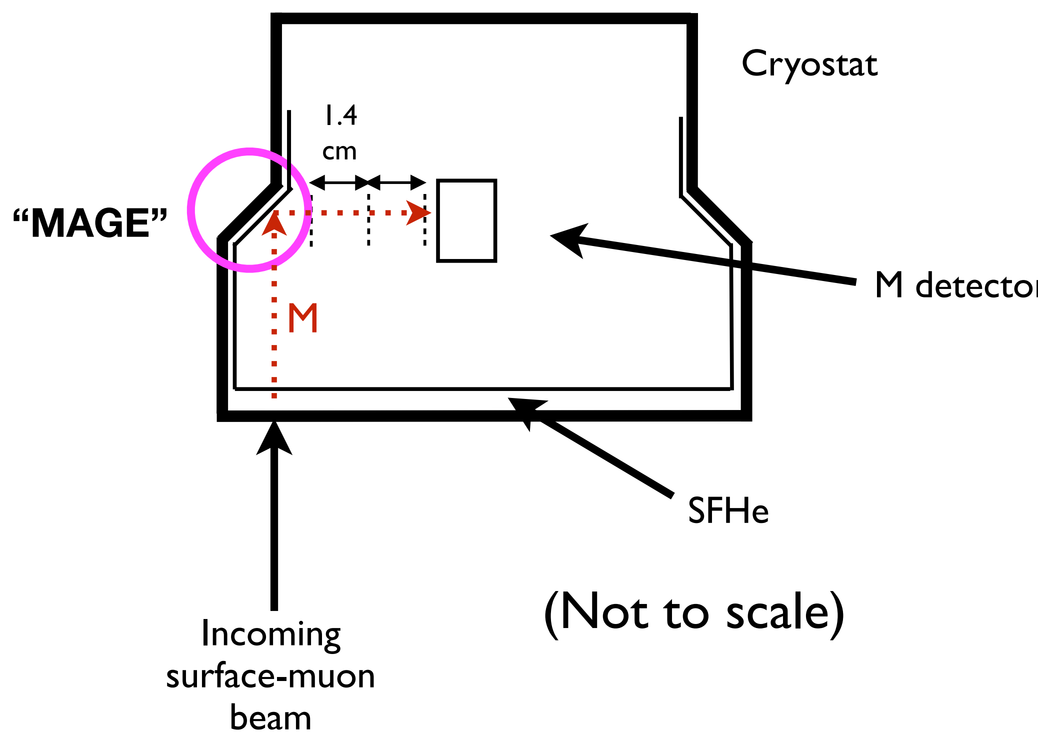
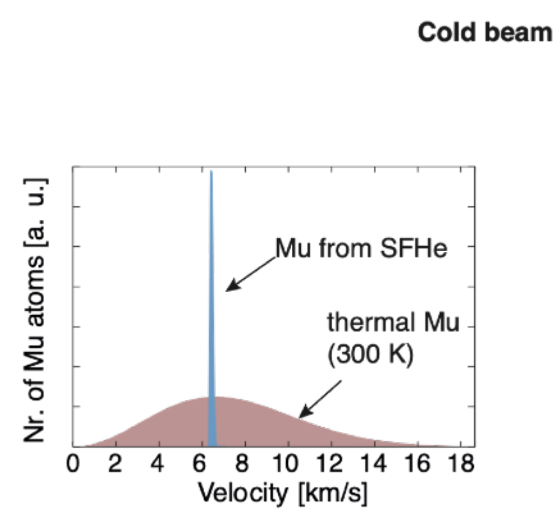
Overview of Slow-Muonium Experiments

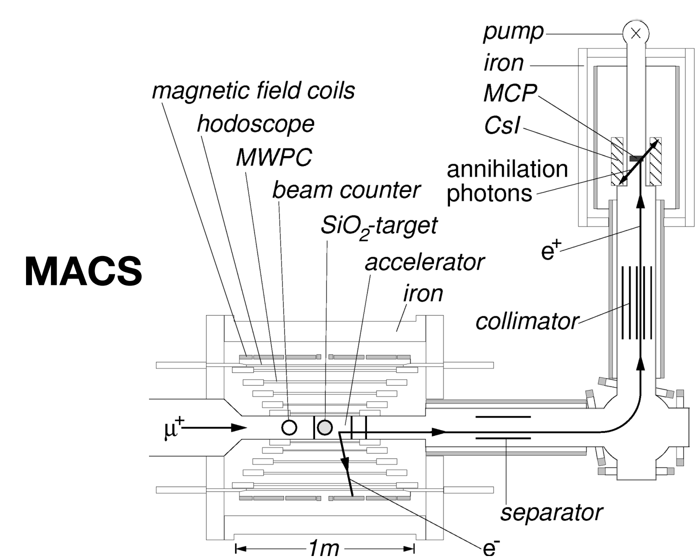


Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Muons, Inc.



