ETH zürich IPA

DISCRETE 2024 in Ljubljana

2–6 Dec 2024

(Some) Fundamental tests with antimatter

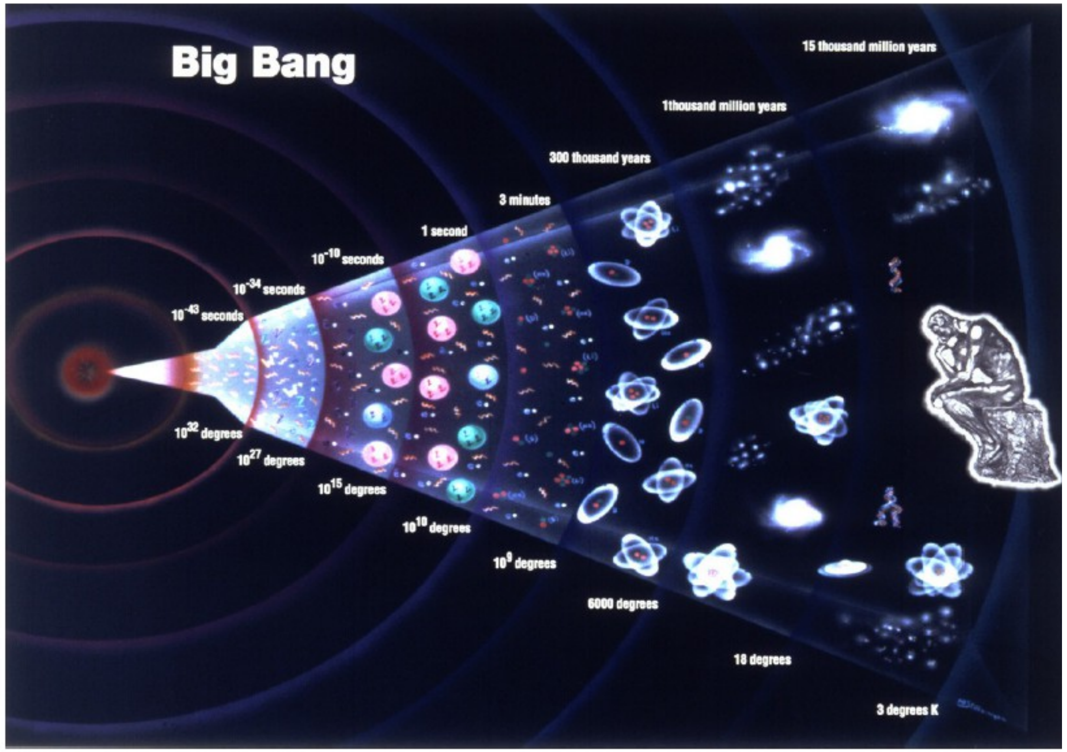
DISCRETE 2024 - 5th of December 2024

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

Outline

- Motivations to study anti-matter
- Experiments at the CERN Antiproton Decelerator (AD)
- Leptonic atoms

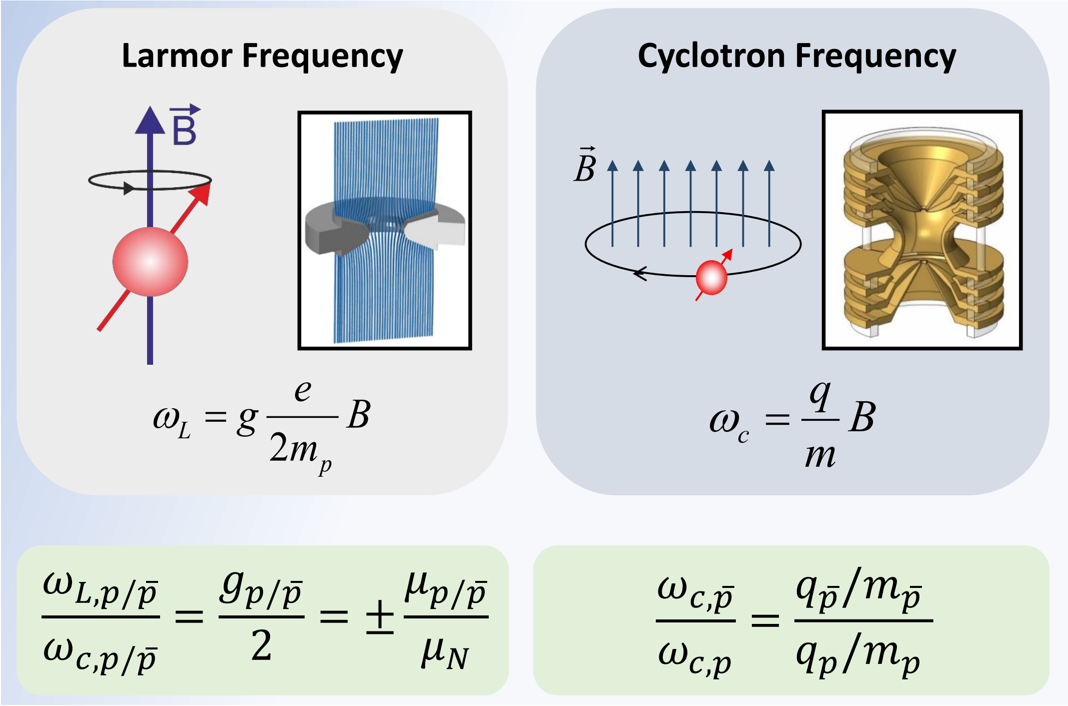
Baryon/anti-baryon asymmetry



- **Why does the universe contain matter?**
  - After the Big Bang equal amounts of matter and anti-matter
- **Where did all the anti-matter go?**
  - We (matter) have annihilated anti-matter.
  - Why was there a tiny asymmetry such that we could survive?
  - The **SM falls short,** it explains only 10^{-10} of what we need!
    - **Need new phenomena** such as:
      - **CP violation in the leptonic sector**
      - **Lorentz/CPT violation**

CPT invariance

- **Gerhart Lüders (1957):** CPT must be conserved in a local Lorentz-invariant QFT
- Some consequences of CPT invariance: $m = \bar{m}$, $\tau = \bar{\tau}$, $\mu = -\bar{\mu}$
- Test with single trapped (anti-)particles or atomic spectroscopy $(e^+e^-, \mu^+e^-, \bar{p}e^+)$

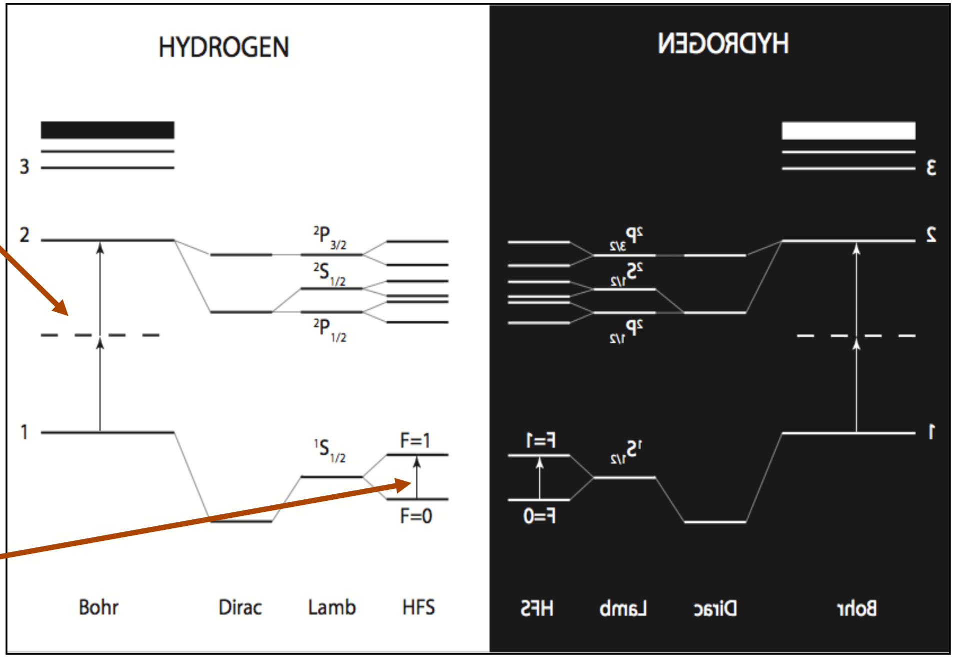


$$\omega_L = g\frac{e}{2m_p}B \qquad \omega_c = \frac{q}{m}B$$

$$\frac{\omega_{L,p/\bar{p}}}{\omega_{c,p/\bar{p}}} = \frac{g_{p/\bar{p}}}{2} = \pm\frac{\mu_{p/\bar{p}}}{\mu_N} \qquad \frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

1s-2s 2-photon Transition λ=243 nm $\frac{\Delta\nu}{\nu} \sim 10^{-14}$

Ground-state hyperfine splitting ν = 1.4 GHz $\frac{\Delta\nu}{\nu} \sim 10^{-12}$



The Standard Model Extension (SME)

$$\mathfrak{L}_{\mathrm{SME}} = \underbrace{\mathfrak{L}_{\mathrm{SM}} + \mathfrak{L}_{\mathrm{GR}}}_{\text{Conventional physics}} + \underbrace{\mathfrak{L}_{\mathrm{LV}}}_{\text{Lorentz violation}}$$

Colladay and Kostelecky., PRD **55**, 6760 (1997)
Colladay and Kostelecky., PRD **58**, 116002 (1998)
Kostelecky., PRD **69**, 105009 (2004)

- **Framework for testing Lorentz and CPT symmetry**
  - Models for Lorentz violation applicable to diverse physical scenarios
  - Compare and classify tests of Lorentz symmetry
  - Predicts signals for Lorentz and CPT violation

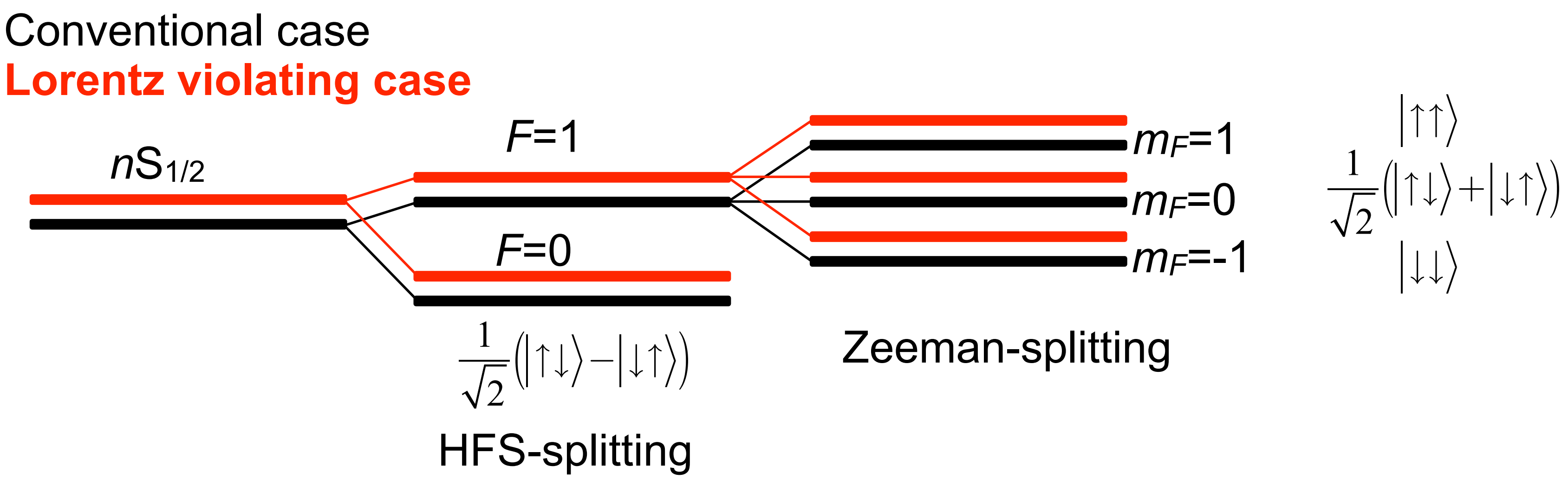
Spectroscopy as a sensitive test of Lorentz/CPT

- For example: $nS_{1/2}$ atomic state of hydrogen in the hyperfine-Zeeman regime
  - Energy of the atomic state

$$\epsilon = \epsilon_0 + \delta\epsilon$$

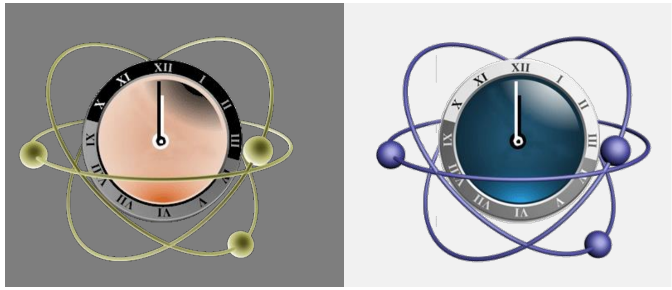
Conventional case (ϵ_0)

Lorentz-violating contribution ($\delta\epsilon$)



