https://www.na64.web.cern.ch

First Results from NA64mu Experiment

MIP 2024 Workshop - Peking (online talk) - 20th of April 2024

Paolo Crivelli, Institute for Particle Physics and Astrophysics, ETH Zurich

Dark sectors and thermal light Dark Matter

- Interactions between **DM and SM** particles could be carried by **a new force through mediators**

$$\mathcal{L} = \mathcal{L}_{\mathrm{DS}} + \mathcal{L}_{\mathrm{Portal}} + \mathcal{L}_{\mathrm{SM}},$$

For a recent review see e.g. Lanfranchi/Pospelov/Schuster Ann. Rev. Nucl. Part. Sci. 71 (2021)

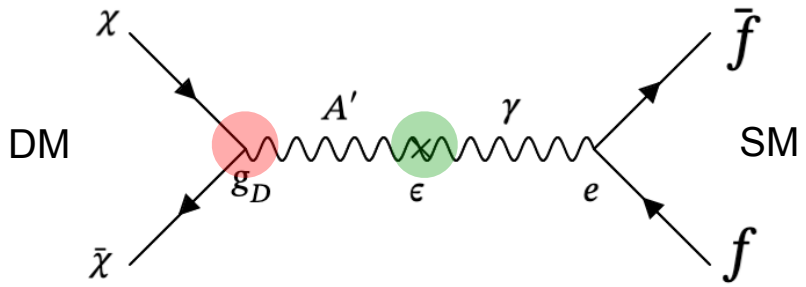
OBSERVED **AMOUNT OF DARK MATTER** TODAY $\Omega_X \propto \frac{1}{<v\sigma>} \sim \frac{m_X^2}{y}$

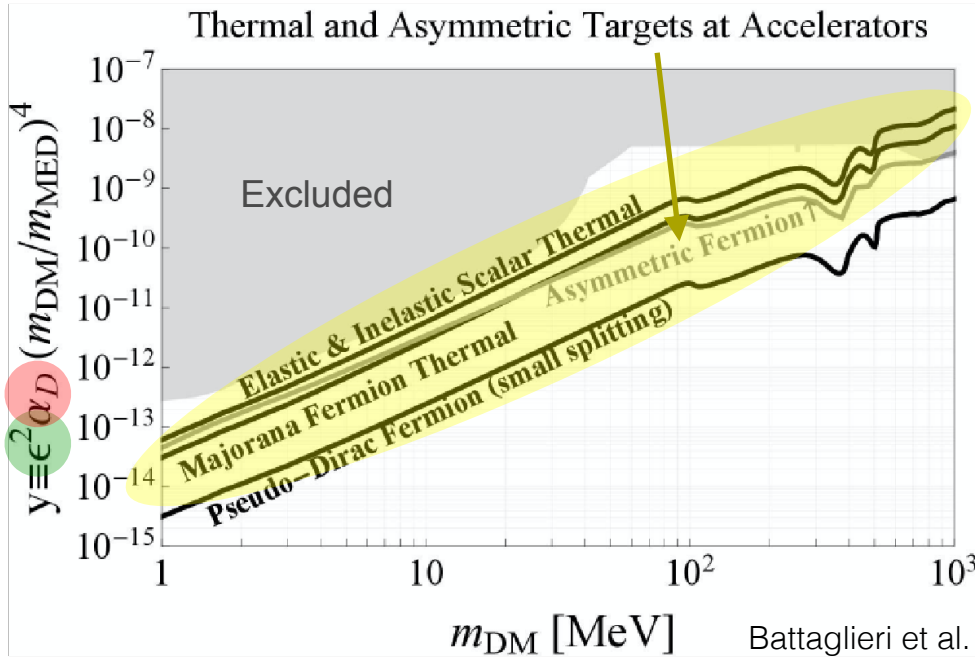
$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

$$\Downarrow$$

- Canonical model with **dark photon A'** model (vector boson from broken U(1) symmetry)

$$\mathcal{L} \supset -g_D \bar{\chi} \gamma^\mu A'_\mu \chi + \frac{m_{A'}^2}{2} A'_\mu A^{\mu\prime} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu},$$