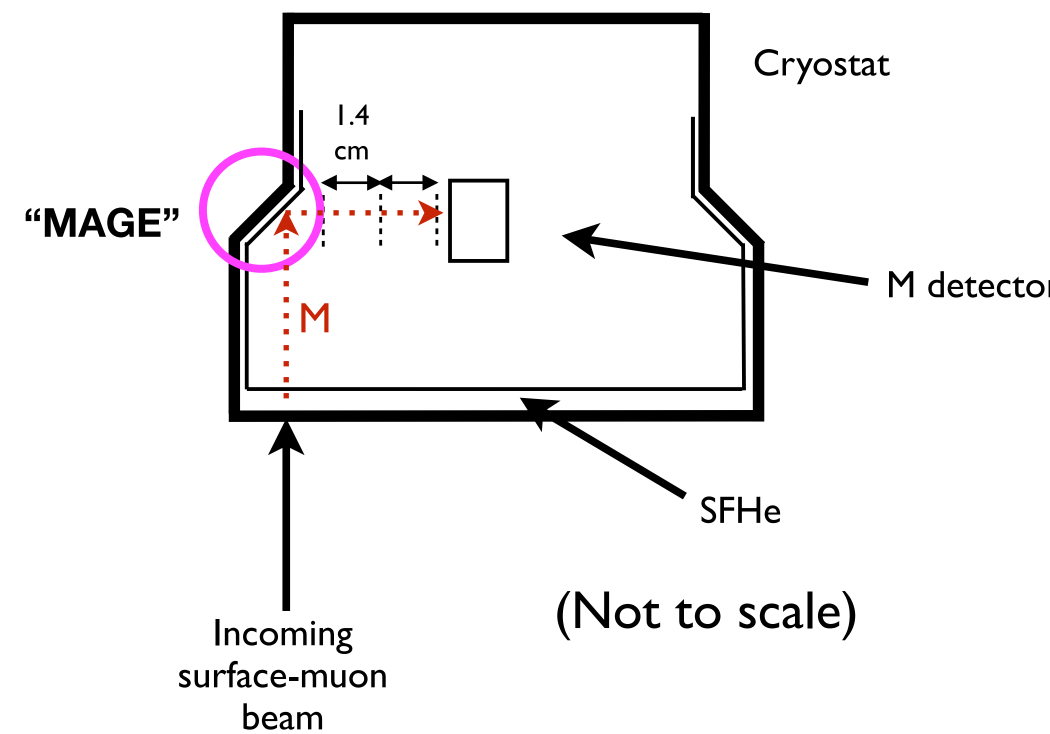


Workshop on Future Muon Program at Fermilab

Caltech

28 March 2023

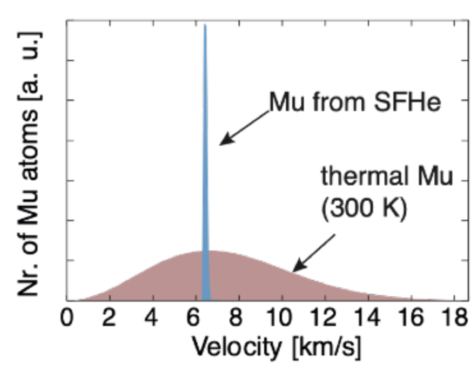
Overview of Slow-Muonium Experiments

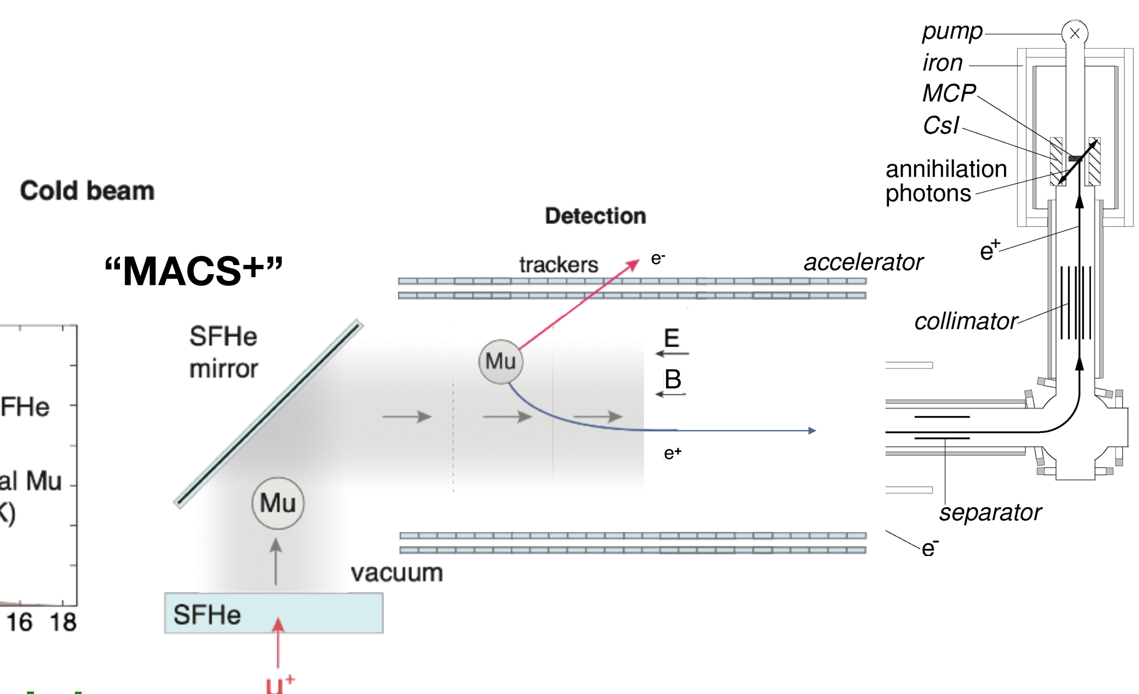


Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Muons, Inc.





Workshop on Future Muon Program at Fermilab

Caltech

28 March 2023

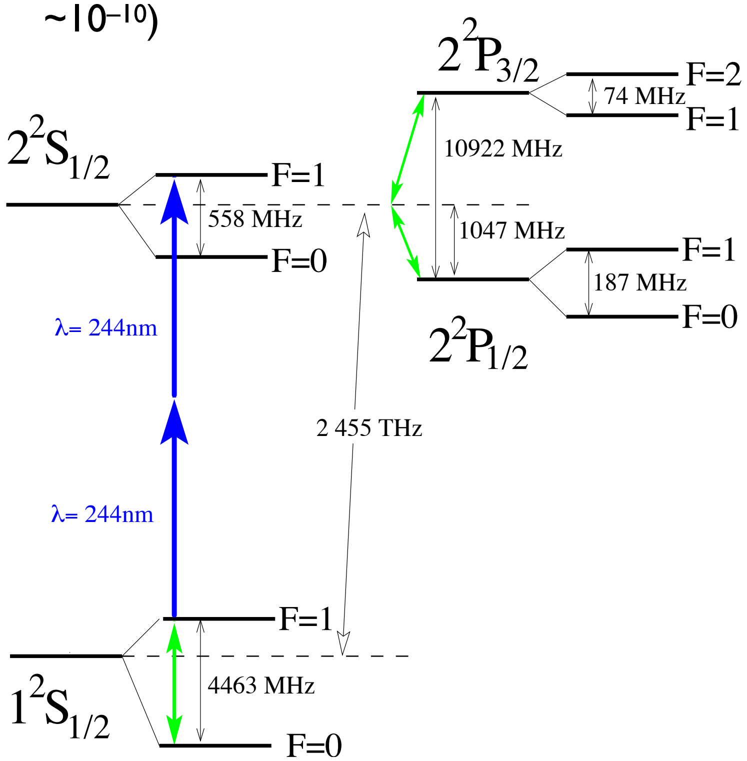
Outline

- Motivation: Muonium
  - oscillation search
  - precision spectroscopy
  - antimatter gravity
- Fermilab advantages
- Conclusions

Why Muonium?

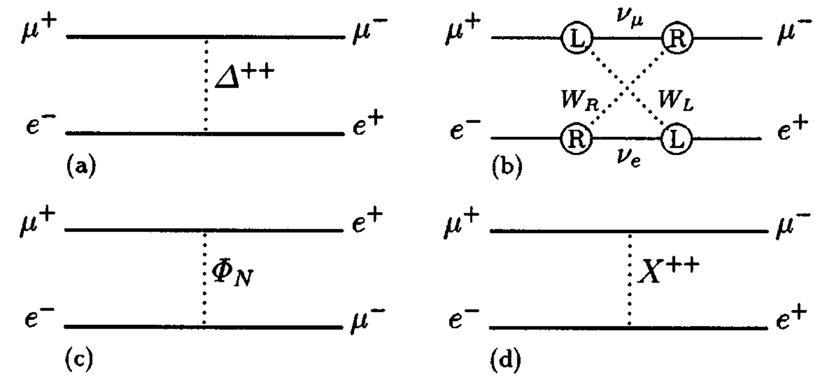
- Much is known about muonium… (AKA M, or Mu)
  - a *purely leptonic atom*, discovered 1960

    [V. W. Hughes et al., "Formation of Muonium and Observation of its Larmor Precession," Phys. Rev. Lett. 5, 63 (1960)]
  - decays to e^+ (fast) + e^- (slow), $\tau_M = \tau_\mu = 2.2\ \mu s$ (bound-state correction ~10^{-10})
  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - forms certain compounds (MuCl, NaMu,...)
  - ideal testbed for QED, the search for new forces, precision measurement of muon properties, etc.
  - also valuable for materials science