Spectroscopy of anti-hydrogen as a sensitive test of Lorentz/CPT

- The SME allows clocks and anti-clocks to tick at different rates



- Lorentz-violating energy shift for matter

≠

- Lorentz-violating energy shift for anti-matter

ELENA/AD at CERN: a new era in anti-hydrogen/antiproton physics

BASE

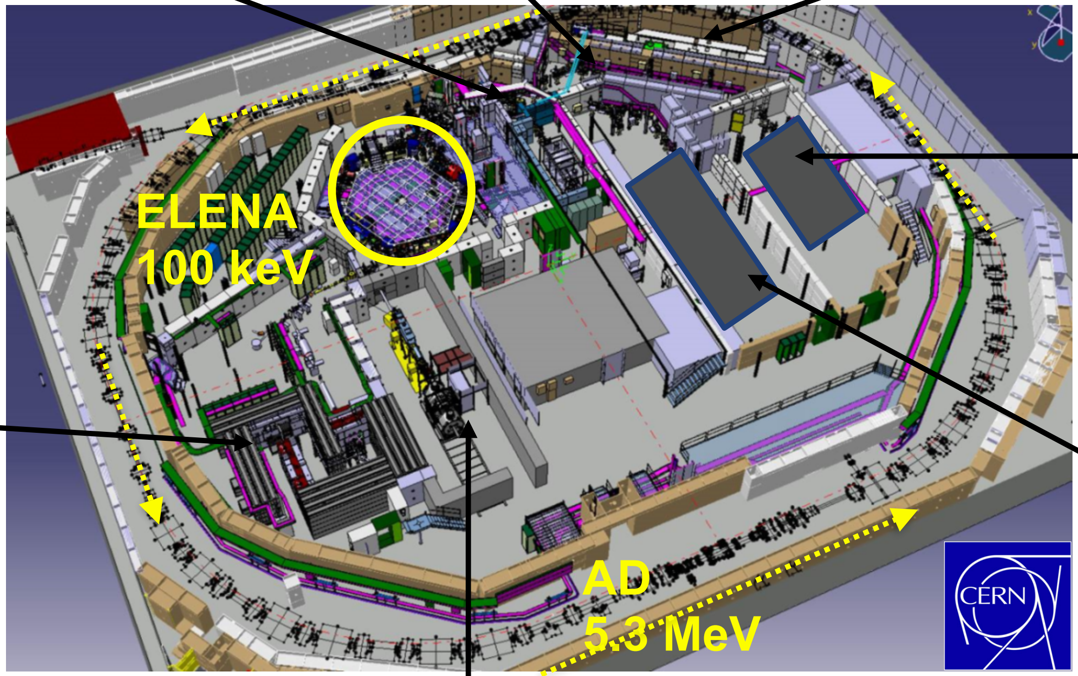
Study antiproton vs proton properties in a penning trap

STE$\bar{p}$

Transportable antiproton trap

AEgIS

-$\bar{H}$ gravity with interferometer



ALPHA

-High precision $\bar{H}$ spectroscopy
- $\bar{H}$ gravity

GBAR

- $\bar{H}$ ion production for free fall measurement
- $\bar{H}$ Lamb shift measurement

ASACUSA

- antiprotonic helium studies
- $\bar{H}$ HFS

PUMA

Transportable antiproton trap

Current status of different tests of CPT at the AD

From https://www.nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf

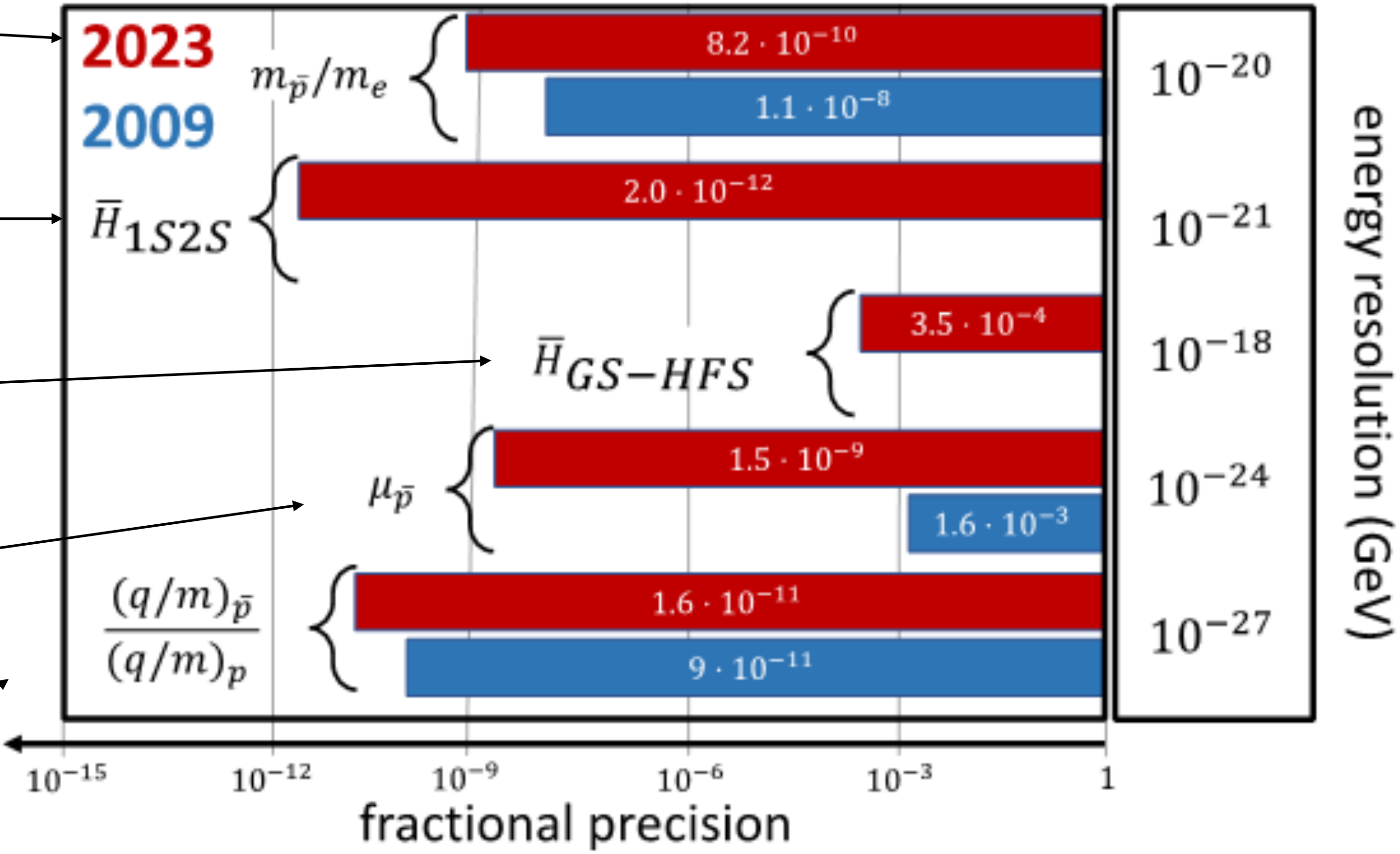
ASACUSA (2016)
M. Hori et al. Science 354, 610-614 (2016)

ALPHA (2018)
M. Ahmadi, Nature 557, 71–75 (2018)

ALPHA (2017)
M. Ahmadi, Nature 548, 66–69 (2017)

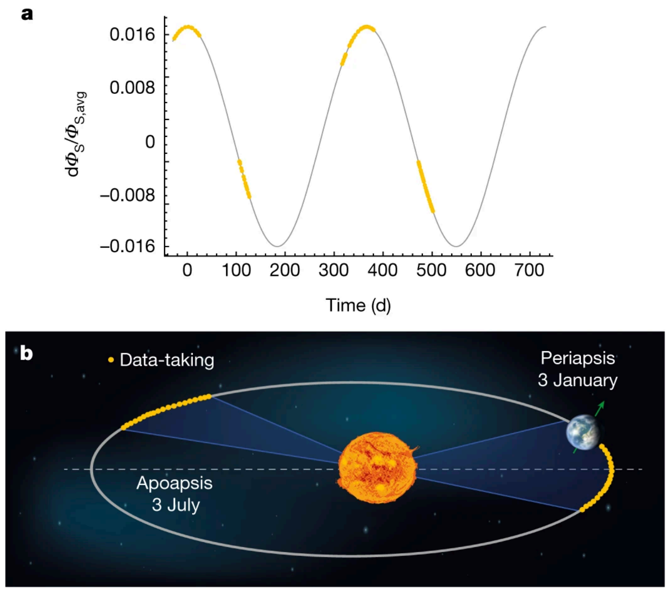
BASE (2017)
C. Smorra et al., Nature. 550, 371–374 (2017)

BASE (2022)
M. Borchert et al., Nature 601 53-57 (2022)



Current results of the effect of gravity on anti-matter

- **BASE: Gravitational Redshift (2022)**



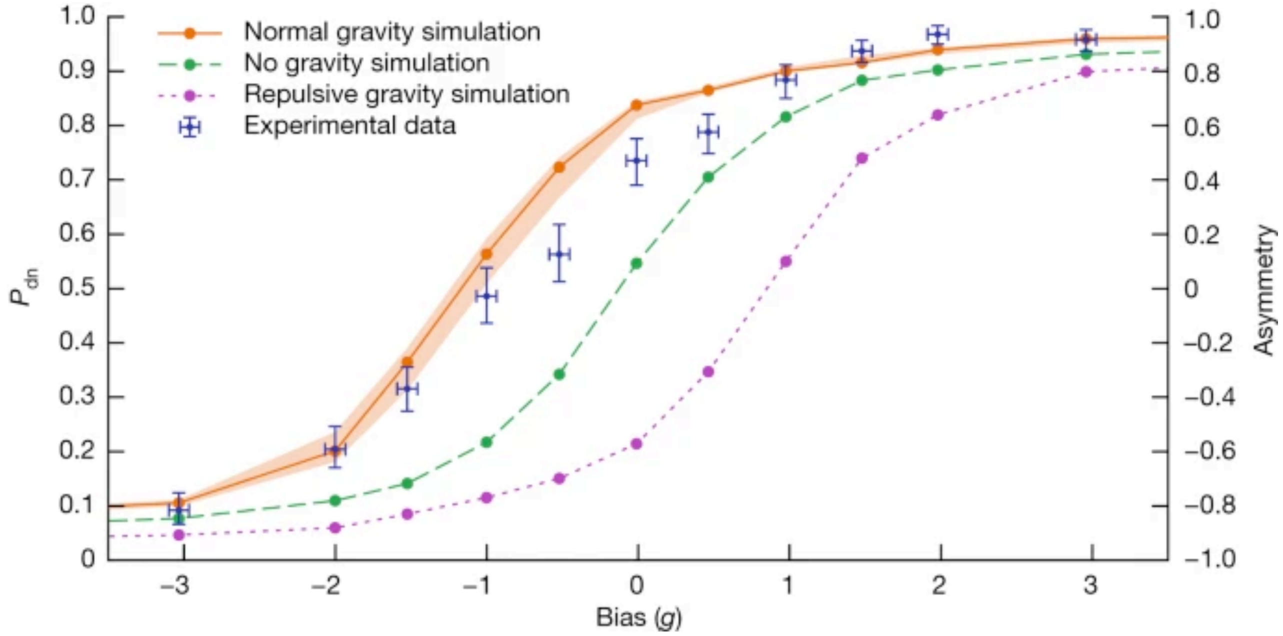
- WEP violation → variation of Ratio

$$\frac{\Delta R(t)}{R_{avg}} = \frac{3GM_{sun}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)}-\frac{1}{O(t_0)}\right)$$

- **Constraint:** $|\alpha_{g,D}-1| < 0.030\ (\mathrm{CL}\ 0.68)$,

M. Borchert et al., Nature 601 53-57 (2022)

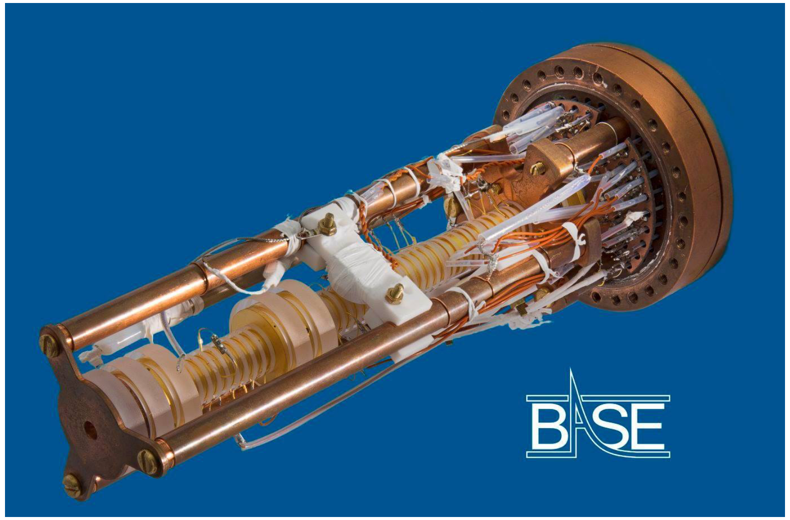
- **ALPHA-g Free Fall (2023)**



- **Constraint :** gravity falls as normal matter with 10% uncertainty

E. K. Anderson, Nature 621, 716–722 (2023)

Prospects for BASE

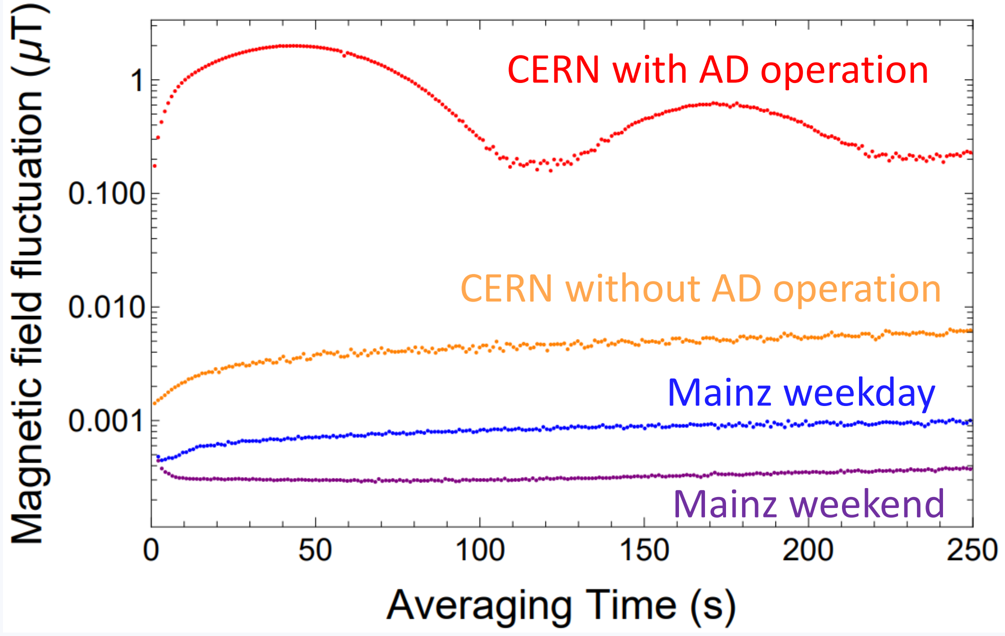


- Great progress in antiproton cooling (15 h to 8 min)
  Latacz et al PRL133 053201 (2024)
  → 10-100 improvement in precision
- New (anti-)proton g-factor data being analysed

BASE experiment takes a big step towards portable antimatter

The experiment successfully transported a box filled with unbonded protons across CERN's main site, thus demonstrating that the same feat could later be possible for antiprotons

25 OCTOBER, 2024 | By Sarah Charley



Link to the article.

