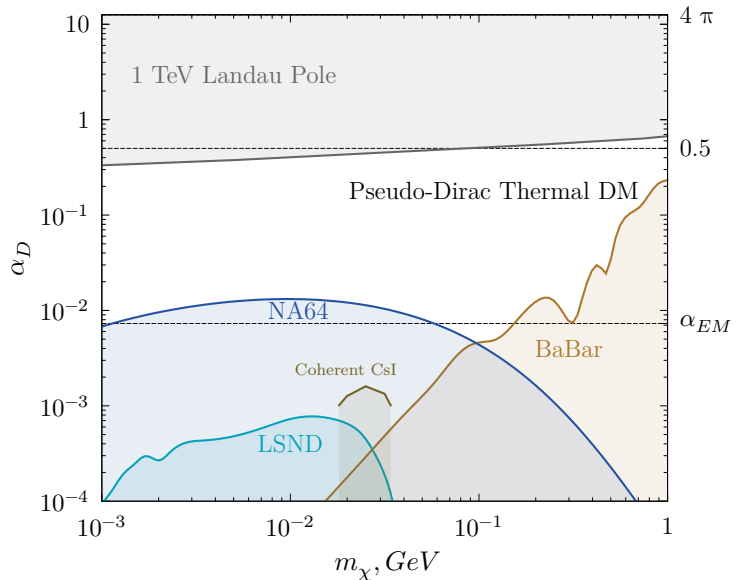
Results obtained with
3x10¹¹ EOT
(2016-2018 statistics)
Analysis in progress of
5x more data on "tape"

NA64 LDM latest results (2016-2022)

NA64, Phys. Rev. Lett. **131**, 161801 (2023)







For **α_D=0.1**, NA64 excludes the **Scalar and Majorana scenarios** for almost all m_χ values.

Exploiting the e^+e^- resonant enhancement, we also exclude the **Pseudo-Dirac Fermion scenario** for a narrow m_χ interval.

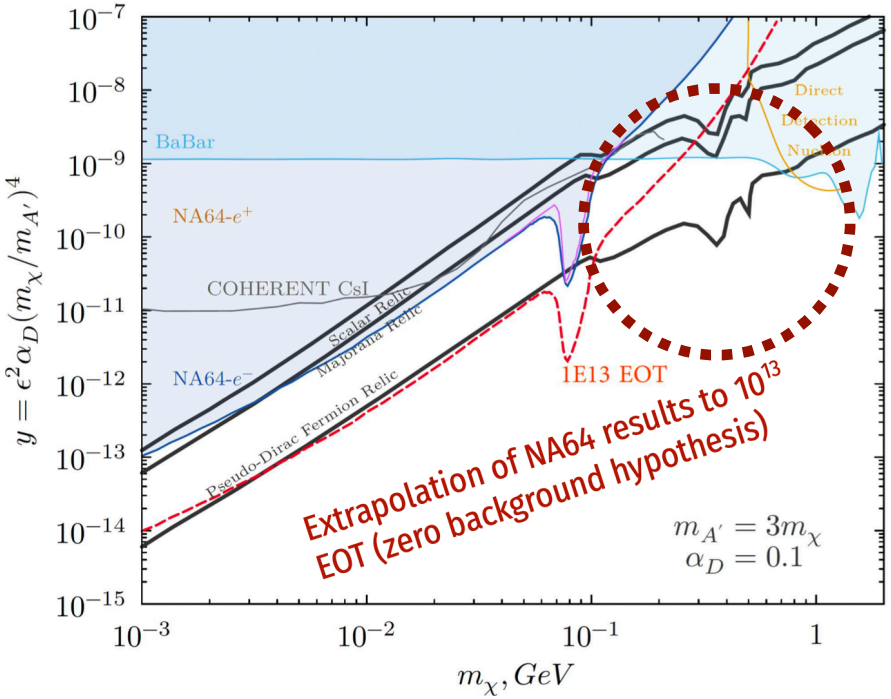
2016-2018	2021	2022	2023	2024	**2025**	**LS3**
NA64e	2.84 × 10^{11} EOT	6 × 10^{10} EOT	~6.3 × 10^{11} EOT	**~5.1× 10^{11} EOT**	**~ 3× 10^{12} EOT**	

