https://www.psi.ch/en/ltp/mu-mass

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

Latest Results from MuMASS and NA64mu Experiments

Muons in Minneapolis Workshop - 8th of December 2023

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

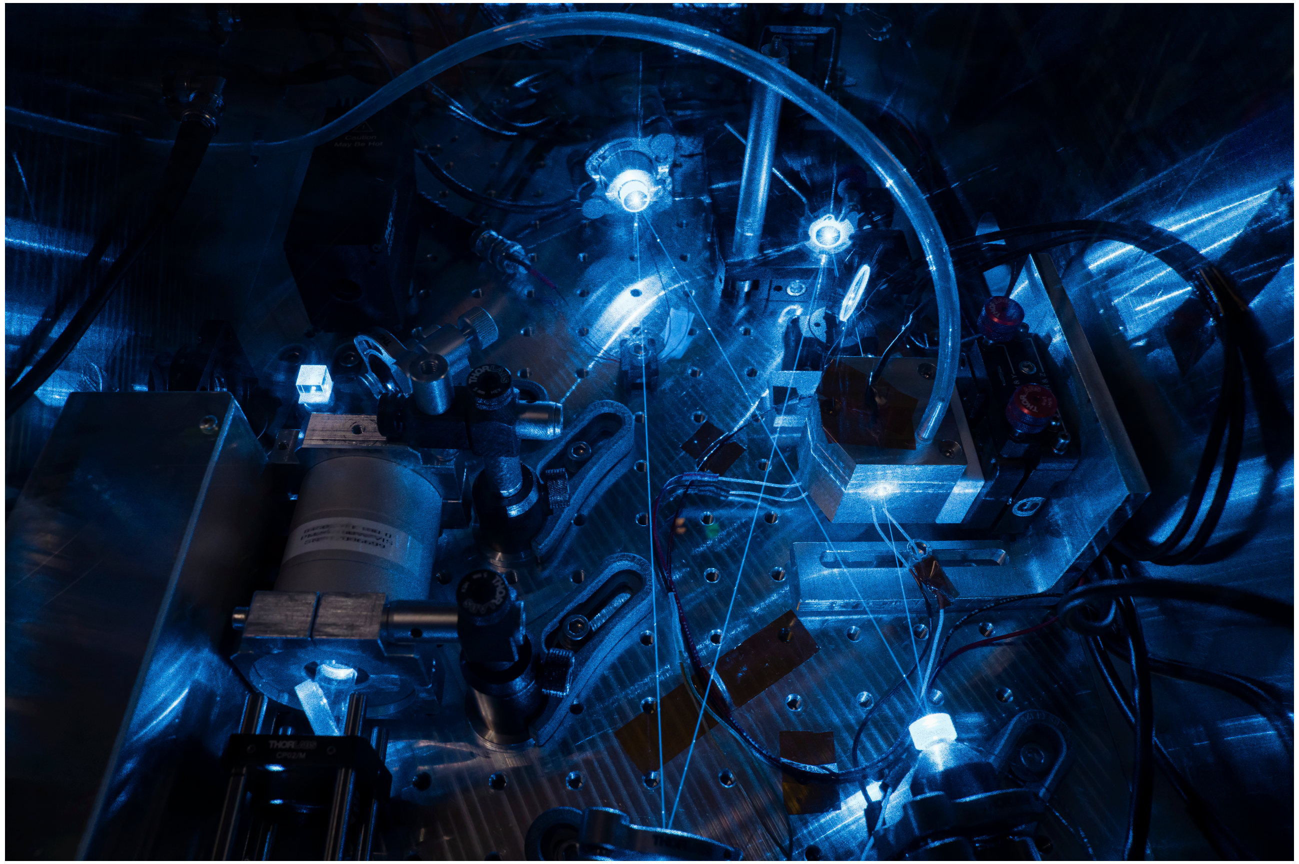
Outline

1) **Few keV muons** for muonium spectroscopy: **MuMASS @ PSI**

2) **Sub TeV muons** for dark sector searches: **NA64mu @ CERN SPS**

ETH zürich

IPA



MU-MASS

https://www.psi.ch/en/ltp/mu-mass

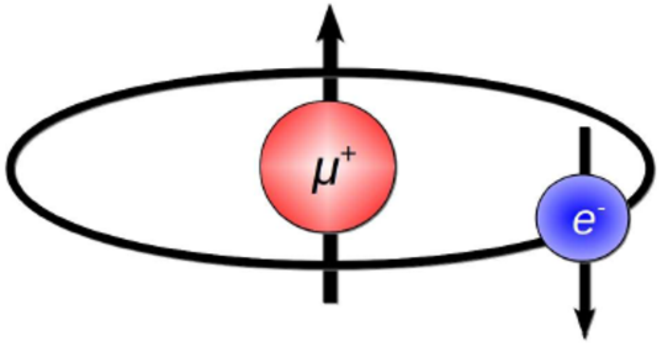
erc
European Research Council
Established by the European Commission

THIS WORK IS SUPPORTED BY an ERC consolidator grant (818053 -Mu-MASS) and by the Swiss National Foundation under the grant 197346.

The Mu-MASS experiment at PSI

Swiss National Science Foundation

The muonium (M)



Vernon Hughes
1921-2003

- **M (positive muon-electron bound state)**

Predicted in 1957 (Friedmann, Telegdi, Hughes)
Unstable with lifetime of **2.2 μs**
Main decay channel: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- **Discovered** in 1960 (Hughes) by detecting **muonium spin** (Larmor) **precession** in an external magnetic field perpendicular to the spin direction.

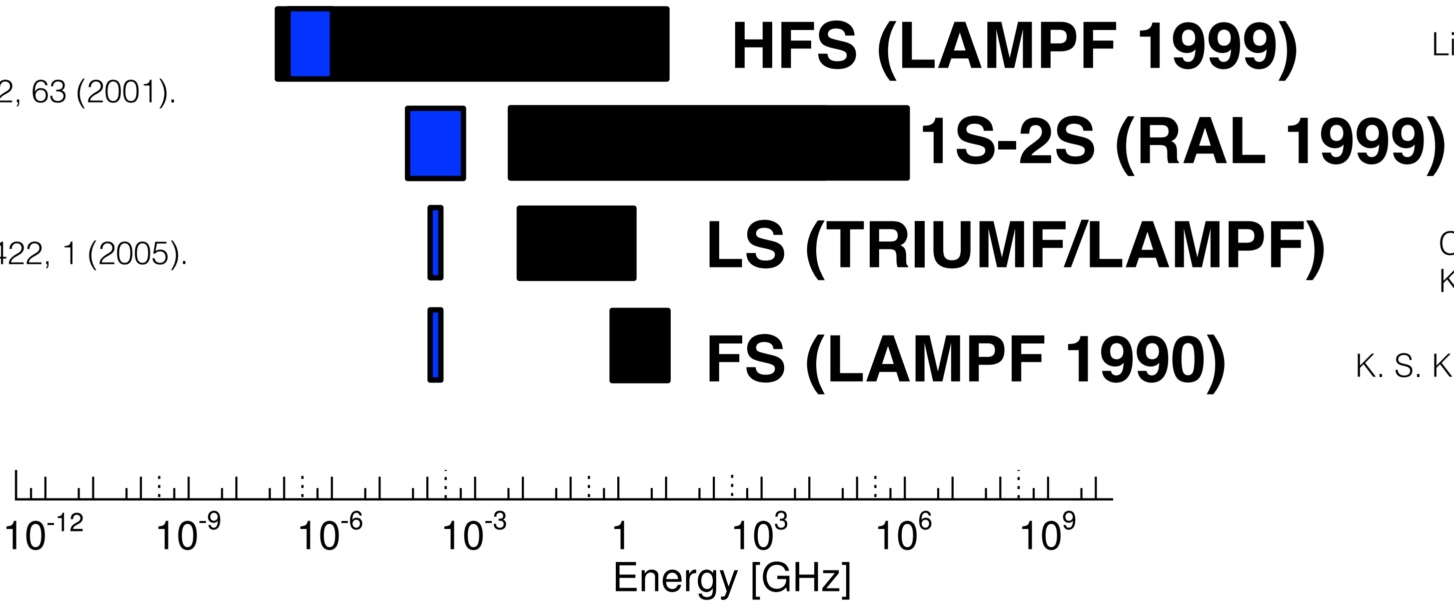
- Being **purely leptonic**, **devoid of uncertainties in the calculations from nuclear size effects** present in normal atoms. Therefore, any deviation between theory and measurements could be a signal of **New Physics.**

- From measurements with M one can extract the **muon mass and muon magnetic moment.**

Muonium spectroscopy Theory and Experiments until recently

M. I. Eides et al., Phys. Rep. 342, 63 (2001).

S. G. Karshenboim, Phys. Rep. 422, 1 (2005).



Liu et al. PRL82, 711 (1999)

Meyer et al. PRL84, 1136 (2000)

C .J. Oram et al., PRL 52, 910 (1984)
K. Woodle et al., PRA 41, 93 (1990)

K. S. Kettel, PhD Thesis, LA—11893-T (1990)

EXP. — **UNCERTAINTY (LEFT EDGE)**
MEASURED QUANTITY (RIGHT EDGE)

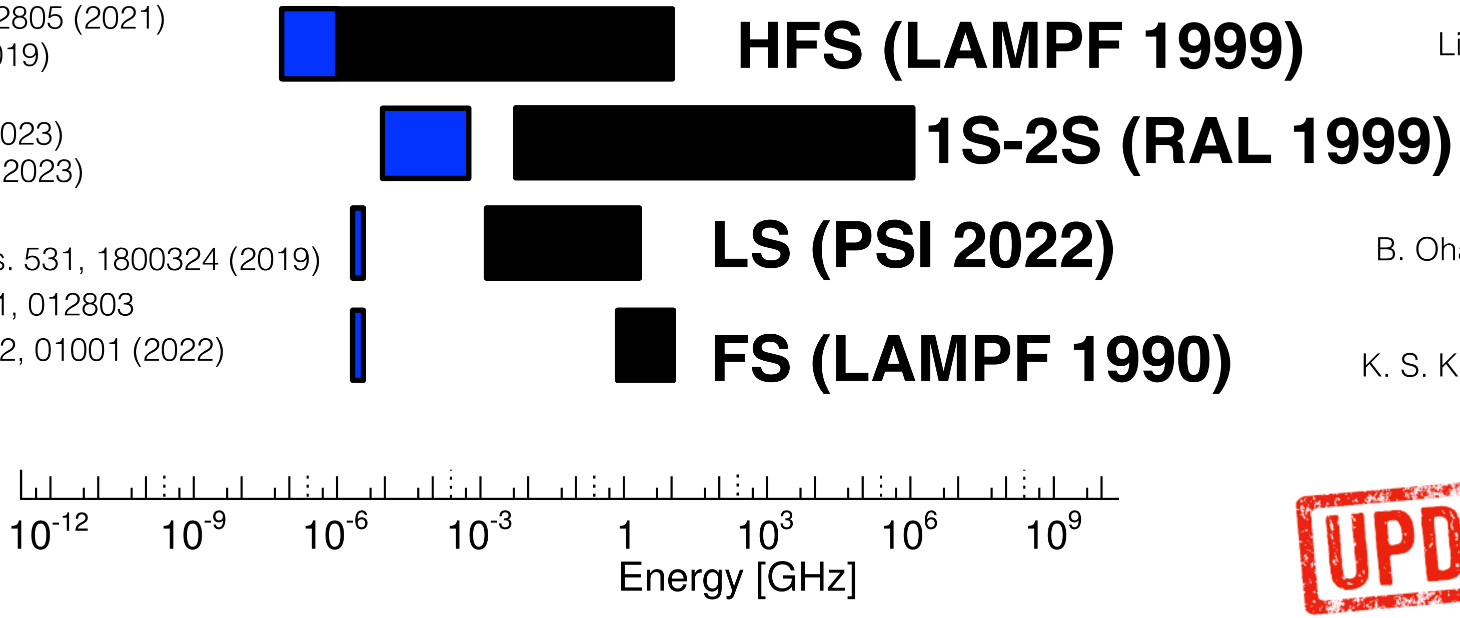
THEORY — **UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)**
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

Muonium spectroscopy current status of Theory and Experiments

Karshenboim et al. PRA 103, 022805 (2021)
Eides, Phys. Lett. B 795, 113 (2019)

Adkins et al. PRL130, 023004 (2023)
I. Cortinovis et al., EPJD 77, 66 (2023)