Status and prospects for the anti-hydrogen studies

AEgIS – The weight of antimatter

Pulsed $\bar{H}$ production achieved in 2021 (Comm. Phys. 4, 19 (2021))
Positronium laser cooling demonstrated (PRL 132, 083402 (2024))
→ with colder Ps dramatic increase in $\bar{H}$ production expected

ALPHA

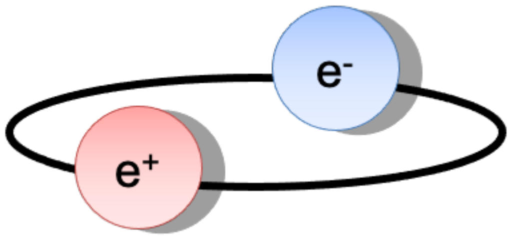
Laser cooling of magnetically trapped $\bar{H}$ (Nature 592, 35-42 (2021))
→ improvement of all measurements (spectroscopy and gravity) by orders of magnitude.

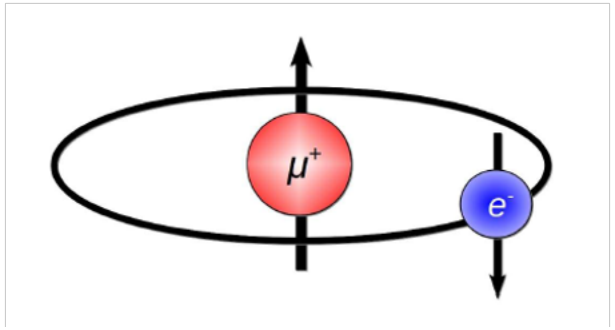
Cold antihydrogen beam produced (Nature Comm. 5, 3089 (2014)), currently being optimised for HFS measurement.

GBAR

$\bar{H}$ produced with Ps charge exchange (EPJC83, 1004 (2023))
In 2024 more than factor 30x $\bar{H}$ and record high positrons accumulated: 10^{10} in 20 min.

Motivations to study leptonic atoms - Positronium and Muonium



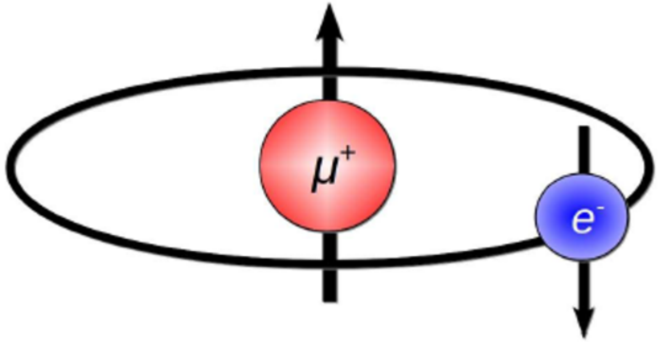


- Being **purely leptonic**, they can be described very precisely by **bound state QED** calculations **devoid of uncertainties from nuclear size effects** present in normal atoms. Therefore, any deviation between theory and measurements could be a signal of **New Physics.**
- Moreover, from these measurements very important values of **fundamental constants** can be extracted such as the **muon mass and muon magnetic moment.**

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: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$



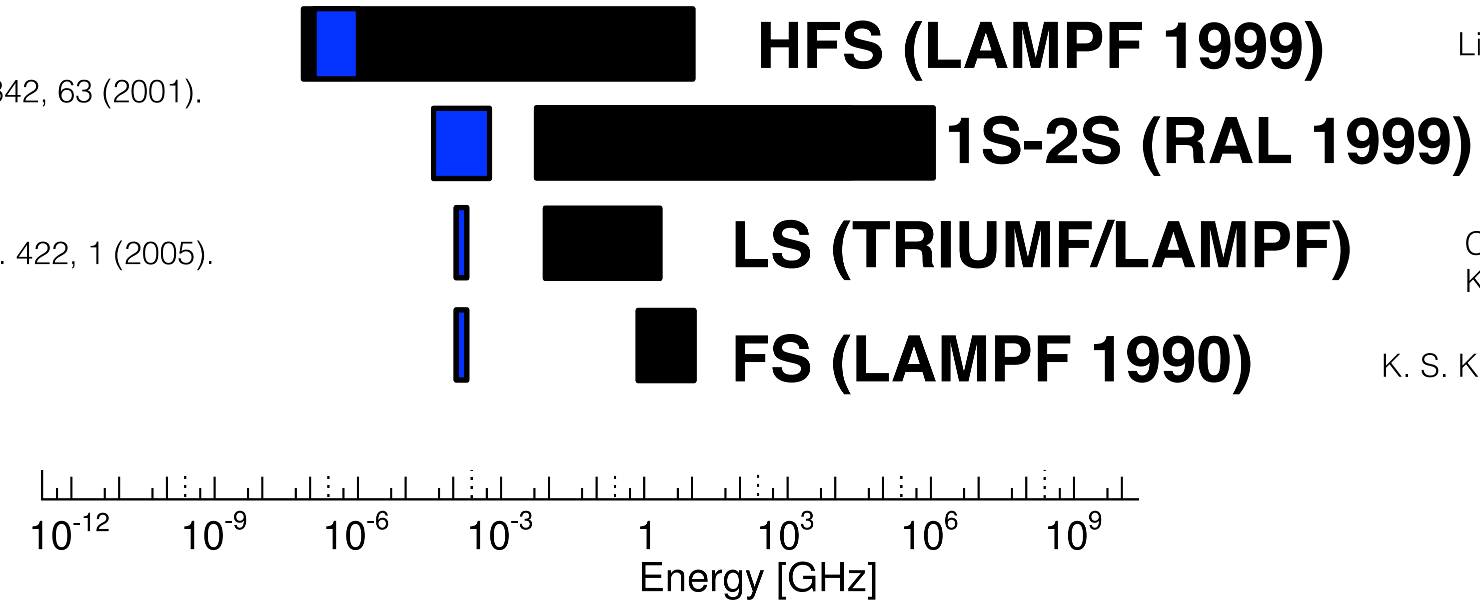
Discovered in 1960 (Hughes) by detecting **muonium spin** (Larmor) **precession** in an external magnetic field perpendicular to the spin direction.

Actually M is not a real -onium atom (particle-antiparticle system).
The true muonium bound state would be $\mu^+\mu^-$ yet to be discovered…

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)

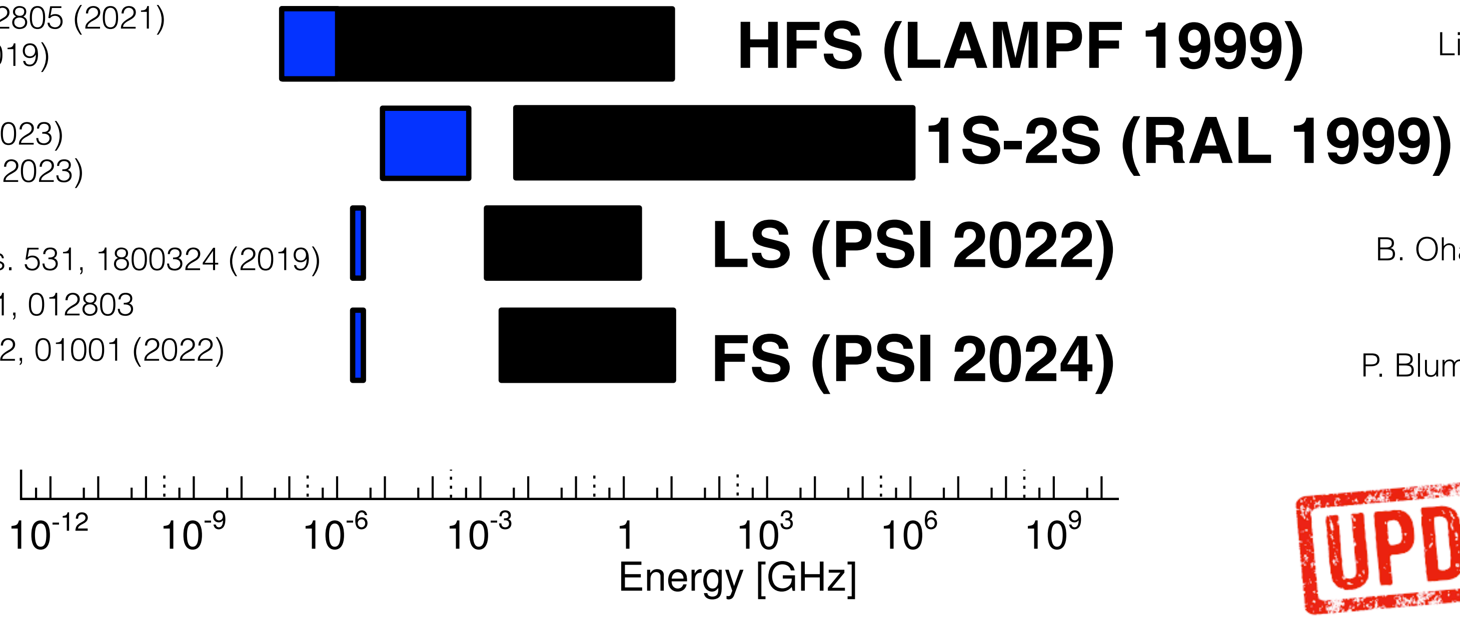
THEORY — **UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)**
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

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)
P. Blumer et al, paper in preparation

UPDATE

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

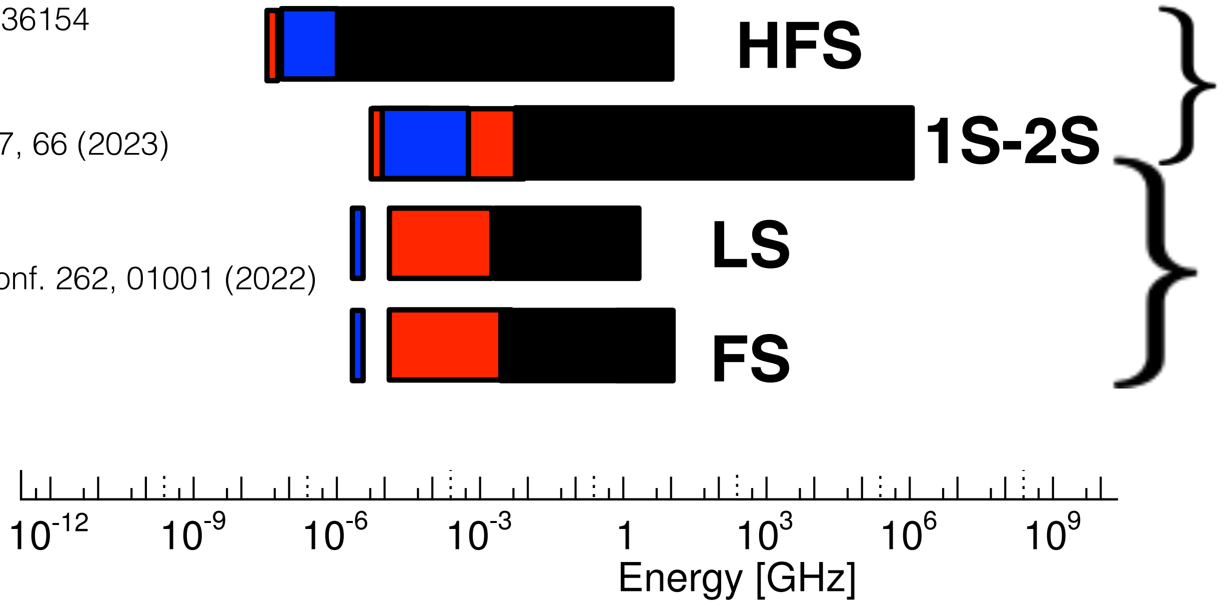
THEORY — UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)
UNCERTAINTY FROM KNOWLEDGE m_μ/m_e (RIGHT EDGE)

Muonium Spectroscopy - ongoing experiments

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

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

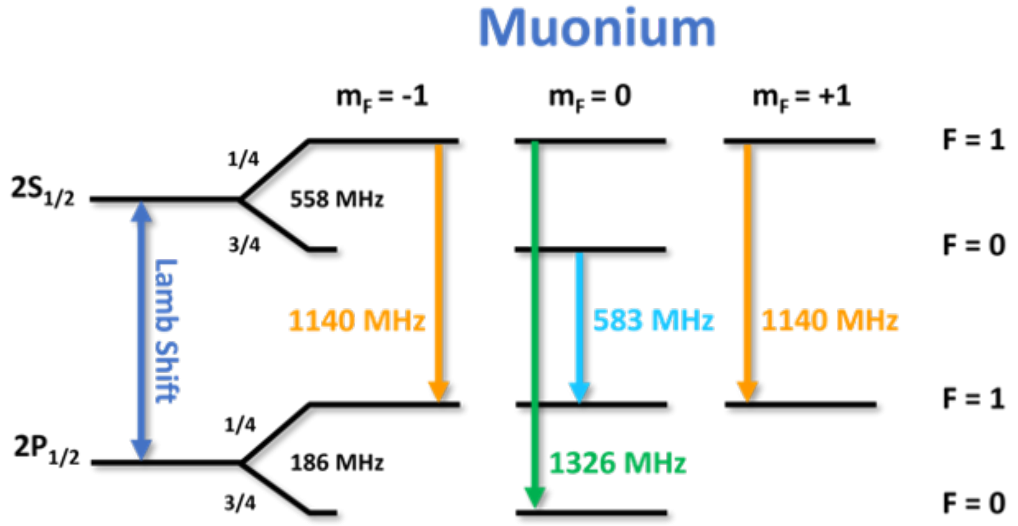
G. Janka, PC, et al. EPJ Web Conf. 262, 01001 (2022)