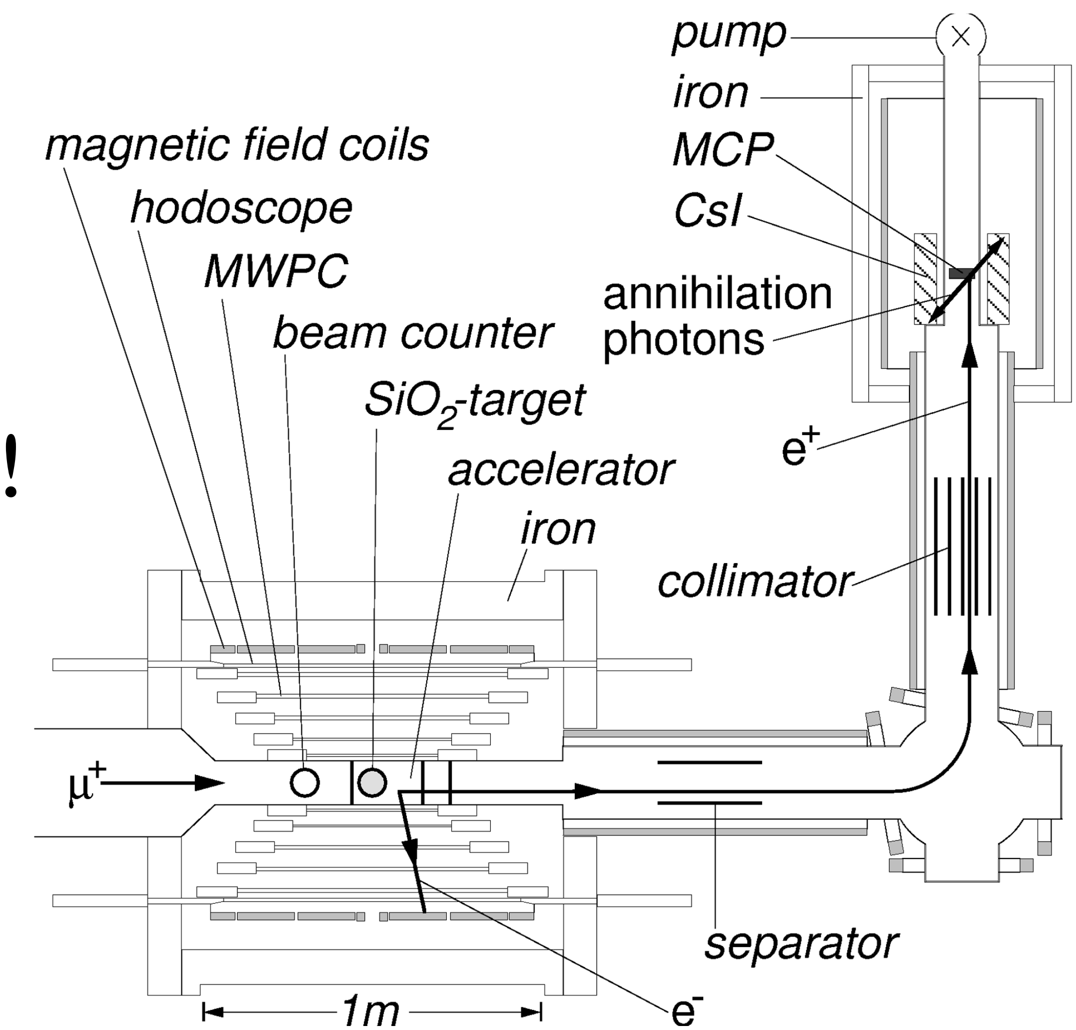


Muonium Double CLFV?

(simultaneous $\left\{ \begin{array}{l} \mu^+ \to e^+ \\ e^- \to \mu^- \end{array} \right.$)



- M-$\overline{\text{M}}$ oscillation: would be *doubly* charged-lepton-flavor violating
- Nothing forbids it *except* lepton-flavor conservation
  - which we know (ν mixing) is violated!
    - but M ↔ $\overline{\text{M}}$ via virtual ν mixing negligible
    - "background-free" search for new physics!
- Current limit set by MACS (1999) at PSI: $P_{M\overline{M}} \leq 8.3 \times 10^{-11}$ (90% C.L.) in 0.1 T field



[L. Willmann et al., "New Bounds from a Search for Muonium to Antimuonium Conversion," PRL **82** (1998) 49]

Muonium Double CLFV?

- Can one now do better?
- Yes!
  - now know how to make slow, quasi-monochromatic M source – a game changer!(?)
    - based on behavior of μ^+ in superfluid He

Zhao talk

Phillips talk

Muonium Spectroscopy

Hyperfine Interact (2018)

- M 1S-2S transition frequency (theory) = 2,455,528,935.4(1.4) MHz
  - 0.6 ppb QED prediction!
  - M atom composed of 2 point-like leptons
    - ▸ hadronic & finite-size corrections negligible!
- Measured (1999) to 9.8 MHz (4 ppb) at RAL
  - & similar story for M hyperfine splitting: measured (1999) to 12 ppb at LAMPF