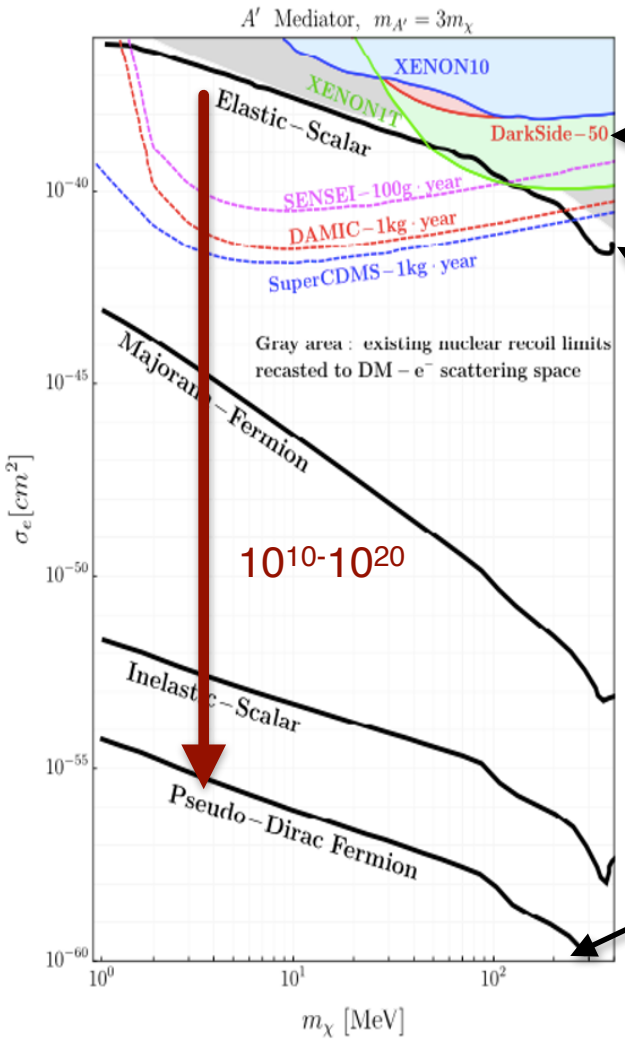


Battaglieri et al. 1707.04591

Complementarity of direct detection and accelerators experiments

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

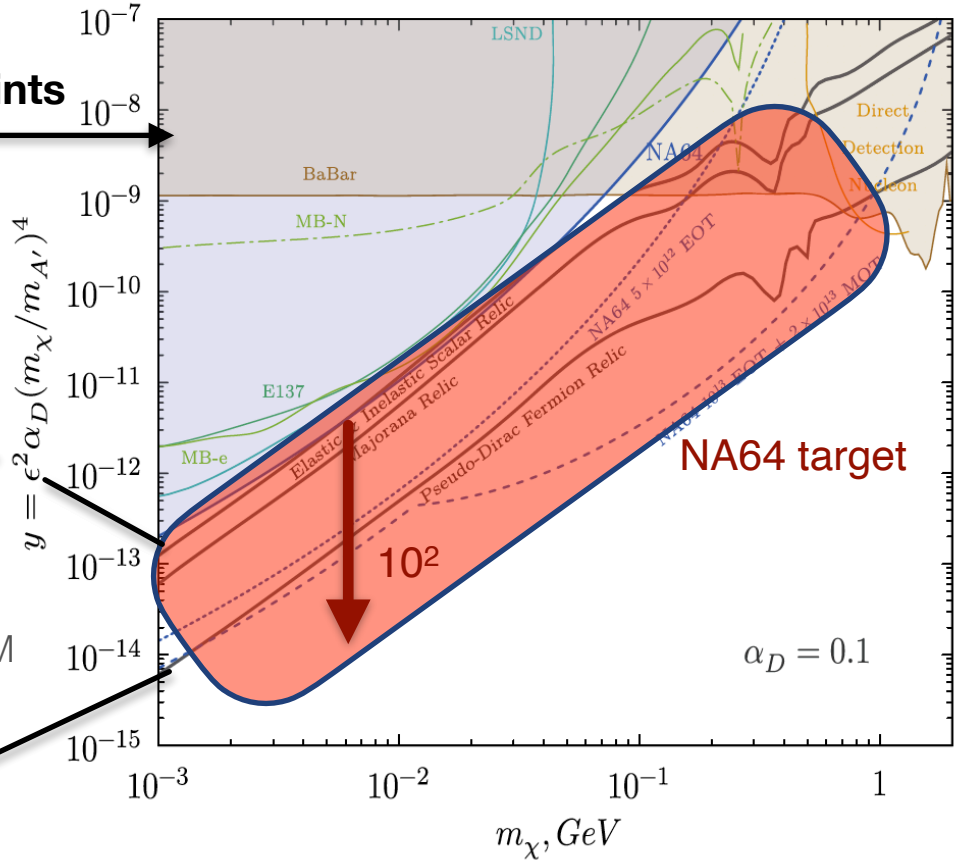
Direct Detection Targets



Current constraints

Solid lines predictions from DM relic abundance

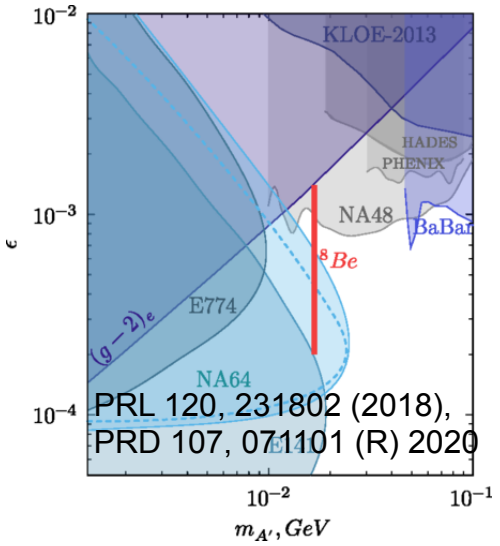
Accelerator Targets



NA64 collaboration, PRL 123, 121801 (2019)

NA64 potential: additional new physics scenarios

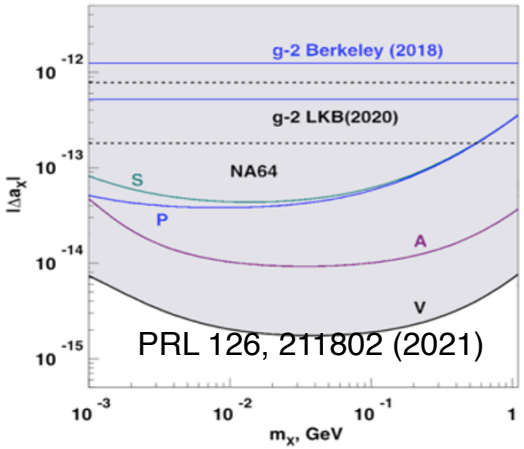
A' -> visible and X17



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

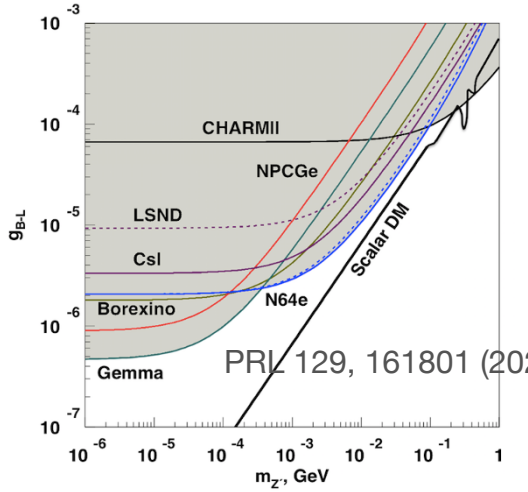
$e^-Z \to e^-ZX; X \to$ invisible

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

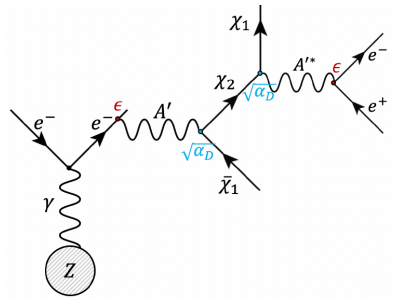


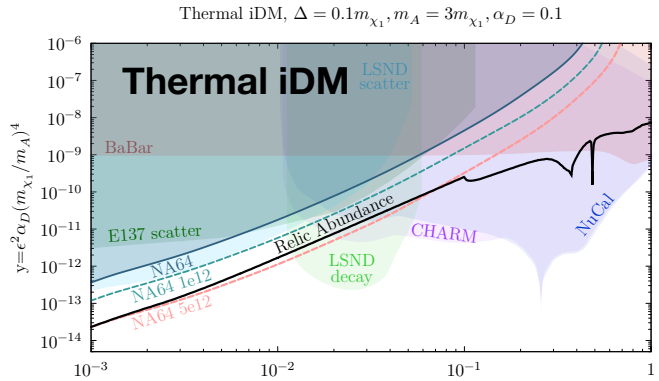
PRL 126, 211802 (2021)

B-L Z´ vs neutrino scattering



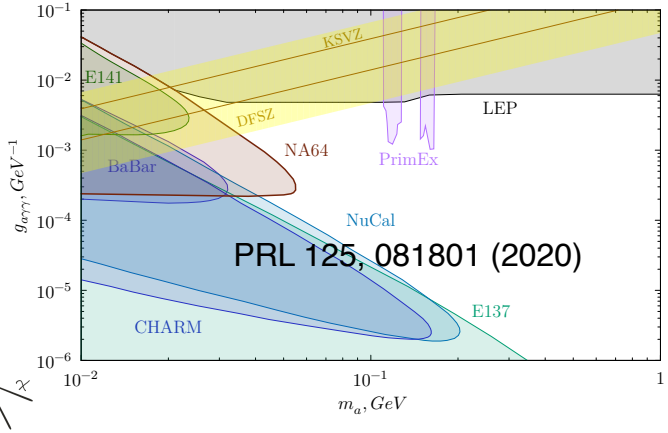
PRL 129, 161801 (2022)





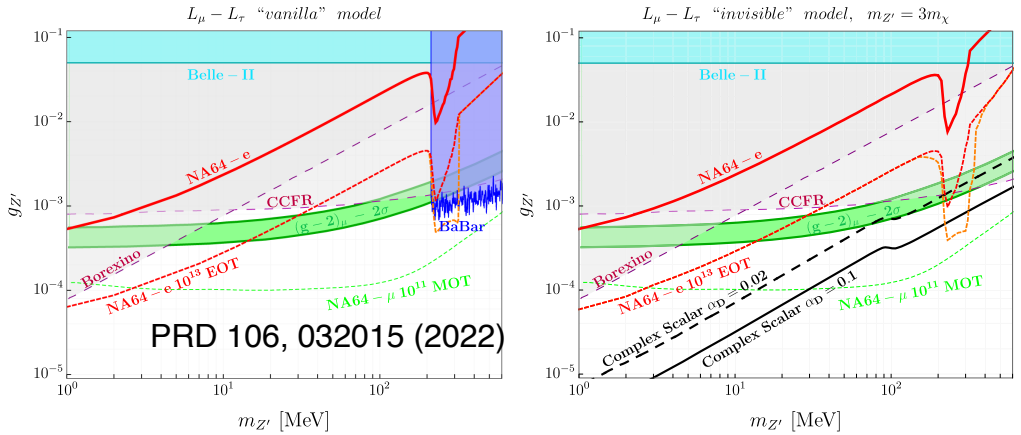
Eur. Phys. J. C (2021) **81**: 959
Eur. Phys. J. C (2023) **83**: 391

QCD axion and ALPs



PRL 125, 081801 (2020)

Lmu-Ltau Z' models

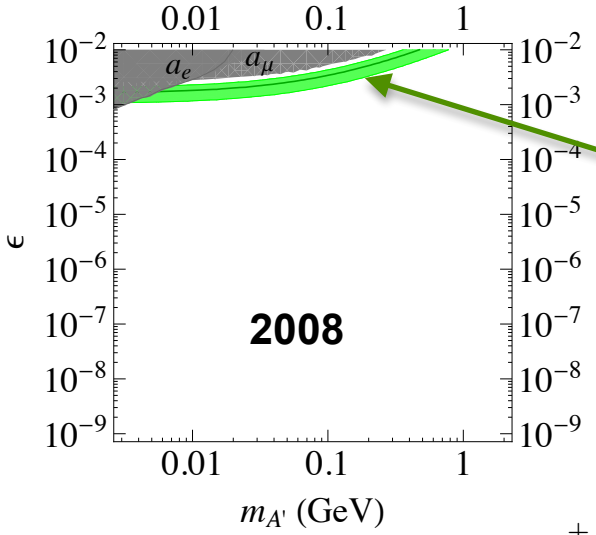


PRD 106, 032015 (2022)

