Searches for New Physics with Exotic (and not so Exotic) Atoms - Workshop at ETHZ 20.01.2022

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The shortcomings of the Standard Model (SM)

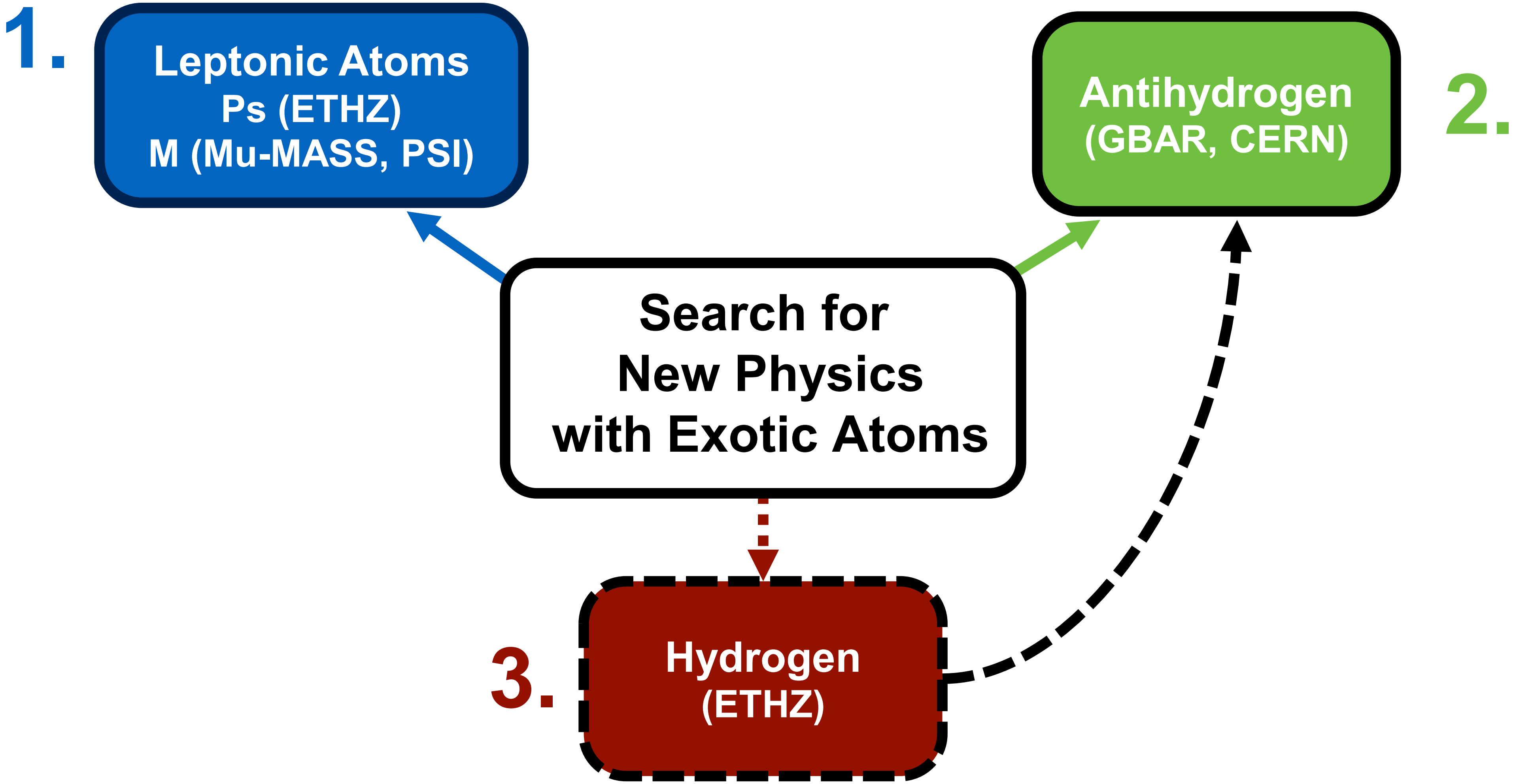
- SM doesn‘t explain origin of dark matter, dark energy, the baryon asymmetry in the Universe and doesn‘t include gravity

SEE TALKS OF:
Prof. Yevgeny Stadnik
Prof. Yonit Hochberg
Prof. Jörg Jaeckel

- Some hints for possible deviations
    - recent muon g-2 (4.2σ) B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)
    - Lepton universality violation (e.g. LHCb 3.1σ) LHCb collaboration, 2021, arxiv.org/abs/2103.11769
    - measurements of Ps FS (4.5σ) L. Gurung et al., Phys Rev. Lett. 125, 073002 (2020)

- New Physics could address some of these problems, e.g. via: Standard Model Extension (SME), new bosons/forces

Outline



1\.

Leptonic Atoms
Ps (ETHZ)
M (Mu-MASS, PSI)

Antihydrogen
(GBAR, CERN)

2\.

Search for
New Physics
with Exotic Atoms

3\.

Hydrogen
(ETHZ)

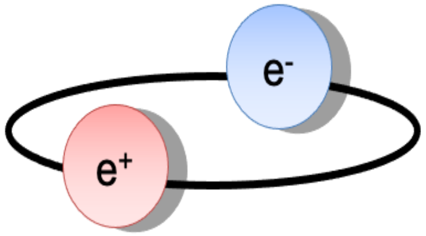
Positronium and Muonium

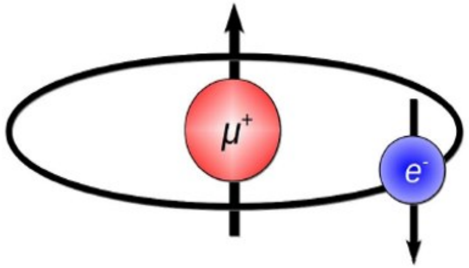
- Purely leptonic

→ described precisely by bound state QED

→ any deviation between theory and measurements a hint of New Physics

→ from agreement with theory, fundamental constants can be extracted





- Ps: electron – positron bound state
- Very short lifetimes of 125ps (p-Ps) and 142ns (o-Ps)
- Main decay channel: p-Ps → 2γ, o-Ps → 3γ