1.5 x 10^{12} EOT

Improved set-up

Post LS3 prospects for LDM searches at NA64

GOAL > 1× 10^{13} EOT



Planned upgrades include:

i) Increase the e- beam intensity up to >~ 10^7 e-/spill

- new readout electronics: 80-> 250 MHz digitisers, trackers APV ->VMM
- DAQ speed up to 30-40 kevent/ spill

ii) Improve detector hermeticity and performance

ECAL: radiation hard central part, improve stability,…

HCAL:, larger acceptance modules, longitudinal segmentation

VHCAL: to reject high P_t hadronic secondaries, 2023 prototype test was successful

New LYSO based SRD: higher granularity, lower SR threshold

To improve our sensitivity in the (high) mass range and on scenarios with alpha$_D$=0.5 →use positron and muon beams

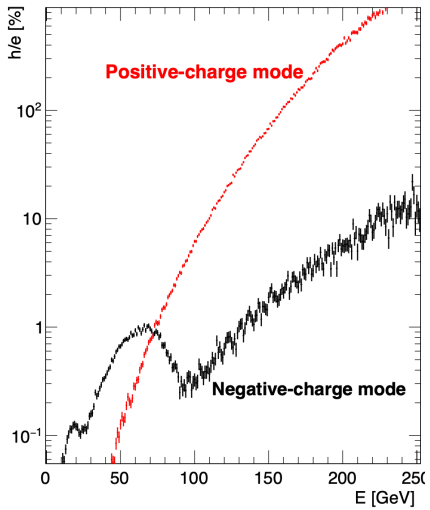
Post LS3 prospects for LDM searches at NA64 with positrons

CERN-SPSC-2024-003 ; SPSC-P-348-ADD-4

Resonance annihilation channel with 100 GeV e⁺beam.

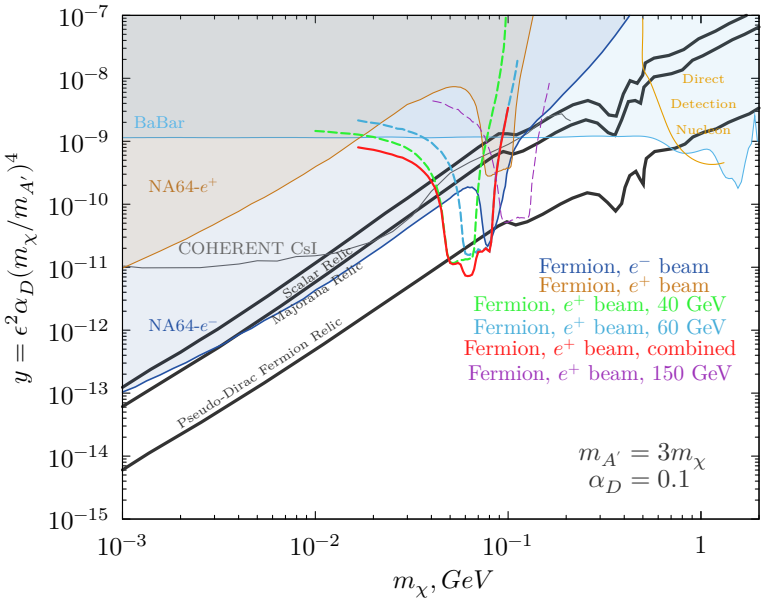
L. Marsicano *et al.* Phys. Rev. Lett. 121, 041802 (2018), NA64 collaboration, ***Phys.Rev.D*** **109 (2024) 3, L031103**