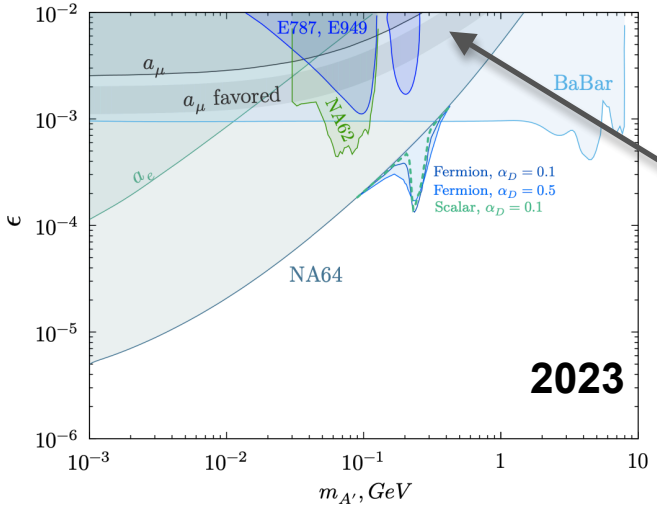
Results obtained with
3x10¹¹ EOT
(2016-2018 statistics)
Analysis in progress of
5x more data on "tape"

The muon (g-2): an additional motivation to search for dark photons

M. Pospelov, A. Ritz and M. B. Voloshin,
Phys. Lett. B 662, 53 (2008)

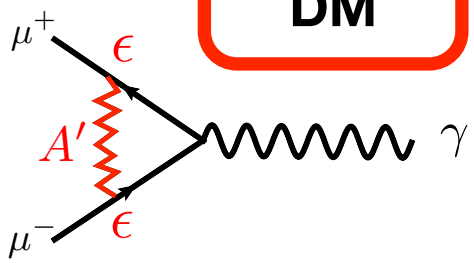


A' may have explained observed anomaly



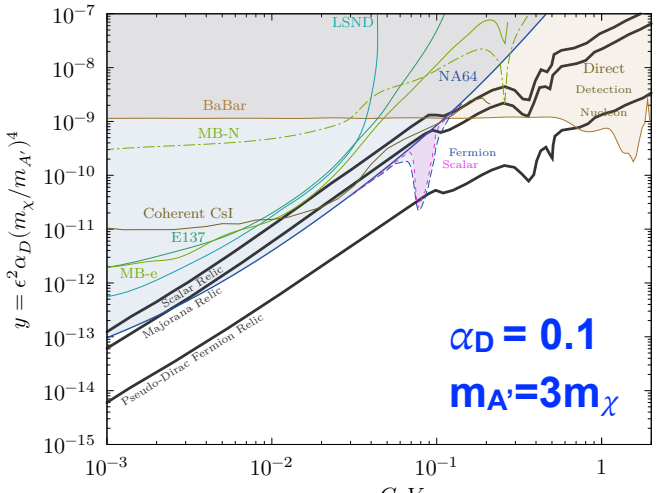
A' in minimal model was ruled out by NA64 &BABAR in 2017

DM



$$(g_s - 2)_\mu^{A'} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \qquad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

LATEST RESULTS NA64 collaboration
Phys. Rev. Lett. 131 (2023) 161801



NA64e with 10^{12} EOT starts probing LTDM

Scenarios with gauged SM symmetries: the $L_\mu - L_\tau$ model

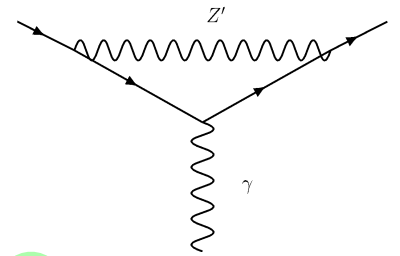
- Light **Z' vector boson** associated with the broken $U(1)_{L_\mu - L_\tau}$ symmetry

$$\mathcal{L} \supset -\frac{1}{4} F'_{\alpha\beta} F^{\alpha\beta\prime} + \frac{m^2_{Z'}}{2} Z'_\alpha Z^{\alpha\prime} - g_{Z'} Z'_\alpha J^\alpha_{\mu-\tau},$$

$$J^\alpha_{\mu-\tau} = \left(\bar{\mu}\gamma^\alpha \mu - \bar{\tau}\gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau\right),$$

He et al. Phys.Rev.D 44 (1991) 2118
Foot et al. Phys.Rev.D 50 (1994) 4571-4580
Gninenko et al. Phys. Rev.D 91 (2015) 095015

Muon $g-2$



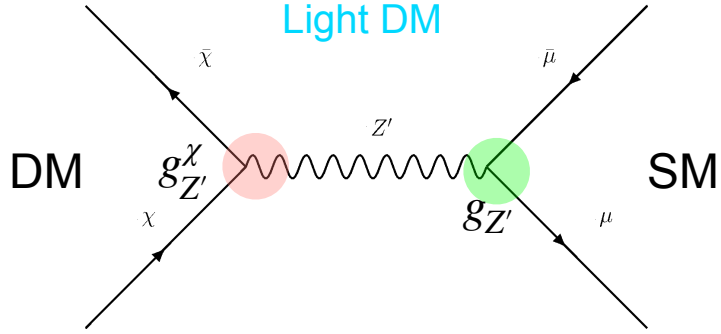
$$\Delta a_\mu^{Z'} = \frac{g^2_{Z'}}{4\pi^2} \int_0^1 dx \, \frac{x^2(1-x)}{x^2 + (1-x)m^2_{Z'}/m^2_\mu},$$

- Extension to **DM** through additional dark current in Lagrangian

$$\mathcal{L} \supset \bar{\chi}(i\gamma^\mu \partial_\mu - m_\chi)\chi + g^\chi_{Z'} \bar{\chi}\gamma^\mu \chi Z'_\mu,$$

Altmannshofer et al. JHEP 12 (2016) 106

Light DM



Z' ($L_\mu - L_\tau$) could solve simultaneously both muon (g-2) and DM problems!

Holst et al. Phys.Rev.Lett. 128 (2022) 14, 141802

The NA64 experiment running with muons at M2 beam line

- **Proposal** to the CERN SPSC for the **NA64 muon program in 2018**
- Exploit unique muon **M2 beamline at the CERN SPS** 160 GeV muons, up to 2x10^8 muons/spill
- First pilot runs in **2021** and **2022,** total of **2x10^{10} MOT**
- **2023** upgraded setup **1.5x10^{11} MOT**
- Plan before LS3 to accumulate **5x10^{11} MOT**

Phase 1 2021 - 2023

$Z' \rightarrow$ invisible

Cover $(g-2)_\mu$ | Start exploring DM parameter space

$N_{MOT} \sim 10^{11}$

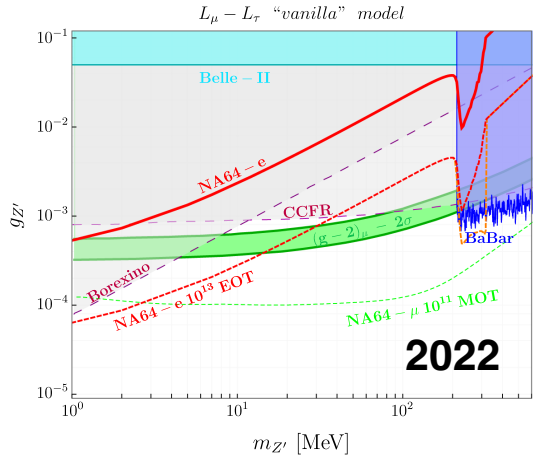
Phase 2 beyond LS3 > 2026

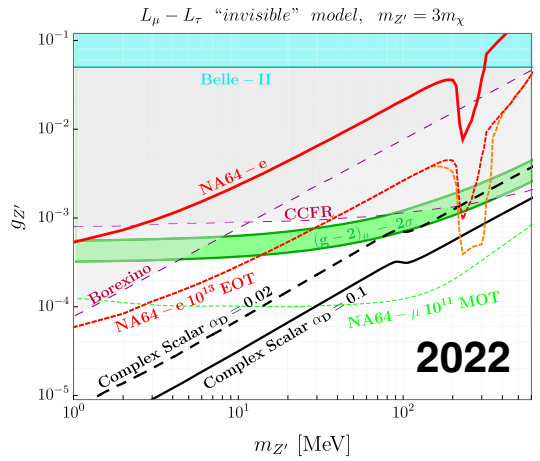
$Z', A' \rightarrow$ invisible, Q_χ, $\mu - \tau$, ...