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



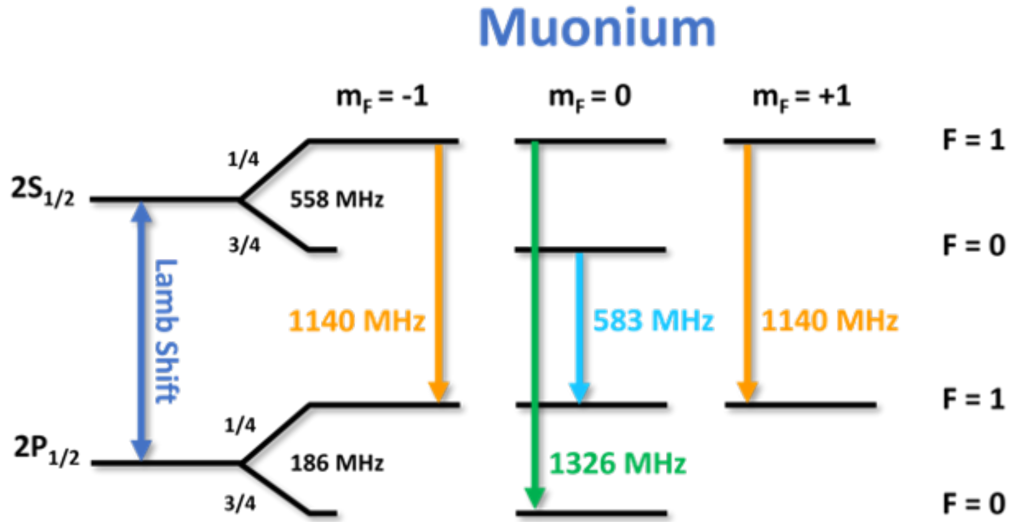
THEORY $$(E(2S_{1/2}) - E(2P_{1/2}))^{\text{th}}_{\text{Mu}} = 1047.498(1)\,\text{MHz}.$$

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

Summary of calculated contributions

	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
$E_{\text{VP}\mu\text{+had}}$	$\alpha\,(Z\alpha)^4(m_e/m_\mu)^2$	−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
$E_{\text{rec,S}}$	$(Z\alpha)^5\;L\,(m_e/m_n)$	0.358	3.138
$E_{\text{rec,R}}$	$(Z\alpha)^6\;(m_e/m_n)$	−0.001	−0.012
$E_{\text{rec,R2}}$	$(Z\alpha)^6\;(m_e/m_n)^2$	−0.000	−0.001(1)
E_{RR}	$\alpha\,(Z\alpha)^5\;(m_e/m_n)$	−0.002	−0.014(1)
$E_{\text{RR2e+p}}$	$\alpha\,(Z\alpha)^5\;(m_e/m_n)^2$	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)

Muonium Lamb shift



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

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

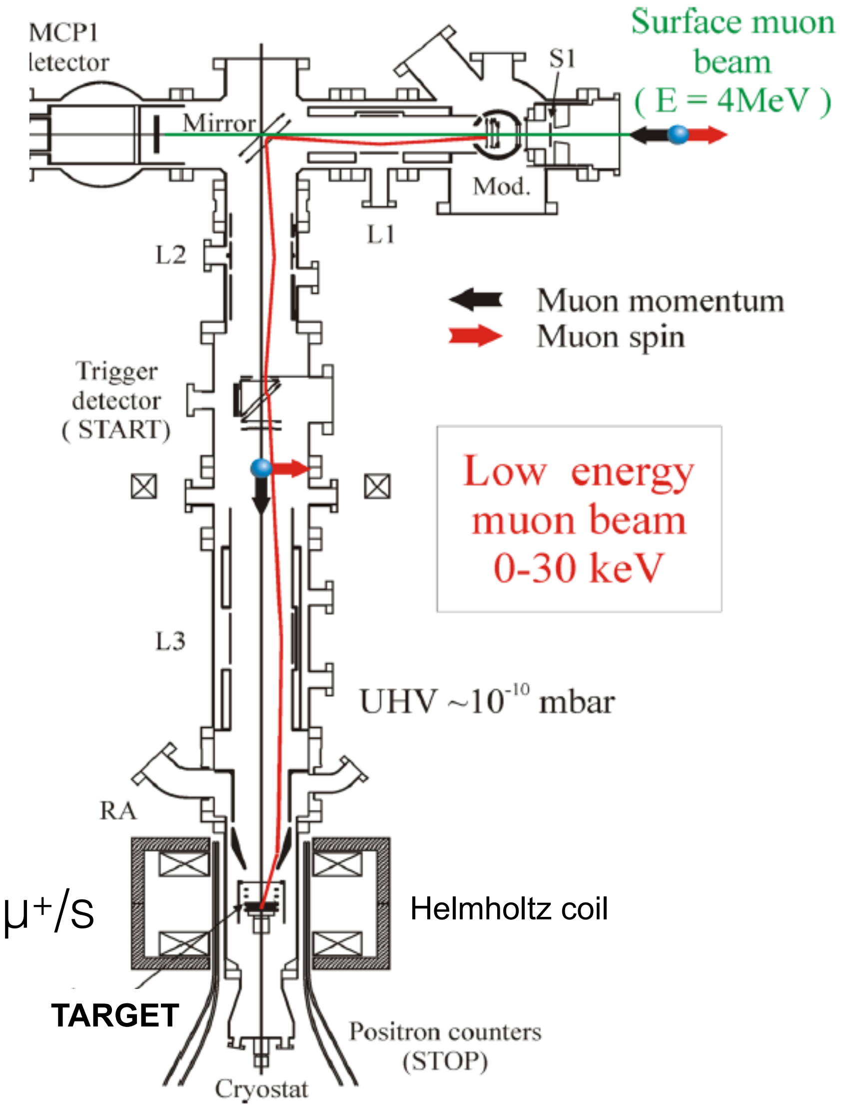
Recoil corrections are enhanced for M (9 times lighter than H)

Summary of calculated contributions

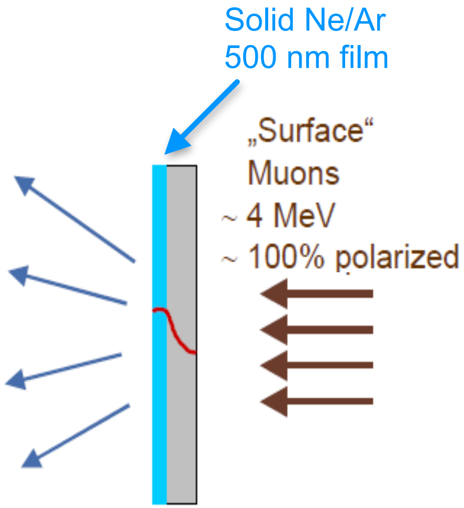
	Largest Order	Hydrogen (MHz)	Muonium (MHz)
$E_{\rm SE}$	$\alpha\,(Z\alpha)^4\,L$	1084.128	1070.940
$E_{\rm VP}$	$\alpha\,(Z\alpha)^4$	−26.853	−26.510
$E_{{\rm VP}\mu+{\rm had}}$	$\alpha\,(Z\alpha)^4(m_e/m_\mu)^2$	−0.001	−0.001
$E_{\rm 2ph}$	$\alpha^2(Z\alpha)^4$	0.065	0.065
$E_{\rm 3ph}$	$\alpha^3(Z\alpha)^4$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

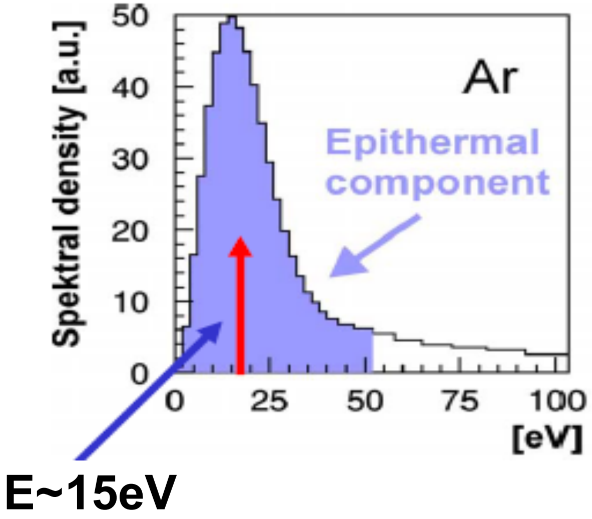
The PSI low energy muon beam (LEM)