V.A. Yerokhin, et al. Ann. der Phys. 531, 1800324 (2019)
M. Heides et al. PRA 105 (2022) 1, 012803
G. Janka et al. EPJ Web Conf. 262, 01001 (2022)



Liu et al. PRL82, 711 (1999)
Meyer et al. PRL84, 1136 (2000)
B. Ohayon et al, PRL 128, 011802 (2022)
K. S. Kettel, PhD Thesis, LA—11893-T (1990)

UPDATE

EXP. UNCERTAINTY (LEFT EDGE)
MEASURED QUANTITY (RIGHT EDGE)

THEORY UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

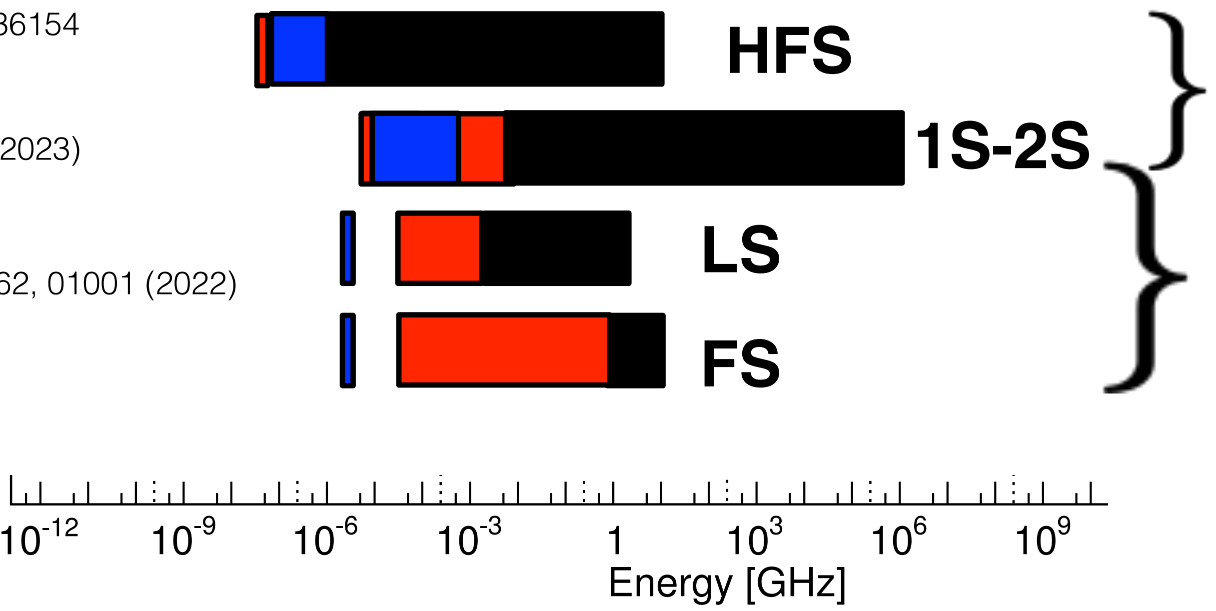
MU-MASS

Muonium spectroscopy - ongoing experiments

S. Kanda et a. PLB 815 (2021) 136154

I. Cortinovis et al., EPJD 77, 66 (2023)

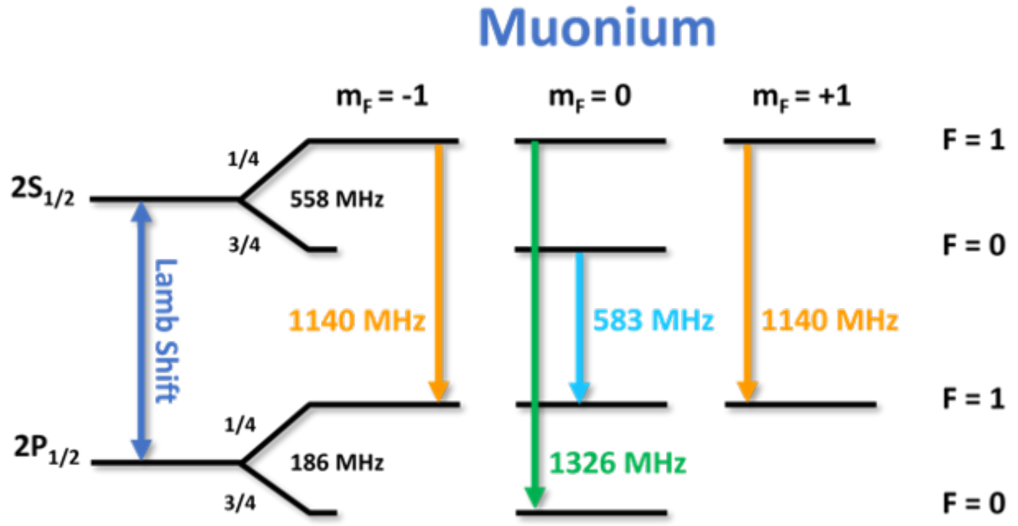
G. Janka et al. EPJ Web Conf. 262, 01001 (2022)



EXP. **PROJECTED UNCERTAINTY (LEFT EDGE)**
MEASURED QUANTITY (RIGHT EDGE)

THEORY **UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)**
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

Muonium Lamb shift



THEORY $$(E(2S_{1/2}) - E(2P_{1/2}))^{\mathrm{th}}_{\mathrm{Mu}} = 1047.498(1)\,\mathrm{MHz}.$$

G. Janka et al. EPJ Web Conf. 262, 01001 (2022)

EXPERIMENT $$(E(2S_{1/2}) - E(2P_{1/2}))^{\mathrm{exp}}_{\mathrm{Mu}} = 1042(22)\ \mathrm{MHz}.$$

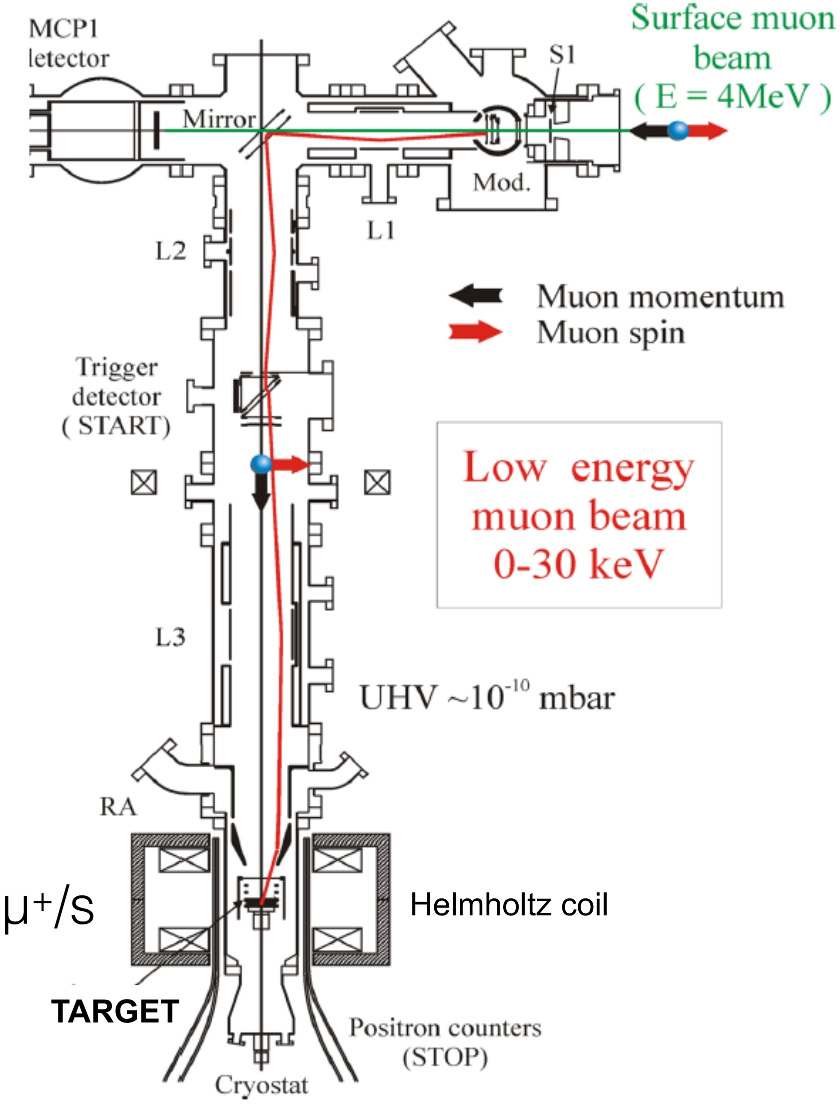
C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984). DOI 10.1103/PhysRevLett.52.910. @ TRIUMF
K. Woodle, et al., Phys. Rev. A 41, 93 (1990). DOI 10.1103/ PhysRevA.41.93 @ LAMPF

Recoil corrections are enhanced for M (9 times lighter than H)

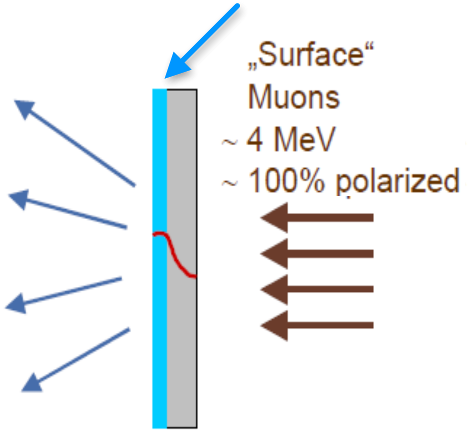
	Largest Order	Hydrogen (MHz)	Muonium (MHz)
E_{SE}	$\alpha\,(Z\alpha)^4\,L$	1084.128	1070.940
E_{VP}	$\alpha\,(Z\alpha)^4$	−26.853	−26.510
$E_{\mathrm{VP}\mu+\mathrm{had}}$	$\alpha\,(Z\alpha)^4(m_e/m_\mu)^2$	−0.001	−0.001
E_{2ph}	$\alpha^2(Z\alpha)^4$	0.065	0.065
E_{3ph}	$\alpha^3(Z\alpha)^4$	0.000	0.000
E_{BKG}	$(Z\alpha)^4\ (m_e/m_n)^2$	−0.002	−0.168
$E_{\mathrm{rec,S}}$	$(Z\alpha)^5\ L\,(m_e/m_n)$	0.358	3.138
$E_{\mathrm{rec,R}}$	$(Z\alpha)^6\ (m_e/m_n)$	−0.001	−0.012
$E_{\mathrm{rec,R2}}$	$(Z\alpha)^6\ (m_e/m_n)^2$	−0.000	−0.001(1)
E_{RR}	$\alpha\,(Z\alpha)^5\ (m_e/m_n)$	−0.002	−0.014(1)
$E_{\mathrm{RR2e+p}}$	$\alpha\,(Z\alpha)^5\ (m_e/m_n)^2$	0.000	0.000
E_{RR3}	$\alpha^2(Z\alpha)^5\ (m_e/m_n)$	−0.000	−0.000
E_{SEN}	$Z^2\alpha\,(Z\alpha)^4\,(m_e/m_\mu)^2$	0.001	0.041
E_{HFS}	$\alpha^2(Z\alpha)^2\,(m_e/m_n)^2$	0.002	0.019
Sum			1047.498(1)