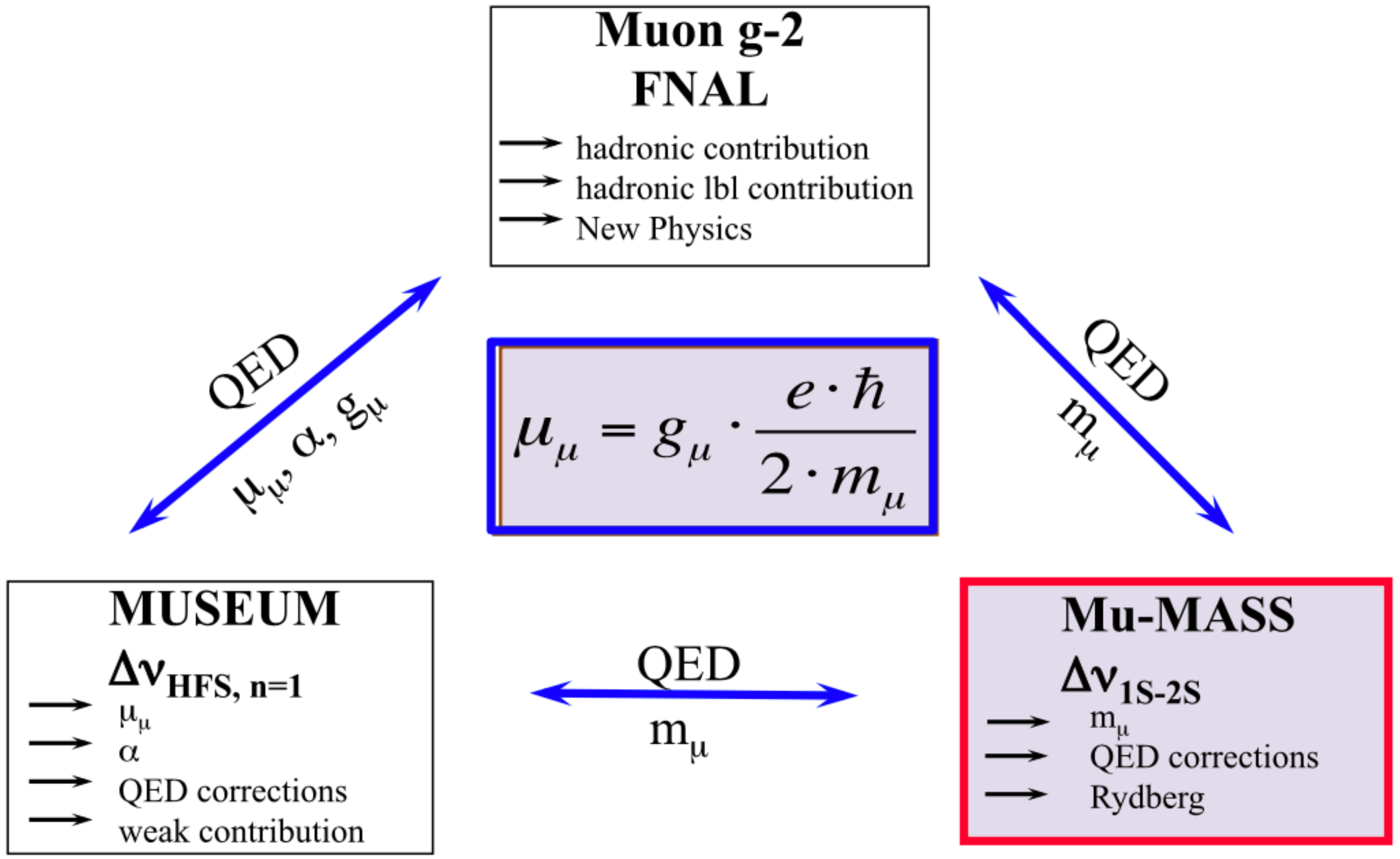


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

[P. Crivelli, "The Mu-MASS (muonium laser spectroscopy) experiment," Hyp. Int. **239** (2018) 1]

Kawall talk

[V. Meyer et al., "Measurement of the 1s–2s Energy Interval in Muonium," Phys. Rev. Lett. 84, 1136 (2000);
I. Fan et al., Phys. Rev. A **89**, 032513 (2014)]

Muonium Spectroscopy

- New 1S-2S experiment, Mu-MASS, now in R&D/commissioning stage at PSI
  - goal: improve sensitivity x1000 (<10 kHz), 4 ppt
  - systematics expected to dominate
    - PIP-II muon rate (~3 orders higher than current PSI) would help – *let's discuss!*
      - will allow better handle on systematics (per Crivelli)
- Also MUSEUM in progress at J-PARC
  - goal: improve hyperfine sensitivity x10 (1 ppb)

Muonium Gravity: Motivation I

- Possibility of "fifth force"?
  - $g-2$, B-decay and W-mass anomalies: possible eμ nonuniversality?
    - stimulated extensive work

[Glashow, Guadagnoli, Lane, "Lepton Flavor Violation in B Decays?" PRL **114 (2015)** 091801;

Buttazzoa, Greljoa, Isidoria, Marzocca, "*B*-physics anomalies: a guide to combined explanations," JHEP **2017** (2017) 44;

R. Aaij et al. (LHCb Collaboration), "Test of lepton universality in beauty-quark decays," Nat. Phys. 18 (2022) 277;

M. Alguer´o et al., "Unified explanation of the anomalies in semileptonic B decays and the W mass," PRD 106 (2022) 033005 and refs. therein;

S. L. Chen et al., "Combined explanations of B-physics anomalies, (g – 2)e,μ and neutrino masses by scalar leptoquarks," EPJC 82 (2022) 959;

M. D. Zheng et al., "Explaining anomalies of B-physics, muon g – 2 and W mass in R-parity violating MSSM with seesaw mechanism," EPJC 82 (2022) 895;

N Desai, A Sengupta, "Status of leptoquark models after LHC Run-2 and discovery prospects at future colliders, arXiv 2301.01754 (2023);

…]

- Observable via M gravity?
  - what $\bar{g}$ sensitivity required? no theor. prediction available
- Experimental 1st step: 10% measurement already worthwhile, and challenging
  - demonstrate M interferometry & calibration at several-pm level
  - can it be pushed to 1% and beyond? systematics + statistics
    - sensible to start with 10% and proceed step by step

Muonium Gravity: Motivation 2

- Weak Equivalence Principle of GR:
  - object's acceleration in gravitational field independent of its composition
    - *assumed* to apply to antimatter as well as matter
- But no direct test of antimatter gravity has been made
- Best limit ($\Delta g_{\mathrm{H}-\bar{\mathrm{H}}}/g \lesssim 10^{-7}$): torsion pendulum ("Eöt-Wash") & lunar laser ranging

[D.S.M. Alves, M. Jankowiak, P. Saraswat, "Experimental constraints on the free fall acceleration of antimatter," arXiv:0907.4110 [hep-ph] (2009)]

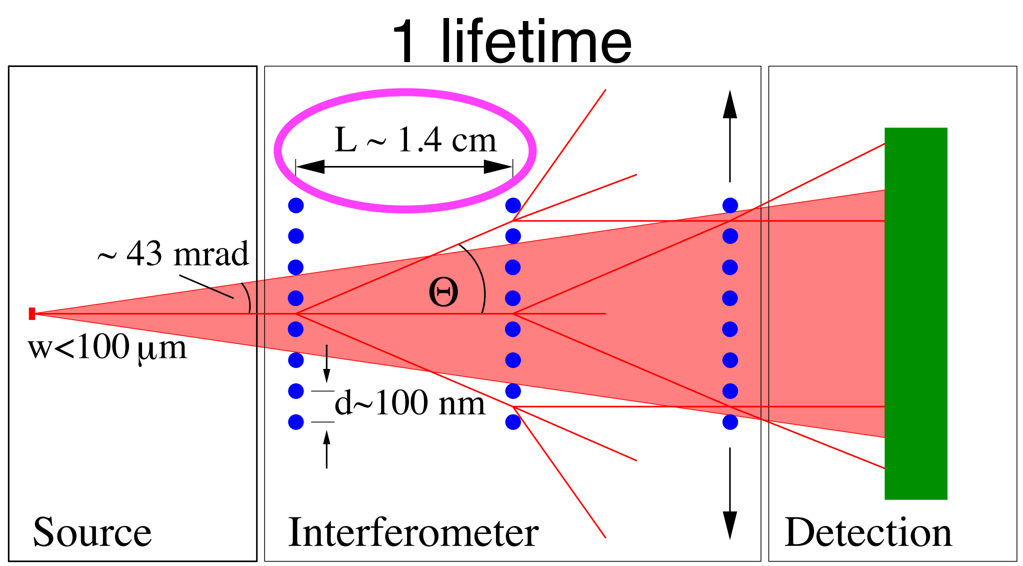
  - relies on assumed contribution of virtual antimatter to nuclear binding energy – untested assumption
  - inapplicable to M
- M provides *only way* to observe 2nd-generation gravity

Studying Muonium Gravity

- M atom-beam interferometer:

[K. Kirch, arXiv:physics/0702143 [physics.atom-ph]]

v ~ 6300 m/s



½ gt^2 = 24 pm!

but grows as t^2 ⇒ easier with *old* muonium

[T. Phillips, Hyp. Int. 109 (1997) 357]

- Adaptation of T. Phillips' $\overline{\text{H}}$ interferometry proposal to an anti-atom with a 2.2 μs lifetime!