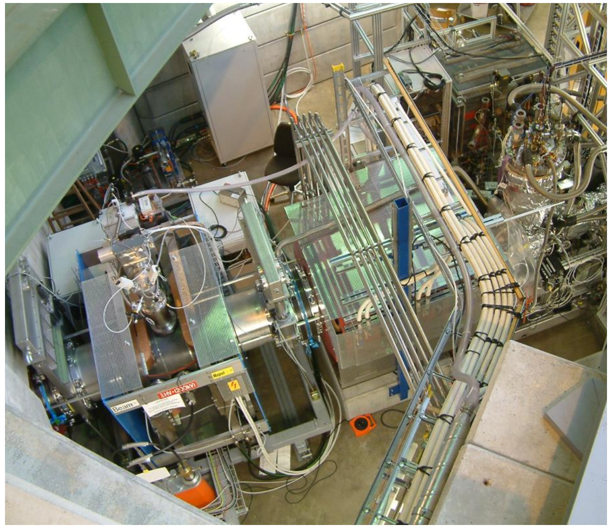
https://www.psi.ch/en/low-energy-muons



Up to 5×10^3 μ^+/s





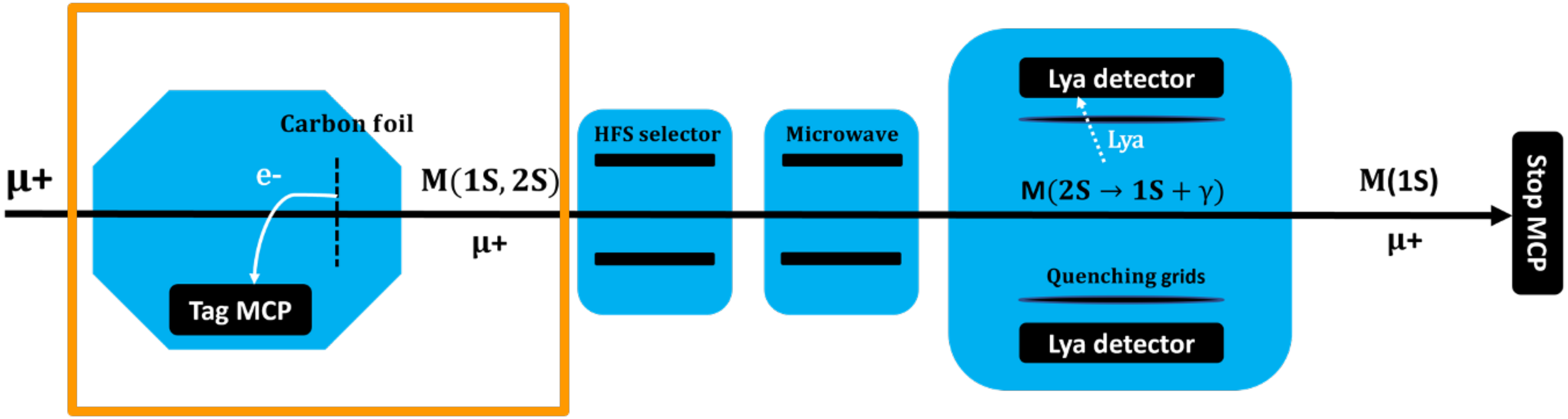


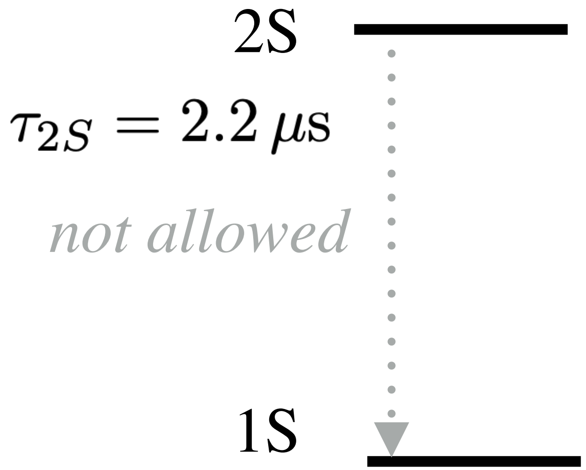
Measurement of M the Lamb shift

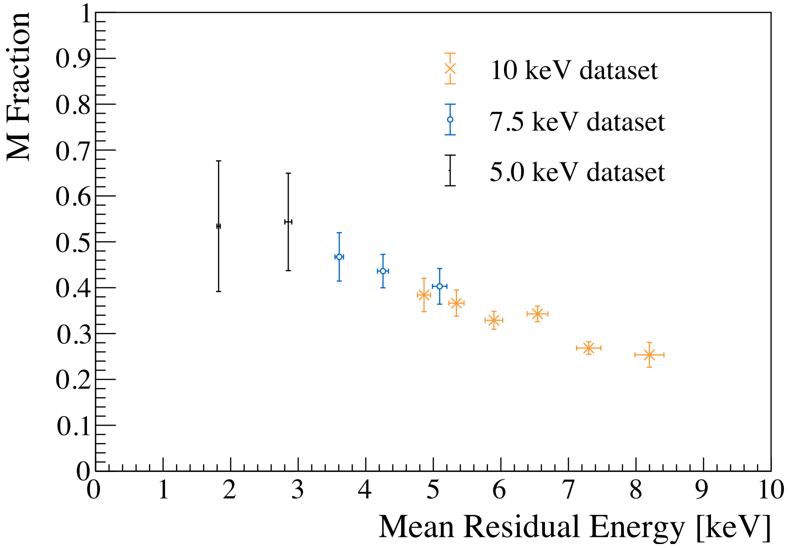
LEM beamline

10 kHz/
10 keV

M(2S) formation & tagging





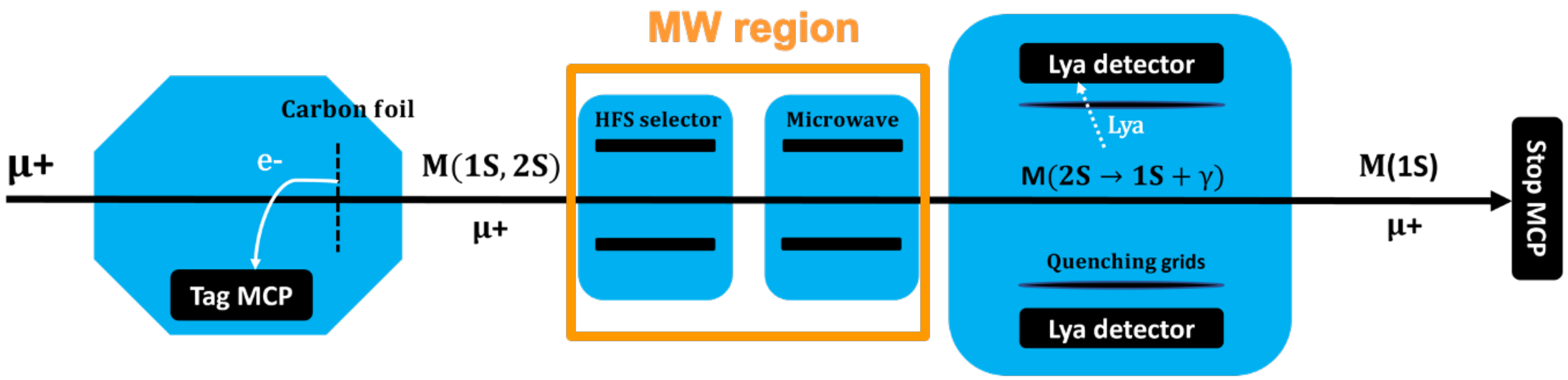


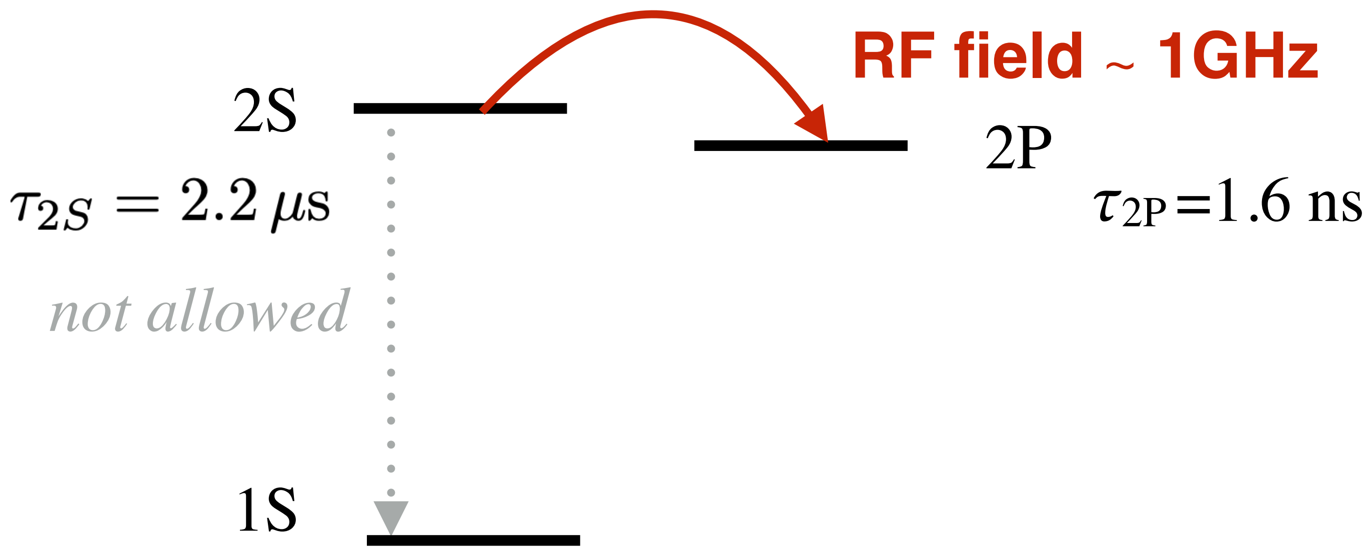
$$f_{M(n=2)/M(n=1)} = (10 \pm 2)\%$$

($1/n^3$ expected from naive scaling)

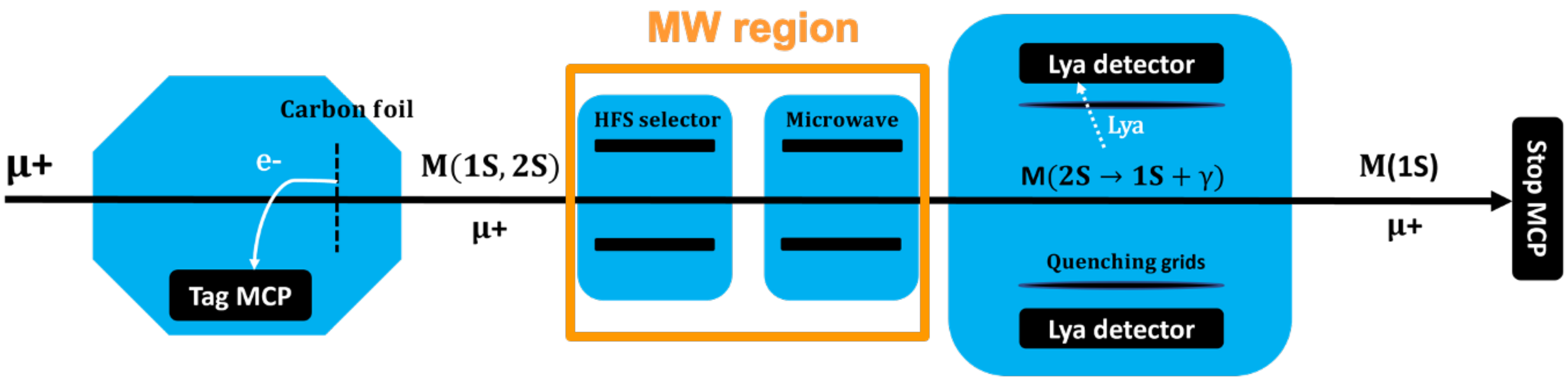
G. Janka, PC, et al., Eur. Phys. J. C (2020) 80: 804

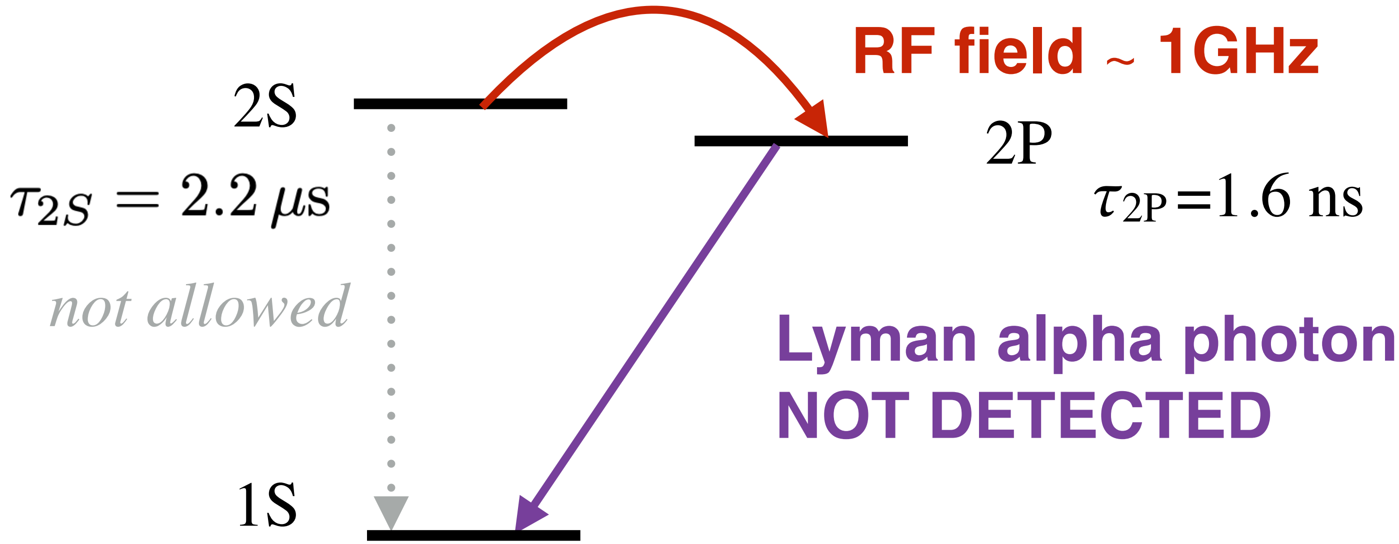
Measurement of M the Lamb shift





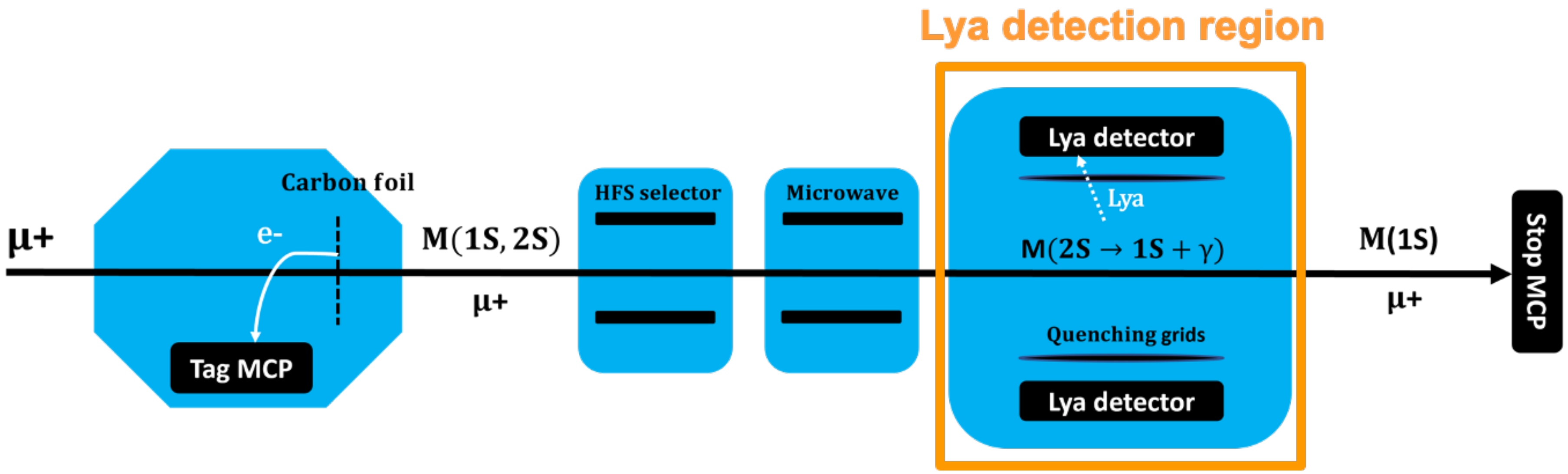
Measurement of M the Lamb shift

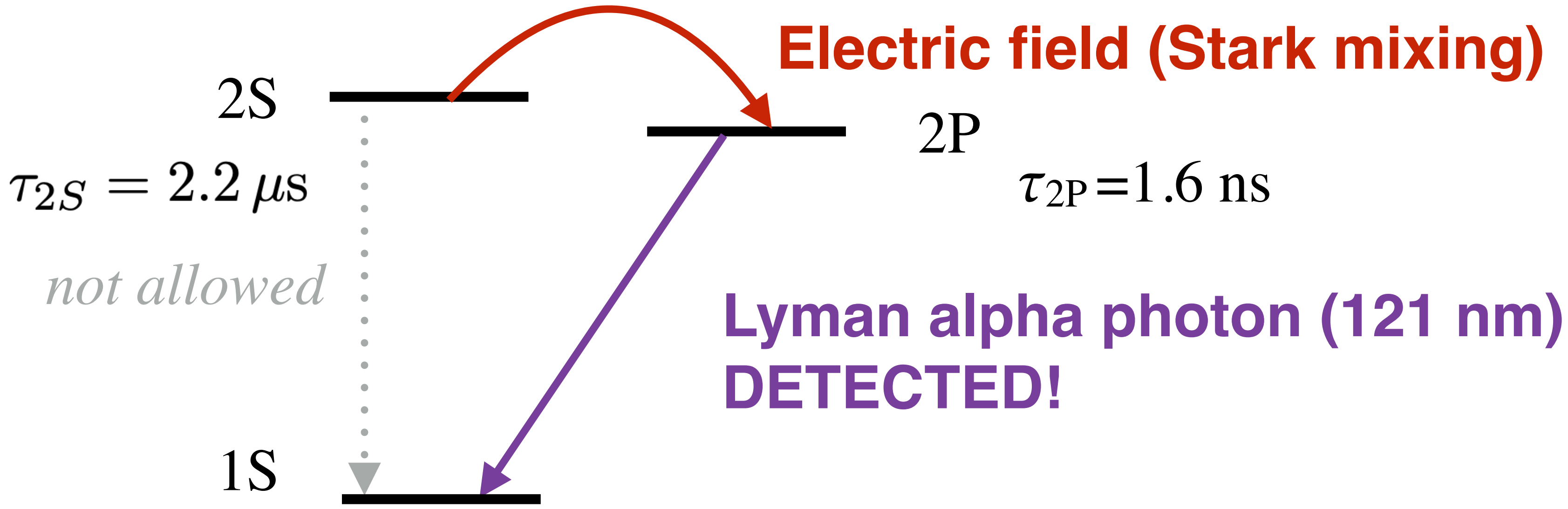




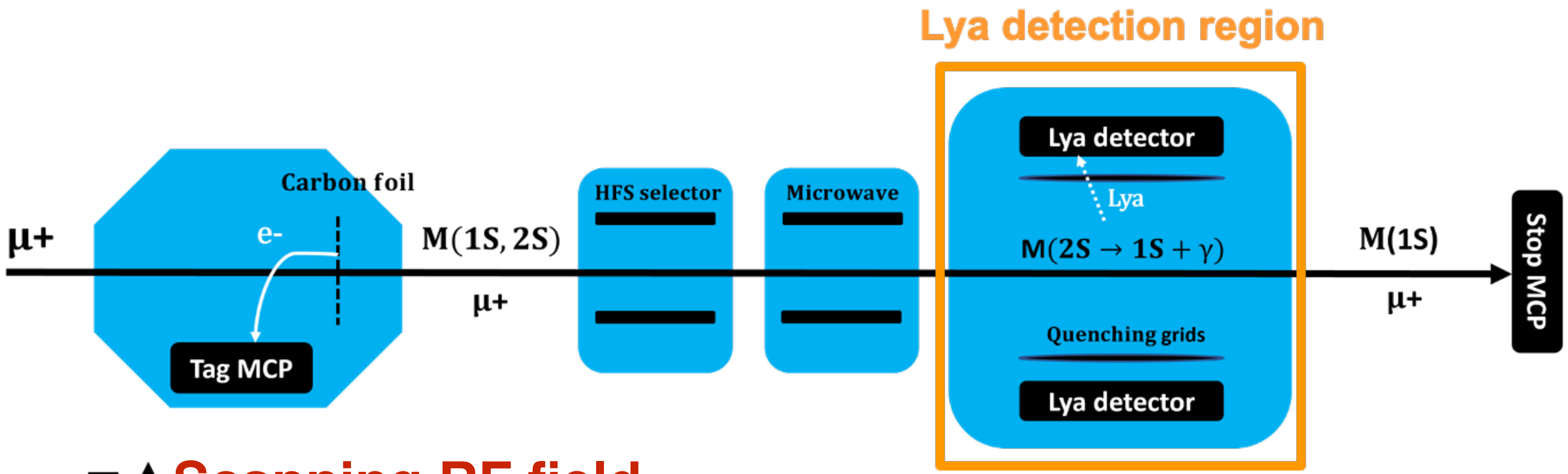
Lyman alpha photon (121 nm)
NOT DETECTED