Fully cover LDM parameter space | Search for milliQ particles, LFV, ...

$N_{MOT} \gtrsim 10^{13}$

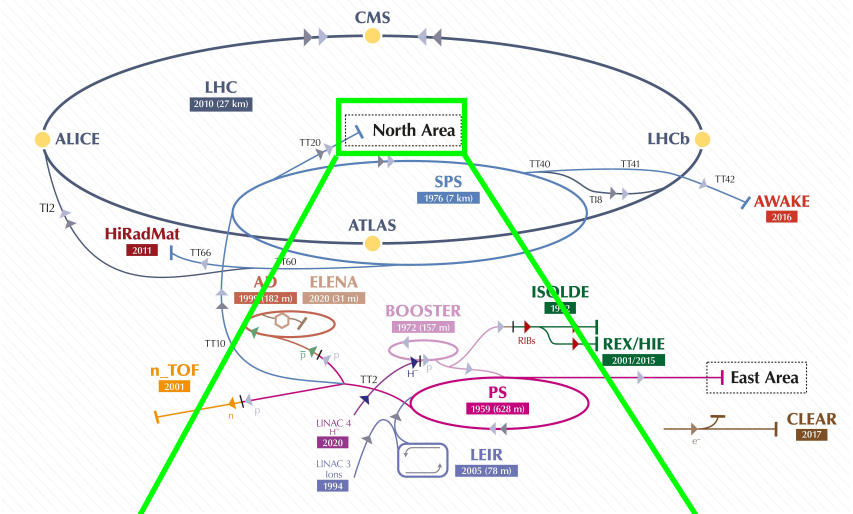
Situation before NA64 muon results:

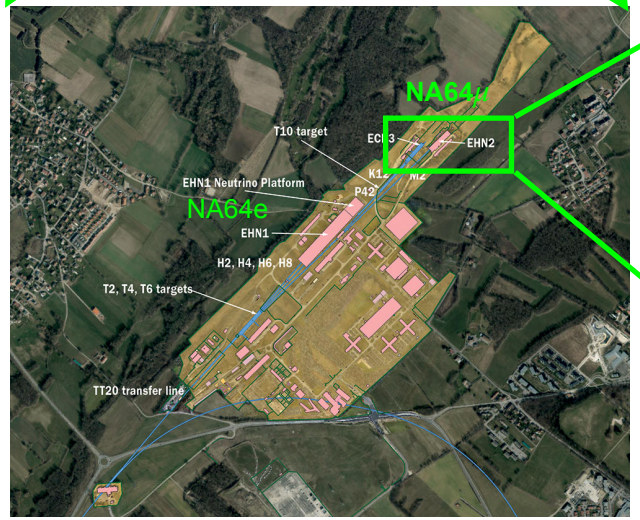




NA64 collaboration PRD 106, 032015 (2022)

The NA64 experiment running with muons at M2 beam line

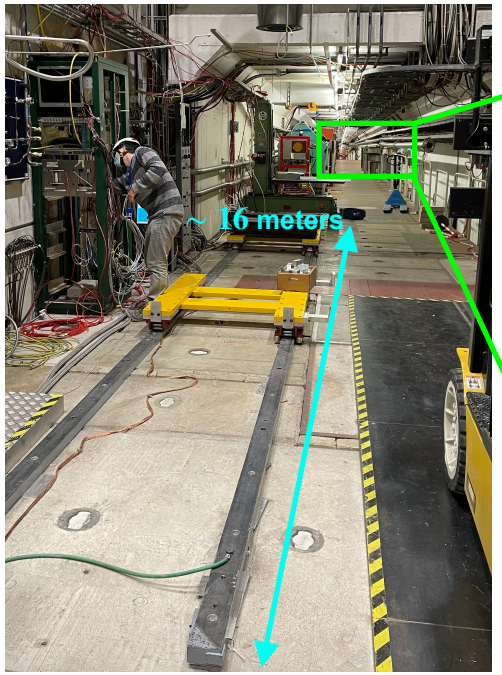




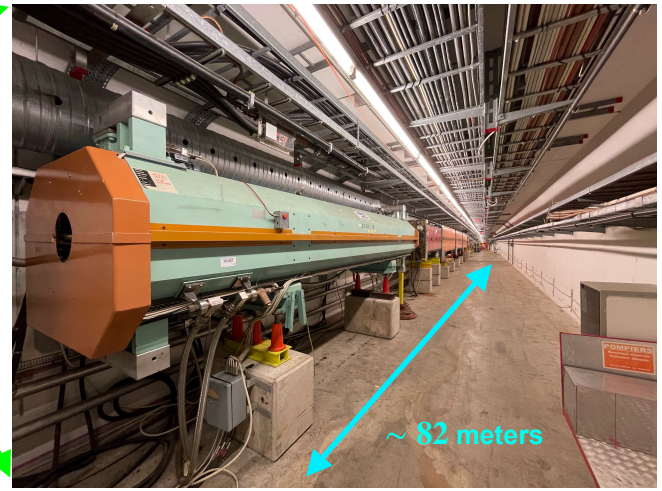
@CERN Courier

- Located at the CERN **North Area (NA)** in the EHN2 building
- Total available space is ~ 100 meters (experiment divided into an upstream and downstream part)

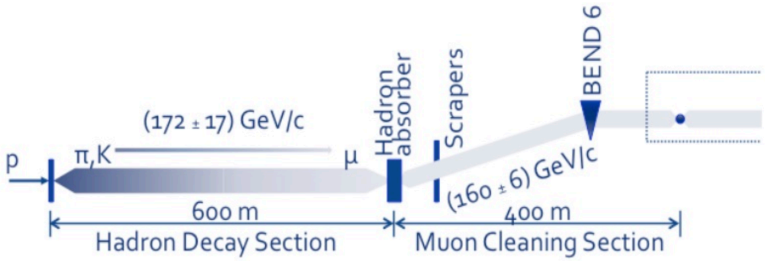
Downstream



Space allocated for the 2021-2023 pilot runs

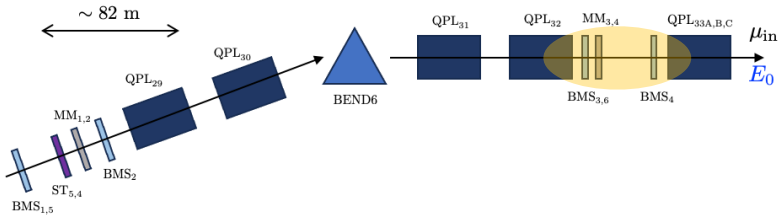


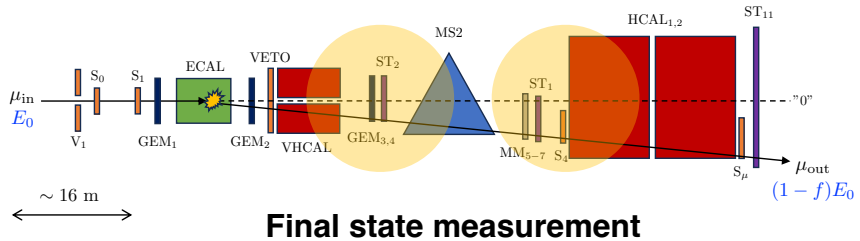
The NA64 experiment running with muons at M2 beam line