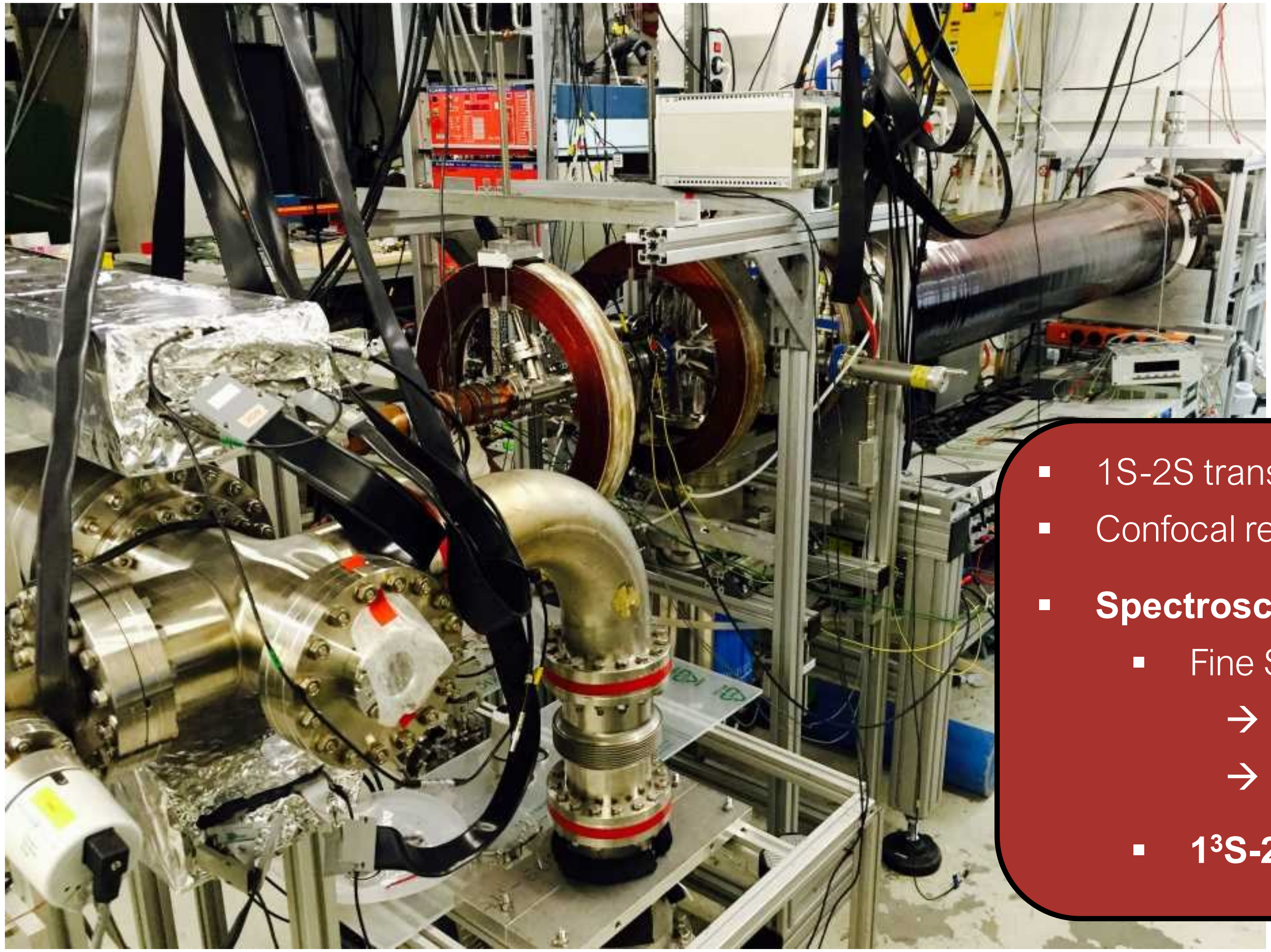
➡ 1S-2S, 2S-FS and 2S-HFS spectroscopy at ETHZ

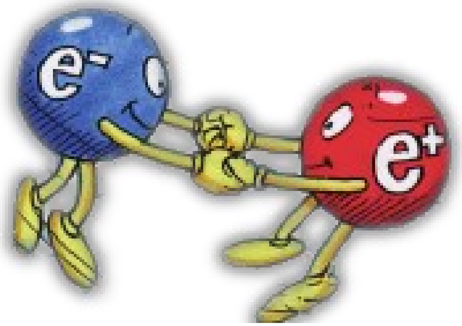
- M: positive muon-electron bound state
- Unstable with lifetime of 2.2 μs
- Main decay channel: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

➡ 1S-2S and 2S-2P spectroscopy at PSI (Mu-MASS exp.)

Ps-Spectroscopy at ETH

M. Heiss, PhD Thesis (2021),
https://doi.org/10.3929/ethz-b-000477081





- 1S-2S transition measured with pulsed laser
- Confocal resonator for MW-spectroscopy built & tested
- **Spectroscopy of:** (In collaboration with Anna Soter)
  - Fine Structure $\mathbf{2^3S_1 \rightarrow 2^3P_0}$,
    - → avoiding systematics such as 1st-order Doppler or from mag. Field
    - → probe recently measured deviation from SM
  - $\mathbf{1^3S\text{-}2^3S_1}$ improvement with CW laser