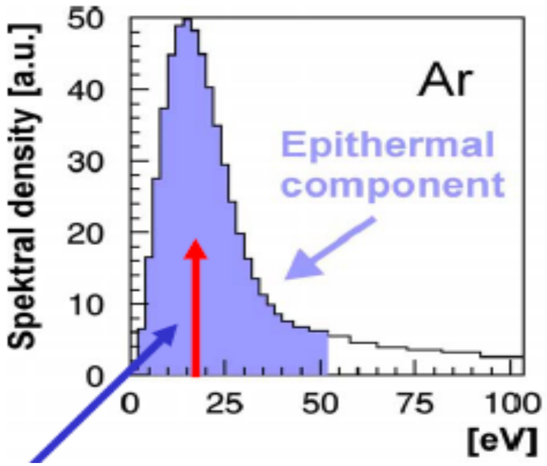
The PSI low energy muon beam (LEM)

https://www.psi.ch/en/low-energy-muons



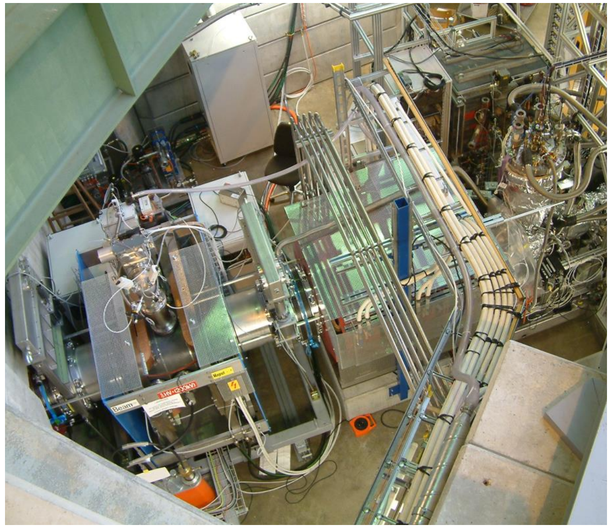
Up to $5x10^3$ μ^+/s





E~15eV

PAUL SCHERRER INSTITUT



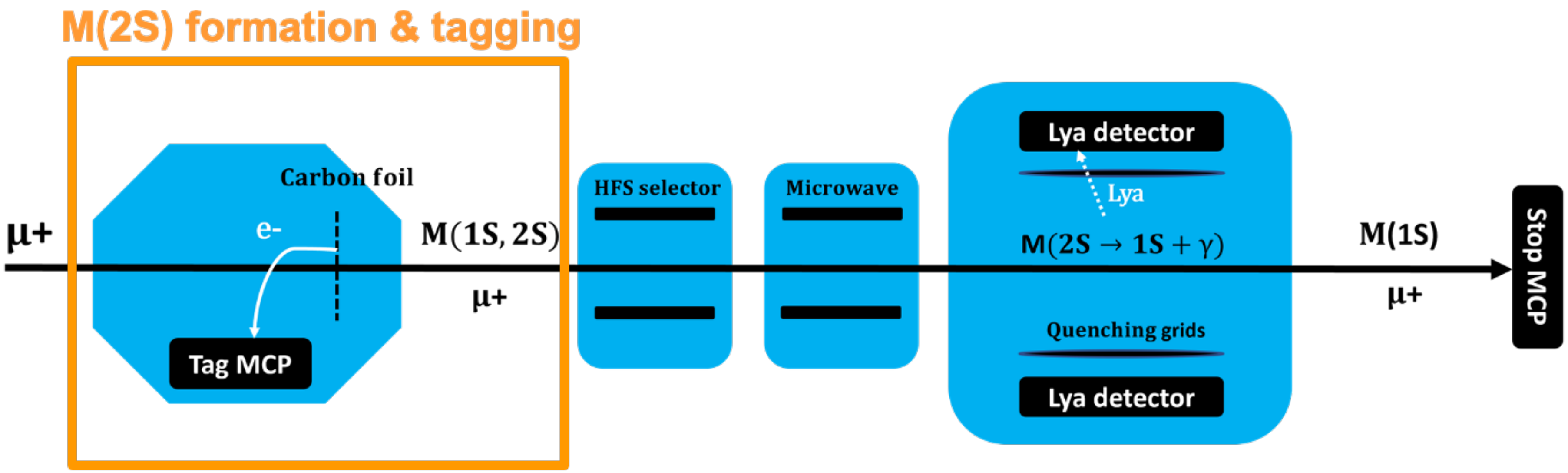
MU-MASS

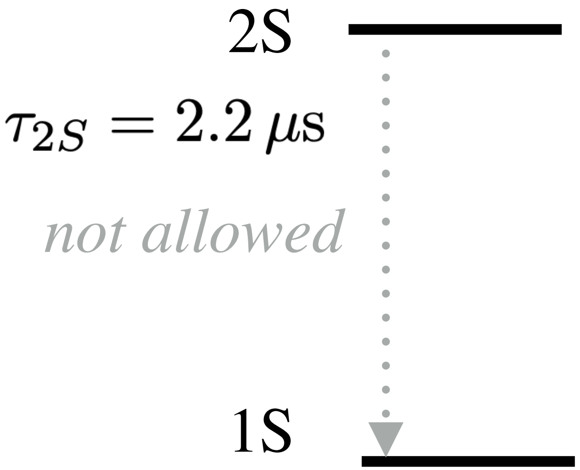
Measurement of M the Lamb shift

LEM beamline

10 kHz/
10 keV

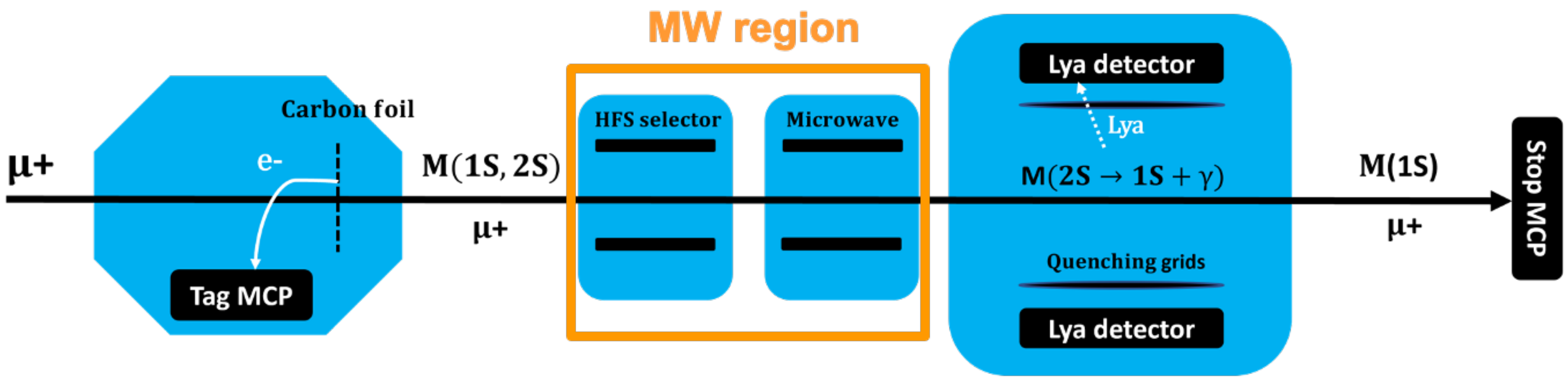
PAUL SCHERRER INSTITUT PSI

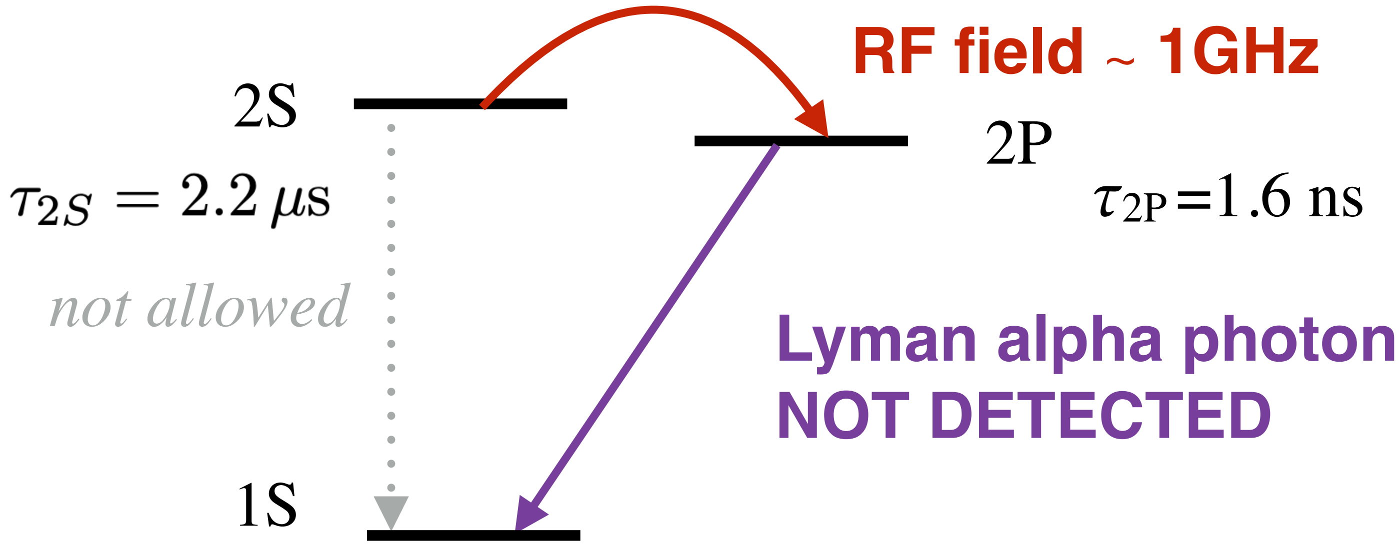




MU-MASS

Measurement of M the Lamb shift

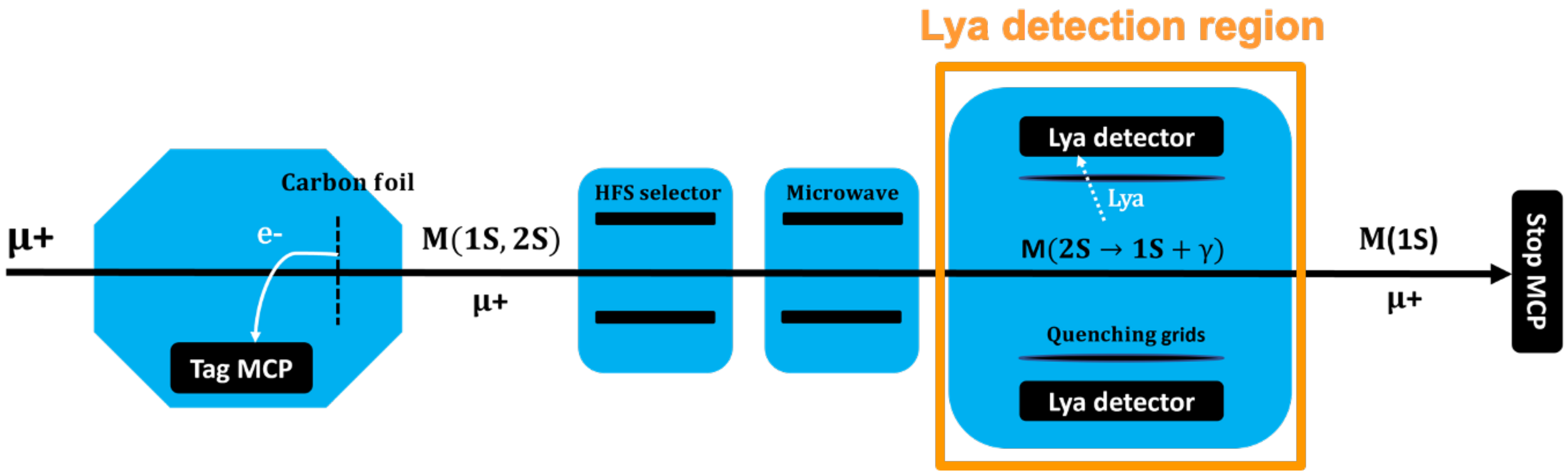


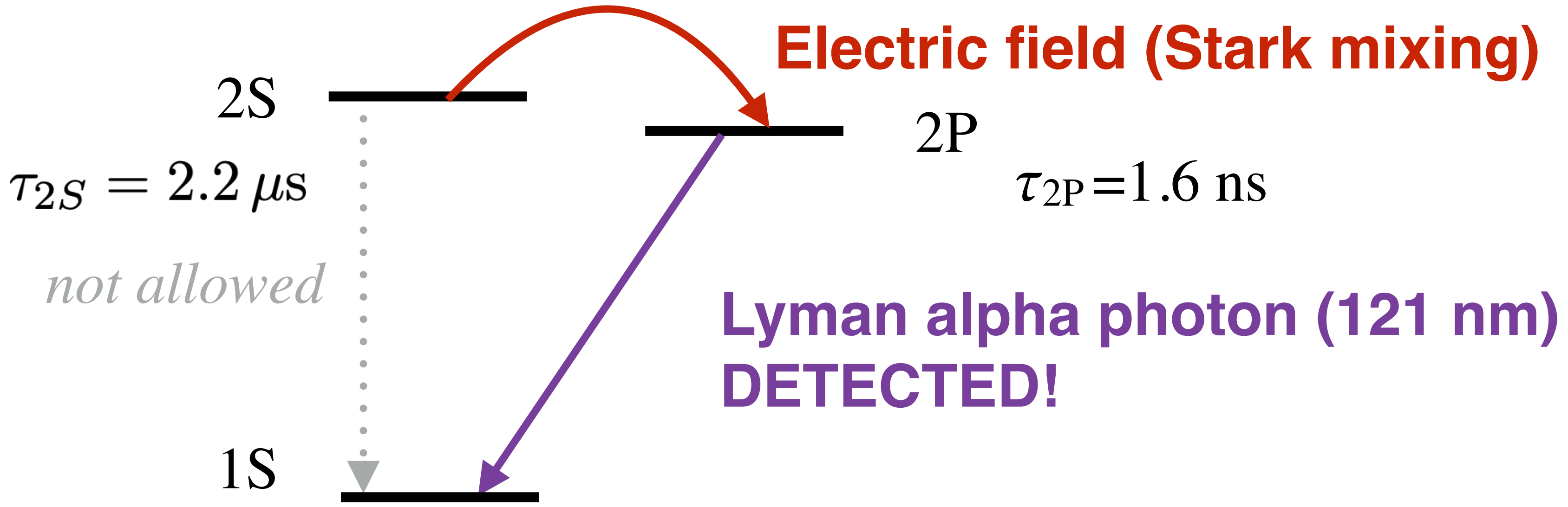


RF field ~ 1GHz

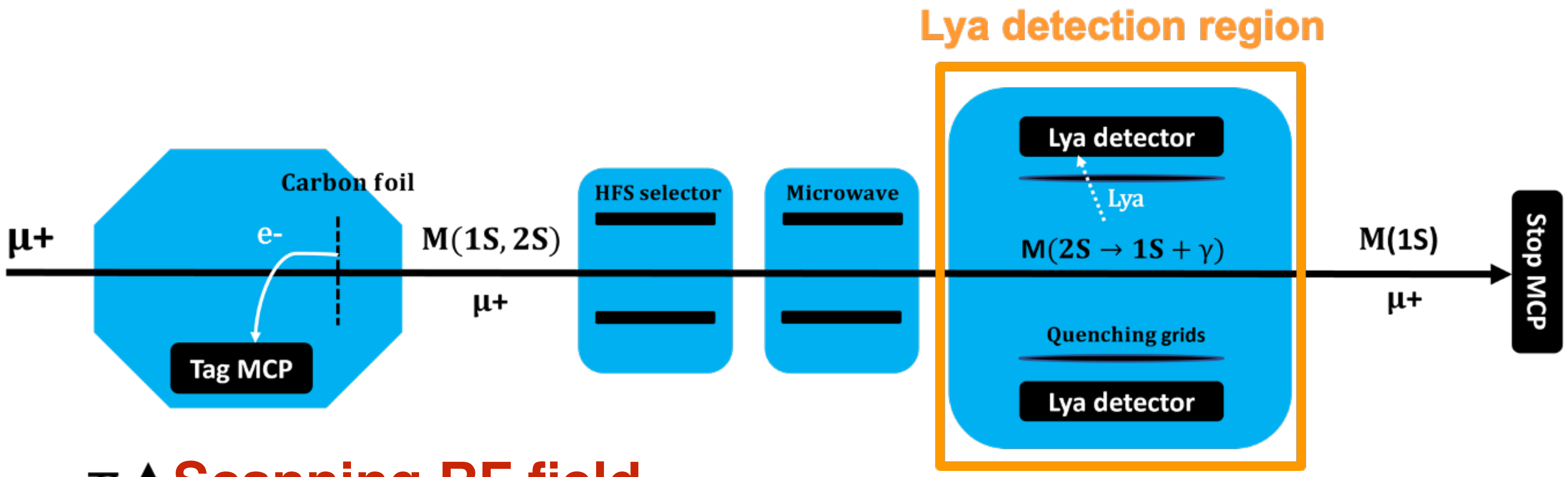
Lyman alpha photon (121 nm)
NOT DETECTED

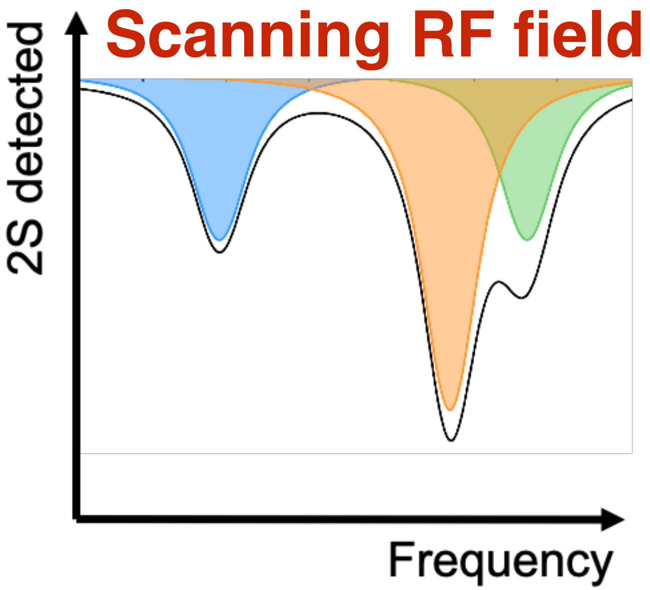
Measurement of M the Lamb shift