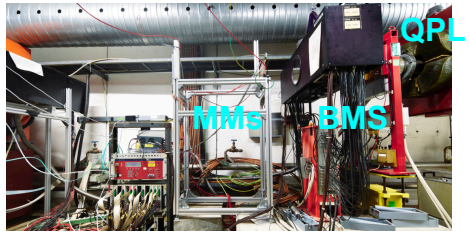
- **450 GeV/c protons** extracted from the CERN SPS to NA
- Interactions in a **beryllium target** produce hadrons (mostly pions and kaons)
- From in-flight decays, **muons** in the range of **100-225 GeV/c** with beam intensity $10^6 - 10^8$ μ/**spill**

Initial state definition
Well-defined incoming μ with $\sim$ 160 GeV/c

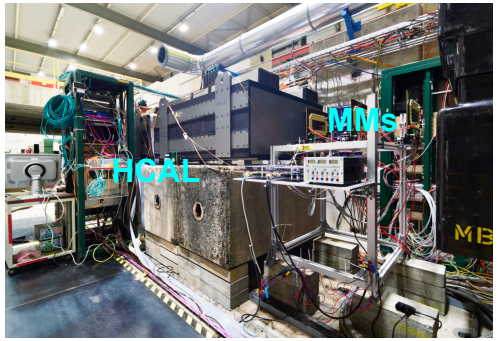


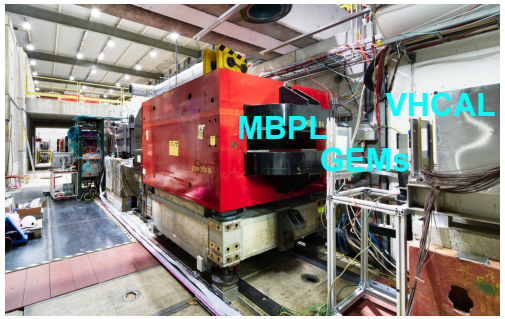


Final state measurement
Single scattered μ with muon compatible energy deposit in the detector and momentum $\lesssim$ 80 GeV/c + missing energy



Upstream ECAL

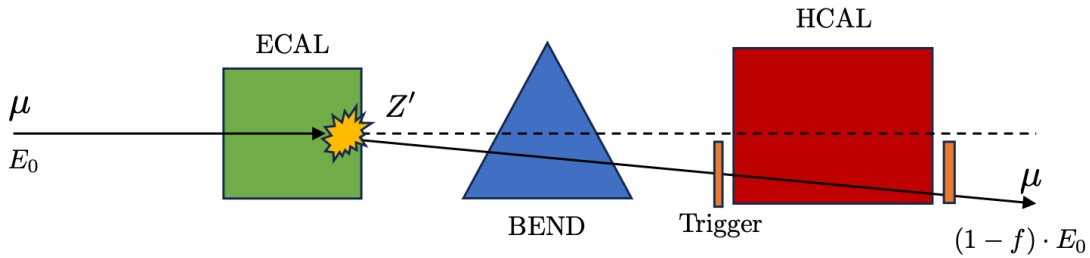




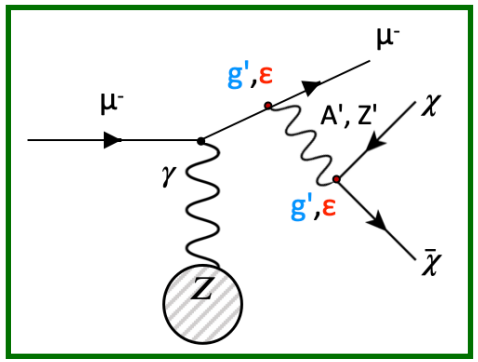
Downstream ECAL

The experimental signature

Initial state
Well-defined incoming μ with ~ 160 GeV/c



Final state
Single scattered μ with muon compatible energy deposit in the detector and momentum $\lesssim$ 80 GeV/c + missing energy

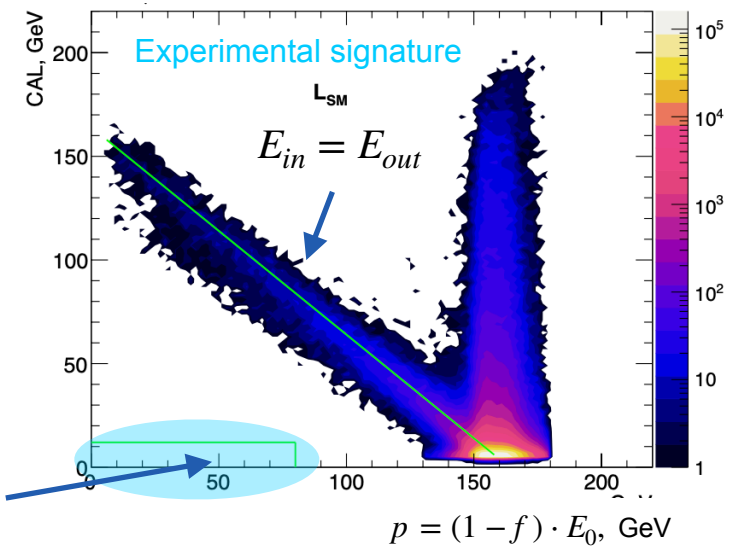


$$\sigma \sim g^2 Z^2 \alpha^2 / m^2_{A'/Z'}$$

Signature and challenge

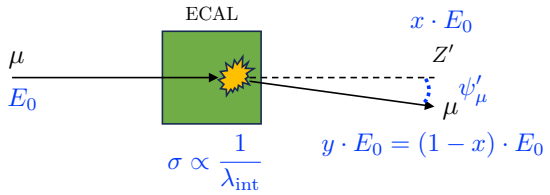
Missing energy + *missing momentum*

DM
$E_{in} > E_{out}$



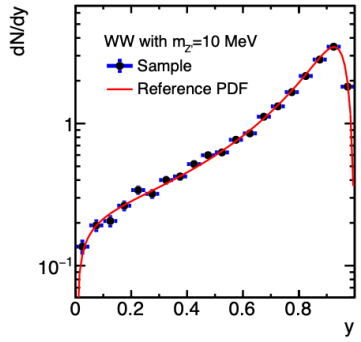
Signal and trigger optimisation

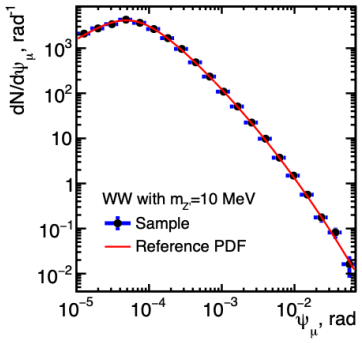
- Implementation of the underlying physics in GEANT4



$$\sigma_{Z'} \sim g_{Z'}^2 \alpha^2 Z^2 / m_{Z'}^2,$$

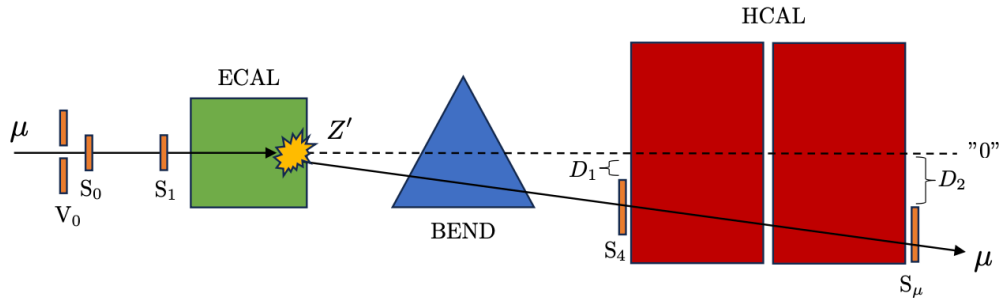
$$\psi'_\mu \sim \frac{m_{Z'}}{E_0}$$

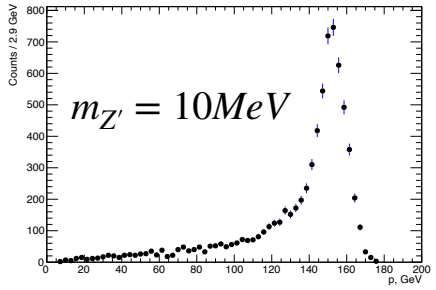


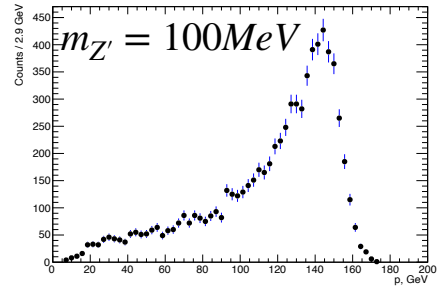


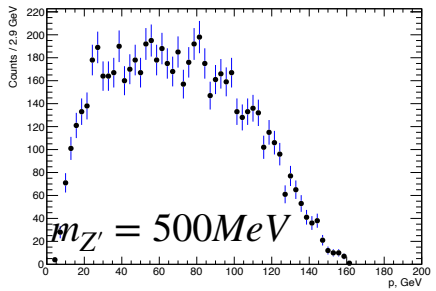
Optimization of the trigger for final state muons