The Mu-MASS experiment at PSI

P. Crivelli, Hyp. Int. 239, 49 (2018)

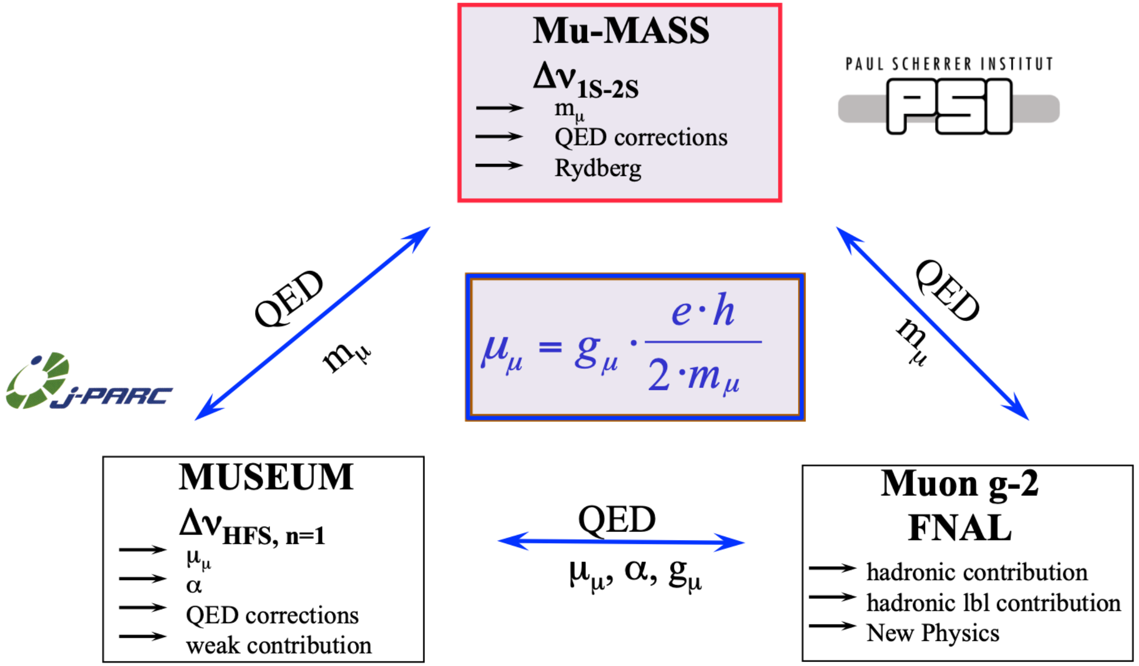
MU-MASS

High precision laser and microwave Muonium spectroscopy experiment

FINAL GOAL : improve 1S-2S transition by 3 orders of magnitude (10 kHz, 4 ppt)

OUTPUT

→ Muon mass @ 1 ppb
→ Ratio of q_e/q_μ @ 1 ppt
→ Test of bound state QED (1×10^{-9})
→ Input to muon g-2 theory
→ Rydberg constant @ ppt level
→ New determination of α @ 1 ppb
→ Search for New Physics



Mu-MASS
$\Delta\nu_{1S\text{-}2S}$
→ m_μ
→ QED corrections
→ Rydberg

PAUL SCHERRER INSTITUT PSI

$$\mu_\mu = g_\mu \cdot \frac{e\cdot h}{2\cdot m_\mu}$$

J-PARC

MUSEUM
$\Delta\nu_{HFS,\ n=1}$
→ μ_μ
→ α
→ QED corrections
→ weak contribution

Muon g-2
FNAL
→ hadronic contribution
→ hadronic lbl contribution
→ New Physics

Fermilab

ERC consolidator grant (818053 -Mu-MASS) and SNF grant (197346)

erc European Research Council
Established by the European Commission

Swiss National Science Foundation

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

Current status and outlook for Mu-MASS

CURRENT STATUS:

- Detection of 2S states achieved but S/N to be improved
- Laser system, CW 20W @ 244 nm circulating power achieved
- Frequency reference for the experiment is ready
- New measurement of the Muonium Lamb shift (see next slides)

Z. Burkley et al. Opt. Express 29, 27450 (2021)

FUTURE PLANS:

2022 first attempts to excite 1S-2S transition using a CW laser + pulsed laser for photoionisation (PI) detecting the PI muons + decaying positron

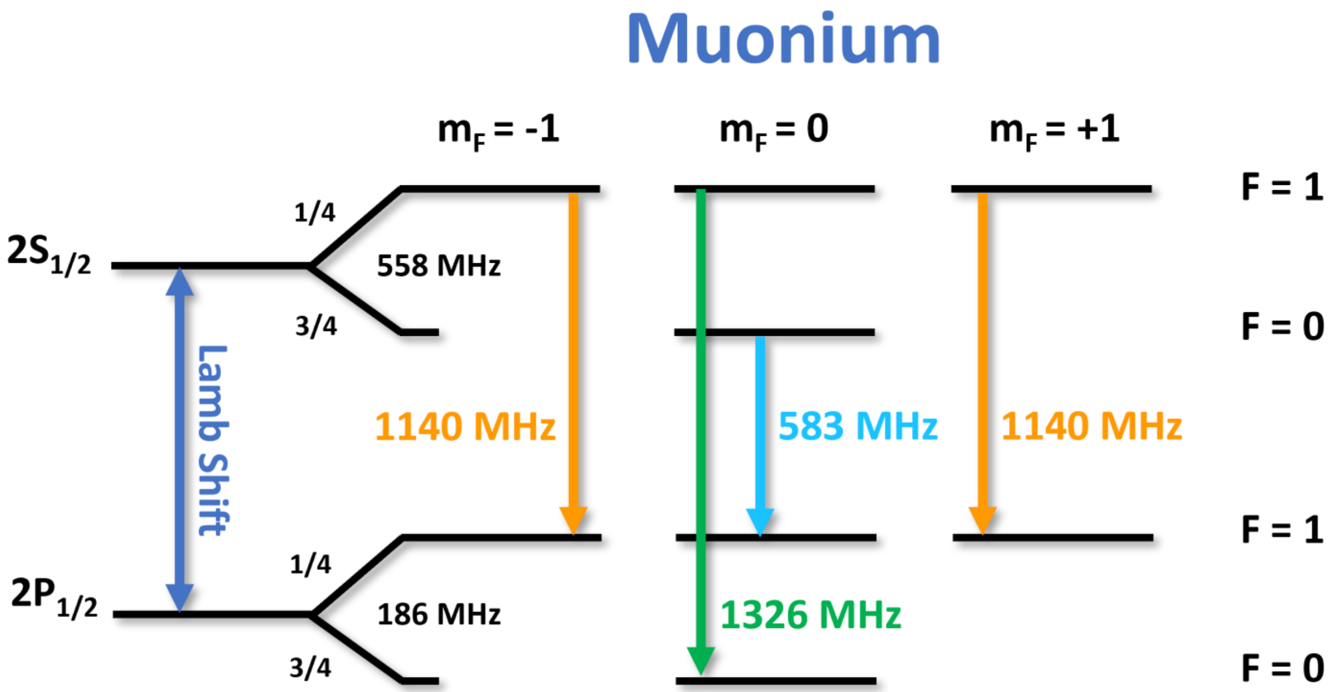
2023-2024 Data taking at the low energy muon beam line