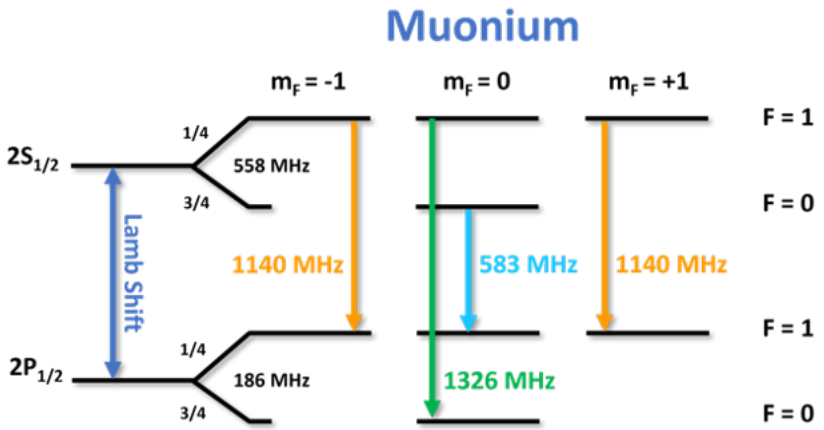




Measurement of M the Lamb shift



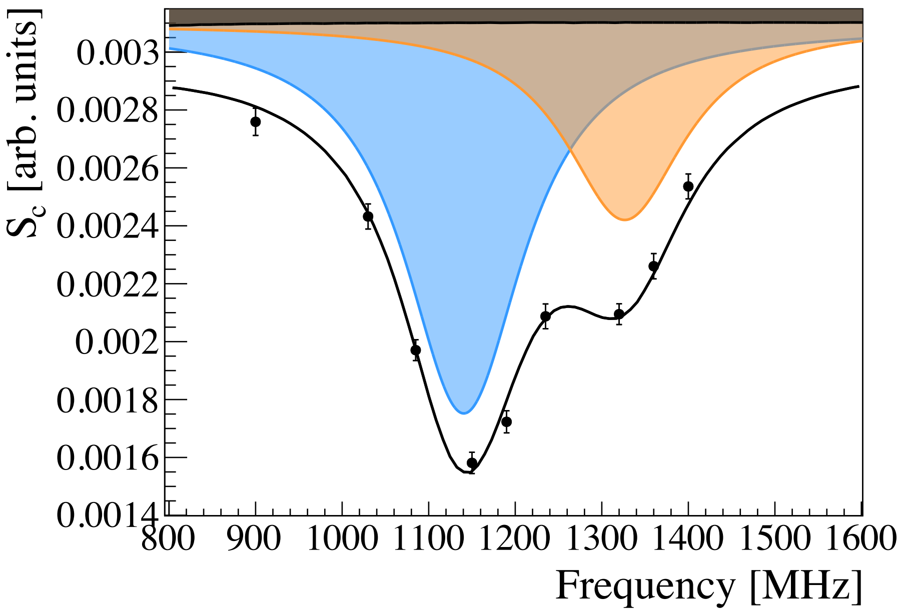




Results of the M Lamb shift

B. Ohayon, P. Crivelli, et al. Phys. Rev Lett. 128, 011802 (2022)
G. Janka, P .Crivelli, et al., NC 13, 7273 (2022)

48 HOURS DATA TAKING (100x statistics compared to previous measurements)



	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	$+0.26$	< 0.02
2^{nd}-order Doppler	$+0.06$	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	-93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value	1047.47	0.02

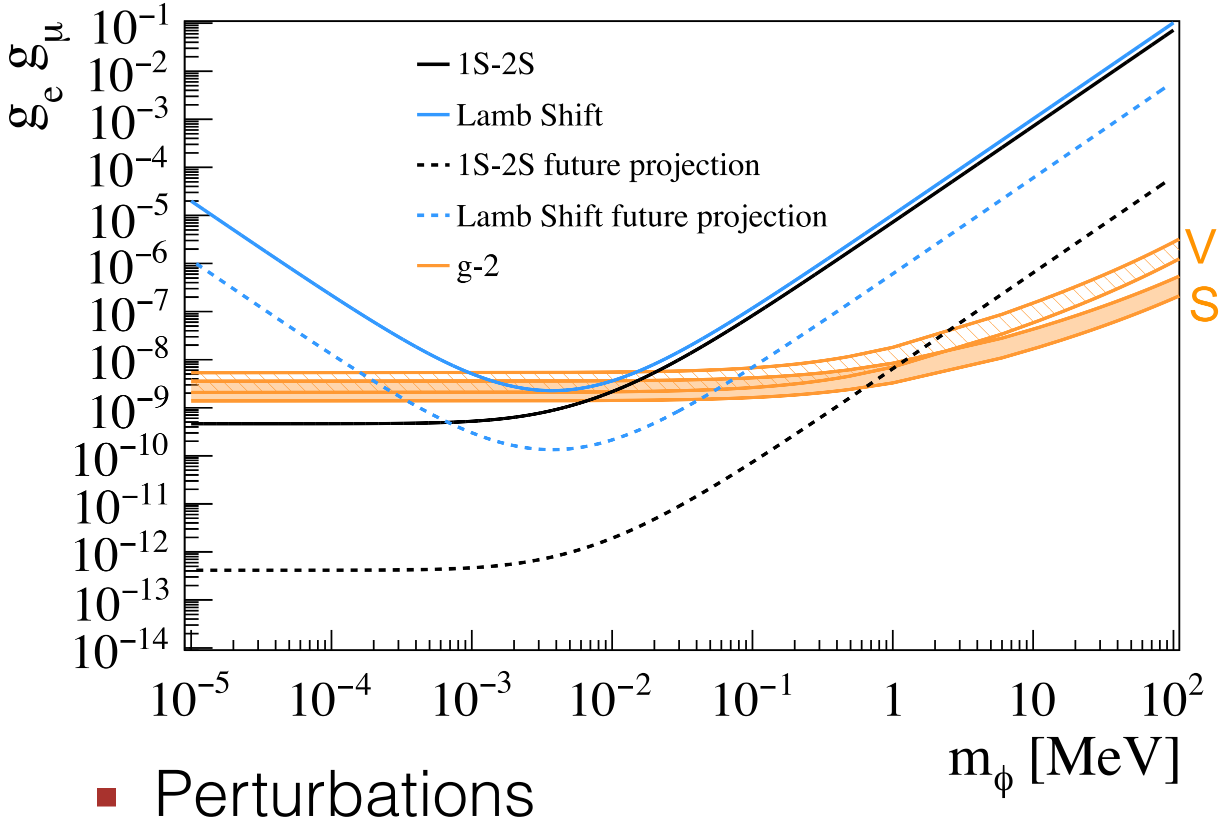
Results in **agreement with theoretical calculations**.
Precision is not enough to test b-QED but can be used to constrain new physics, e.g. SME coefficients.