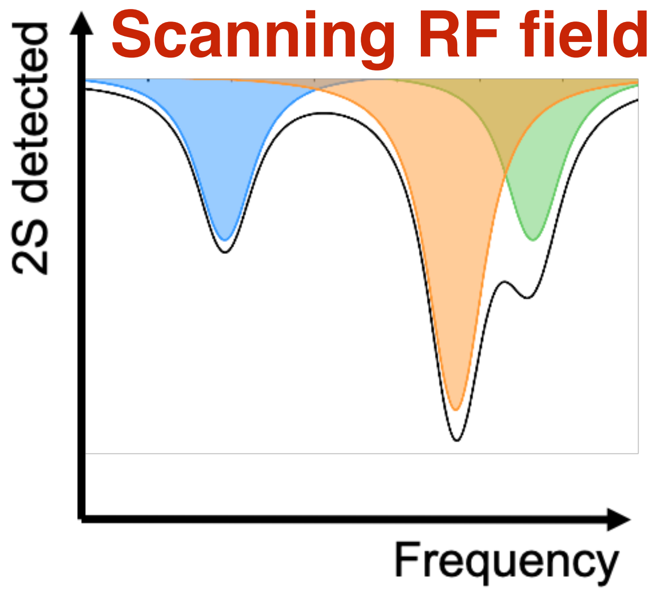
Measurement of M the Lamb shift

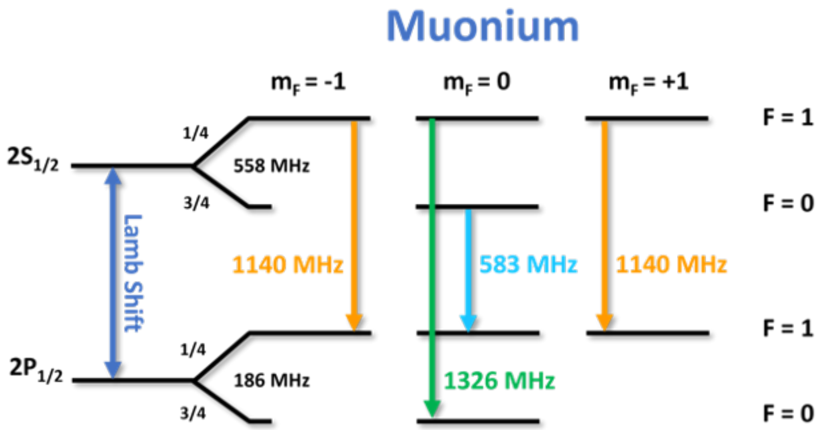




Measurement of M the Lamb shift



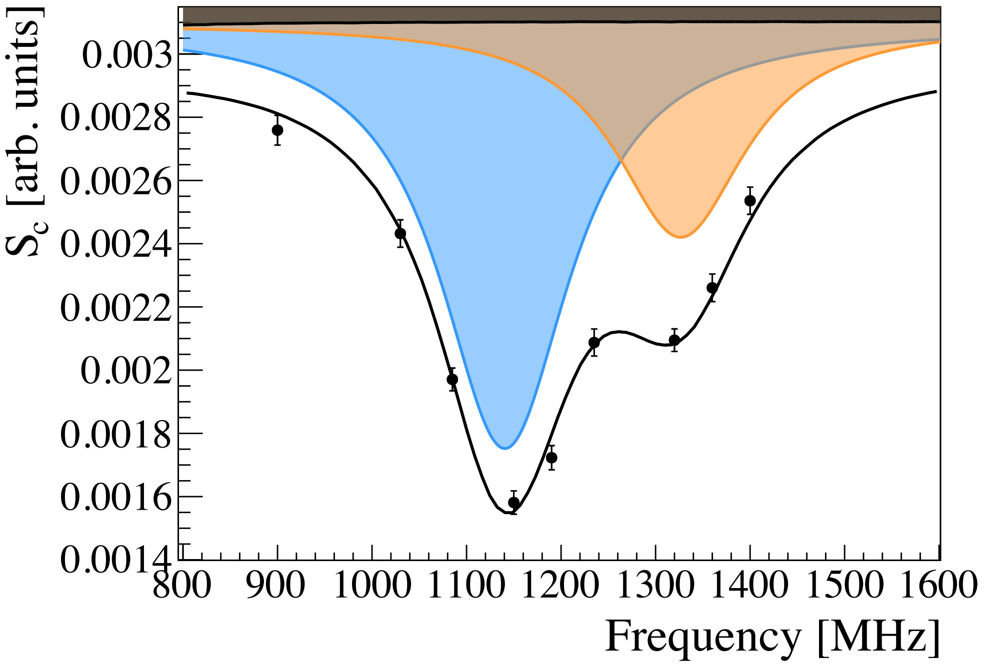




Results of the M Lamb shift

B. Ohayon, P. Crivelli, et al. Phys. Rev Lett. 128, 011802 (2022)

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.

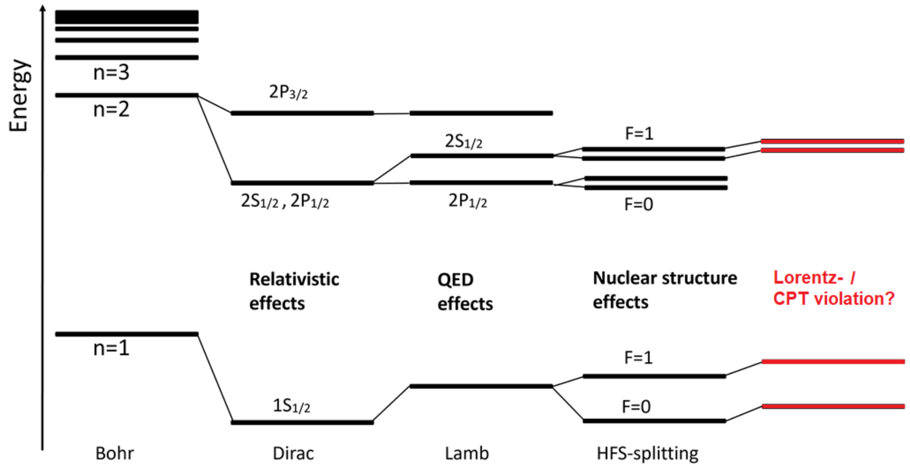
Constraints on Lorentz- and CPT violation

D. Colladay and V. A. Kostelecký. Phys. Rev. D, 55:6760–6774, 1997

$$\mathcal{L}_{\text{SME}} = \underbrace{\mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{GR}}}_{\text{Conventional physics}} + \underbrace{\mathcal{L}_{\text{LV}}}_{\text{Lorentz violation}}$$

Conventional physics

Lorentz violation



Additional energy term for Muonium Lamb Shift:

$$2\pi\delta\nu_{\text{Lamb}} = -\frac{2}{3}(\alpha m_{\text{r}})^4(\overset{\circ}{a}{}^{\text{NR}}_4 + \overset{\circ}{c}{}^{\text{NR}}_4)$$

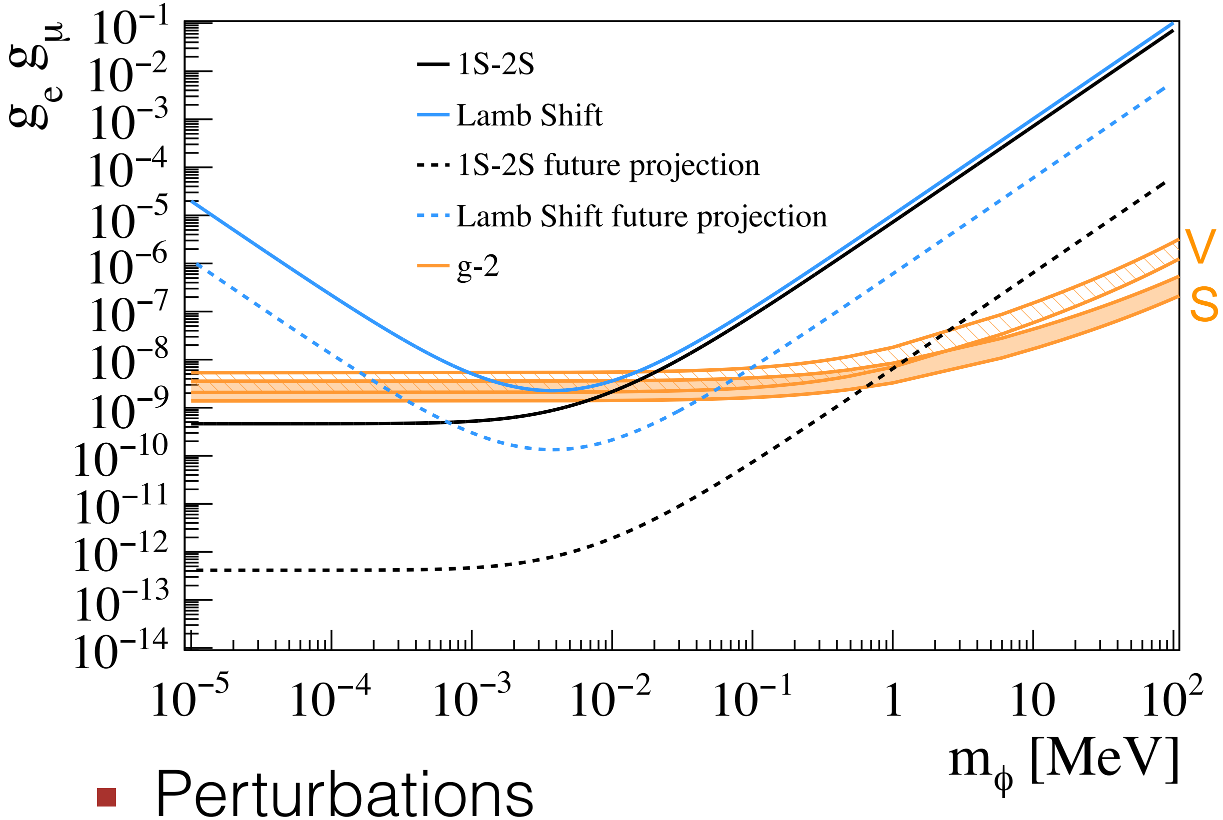
A. H. Gomes et al., Phys. Rev. D, 90:076009, 2014.

Lorentz and CPT: **< 1.7 x 10^5 GeV^{-3}**

Only Lorentz: **< 1.7 x 10^5 GeV^{-3}**

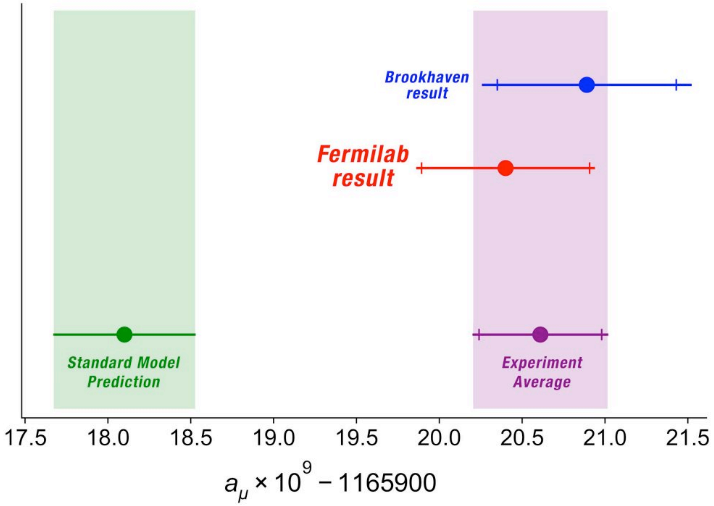
- Our results improve an order of magnitude the previous limits

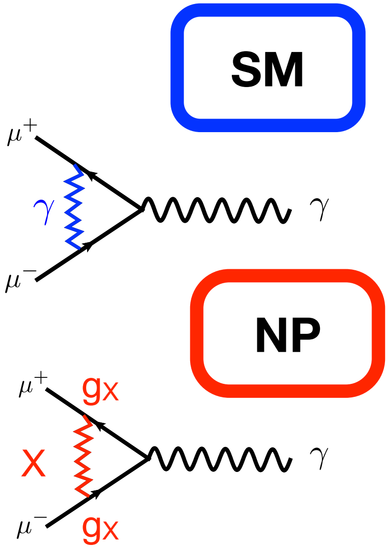
Muonium spectroscopy as a probe for new muonic forces