SEE TALK OF ANNA SOTER

MuCool Beamline and **HiMB** UPGRADES and new M targets @ PSI (2 orders of magnitude larger muon flux)
WOULD GREATLY EXPAND THE PHYSICS REACH OF Mu-MASS

MuCool: A. Antognini and D. Taqqu. SciPost Phys. Proc., 5:030, (2021)
HiMB: M. Aiba, A. Amato, et al. (2021), arXiv 2111.05788

Muonium Lamb shift



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

G. Janka, B. Ohayon and P. Crivelli, arXiv:2111.13951 (2021)

V. Yerokhin et al. ,Annalen der Physik 531, 1800324 (2019)

M. I. Eides, H. Grotch, and V. A. Shelyuto, Phys. Rep. 342, 63 (2001).

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

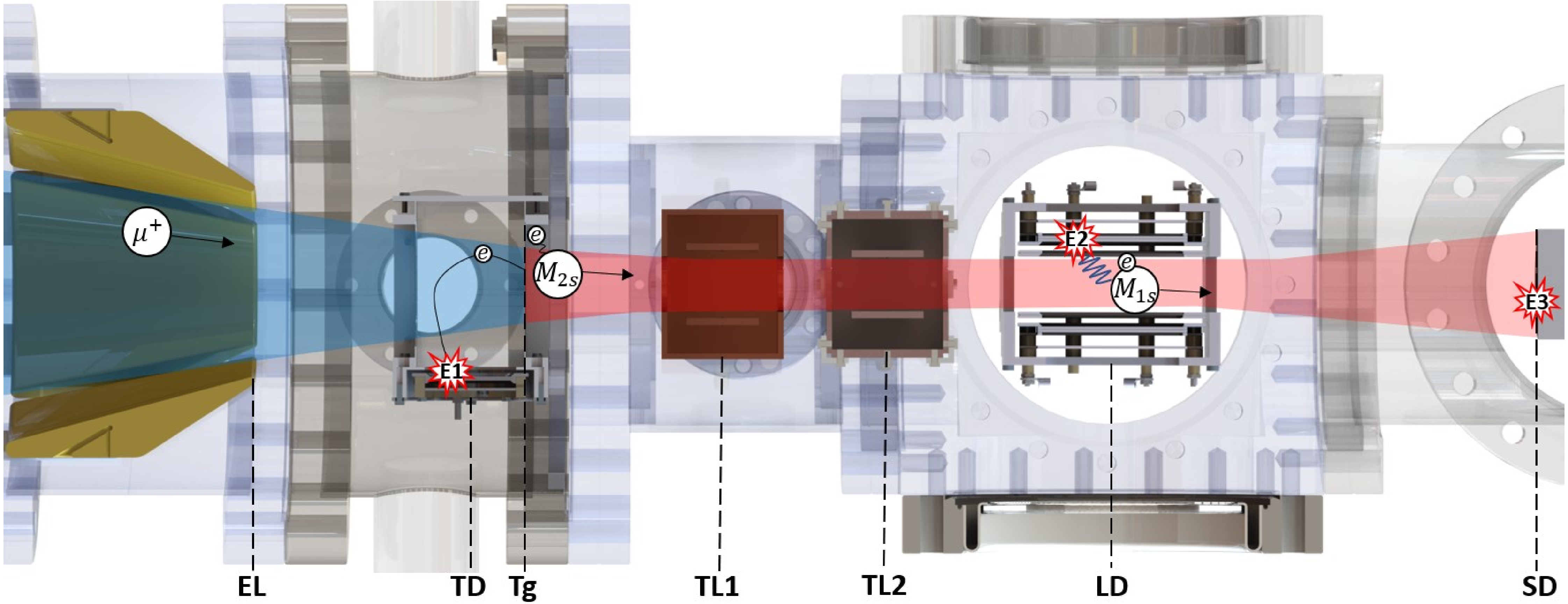
@ TRIUMF: C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984).

@ LAMPF: K. Woodle, et al., Phys. Rev. A 41, 93 (1990).