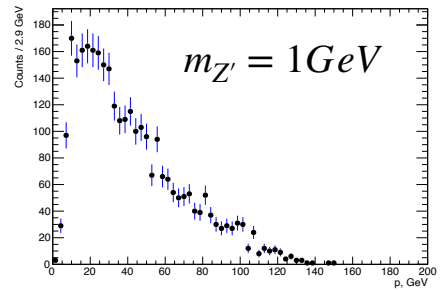
- $m_{Z'} < 100$ MeV: **high** yield, **low** acceptance
- $m_{Z'} > 100$ MeV: **low** yield, **high** acceptance











Data analysis

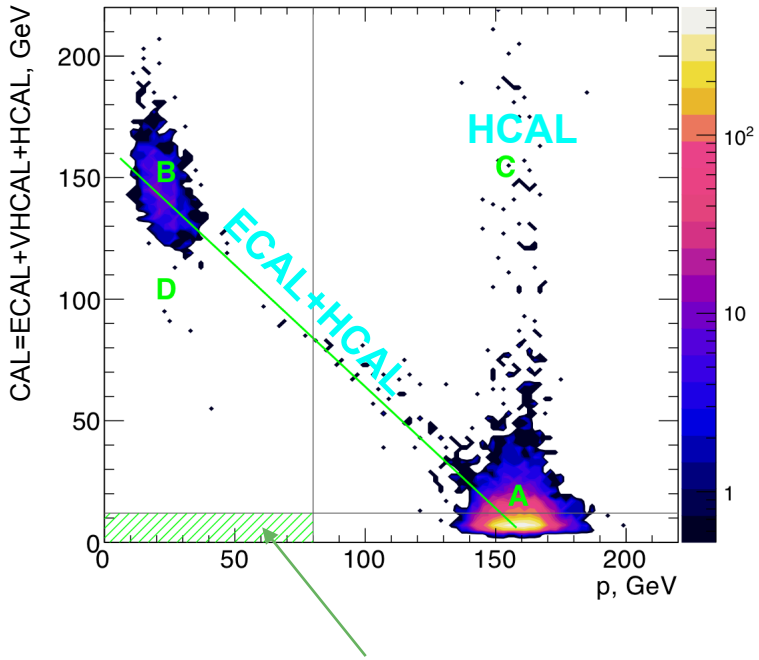
- **Main selection criterion**
  - Incoming momentum in the range [140, 180] GeV/c
  - Single reconstructed track in the downstream set-up (momentum < 80 GeV/c)
  - No activity in the VHCAL and Veto, energy compatible with a muon (MIP) in ECAL and HCAL

- Study of the **background sources**, with dominant contributions e**xtrapolated to the blinded signal region**

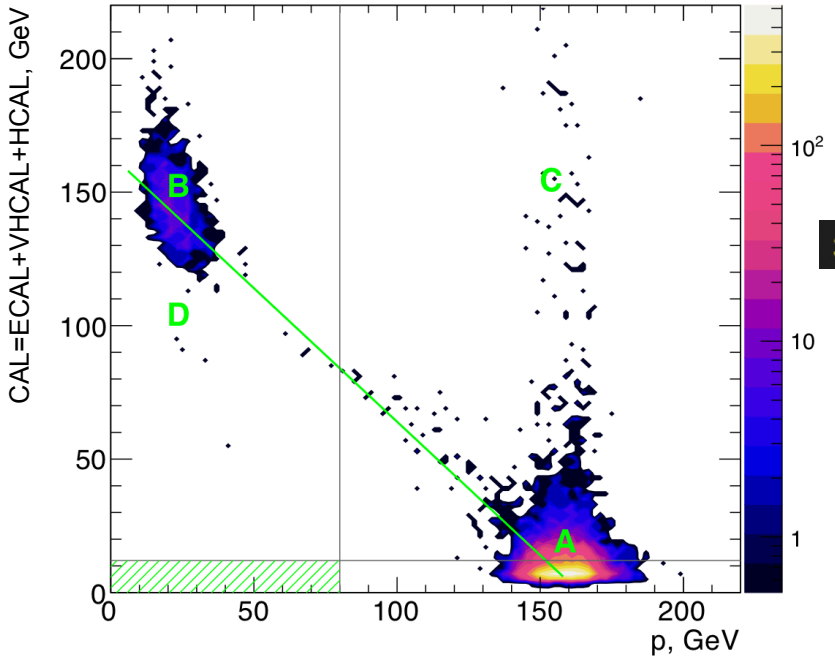
Background source	Background level
1) Momentum mis-reconstruction	0.045±0.031
2) Hadron in-flight decays	0.010±0.001
3) Calorimeter non-hermeticity	<0.01
Total (conservatively)	**0.07±0.03**

- Systematics of 8% in the signal yield (MC accuracy, underlying Z' physics, trigger alignment…)

Statistics
$(1.98 \pm 0.02) \times 10^{10}$ MOT

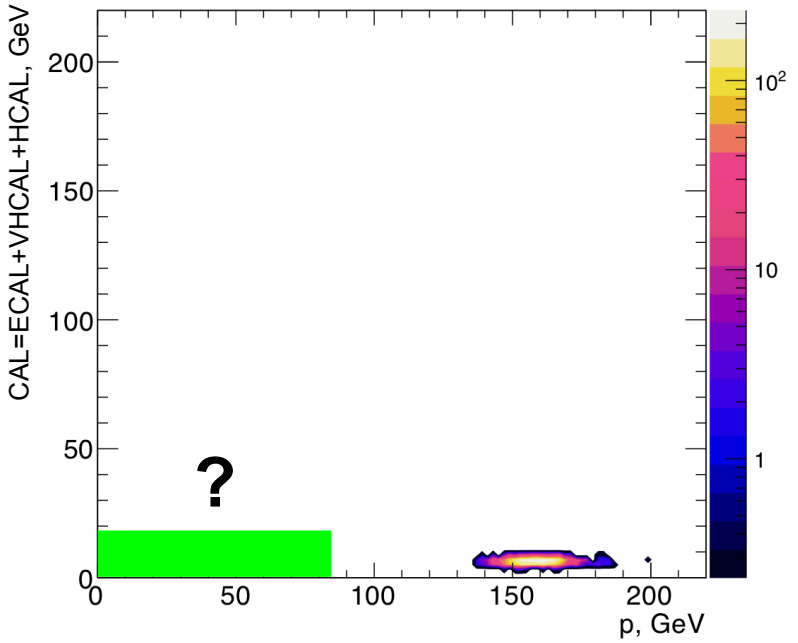


Unblinding

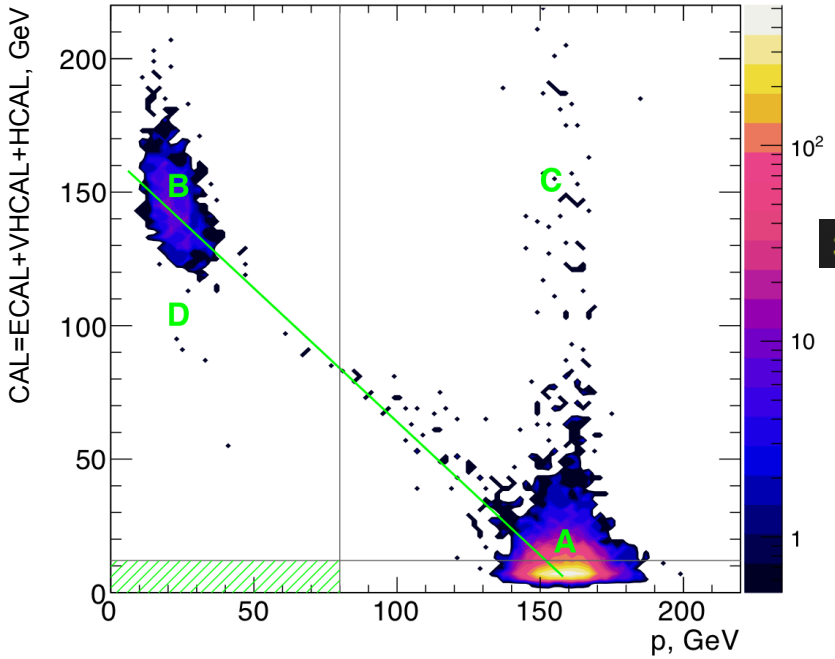



```
37 #define BLIND_ANALYSIS 1
```

Apply **all selection criteria**!