MU-MASS

D. Colladay and V. A. Kostelecký. Phys. Rev. D, 55:6760–6774, 1997
A. H. Gomes et al., Phys. Rev. D, 90:076009, 2014.

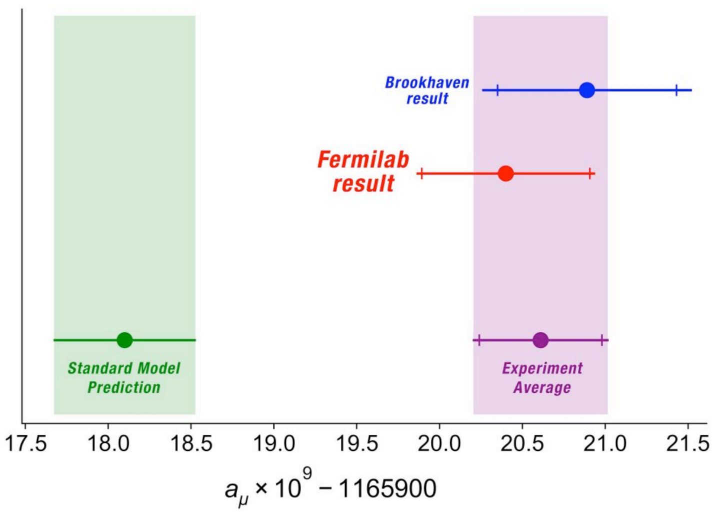
Muonium spectroscopy as a probe for new muonic forces

C Frugiuele et al., Phys. Rev. D100, 015010 (2019)



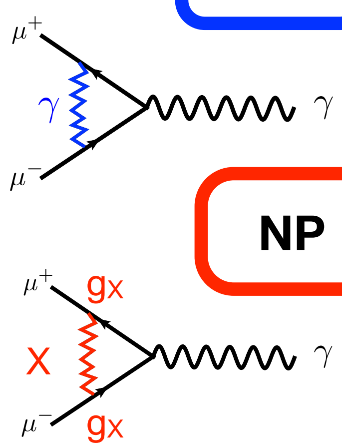
Bands: region suggested by $(g\text{-}2)_\mu$

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)



SM

NP



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

- Perturbations

$$\Delta E_{ss}(2S^0 \to 1S^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

$$\Delta E_{ss}(2S^0 \to 2P^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

combined with bound from $(g\text{-}2)_e$

L. Morel et al, Nature 588, 61 (2020),
R. H. Parker et al., Science 360, 191 (2018).
D. Hanneke et al. e Phys. Rev. Lett. 100, 120801 (2008)

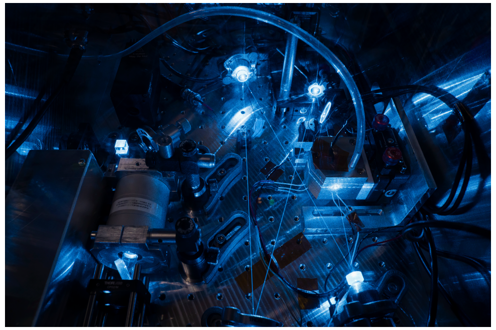
MU-MASS

Summary & Outlook - MuMASS

- Prospects for improved Lamb shift and fine structure ($2S_{1/2} \rightarrow 2P_{3/2}$) measurements

Beamline	Target	Timeline	M(2S) (Hz)	LS Uncertainty (kHz / 10 d)	Contributions
PiE4/LEM	C-Foil	2023	20	<1000	E_{SE}, E_{VP}, $E_{rec,S}$
PiE4/LEM	Graphene	2025	100	200	E_{BKG}
PiE1/muCool	Graphene	2026	1000	70	E_{2ph}
HiMB/muCool	Gas	2029	100 000	10	E_{RR}, E_{HFS}, $E_{rec,R}$, E_{SEN}

[muCool] A. Antognini, D. Taqqu, SciPost Phys. Proc. 5, 030 (2021)
[HiMB] M. Aiba et al. (2021), 2111.05788



- Measurement of **1S-2S transition** with Doppler free **CW** laser spectroscopy in preparation.

N. Zhadnov, P .Crivelli, et al., Optics Express 31, 28470 (2023)

Aim to 10 kHz accuracy → Muon mass @ 1 ppb P .Crivelli, arXiv:1811.00310

Beamline	Target	Timeline	1S-2S Uncertainty (kHz)
PiE4/LEM	SiO2 @ 300K	2024-2025	100
PiE1/muCool	SiO2 @ 100K	2026	10
HiMB/muCool	SFHe	2029-	1

MU-MASS

ETH zürich

IPA

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

THIS WORK IS SUPPORTED BY ETH Zurich, and SNSF Grants No. 169133, 186181, 186158, No. 197346

The NA64 experiment in muon mode at the CERN SPS

Swiss National Science Foundation

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

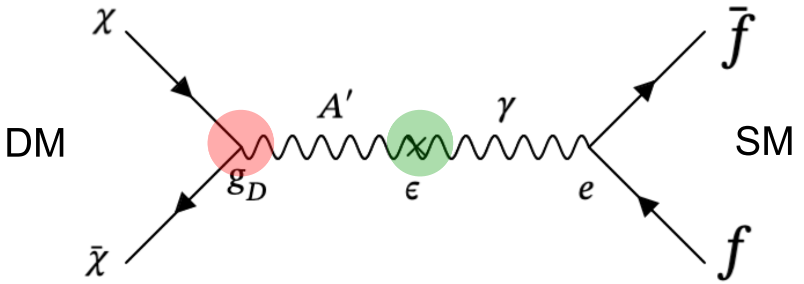
$$\Omega_X \propto \frac{1}{< v\sigma >} \sim \frac{m_X^2}{y}$$

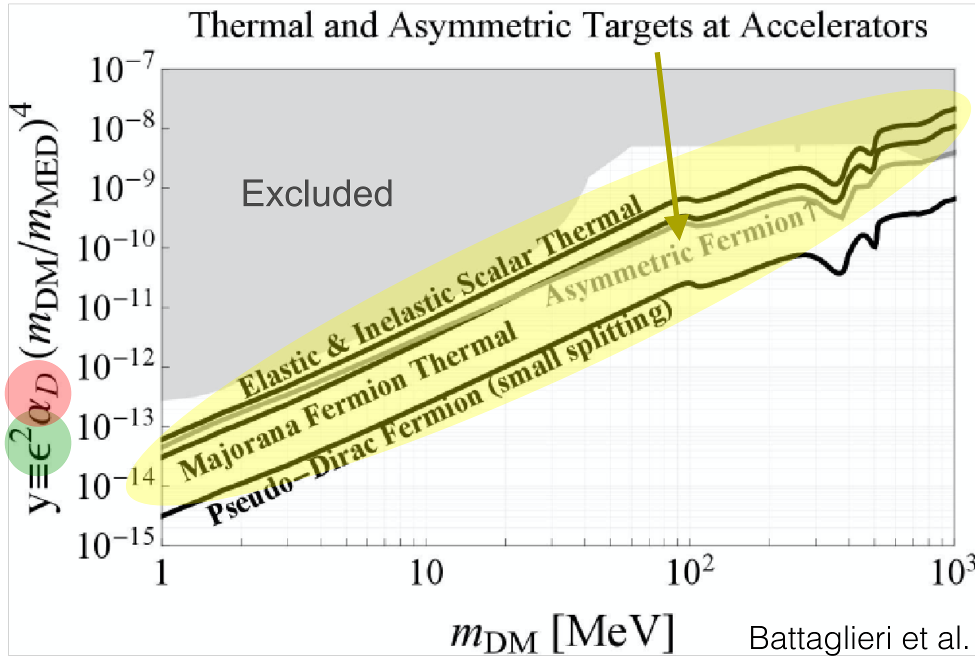
$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

$$\Downarrow$$

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

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



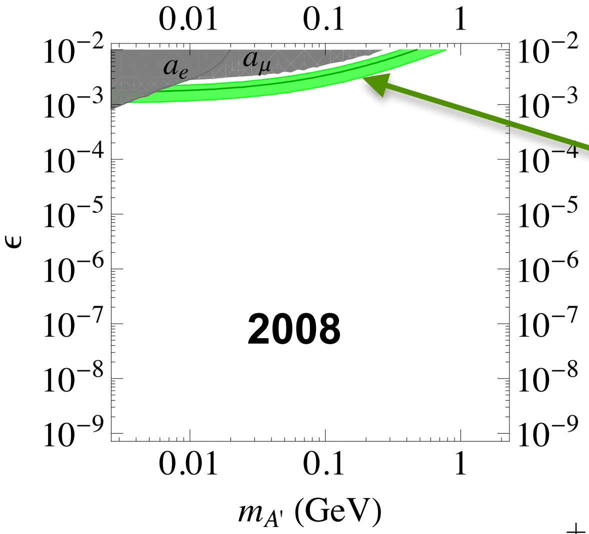


Battaglieri et al.
1707.04591

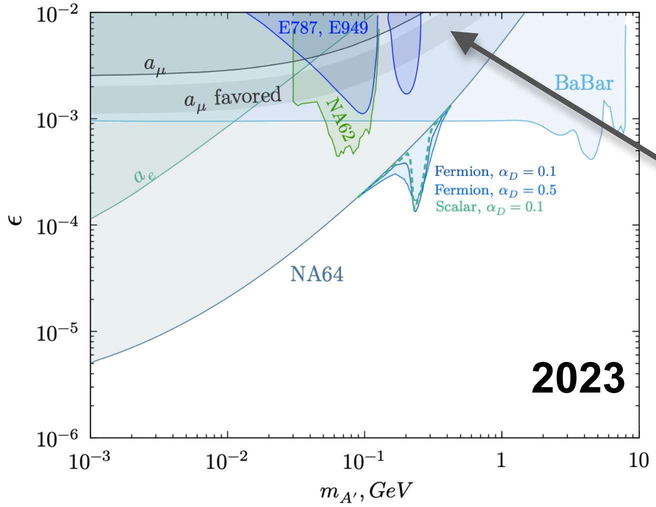
DISCLAIMER: slides adapted from **PhD defence of Henri Sieber** who successfully defended his thesis at ETH last Monday :-)

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)

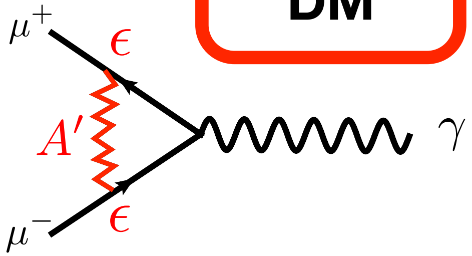


A' may have explained observed anomaly



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

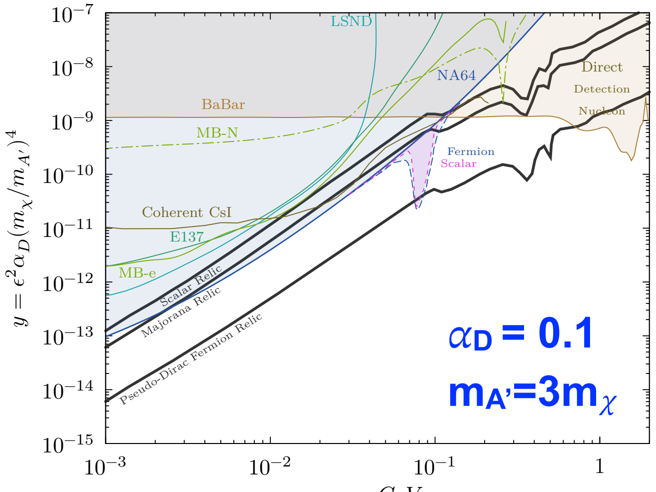
DM



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

$$\simeq 10^{-3} \times \epsilon^2$$

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

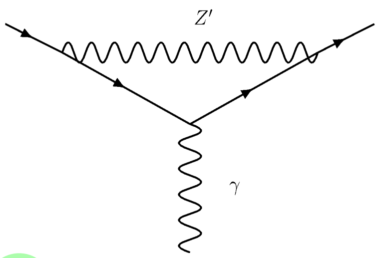
- Light **Z' vector boson** associated with the broken $U(1)_{L_\mu - L_\tau}$ symmetry

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

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

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 $g-2$



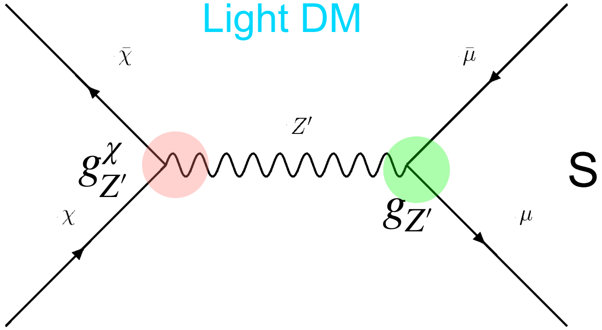
$$\Delta a_\mu^{Z'} = \frac{g_{Z'}^2}{4\pi^2}\int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)m_{Z'}^2/m_\mu^2},$$