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

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





- Perturbations

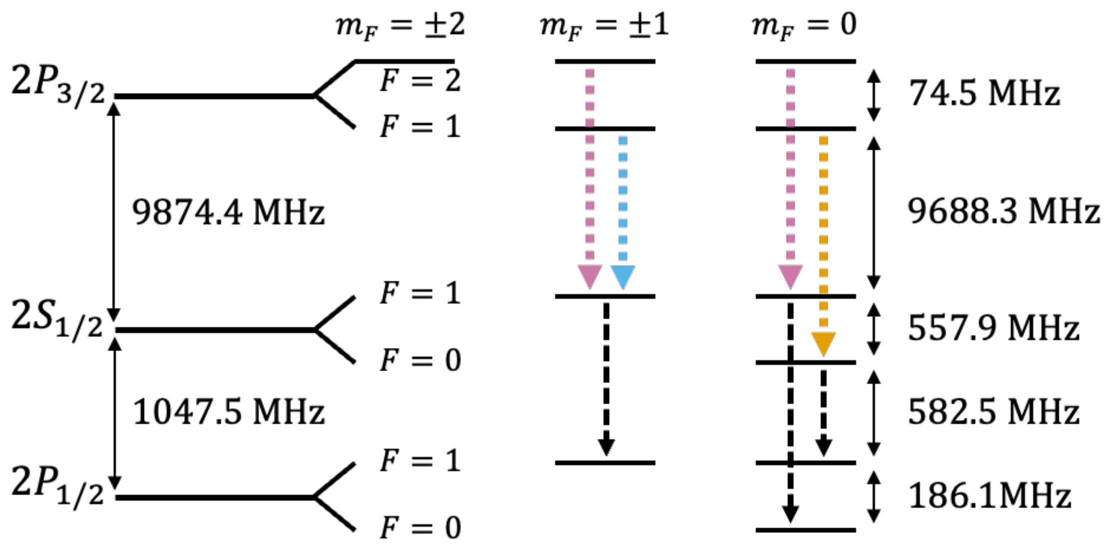
$$\Delta E_{ss}(2S^0 \rightarrow 1S^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

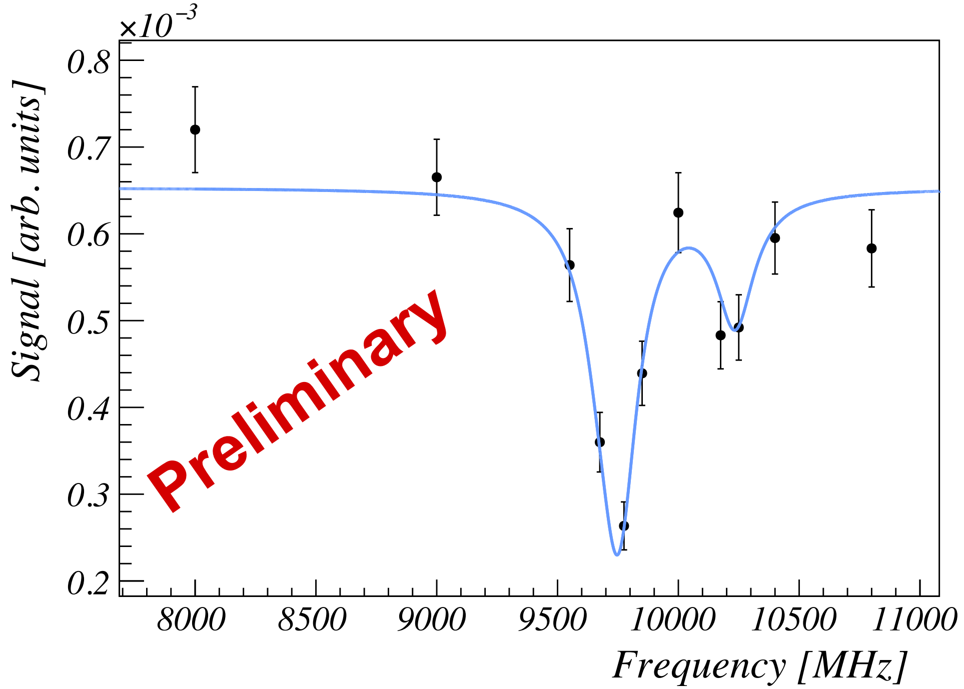
$$\Delta E_{ss}(2S^0 \rightarrow 2P^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

combined with bound from (g-2)$_e$

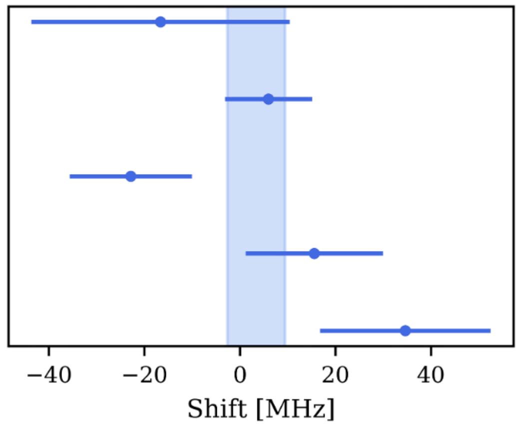
L. Morel et al, Nature 588, 61 (2020),
R. H. Parker et al., Science 360, 191 (2018).
D. Hanneke et al. e Phys. Rev. Lett. 100, 120801 (2008)

Latest results (2024) - Fine structure





Different data sets varying some Exp. parameters



Measurement of the **$2S_{1/2}$ → $2P_{3/2}$** at the same level of precision as the LS.

<u>Advantage: </u>free from systematic due excited states.

P. Blumer, PC et al., in preparation

Summary & Outlook - Muonium LS&FS

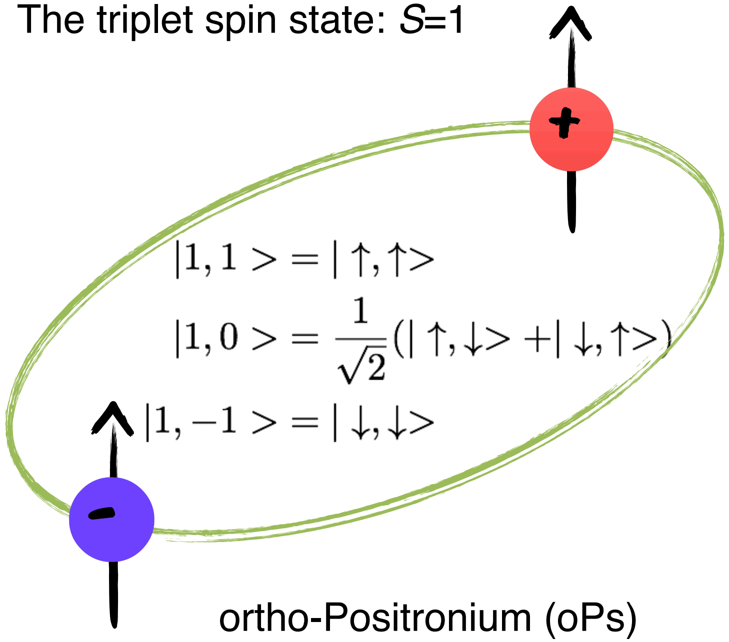
- Planned **High intensity muon beam line at PSI upgrade** (2027) combined with **muCOOL** scheme will allow to boost current statistics by **two orders of magnitude.**

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

Beamline	Target	Scheme	Timeline	M(2S) (Hz)	LS Uncertainty (kHz / 10 d)	Contributions
PiE4/LEM	C-Foil	Rabi	2024	20	$\sim 10^3$	E_{SE}, E_{VP}, $E_{rec,S}$
PiE4/LEM	Graphene	SOF	2025	100	200	E_{BKG}
PiE1/muCool	Graphene	SOF	2026	1000	70	E_{2ph}
HiMB/muCool	Gas	FOSOF	2029	10^5	10	E_{RR}, E_{HFS}, $E_{rec,R}$, E_{SEN}

Now to the Positronium (Ps) laser experiment….

The triplet spin state: S=1



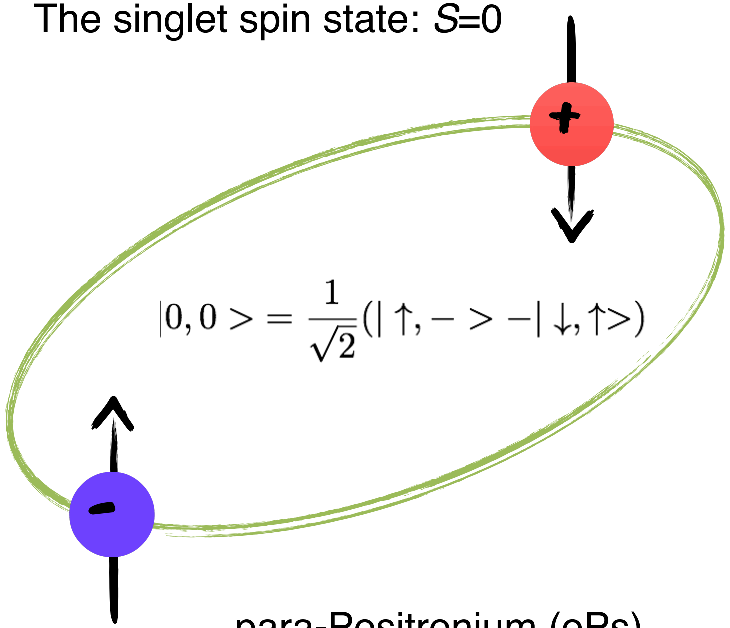
$$|1,1> = |\uparrow,\uparrow>$$

$$|1,0> = \frac{1}{\sqrt{2}}(|\uparrow,\downarrow> + |\downarrow,\uparrow>)$$

$$|1,-1> = |\downarrow,\downarrow>$$

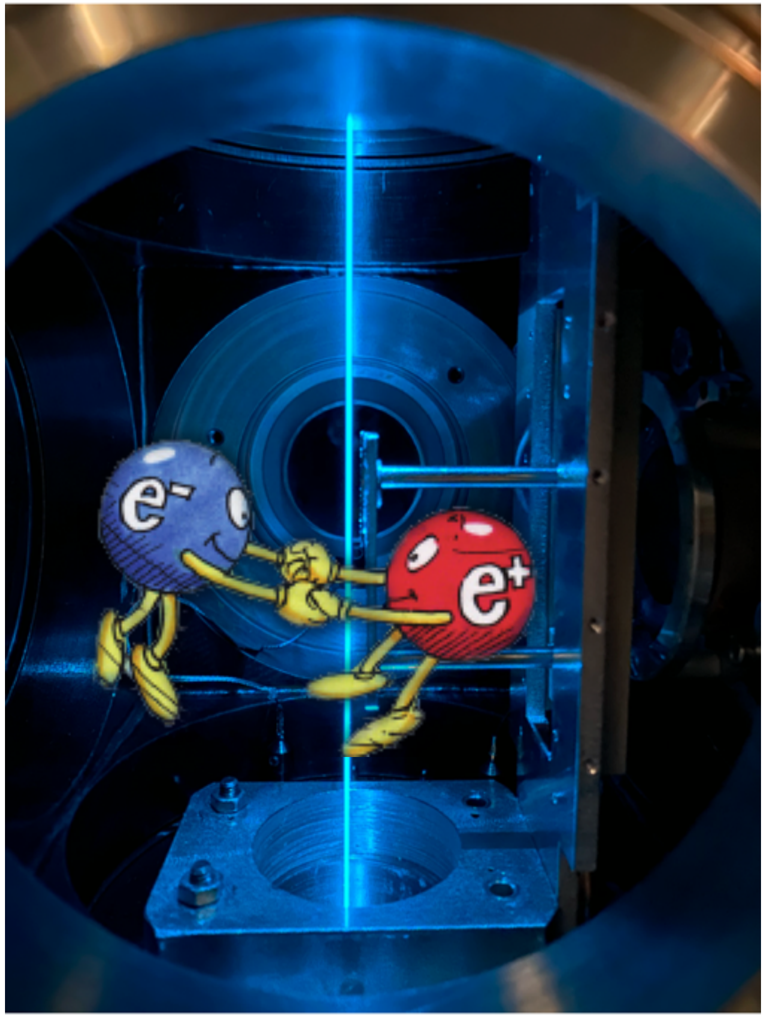
ortho-Positronium (oPs)
Ground state $^3S_1$
$\tau \simeq$ 142 ns, 3γ