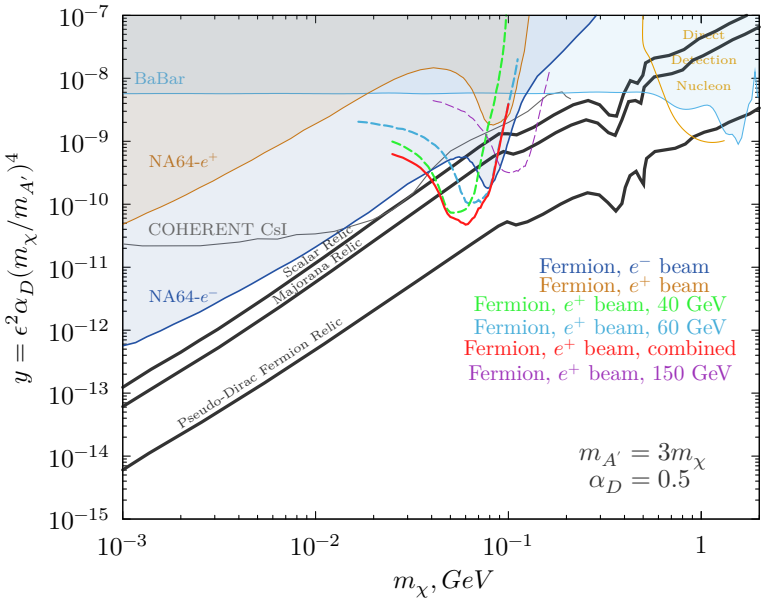
$$e^+e^- \rightarrow A' \rightarrow \chi\bar{\chi}$$



NA64 collaboration, NIM. A 1057 (**2023**), 168776

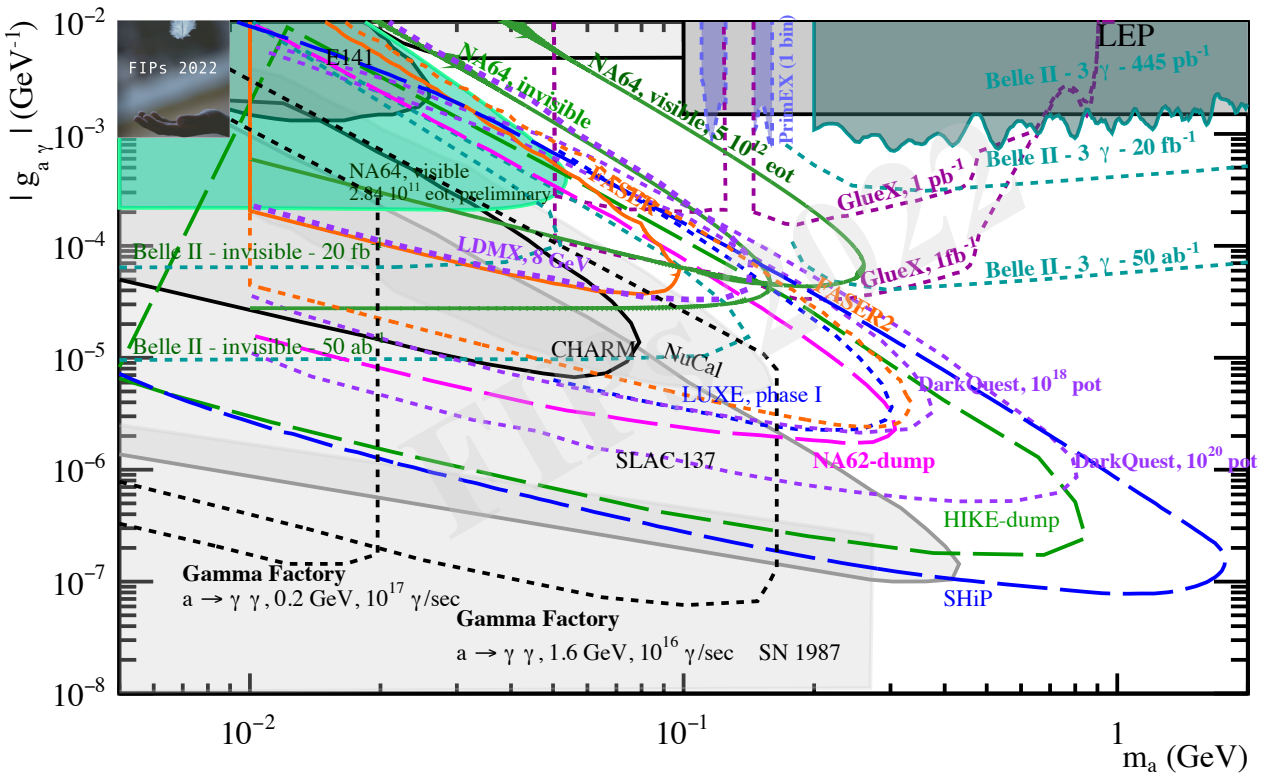
Main challenge:
Hadron contamination in H4 beam in e⁺ mode is significantly higher at 100 GeV