Measurement of the Lamb shift (June 2021)

LEM beamline T. Prokscha et al., NIMA 595, 317 (2008)

LYMAN-ALPHA DETECTOR



TAGGING+M(2S) FORMATION

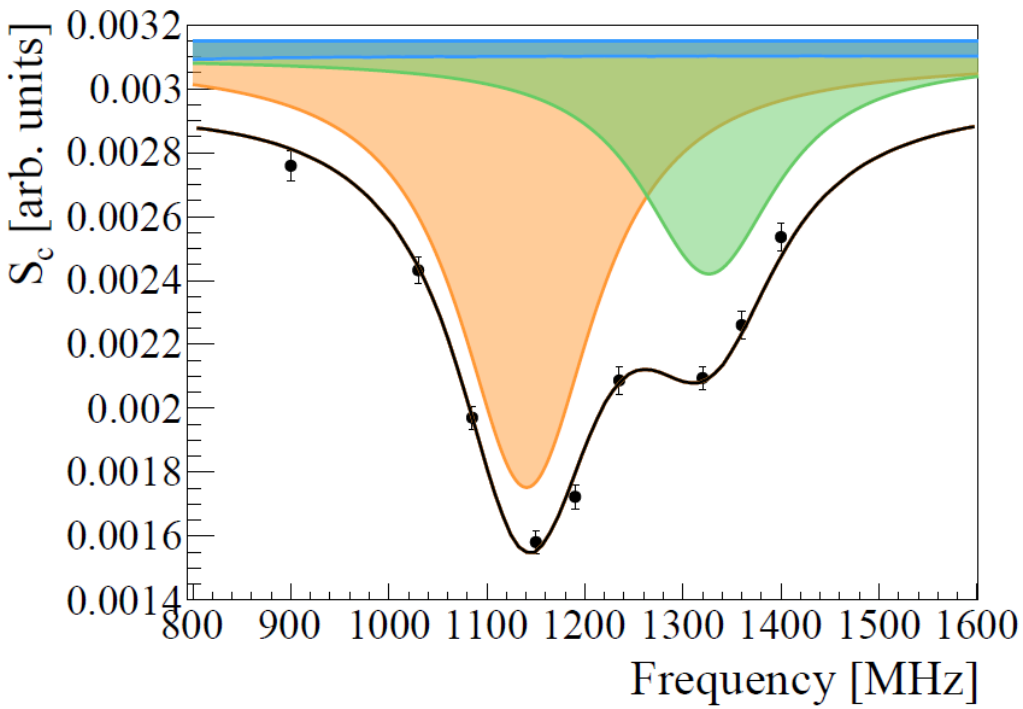
MW REGION (HFS SELECTOR + MW TRANSITION)

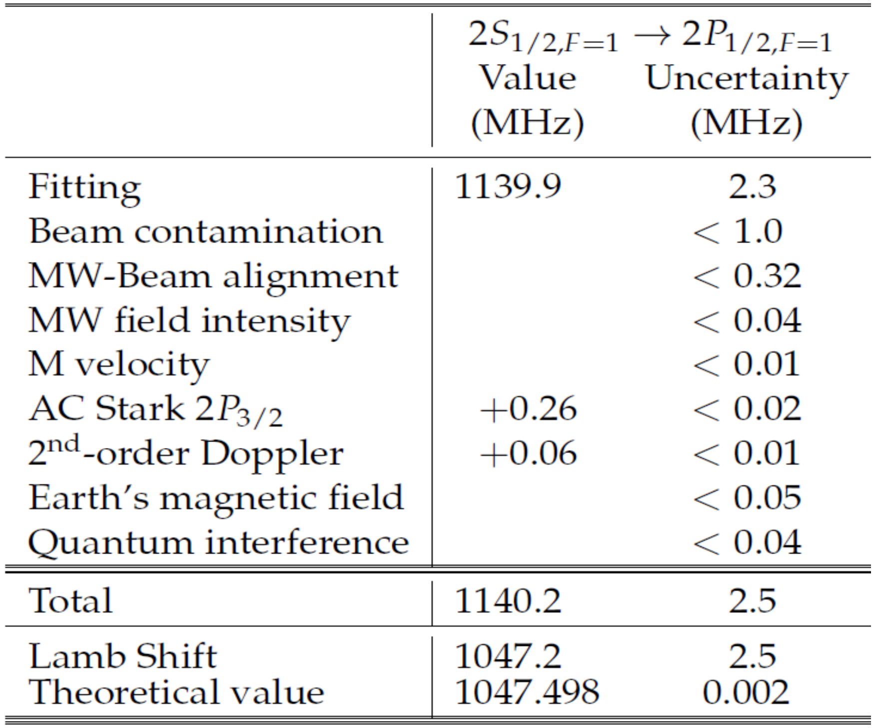
STOP DETECTOR

Results of the M Lamb shift

B. Ohayon, G. Janka, et al., PRL 128, 011802 (2022)

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





	$2S_{1/2,F=1} \rightarrow 2P_{1/2,F=1}$ Value (MHz)	Uncertainty (MHz)
Fitting	1139.9	2.3
Beam contamination		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's magnetic field		< 0.05
Quantum interference		< 0.04
Total	1140.2	2.5
Lamb Shift	1047.2	2.5
Theoretical value	1047.498	0.002

→ Result agrees with theory

→ Precision not enough to test b-QED but can be used to constrain new physics

Searches for new bosons via Ps / M spectroscopy

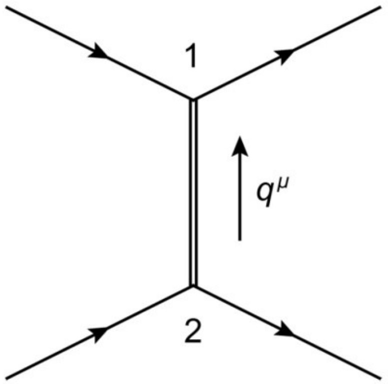
- New bosons could mediate new forces resulting in shifts of Ps and M energy levels.