The singlet spin state: S=0

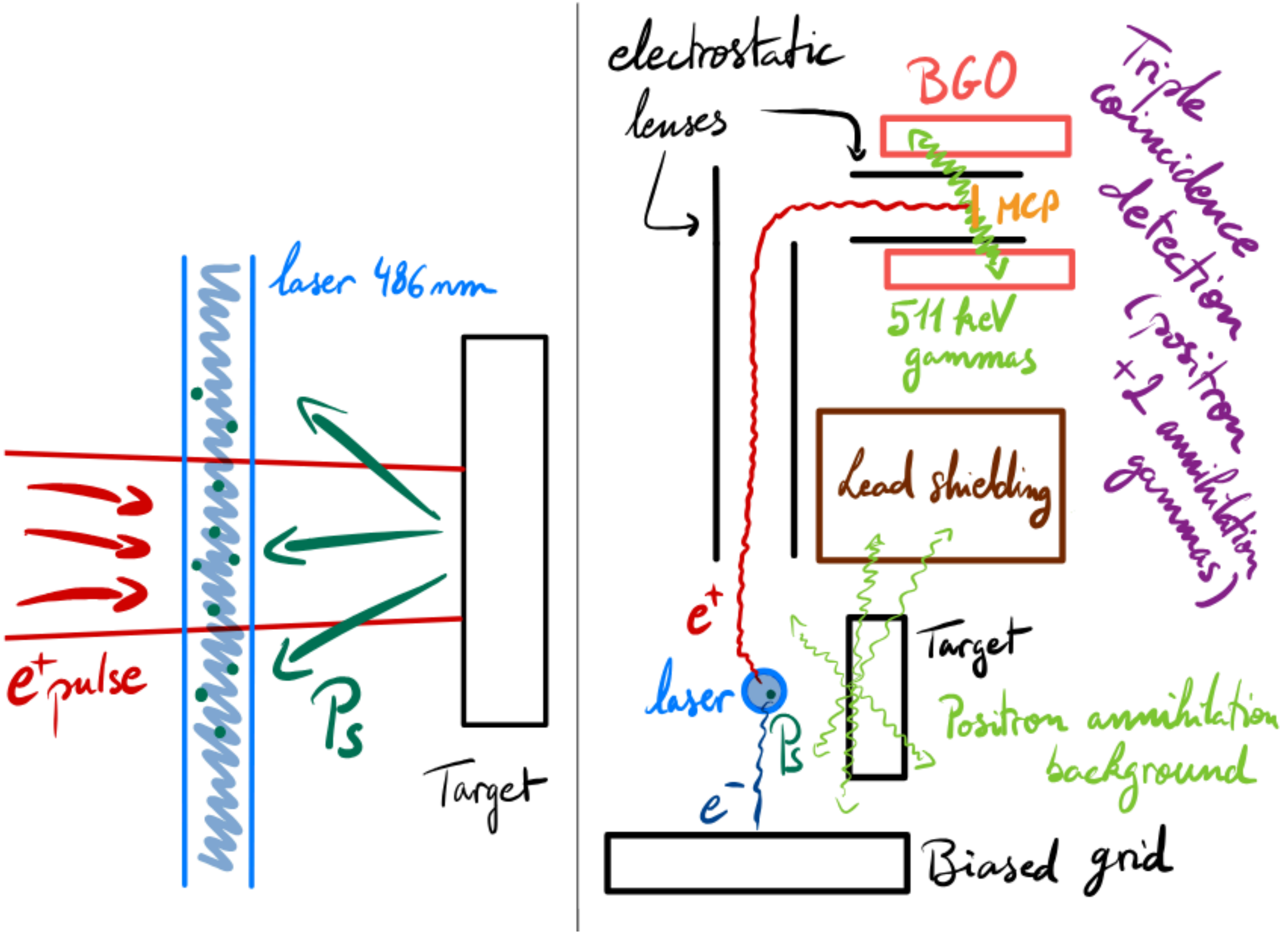


$$|0,0> = \frac{1}{\sqrt{2}}(|\uparrow,- > -|\downarrow,\uparrow>)$$

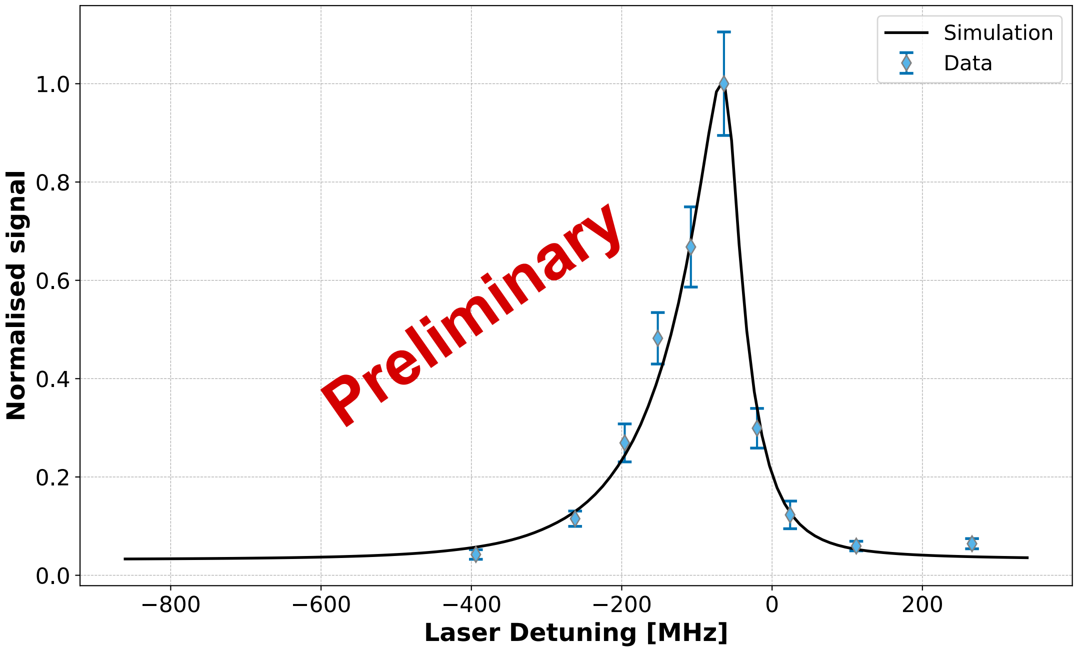
para-Positronium (oPs)
Ground state $^0S_1$
$\tau \simeq$ 125 ps, 2γ

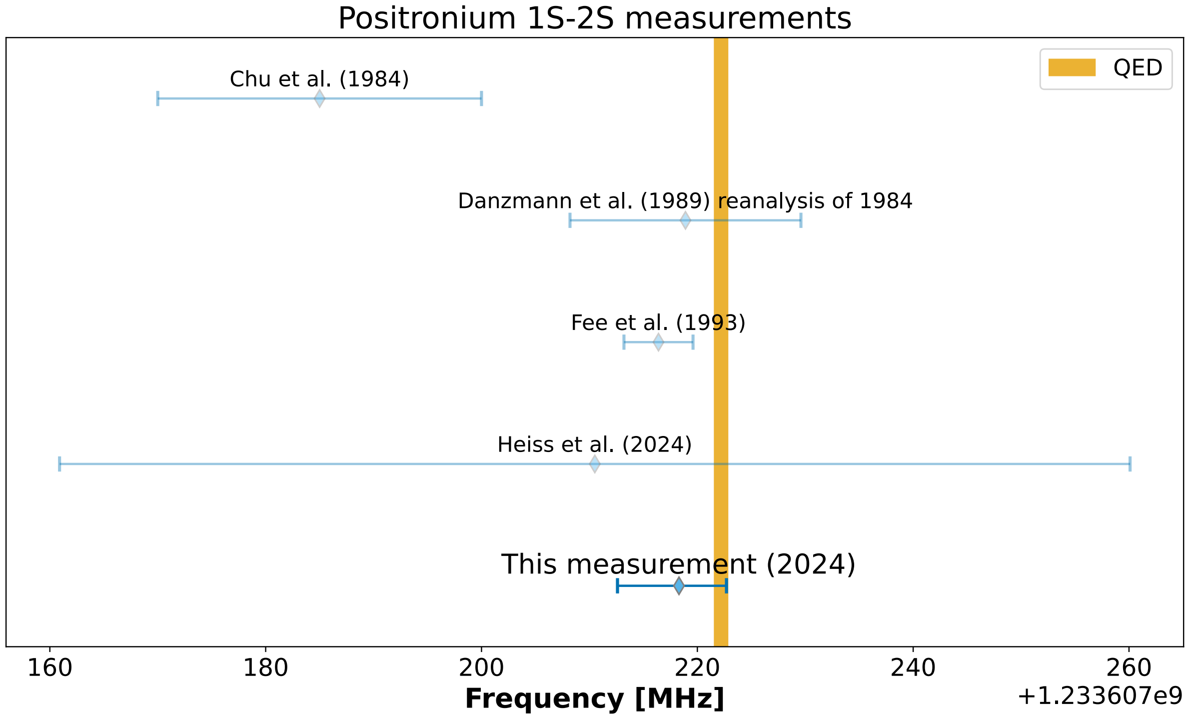


Idea of the 1S-2S positronium experiment at ETH



Latest results





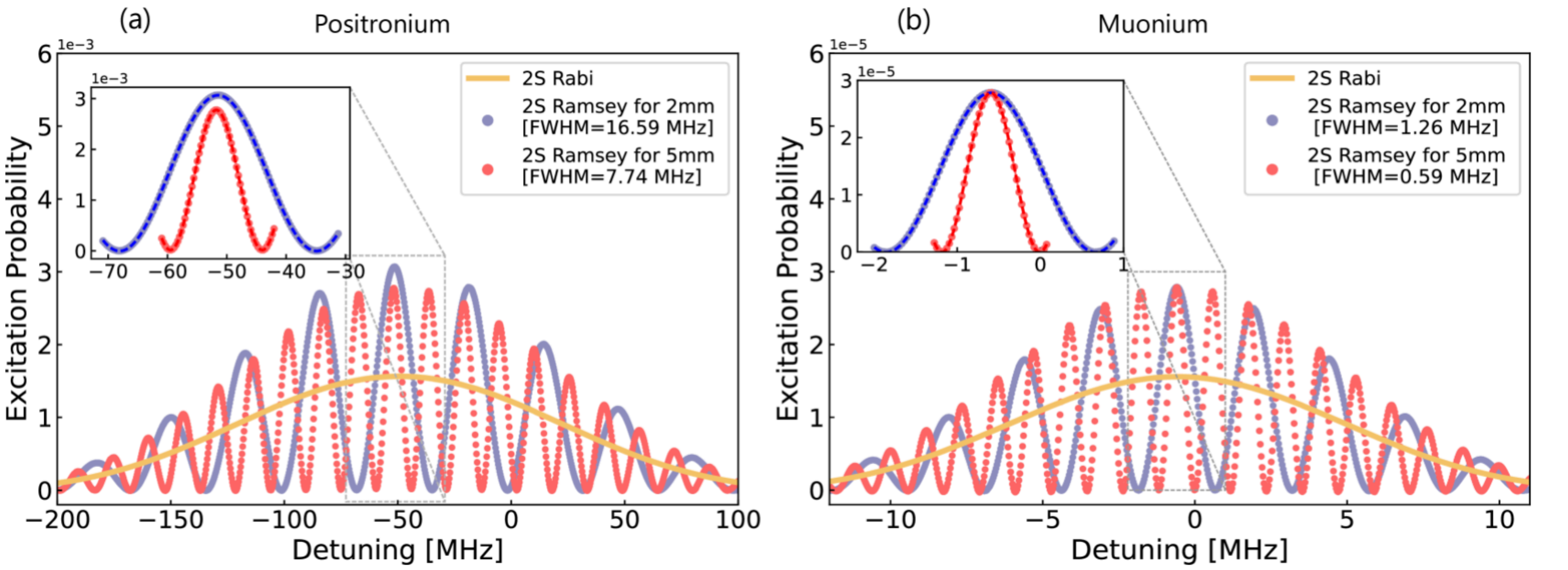
	Uncertainty [MHz]
Fitting error	$^{+0.6}_{-3.5}$
Frequency measurement	4.0
Frequency Correction	1.2
Wavemeter Systematic	0.7
Velocity distribution	0.8
Laser Position	0.6
AC Stark	0.3
Deviation to theory	$-3.9^{+4.4}_{-5.6}$

- Frequency limitation can be decreased < 1 kHz using a **frequency comb**
- Precision limited by **transit time broadening** and second-order Doppler shifts.

L. de Sousa Borges, PC et al., in preparation

Prospects for Ps/M 1S-2S spectroscopy- two photon Ramsey-Doppler

With Ramsey-Doppler method could improve the measurement precision of the 1S-2S transition by more than two orders of magnitude compared to the current state of the art



E. Javary, PC et al. arXiv.2411.19872

Prospects for Ps/M 1S-2S spectroscopy with laser cooling

Positronium Laser Cooling via the 1^3S–2^3P Transition with a Broadband Laser Pulse

L. T. Glöggler[1], N. Gusakova[1,2], B. Rienäcker[3], A. Camper[4], R. Caravita[5], S. Huck[1,6], M. Volponi[1,7,5], T. Wolz[1], and L. Penasa[7,5] et al. (AEḡIS Collaboration)

Show more

Phys. Rev. Lett. **132**, 083402 – **Published 22 February, 2024**

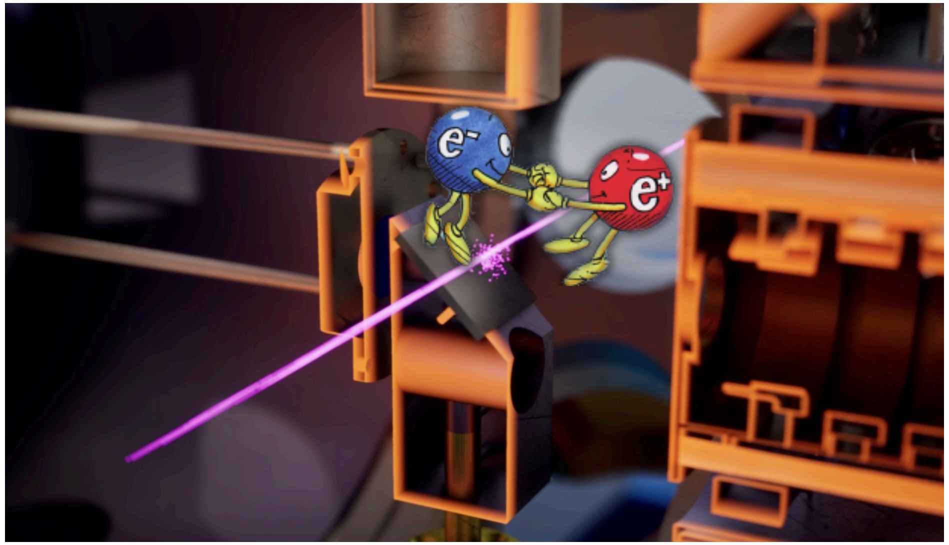
DOI: https://doi.org/10.1103/PhysRevLett.132.083402

Cooling positronium to ultralow velocities with a chirped laser pulse train

K. Shu, Y. Tajima, R. Uozumi, N. Miyamoto, S. Shiraishi, T. Kobayashi, A. Ishida, K. Yamada, R. W. Gladen, T. Namba, S. Asai, K. Wada, I. Mochizuki, T. Hyodo, K. Ito, K. Michishio, B. E. O'Rourke, N. Oshima & K. Yoshioka

Nature **633**, 793–797 (2024) | Cite this article

Breakthrough: Ps 1D laser cooling!
(extremely challenging due to limited Ps lifetime)



Summary and conclusion

Impressive progress in antimatter research in the recent years driven by:
- Techniques for anti-particle and anti-atoms trapping and manipulation
- Developments in laser physics and detector technology

New online and future facilities: **ELENA at CERN** boosting anti-proton and anti-hydrogen physics, upcoming **HiMB at PSI** will improve muon rates by two order of magnitude

New interesting results are expected in the next few years:
improved test of CP and CPT, bound state QED, values of fundamental constants (e.g. muon mass and magnetic moment, test of new physics such as dark sectors and the effect of gravity on antimatter

Thank you!

European Research Council
Established by the European Commission

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Swiss National Science Foundation