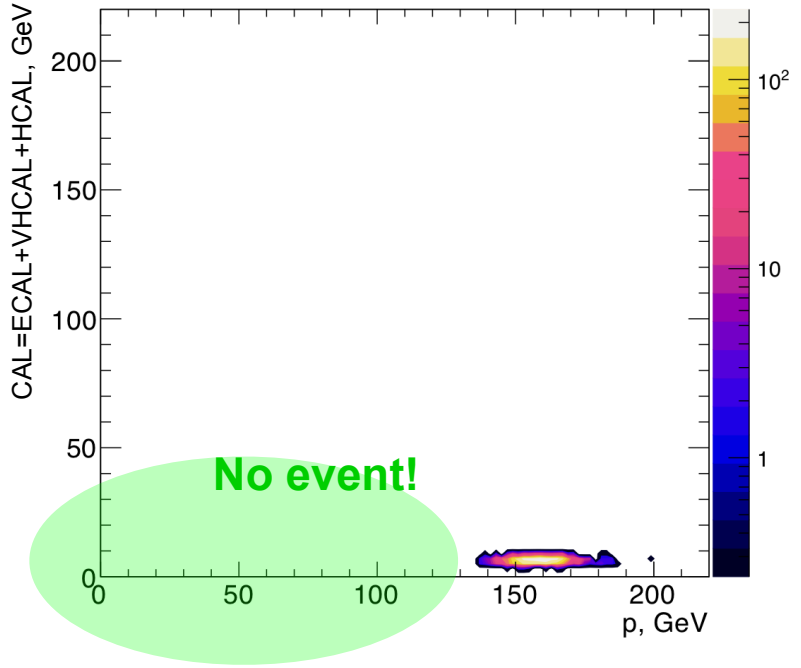


Unblinding




```
37 #define BLIND_ANALYSIS 0
```

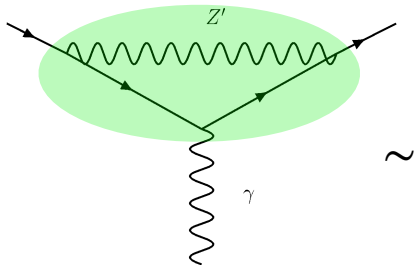
Apply **all selection criteria**!



Constraints on the muon $(g-2)_\mu$ in the $U(1)_{L_\mu - L_\tau}$ scenario

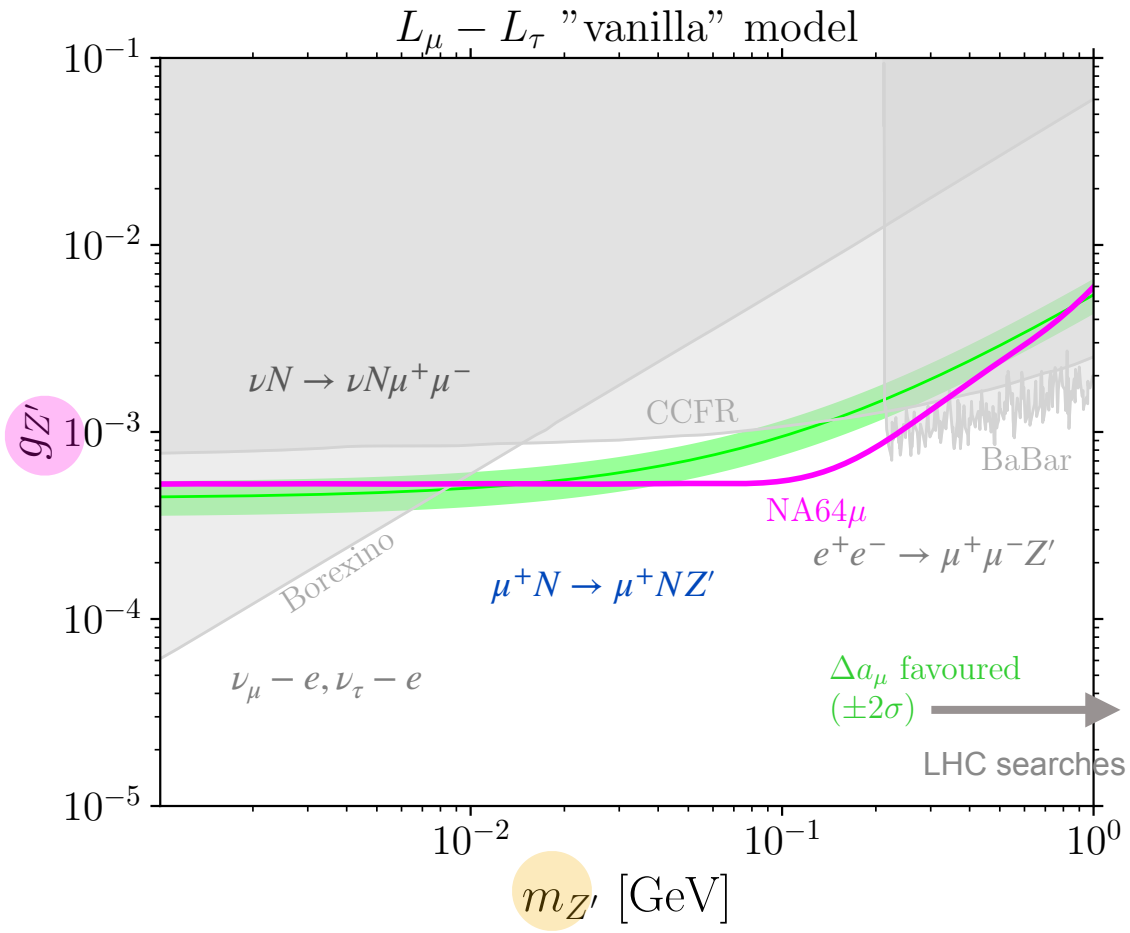
- Upper limits computed at 90% CL in the **modified frequentist approach** → **first results** in the search for a light *Z'* with a muon beam

- Part of the remaining parameter space compatible with the muon $(g-2)_\mu$ **excluded**



$$\sim \quad \Delta a_\mu \simeq \frac{(g_{Z'})^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$

- **Complement** previous experiments in the mass region $\mathcal{O}(10-100\ \text{MeV})$ with $g_{Z'} \leq 6\times10^{-4}$



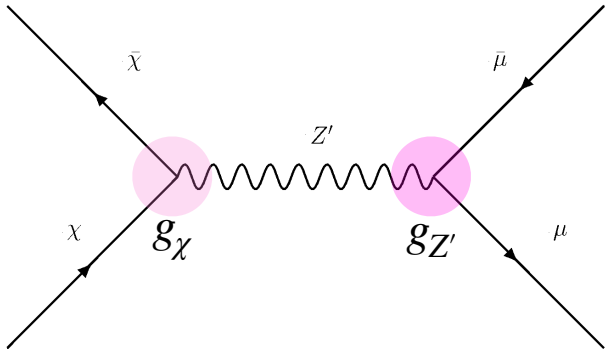
arXiv:2401.01708 , Accepted in PRL 08/04/2024