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

- Scattering between two fermions described by different potentials (scalar-scalar, vector-vector…)

P.Fadeev et al.,Phys. Rev. A 99, 022113 (2019)

$$V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$$



- Leading order corrections: $\langle V_{ss}\rangle = -\frac{g_1^s g_2^s}{4\pi} F_{n,l}^1(M)$

$$F_{n,l}^k(M) = \langle \frac{e^{-Mr}}{r} \rangle_{n,l}$$

	$l = 0$	$l = 1$	$l = 2$
$n = 1$	$\frac{4}{a_0(Ma_0+2)^2}$	X	X
$n = 2$	$\frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}$	$\frac{1}{4a_0(Ma_0+1)^4}$	X
$n = 3$	$\frac{4(243M^4a_0^4+216M^2a_0^2+16)}{9a_0(3Ma_0+2)^6}$	$\frac{64(9M^2a_0^2+1)}{9a_0(3Ma_0+2)^6}$	$\frac{64}{9a_0(3Ma_0+2)^6}$

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

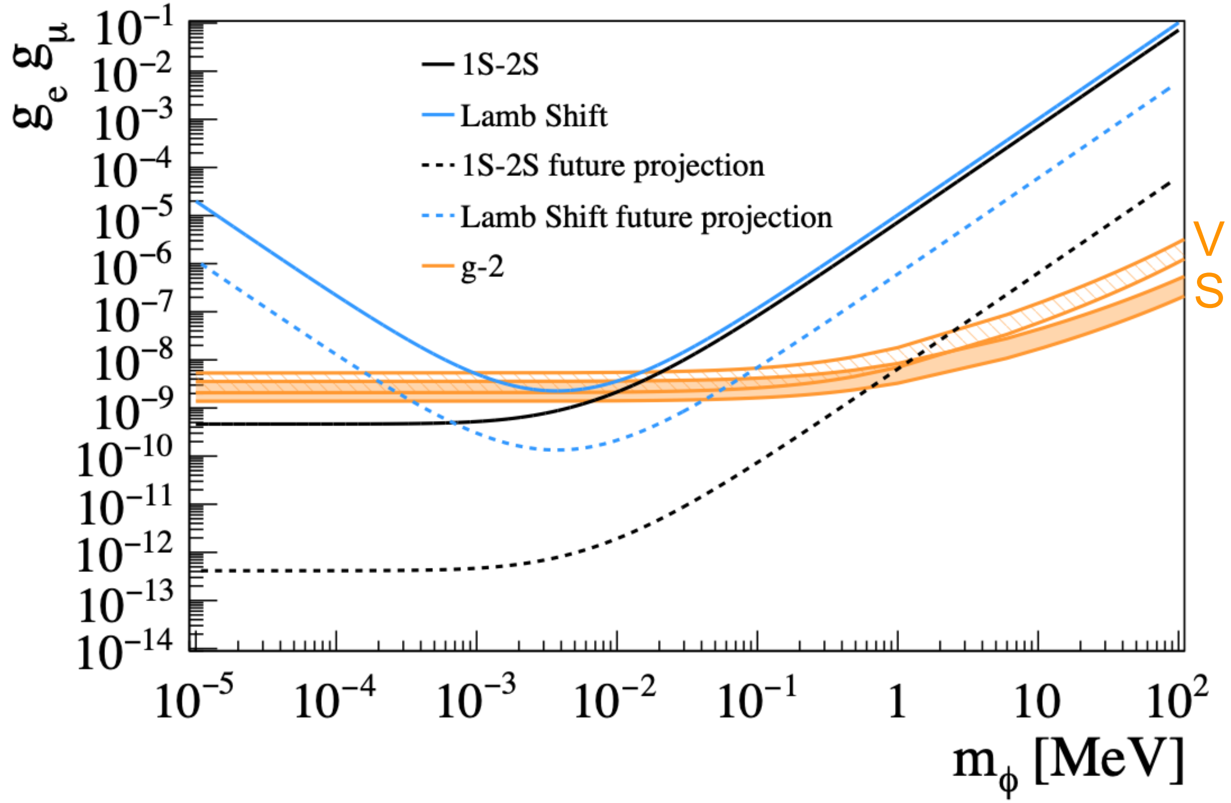
$$\Delta E_{ss}(2S^0 \to 1S^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

Muonium spectroscopy as a probe for new muonic forces

$\rho_{the,exp} = \sqrt{\rho_{the}^2 + \rho_{exp}^2}$

$C_{transition}(M) = \frac{\Delta E_{\zeta\zeta}(transition)}{g_\zeta^1 g_\zeta^2}$

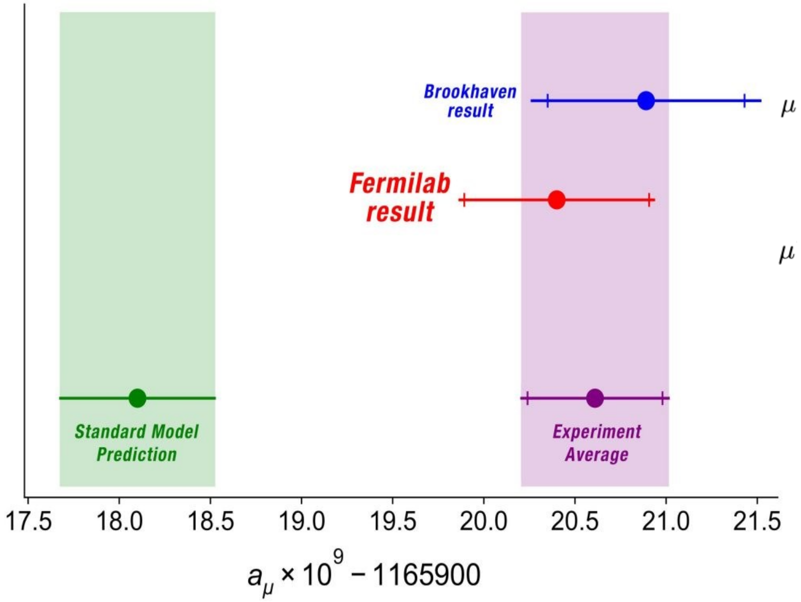
$$g_\zeta^1 g_\zeta^2 > \frac{h \max_{\pm} \left|(\nu_{exp} - \nu_{the}) \pm 2\rho_{the,exp}\right|}{C_{transition}(M)}$$