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

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

Altmannshofer et al. JHEP 12 (2016) 106

Light DM



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

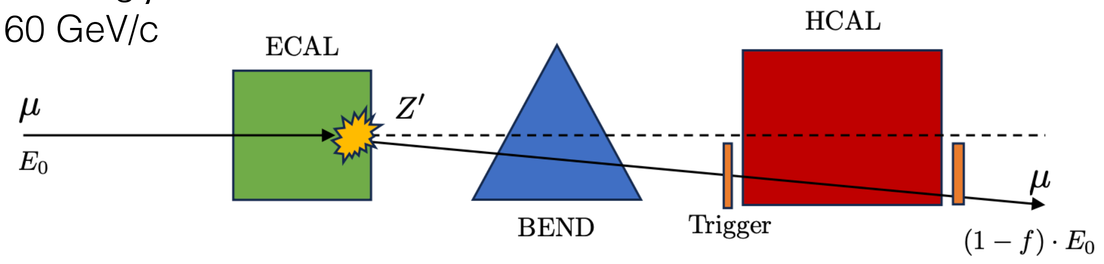
Holst et al. Phys.Rev.Lett. 128 (2022) 14, 141802

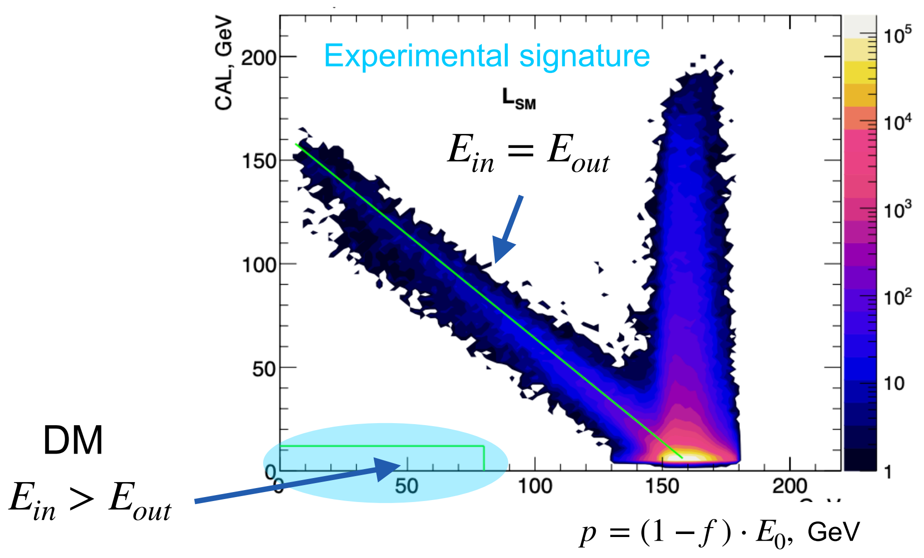
The NA64 experiment running with muons at M2 beam line

- **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 **10[12] MOT** of the statistics

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

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





Phase 1 2021 - 2023

Phase 2 beyond LS3 > 2026

$Z' \rightarrow$ invisible

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

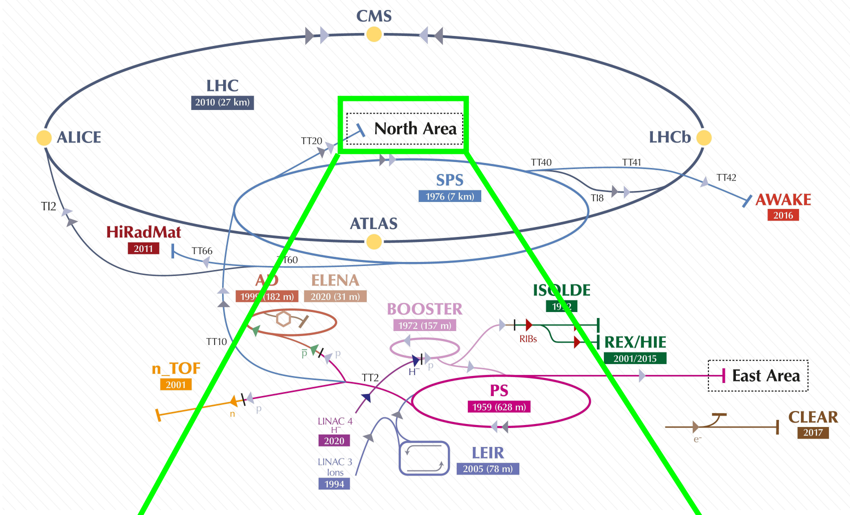
$N_{MOT} \sim 10^{11}$

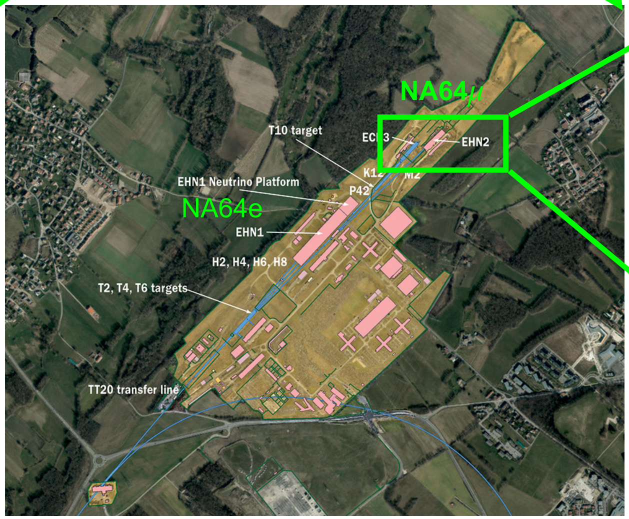
$Z', A' \rightarrow$ invisible, Q_χ, $\mu - \tau$, …

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

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

The NA64 experiment running with muons at M2 beam line

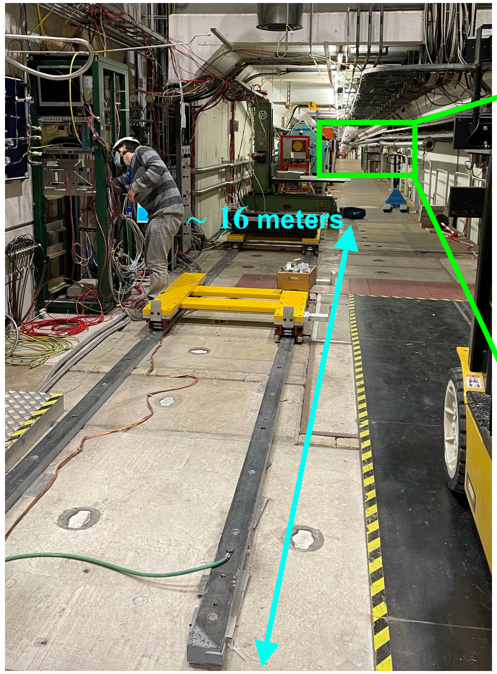




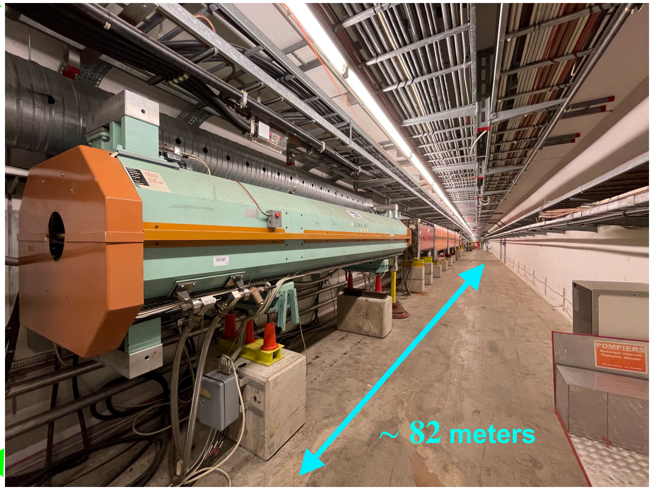
@CERN Courier

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

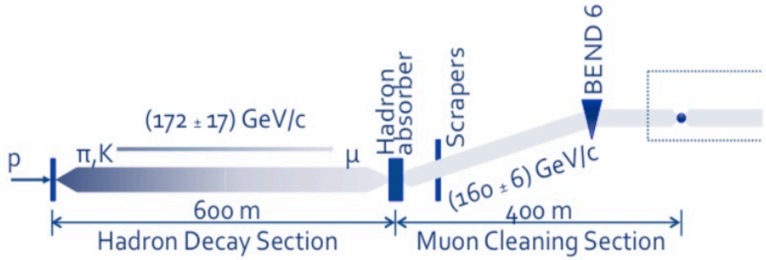
Downstream



Space allocated for the 2021-2023 pilot runs

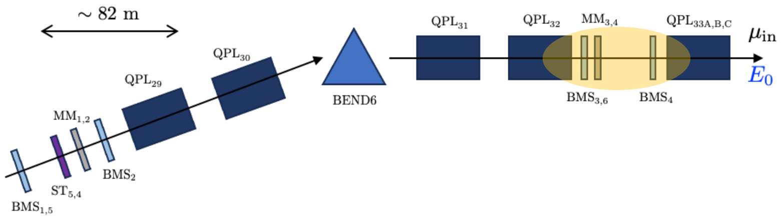


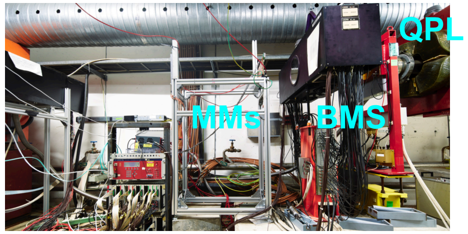
The NA64 experiment running with muons at M2 beam line



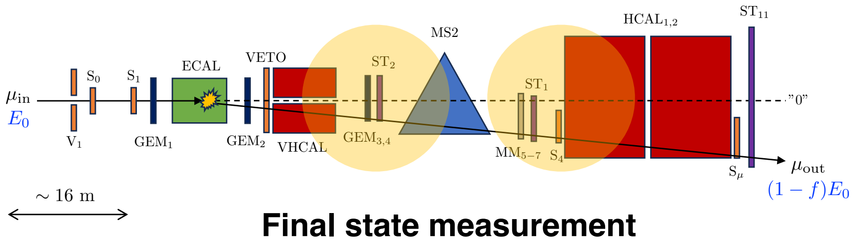
- **450 GeV/c protons** extracted from the CERN SPS to NA
- Interactions in a **beryllium target** produce hadrons (mostly pions and kaons)
- From in-flight decays, **muons** in the range of **100-225 GeV/c** with beam intensity $10^6 - 10^8$ μ/**spill**