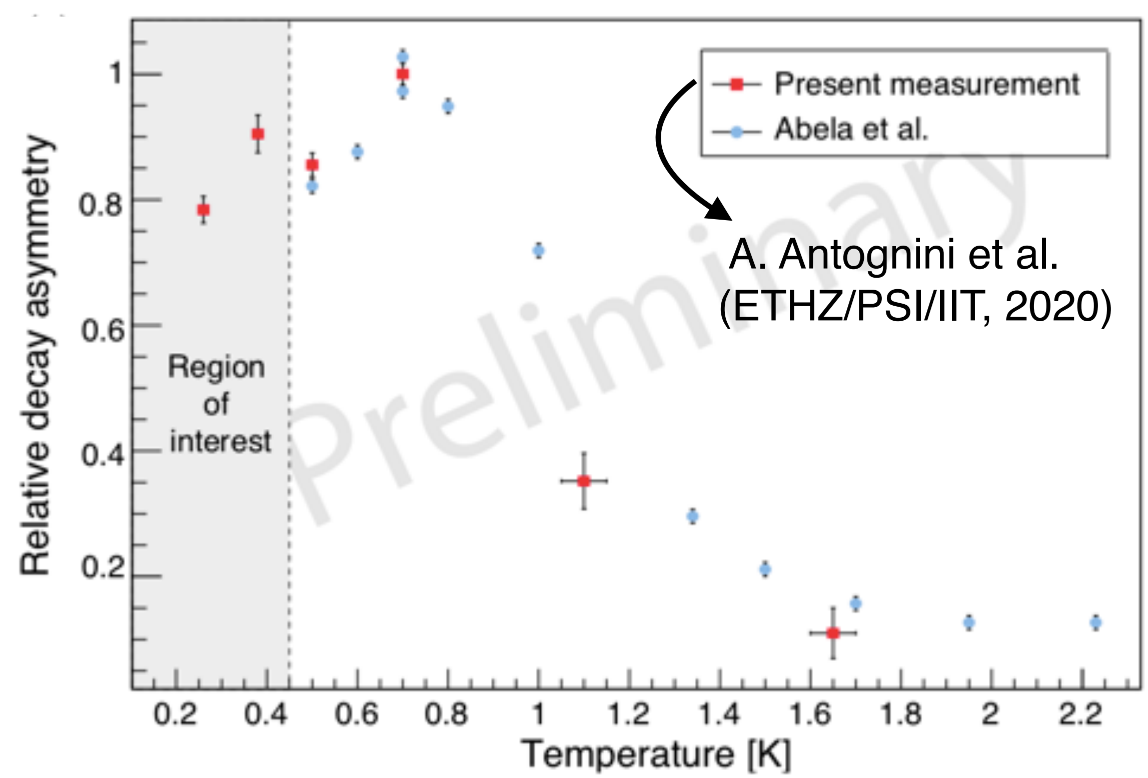
- Need low-divergence source of slow muonium traveling in vacuum

Novel Cryogenic M Source

- Need low-divergence source of slow muonium traveling in vacuum – ∃ nowhere

- Proposals by D. Taqqu of Paul Scherrer Institute (Swiss national laboratory ≠ CERN):
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)
    - or (T. Phillips) use ~ 100 μm SFHe layer for ~ 10^2 ↑ intensity?
  - R&D in progress @ PSI & proposed @ Fermilab

H immiscible in SFHe ⇒ μ_M should expel M atoms at 6,300 m/s, ⊥ to SFHe surface



VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

Focusing a Beam of Ultracold Spin-Polarized Hydrogen Atoms with a Helium-Film-Coated Quasiparabolic Mirror

V. G. Luppov
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
and Joint Institute for Nuclear Research, Dubna, Russia

W. A. Kaufman, K. M. Hill,* R. S. Raymond, and A. D. Krisch
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
(Received 7 January 1993)

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a quasi-parabolic polished copper mirror coated with a hydrogen-atom-reflecting film of superfluid ^{4}He. The mirror was located in the gradient of an 8-T solenoidal magnetic field and mounted on an ultracold cell at 350 mK. After the focusing by the mirror surface, the beam was again focused with a sextupole magnet. The mirror, which was especially designed for operation in the magnetic field gradient of our solenoid, increased the focused beam intensity by a factor of about 7.5.

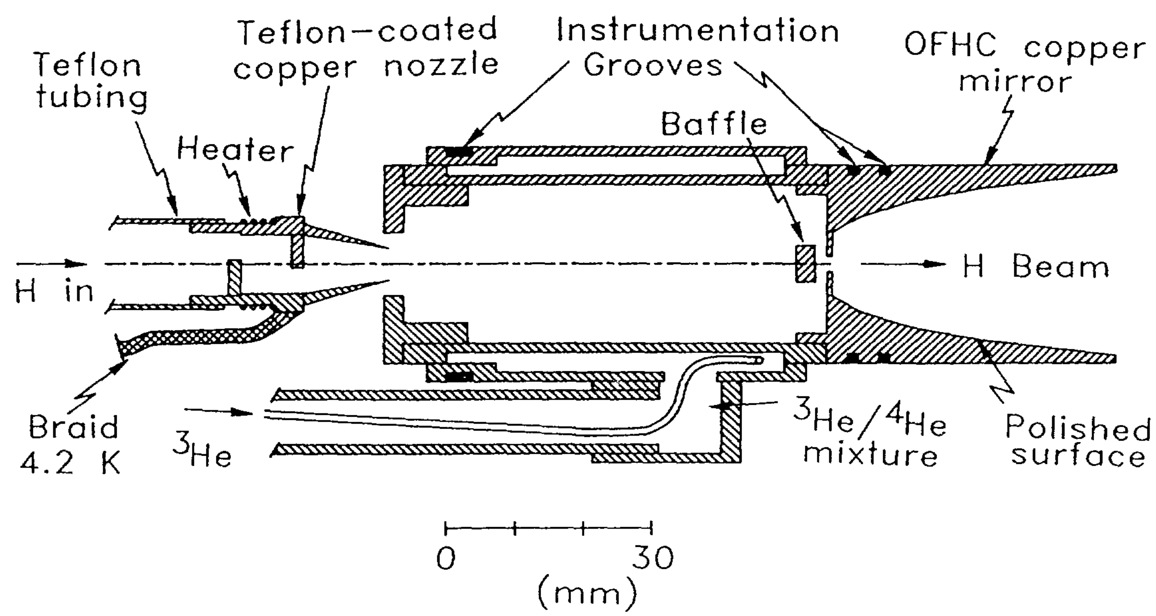


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

muCool @ PSI

PHYSICAL REVIEW LETTERS **125**, 164802 (2020)