Exploring the thermal DM parameter space

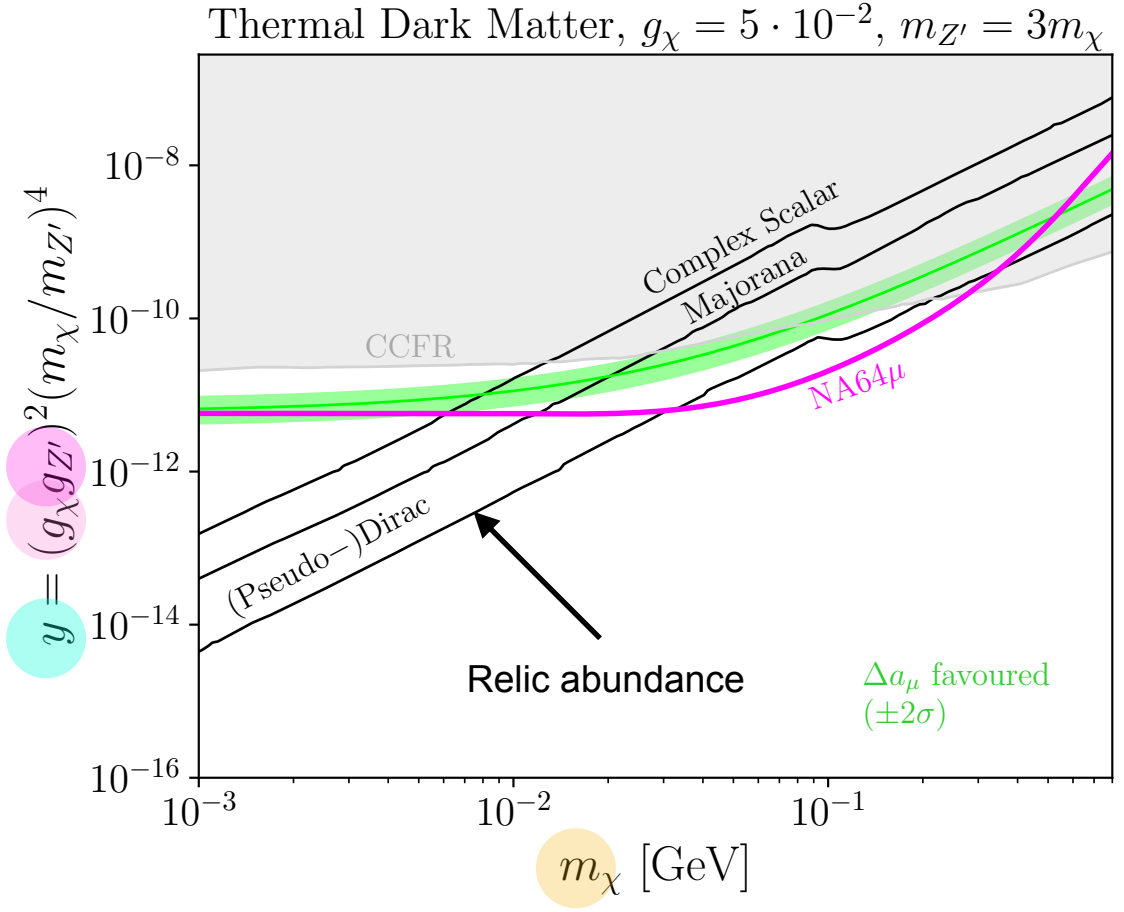
- Results also allow one to constrain predictive scenarios for **thermal DM**

$$\mu + N \to \mu + N + (Z' \to \bar{\chi}\chi)$$

- **First results with a muon beam** constraining $y \lesssim 6 \times 10^{-12}$



$$\sim \langle \sigma v \rangle \sim \frac{y}{m_\chi^2}$$



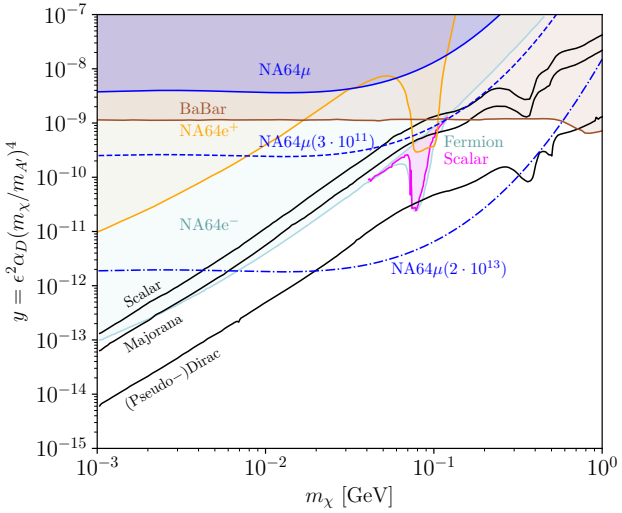
arXiv:2401.01708 , Accepted in PRL 08/04/2024

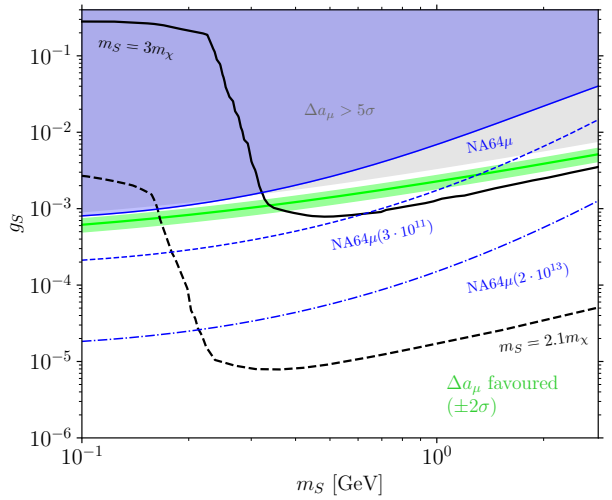
Post LS3 prospects for NA64μ

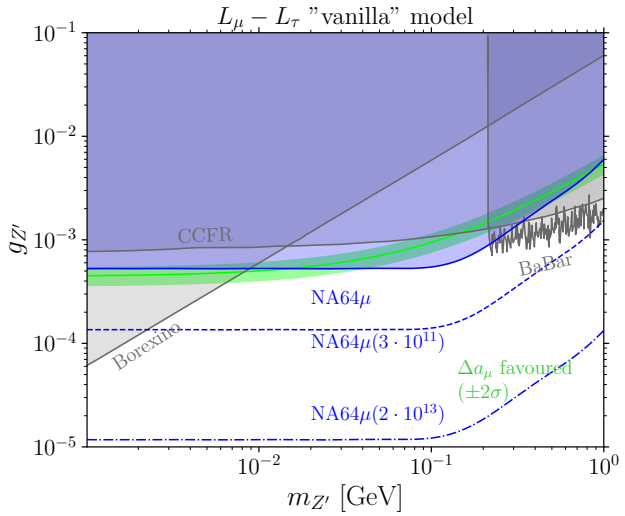
During LS3:
setup upgrade to run up to 5x10^7 muons/spill

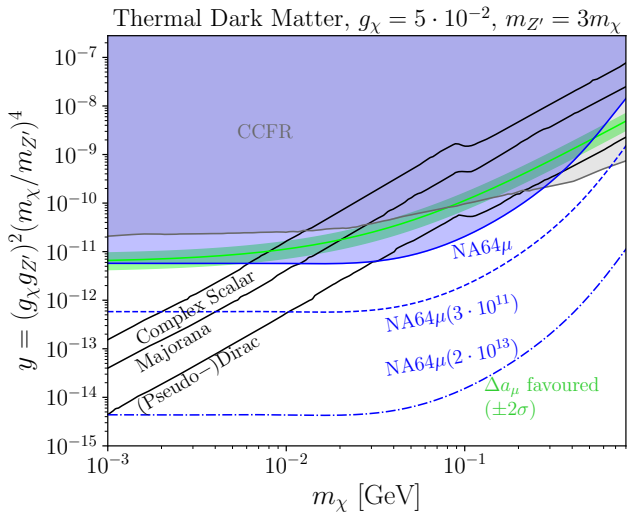
GOAL > 2× 10^{13} EOT

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









H. Sieber, PhD Thesis, ETH Zurich, December, 2023

Summary and Outlook for the NA64 physics program

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.**

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