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

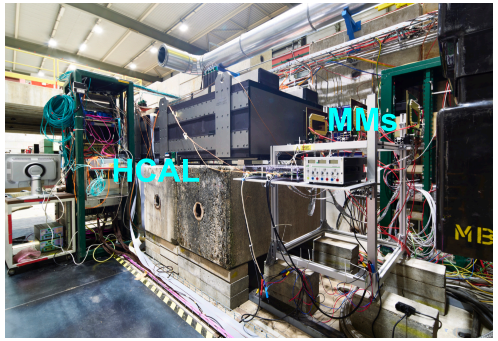


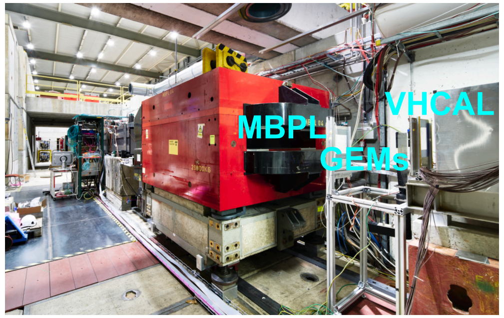


Upstream ECAL



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

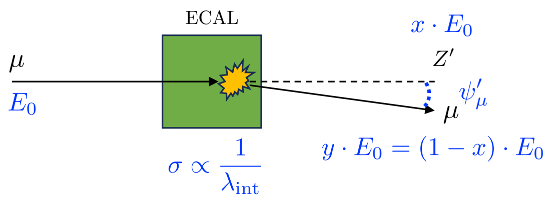




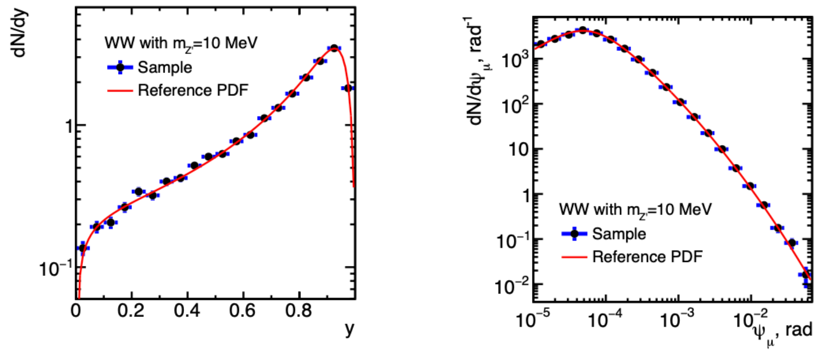
Downstream ECAL

Signal and trigger optimisation

- Implementation of the underlying physics in GEANT4

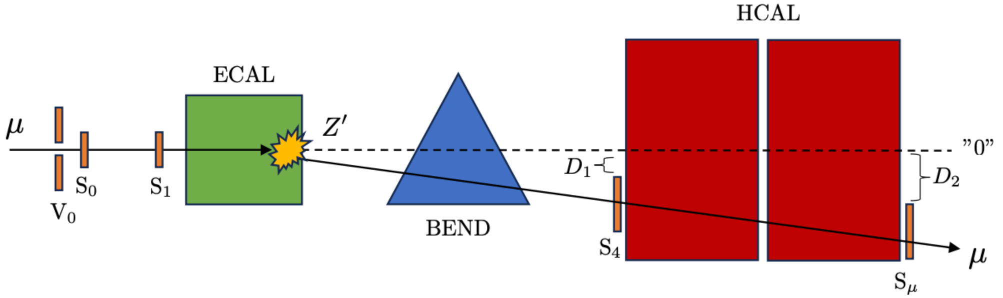


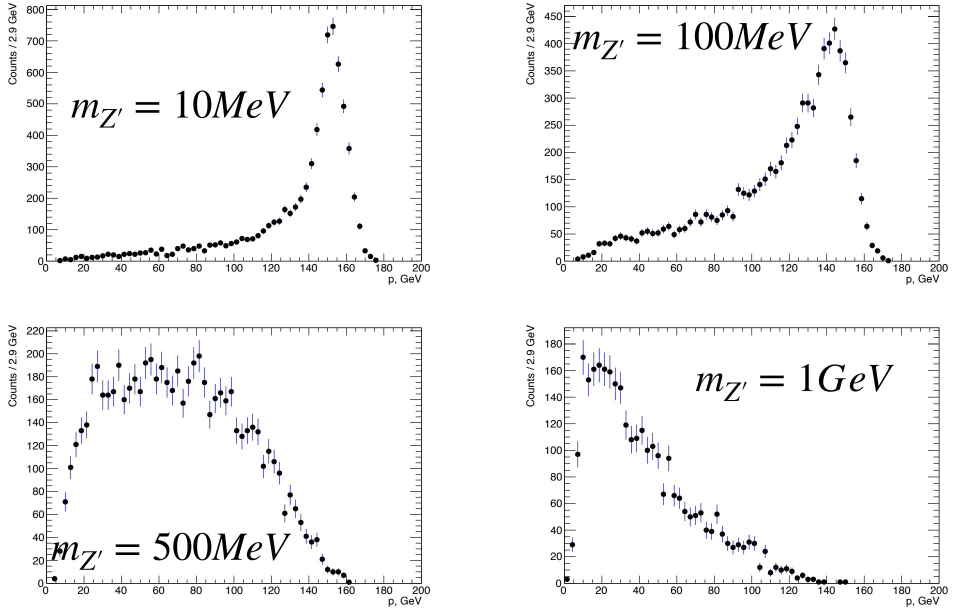
$$\sigma_{Z'} \sim g_{Z'}^2 \alpha^2 Z^2 / m_{Z'}^2, \qquad \psi'_\mu \sim \frac{m_{Z'}}{E_0}$$



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

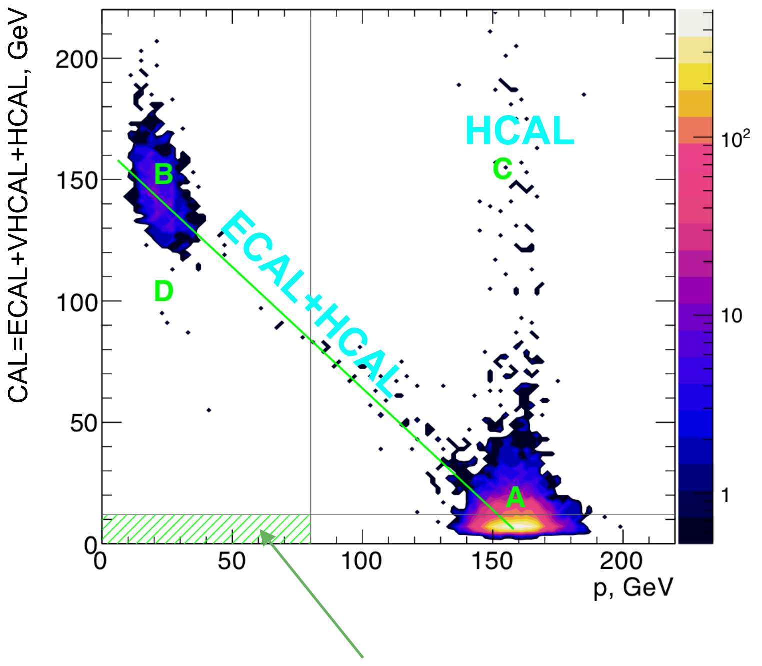
- **Main selection criterion**
  - Incoming momentum in the range [140, 180] GeV/c
  - Single reconstructed track in the downstream set-up (momentum < 80 GeV/c)
  - No activity in the VHCAL and Veto, energy compatible with a muon (MIP) in ECAL and HCAL

- 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…)

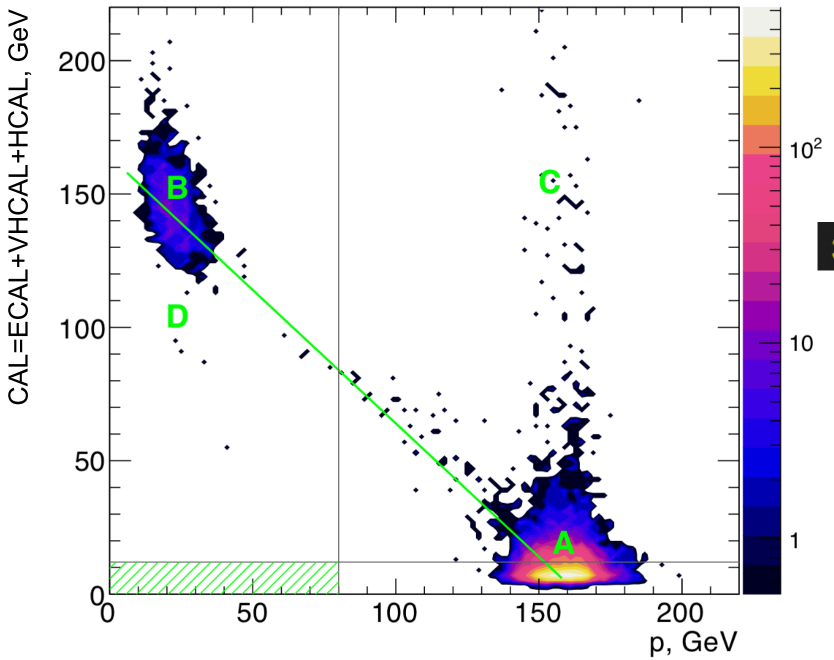
Statistics
$(1.98 \pm 0.02) \times 10^{10}$ MOT



box $\sim (p < 80,$ CAL $< 12)$ GeV

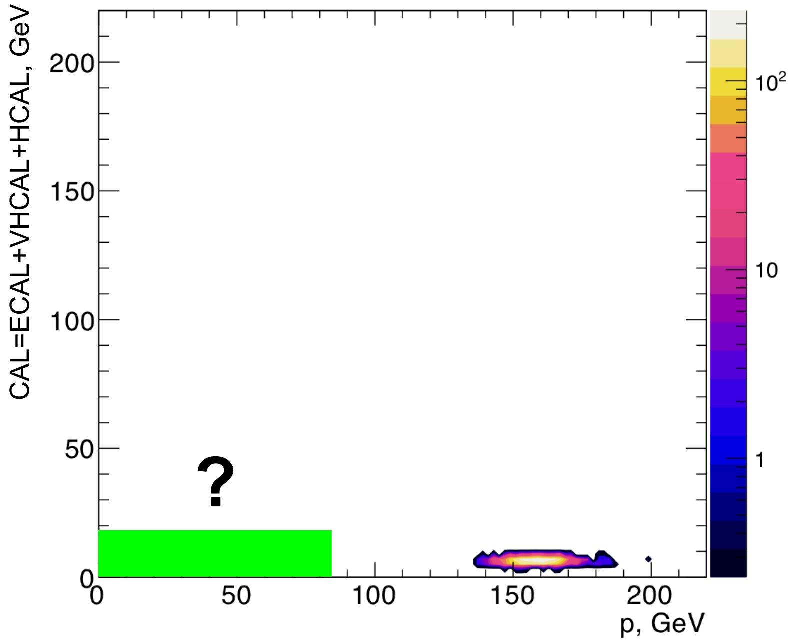
Unblinding

- Analysis note (H. Sieber, Molina Bueno, Crivelli, and Tuzi, NA64-NOTE-22-05) was reviewed by the collaboration



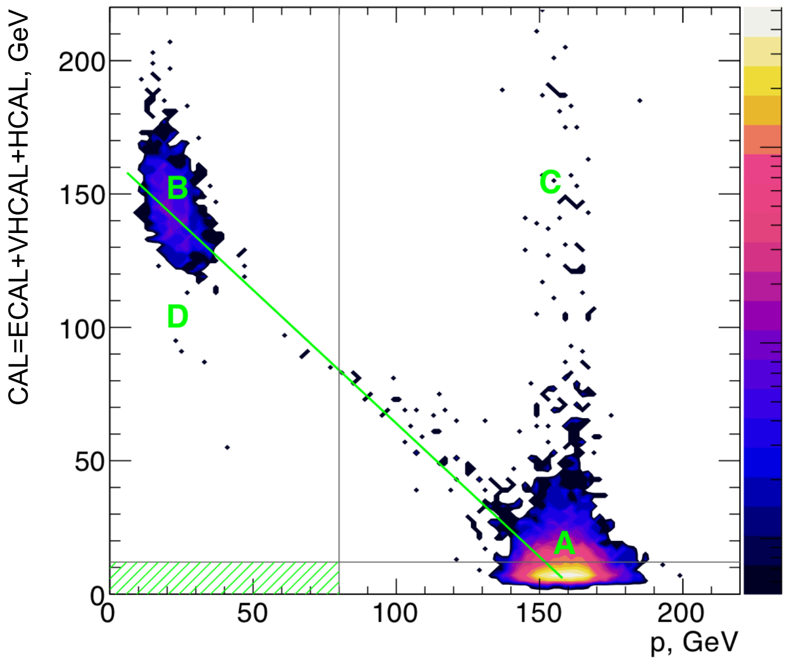

```
37 #define BLIND_ANALYSIS 1
```

Apply **all selection criteria**!