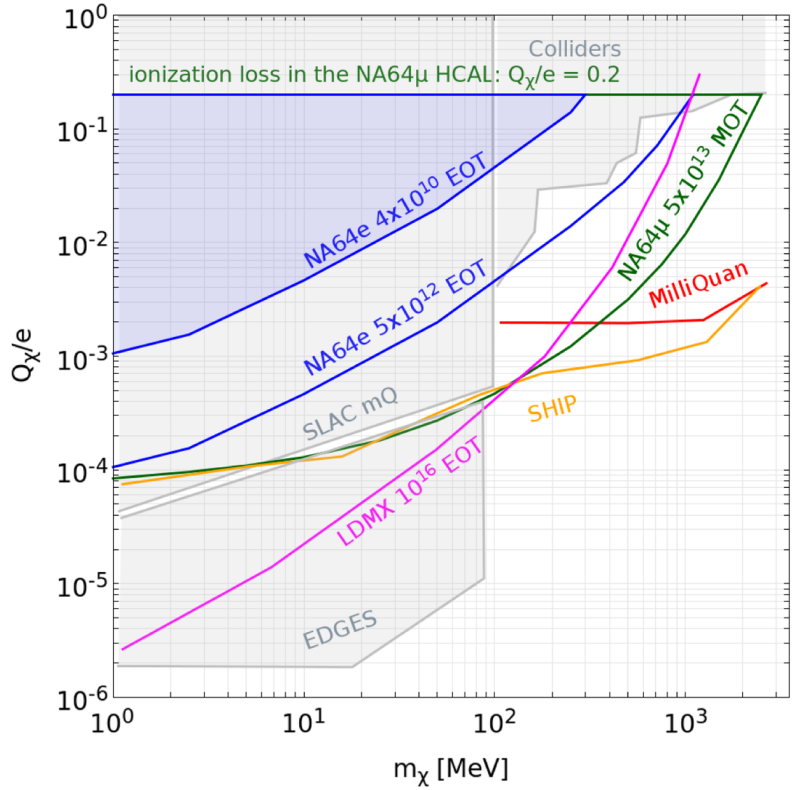


2021	2022	2023	2024	2025	LS3
NA64e+	1×10^{10} E+OT @ 100 GeV	1×10^{11} E+OT @ 70 GeV	@ 40, 60 150 GeV	Tests @ 40 GeV	

Some additional post LS3 prospects at NA64e



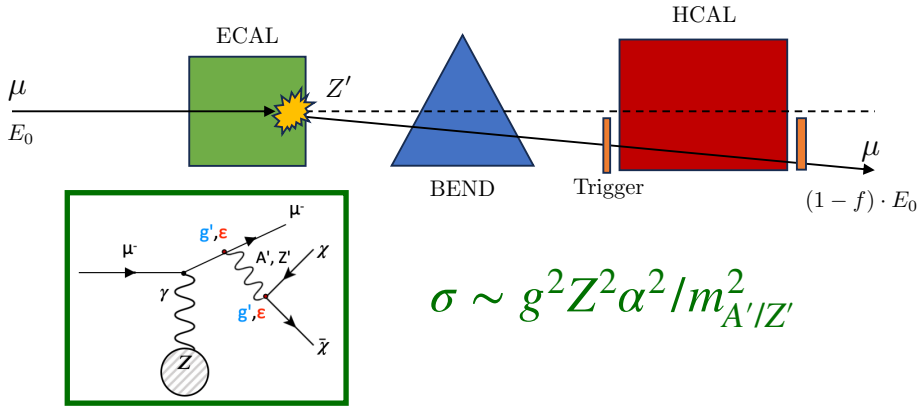
FIPs 2022 workshop: arXiv 2305.01715



Gninenko et al., PHYS. REV. D 100, 035003 (2019)

Some very nice examples of complementarity with FASER and SHiP and other experimental efforts!