Editors' Suggestion

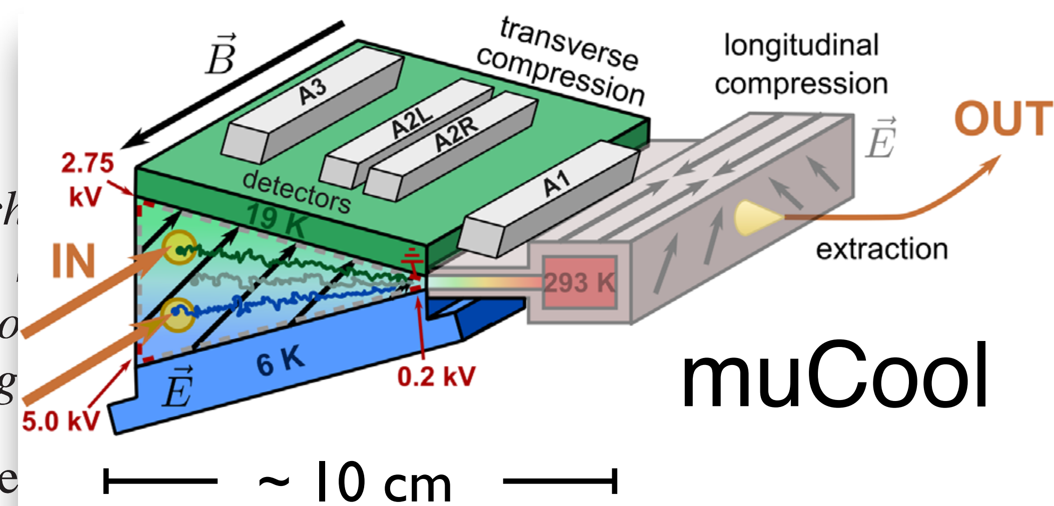
Make M beam suitable for stopping in ~μm SFHe layer

Demonstration of Muon-Beam Transverse Phase-Space Compression

A. Antognini,[1,2,*] N. J. Ayres,[1] I. Belosevic,[1,†] V. Bondar,[1] A. Eggenberger,[1] M. Hildebrandt,[2] R. Iwai,[1] D. M. Kaplan,[3] K. S. Khaw,[1,‡] K. Kirch,[1,2] A. Knecht,[2] A. Papa,[2,4] C. Petitjean,[2] T. J. Phillips,[3] F. M. Piegsa,[1,§] N. Ritjoho,[2] A. Stoykov,[2] D. Taqqu,[1] and G. Wichmann[1,∥]

(muCool Collaboration)

[1]*Institute for Particle Physics and Astrophysics, ETH Zürich*
[2]*Paul Scherrer Institute, 5232 Villigen-PSI,*
[3]*Illinois Institute of Technology, Chicago, Illino*
[4]*Dipartimento di Fisica, Università di Pisa and INFN sez. Pisa, Larg*



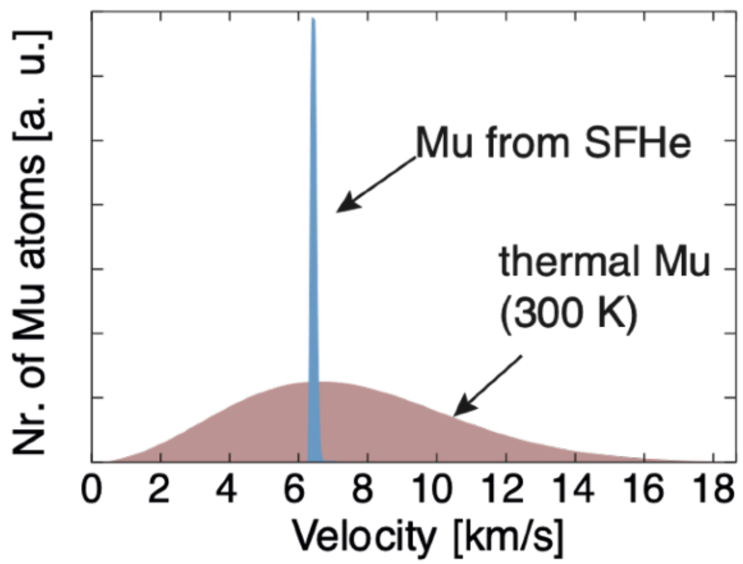
(Received 5 April 2020; revised 17 August 2020; accepted 15 Septe

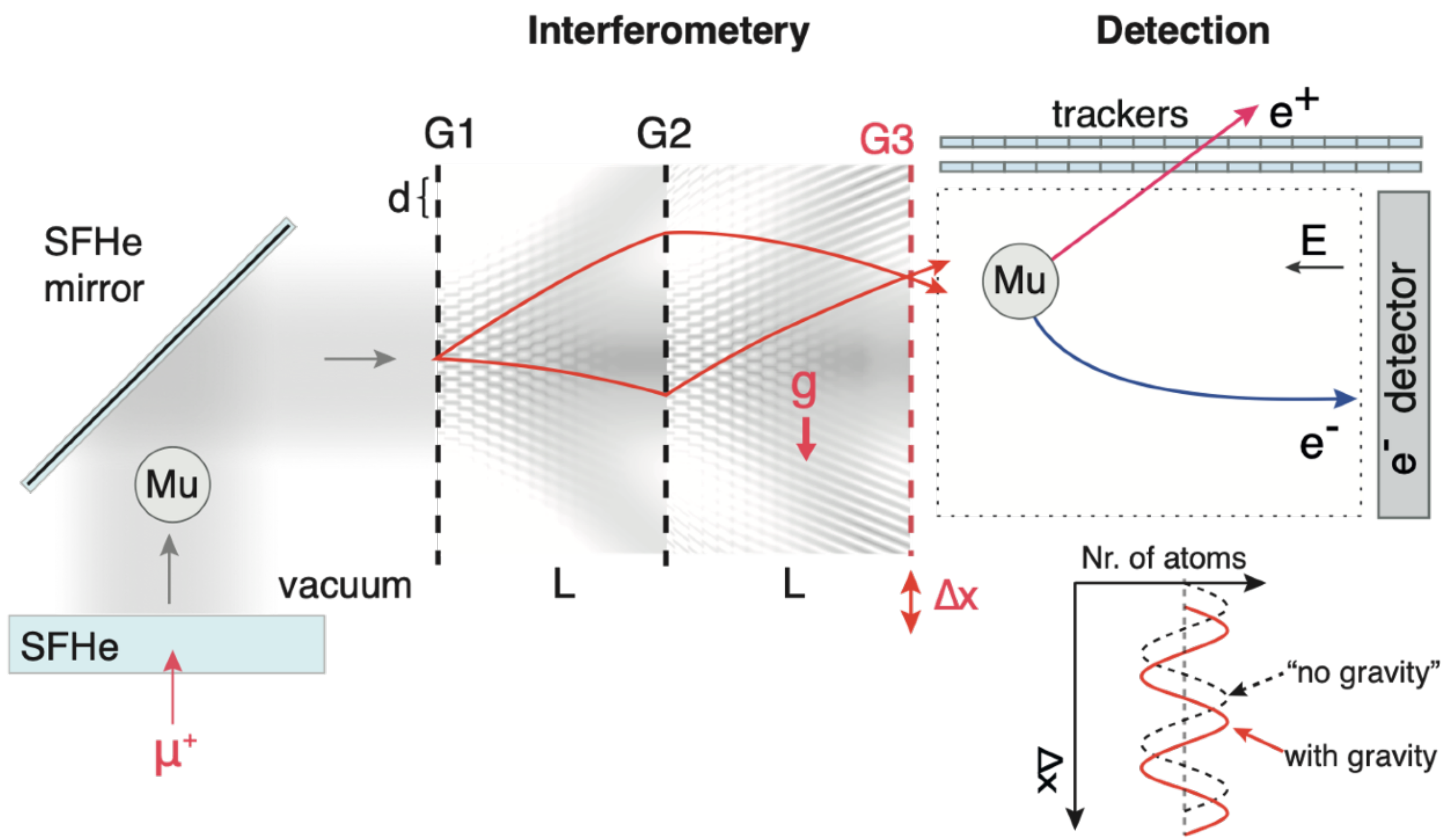
We demonstrate efficient transverse compression of a 12.5 MeV/c muon beam stopped in a helium gas target featuring a vertical density gradient and crossed electric and magnetic fields. The muon stop distribution extending vertically over 14 mm was reduced to a 0.25 mm size (rms) within 3.5 μs. The simulation including cross sections for low-energy μ^+-He elastic and charge exchange ($\mu^+ \leftrightarrow$ muonium) collisions describes the measurements well. By combining the transverse compression stage with a previously demonstrated longitudinal compression stage, we can improve the phase space density of a μ^+ beam by a factor of 10^{10} with 10^{-3} efficiency.