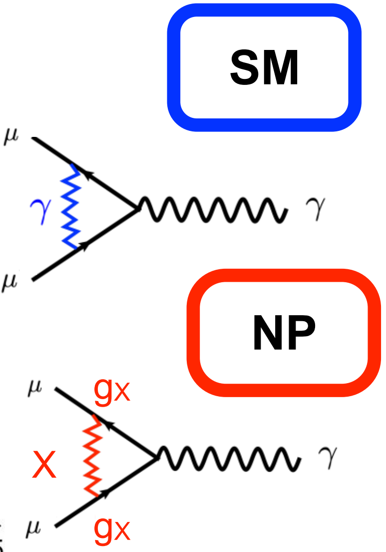


B. Ohayon, G. Janka et al., PRL 128, 011802 (2022)

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

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





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)

The Standard Model Extension (SME)

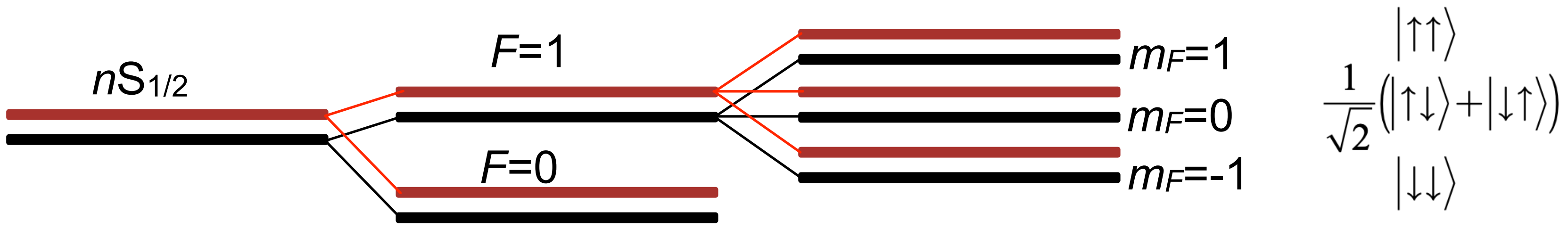
$$\mathfrak{L}_{\text{SME}} = \underbrace{\mathfrak{L}_{\text{SM}} + \mathfrak{L}_{\text{GR}}}_{\text{Conventional physics}} + \underbrace{\mathfrak{L}_{\text{LV}}}_{\text{Lorentz violation}}$$

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

Lorentz-violating contribution

Conventional case

$$\epsilon = \epsilon_0 + \boxed{\delta\epsilon}$$



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

E.g. additional shift for Muonium:

1S-2S $$\delta\nu_{1S2S} = \frac{3(m_r\alpha)^2}{8\pi}\left[\mathring{a}_2^{\text{NR}} + \mathring{c}_2^{\text{NR}} + \frac{67}{12}(m_r\alpha)^2(\mathring{a}_4^{\text{NR}} + \mathring{c}_4^{\text{NR}})\right]$$

2S-2P $$2\pi\delta\nu_{\text{Lamb}} = -\frac{2}{3}(\alpha m_r)^4(\mathring{a}_4^{\text{NR}} + \mathring{c}_4^{\text{NR}})$$

Lorentz and CPT

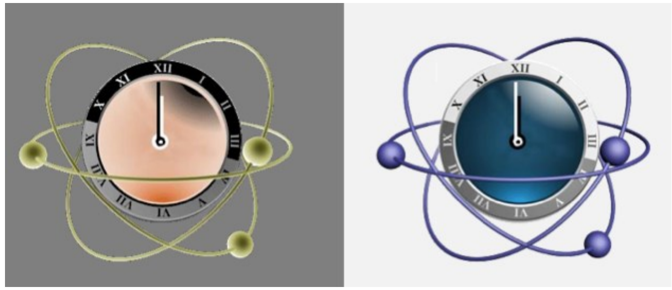
Only Lorentz

Transition	Coefficient	Constraint
$1S_{1/2}$-$2S_{1/2}$	$\lvert\mathring{a}_2^{\text{NR}}\rvert$	$< 8 \times 10^{-6}$ GeV^{-1}
	$\lvert\mathring{c}_2^{\text{NR}}\rvert$	$< 8 \times 10^{-6}$ GeV^{-1}
	$\lvert\mathring{a}_4^{\text{NR}}\rvert$	$< 1 \times 10^{5}$ GeV^{-3}
	$\lvert\mathring{c}_4^{\text{NR}}\rvert$	$< 1 \times 10^{5}$ GeV^{-3}
Lamb shift	$\lvert\mathring{a}_4^{\text{NR}}\rvert$	~~$< 1 \times 10^{6}$ GeV^{-3}~~ < 1.7 x 10^5 GeV^{-3}
	$\lvert\mathring{c}_4^{\text{NR}}\rvert$	~~$< 1 \times 10^{6}$ GeV^{-3}~~ < 1.7 x 10^5 GeV^{-3}

B. Ohayon, G. Janka, et al., PRL 128, 011802 (2022)

Spectroscopy of Exotic Atoms as a sensitive test

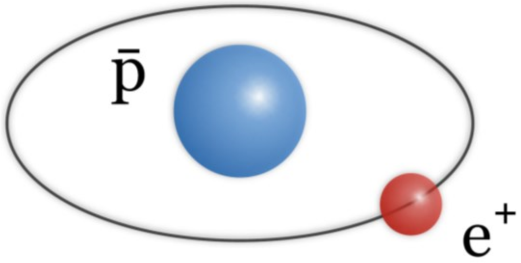
- The SME allows clocks and anti-clocks to tick at different rates



Lorentz-violating energy shift for matter $\overset{?}{\neq}$ Lorentz-violating energy shift for anti-matter

*More details: see slides „*CPT violation, Lorentz violation, and low-energy antiprotons" by A. Vargas, LEAP 2018

The Antihydrogen



- $\overline{H}$: negative antiproton – positron bound state
- provides stringent tests of CPT symmetry, to give insight about matter-antimatter asymmetry