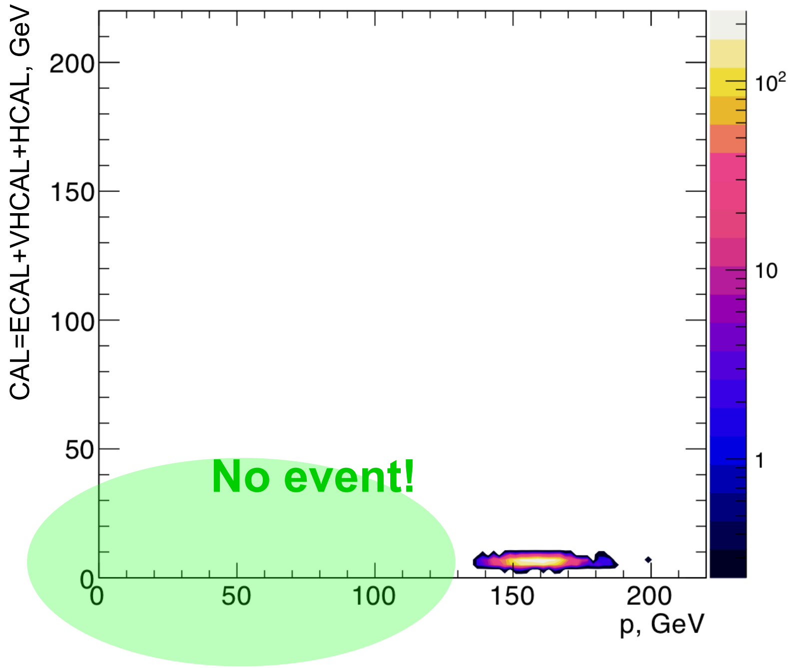
Unblinding

- Analysis note (H. Sieber, Molina Bueno, Crivelli, and Tuzi, NA64-NOTE-22-05) was reviewed by the collaboration
- Analysis approved and green light for unblinding → **no event** within the signal box!




```
37 #define BLIND_ANALYSIS 0
```

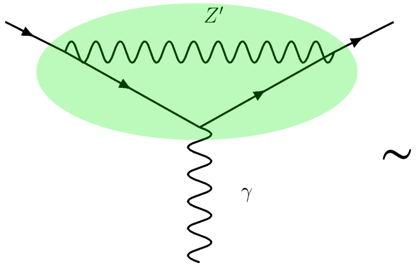
Apply **all selection criteria**!



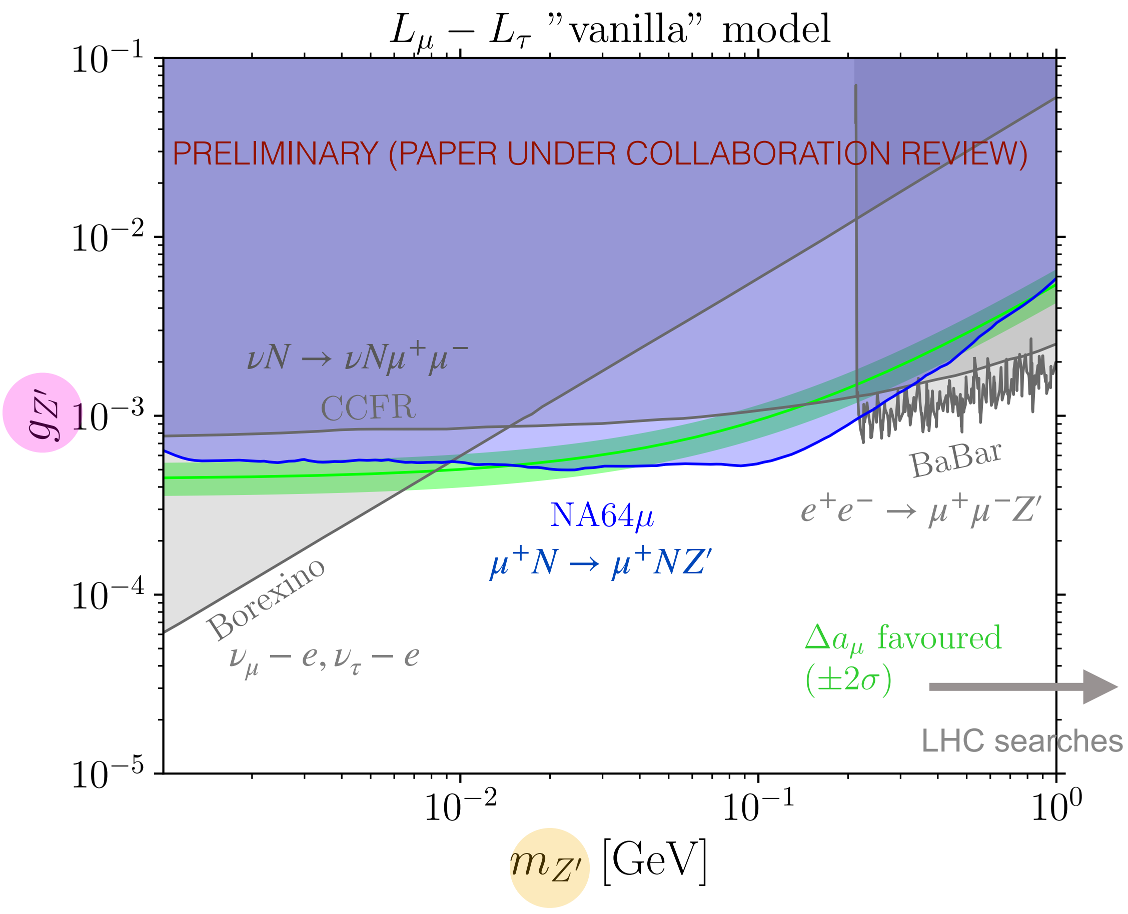
Constraints on the muon $(g-2)_\mu$ in the $U(1)_{L_\mu - L_\tau}$ scenario

- 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**



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



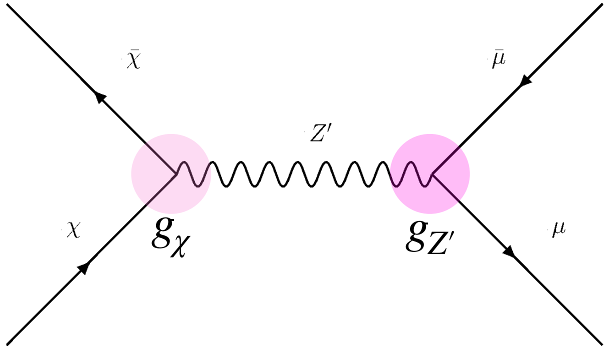
- **Complement** previous experiments in the mass region $\mathcal{O}(10-100$ MeV) with $g_{Z'} \leq 6\times10^{-4}$

Exploring the thermal DM parameter space

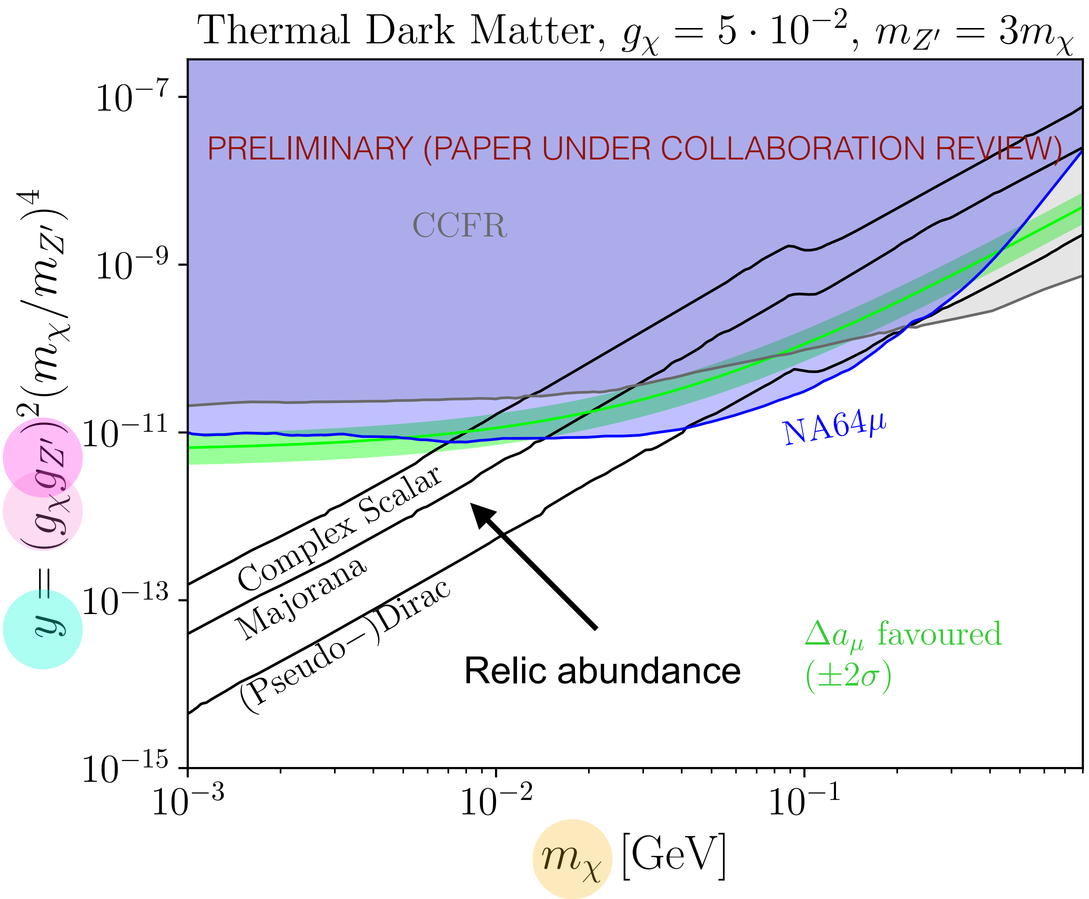
- Results also allow one to constrain predictive scenarios for **thermal DM**

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

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



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



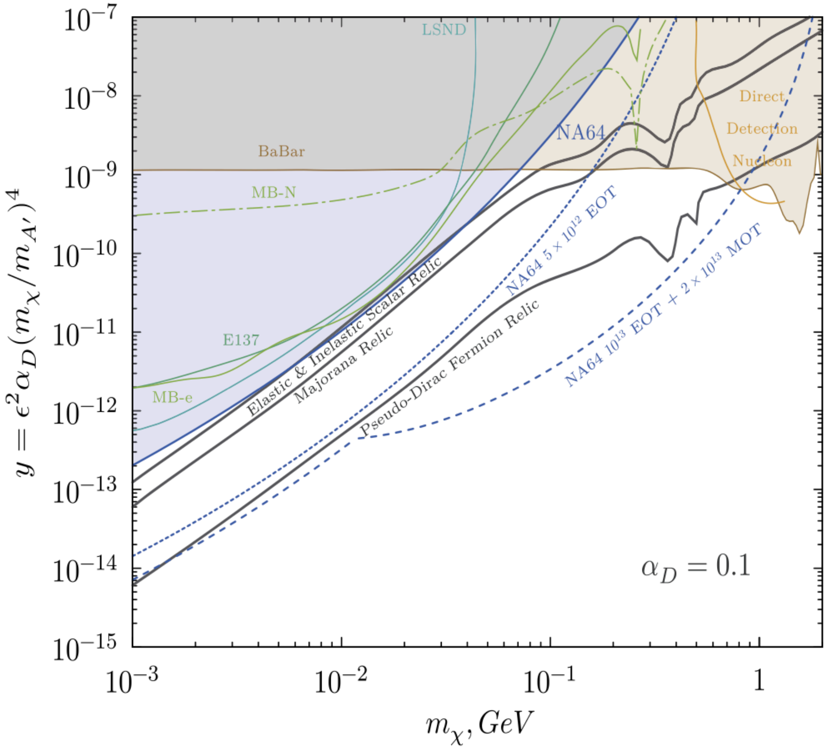
- Paper under internal review of the collaboration -> submission to the arXiv coming soon (include scalar mediator)

Future prospects of NA64 in muon mode

- **NA64 in muon mode** is planned to run until the CERN Long Shutdown 3 (LS3) and beyond to fully exploit its potential to explore DS weakly coupled to muons

- **Plans before LS3**
  - Probe the remaining $(\mathbf{g-2})_\mu$ parameter space (in 2023 1.5×10^{11}MOT already accumulated)
  - Complement NA64 in the high mass region (> 0.1 GeV) in the search for invisible A' (in 2024/25 accumulate $\sim 10^{12}$ MOT but this depends on the beam time availability at M2)

- **Plans beyond LS3**
  - **Upgrade** the experiment to fully exploit the M2 beamline capabilities (running at few 10^7 μ/spill)
  - Cover the A' high-mass region in the thermal target with > 2×10^{13} MOT
  - Explore scenarios involving ALPs, milli-charged (milliQ)particles, lepton flavour conversion (LFC), …Any new idea?



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Phys. Lett. B 796 (2019) 117-122

Thank you!

European Research Council
Established by the European Commission

THIS WORK IS SUPPORTED BY an ERC consolidator grant (818053 -Mu-MASS) and by the Swiss National Foundation under the grant 197346.

Mu-Mass

Swiss National Science Foundation

Acknowledgments

NA64 collaboration and in particular H. Sieber and L. Molina-Bueno

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

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

This work is supported by ETH Zurich and SNSF Grant No. 169133 and 186158 (Switzerland)

Swiss National Science Foundation