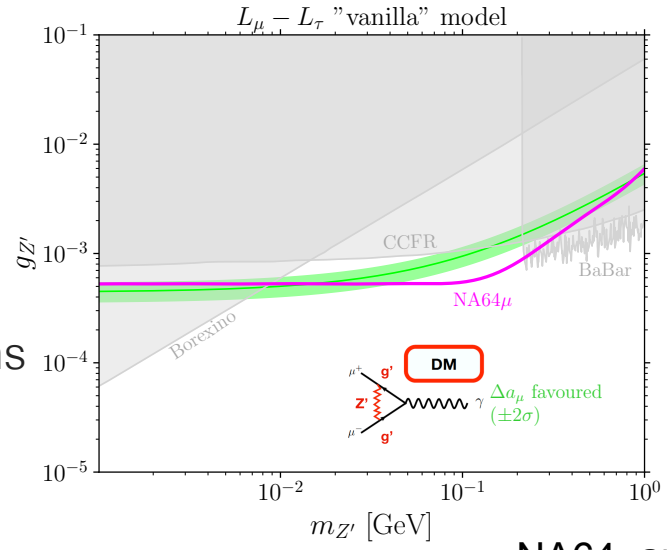
NA64μ: Searching for Lmu-Ltau Z' and A' with muon beams

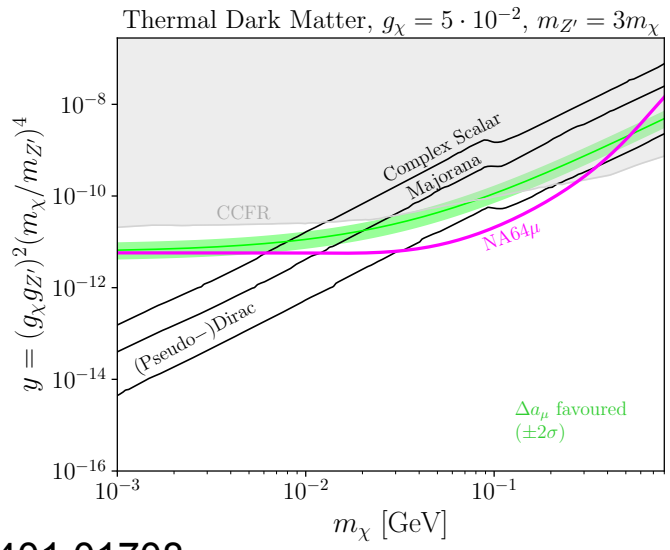


$$\sigma \sim g^2 Z^2 \alpha^2 / m^2_{A'/Z'}$$

Signature and challenge

Missing energy + *missing momentum*





NA64, arXiv:2401.01708

Goals

- testing g-2 muon anomaly explanation with Z'
- searching for LDM coupled predominantly to muons
- probing high-mass region of canonical LDM model with A' mediator

	2021	2022	2023	2024	2025	LS3
NA64mu	2×10^9 MOT @ 160 GeV	2×10^{10} MOT @ 160 GeV	1.5×10^{11} MOT @ 160 GeV	3×10^{11} MOT @ 100/160 GeV		