Can photo-ionize for unique slow-μ^+ beam

DOI: 10.1103/PhysRevLett.125.164802

The LEMING experiment at PSI, Switzerland





In R&D phase

- **LEMING**: **LE**ptons in **M**uonium **IN**teracting with **G**ravity
- Approved at the Paul Scherrer Institute (PSI) in 2022 January, taking advantage of the world's highest intensity cw muon source.
- A novel, ultracold muonium beam development for next generation laser spectroscopy and atom interferometry to measure the gravitational acceleration of (anti)leptons

doi: 10.21468/SciPostPhysProc.5.031

Anna Soter, ETH Zurich

1

World Surface-μ Beams

Table 1: Comparison of Surface Muon Facilities and Mu2e*

Facility		Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	Switzerland	9×10^8	CW	
TRIUMF [15]	Canada	2×10^6	CW	
MuSIC at Osaka [16]	Japan	10^8	CW	
J-PARC [17]	"	6×10^7	pulsed	
ISIS [17]	UK	6×10^5	pulsed	
HIMB at PSI [13]	Switzerland	10^{10}	CW	(design goal)
Mu2e at Fermilab		10^{11}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$
Mu2e with PIP-II		10^{12}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$

* R. H. Bernstein et al., "Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab," SNOWMASS21-RF0-AF0-007

- Used for fundamental physics, μSR (MatSci, chemistry), μCF R&D…
- Oversubscribed, until now none in U.S.
- PSI: current world leader
  - x10 upgrade ("HIMB") in the works

- PIP-II could surpass HIMB (by ~ x10² ?)
- Is FNAL 400 MeV Linac potentially competitive with PSI???
  - at minimum, invaluable R&D opportunity

Johnstone talk

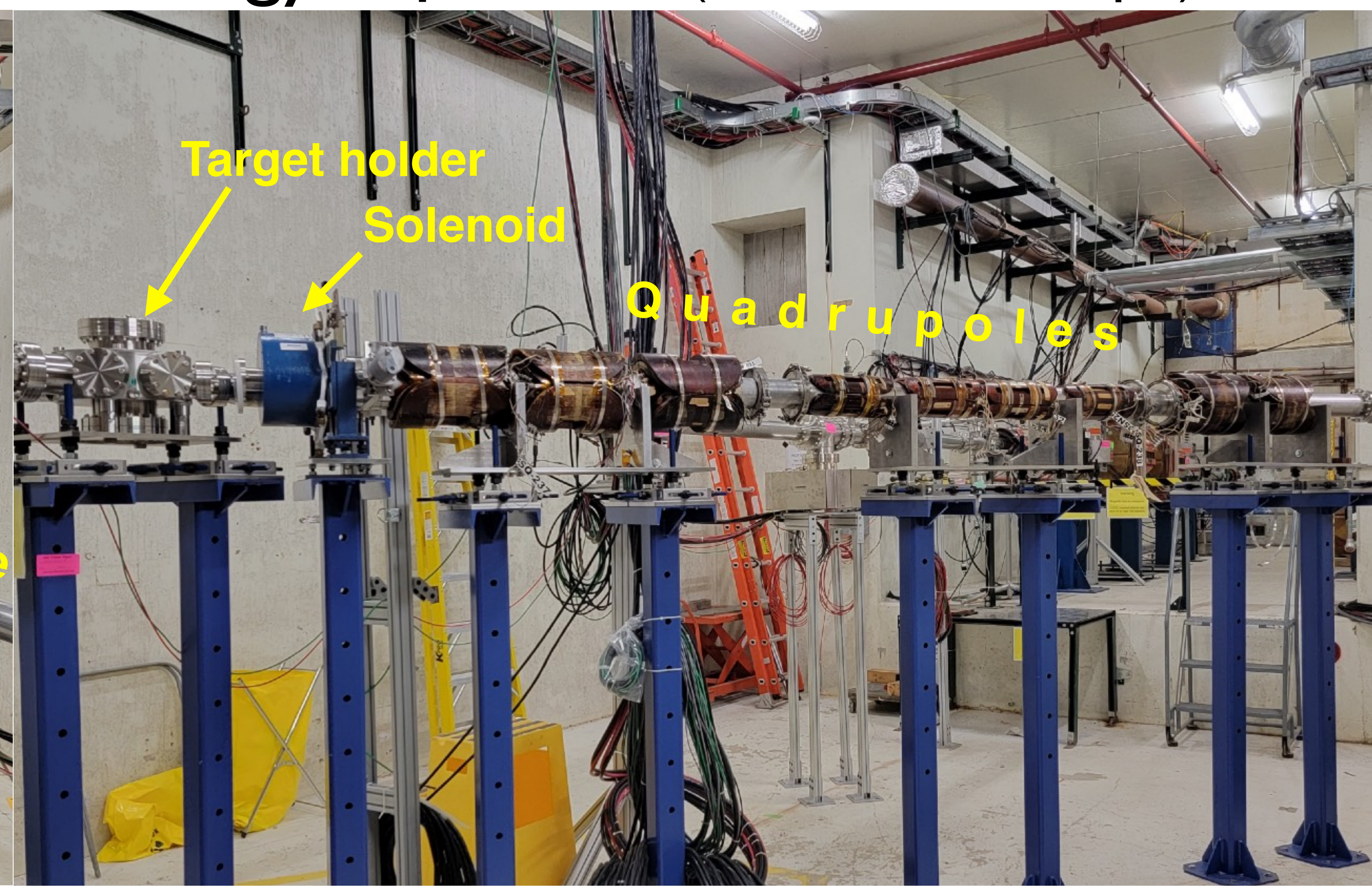
Potential Fermilab Advantages

- PSI protons heavily shared – limits LEMING intensity
  - whereas most Linac *p don't* go to MI (only ~1% of PIP-II will)
- PSI uses thin C targets so as not to disrupt proton beam en route to spallation target
  - @ Fermilab, can use thick, high-Z target
- In longer term, PIP-II linac → x10^n intensity advantage w.r.t. PSI HIMB

Fermilab "MuCool Test Area"

- Built ~20 years ago for muon collider R&D
  - served by 400 MeV H⁻ Linac
  - can be Linac major user – ~10% (?) goes to Booster
- Now repurposed as Irradiation Test Area (ITA)
- Also provides low-energy π/μ beam (ARPE-E μCF expt.)