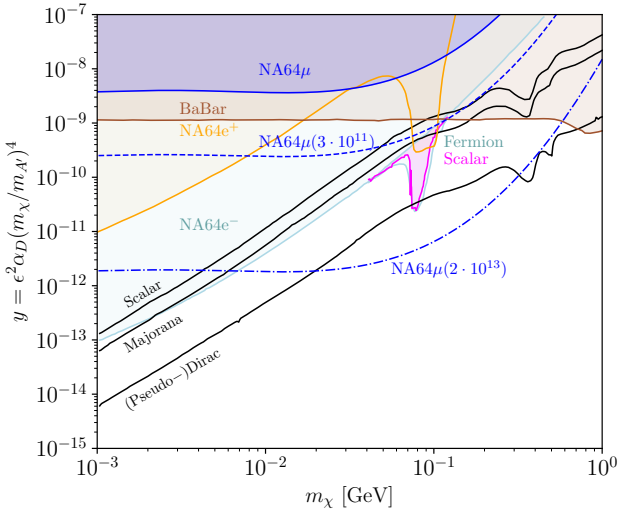
Improved set-up

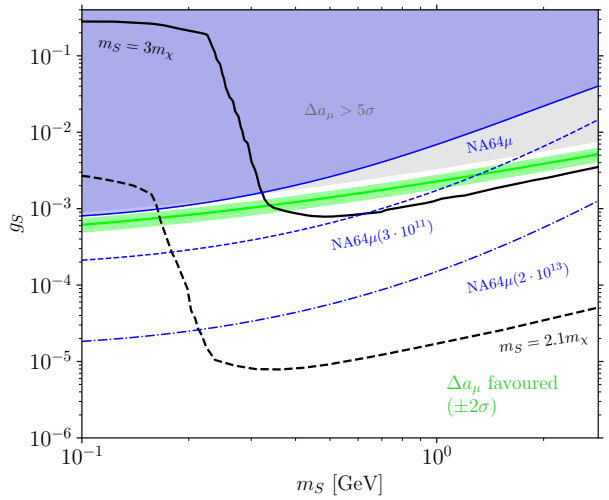
Post LS3 prospects for NA64μ

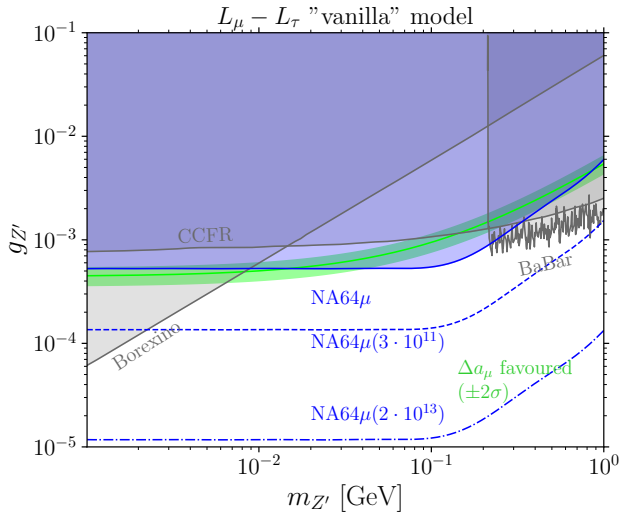
During LS3:
setup upgrade to run up to
5x10^7 muons/spill

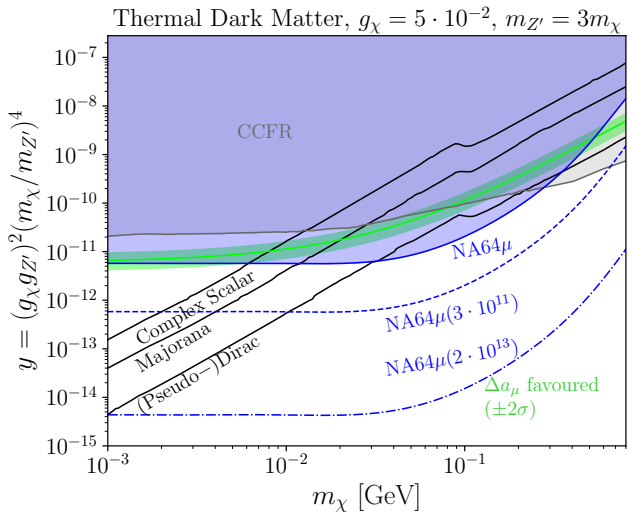
GOAL > 2× 10^{13} EOT

Planned upgrades include:
ECAL (readout)
HCAL (larger acceptance modules)
VHCAL (optimisation of prototype, 2 modules)
Second spectrometer with double magnet
Segmented trigger (hodoscope)
DAQ & readout