Johnstone talk



What we (MAGE) want to do

- ETHZ/PSI group investigating option of thin SFHe layer illuminated by "muCool" beam
  - requires narrow μ^+ energy spread ΔE
  - costs ~10^3 in intensity (muon decay in muCool cooler)
- We will explore use of much thicker SFHe layer (can use larger ΔE, without muon cooling)
  - requires maintaining e^- pool on top of SFHe, via W needle electrode (established technique)
  - some MTA time potentially available in ≈ 1 year
  - still need to obtain funding!

Also potential game-changer for spectroscopy, M-$\bar{\text{M}}$ oscillation?

arXiv:2212.04897 [physics.ins-det]

Letter of Intent: Muonium R&D/Physics Program at the MTA

S. Corrodi,[0] C. Gatto,[5,6] C. Izzo,[2] C. J. Johnstone,[2] D. M. Kaplan,[*3,4] K. R. Lynch,[2] D. C. Mancini,[3] A. Mazzacane,[2] B. McMorran,[7] J. P. Miller,[1] J. D. Phillips,[3†] T. J. Phillips,[3] R. D. Reasenberg,[8] T. J. Roberts,[3,4] J. Terry[3]

[0]*ANL*, [1]*Boston U.*, [2]*Fermilab*, [3]*Illinois Institute of Technology*, [4]*Muons, Inc.*, [5]*INFN Napoli*, [6]*Northern Illinois U.*, [7]*U. Oregon*, [8]*U. California San Diego CASS*

[*] Spokesperson [†]Also at Zurich Instruments

December 5, 2022

1 Introduction

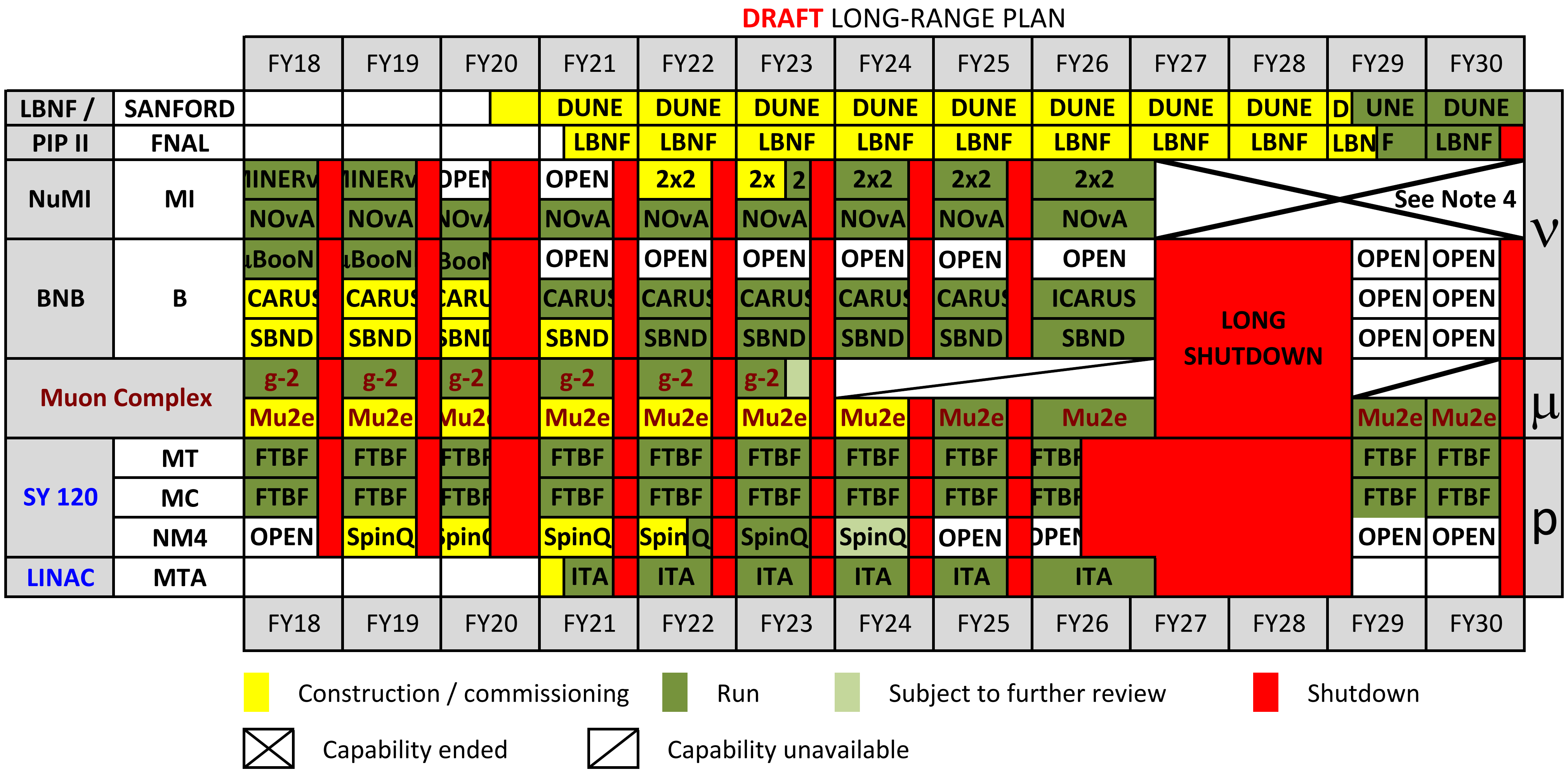
There is a need for a high-efficiency source of muonium (M $\equiv \mu^+e^-$, chemically a light isotope of hydrogen), traveling as a beam in vacuum, for fundamental muon measurements, sensitive searches for symmetry violation, and precision tests of theory [1]. Currently PSI in Switzerland is the world leader for such research. With PIP-II Fermilab has the potential to eclipse PSI and become the new world leader. It is prudent to begin the R&D now in order to be ready when PIP-II comes online. Fermilab's MeV Test Area (MTA) at the 400 MeV H^- Linac has a low-energy muon beamline suitable for this R&D, with the potential to compete with PSI for this physics in the pre-PIP-II near term as well.

Key muonium measurements include the search for M-$\overline{\text{M}}$ conversion, precision measurement of the M atomic spectrum, and the study of antimatter gravity using M. Furthermore, the J-PARC $g-2$ experiment proposes to use a low-energy μ^+ beam produced by photo-ionizing a slow beam of muonium, but the needed high-intensity muonium beam has yet to be demonstrated. The technique we propose may form a suitable muonium source for such a $g-2$ measurement as well as for other applications of slow muon beams.

M-$\overline{\text{M}}$ conversion is a double charged-lepton flavor-violating (CLFV) reaction, allowed (albeit at an undetectably small rate) via neutrino mixing. It may be no less likely — and in some models, *more* likely — than μ to e conversion [1]. Thus in a thorough CLFV research program it should be

Timeline

Office of the CRO January 2022



- Linac experiments possible until FY27
- PIP-II starts ~ FY29

Conclusions

- M-$\overline{\text{M}}$ oscillations, M spectroscopy: previous results >20 years old – can now do substantially better

  ⇒ good time for new efforts

- M gravity: never feasible before
  - new techniques make it feasible
  - could it provide clue to a new, QM theory of gravity? or to 5th force coupling to 2nd-gen. leptons?

- 400 MeV Linac: competitive with PSI?
- PIP-II: could enable world-leading M studies