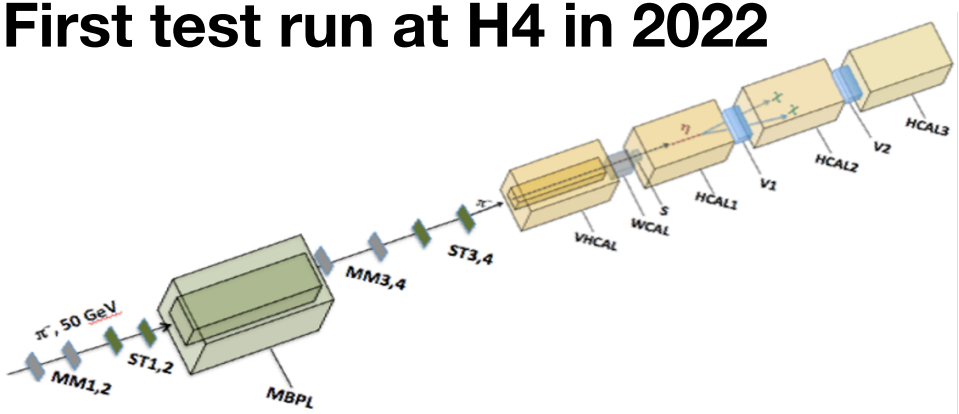




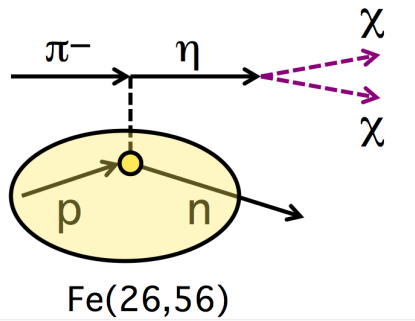


NA64h: Search for dark sector coupled to quarks with hadronic beams

First test run at H4 in 2022



Production charge exchange



Striking signature η, η′ $K^0_{S,L}$.. → invisible:

- incoming pion of ~ 50 GeV
- complete disappearance of beam energy in the HCAL target

Process highly suppressed in SM

$$\Gamma(M^0 \to \nu\bar{\nu}) \sim \left(\frac{m_\nu}{m_{M^0}}\right)^2 \lesssim 10^{-16}$$

Current limit:

Br(η-> inv) < ~ 10^{-5}-10^{-4} (BaBar/BESIII)

First proof-of-concept results to be submitted soon.

BESIII limits improved by ~ 3 during a one-day run
(BESIII collected data for a few months)

Summary and Outlook

NA64e⁻

- **Tot.** collected statistics **~1.5 x 10^{12} EOT ->** probing **LDM benchmark model** and improve sensitivity **ALPs, L_μ-L_τ, and B-L Z', iDM,…**
  Plan: 2x statistics before and total of ~1. x 10^{13} EOT after LS3

NA64μ

- **2022:** 2x10^{10} MOT, **2023:** 1.5x10^{11} MOT(upgraded setup)->*$(g-2)_\mu$ and L_μ-L_τ Z'*
- **Plan: 2x statistics before and tot. ~2. x 10^{13} EOT after LS3** -> LDM

NA64e⁺

- Pilot run 2022 (2 days) ~1x10^{10} E+OT, 2023 run at 70 GeV (1 day)
- **Plan: 40, 60 GeV ~2. x 10^{11} E+OT after LS3** -> LDM

NA64h

- **2022** ~2x10^{9} pions (1 day) -> proof of principle (DS coupled to quarks)
- p+ A -> E_{miss} (S,P,Z', HNL, ..) + X , technique à la NA64e under study

The **exploration of the NA64 physics potential has just begun**. Proposed searches with **leptonic and hadronic beams**: unique sensitivities **highly complementary to similar projects.**

Acknowledgments

NA64 collaboration and in particular S: Gninenko and L. Molina-Bueno

Special thanks to: E. Depero, H. Sieber, B. Banto-Oberhauser, M. Mongillo, A. Ponten

Beam department: D. Banerjee, J. Bernhard, N. Charitonidis, L. Gattignon, M. Brugger

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