➡ MW spectroscopy at GBAR

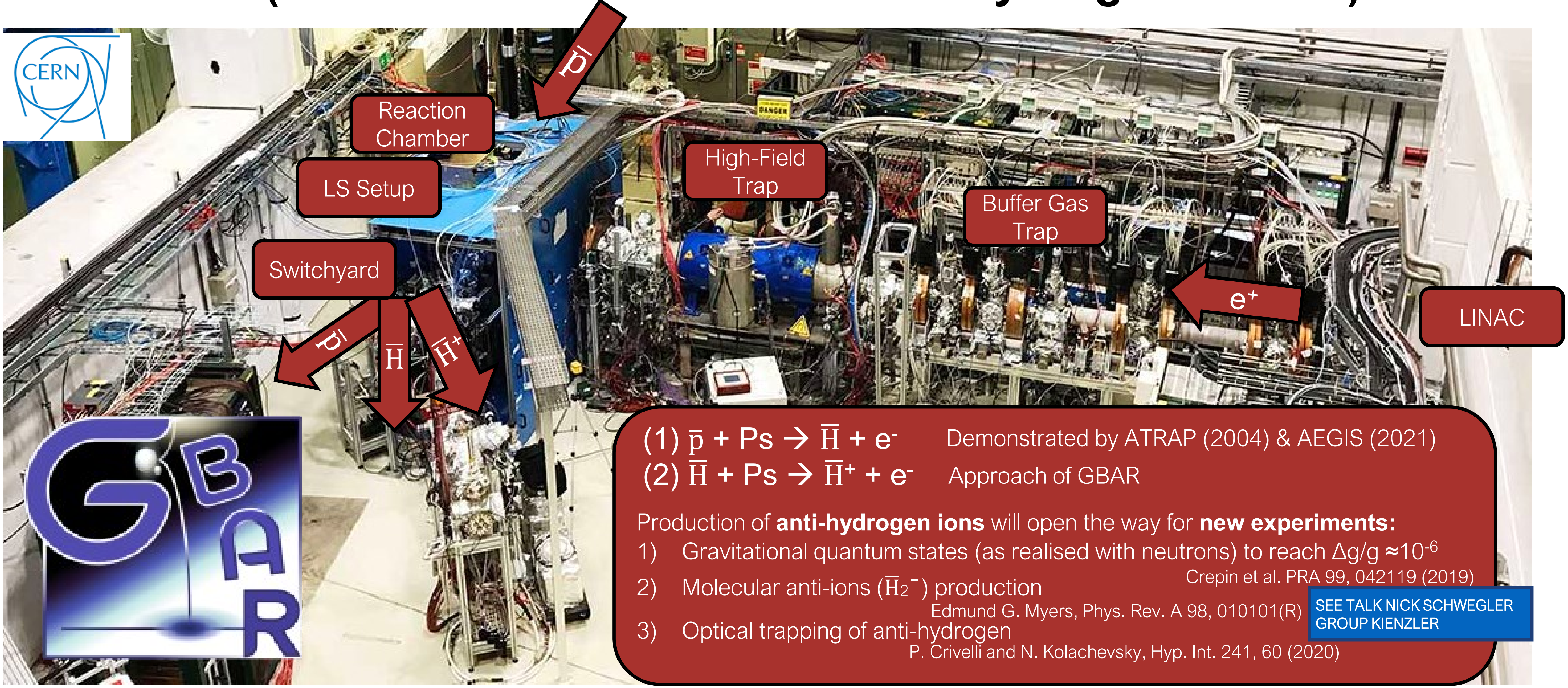
ALPHA collaboration. Nature, 541:506–510, 2016
ALPHA collaboration. Nature, 548(7665):66–69, 2017
ALPHA collaboration. Nature, 578(7795):375–380, 2020

- Good candidate for first direct test of Weak Equivalence Principle (WEP) for antimatter
- Best (and only) result from free fall: ALPHA with -65g < $\bar{g}$ < 150g ALPHA Collaboration, Nat Commun 4, 1785 (2013)
- (Recently, BASE collaboration extracted $\bar{g}$ from gravitational redshift to $\frac{\Delta\bar{g}}{\bar{g}} \approx 3\%$)

➡ Free Fall experiment at GBAR

BASE Collaboration, Nature volume 601, pages 53–57 (2022)

The GBAR (Gravitational Behaviour of Antihydrogen at Rest) EXP.



(1) $\bar{p} + Ps \rightarrow \bar{H} + e^-$ Demonstrated by ATRAP (2004) & AEGIS (2021)

(2) $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ Approach of GBAR

Production of **anti-hydrogen ions** will open the way for **new experiments:**

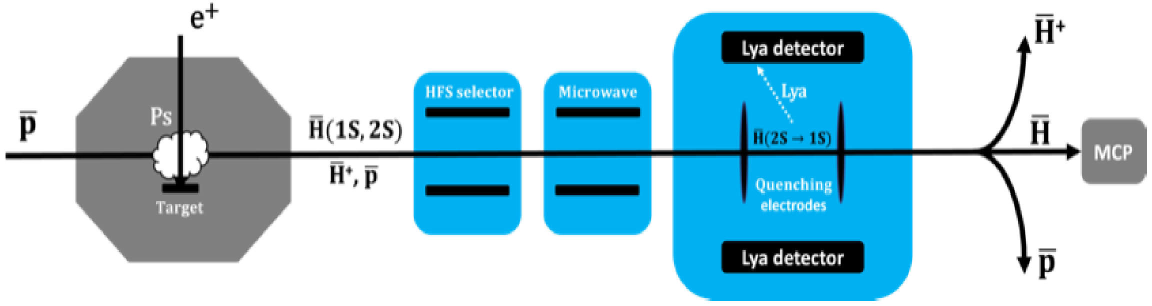
1) Gravitational quantum states (as realised with neutrons) to reach $\Delta g/g \approx 10^{-6}$
Crepin et al. PRA 99, 042119 (2019)
2) Molecular anti-ions ($\bar{H}_2^-$) production
Edmund G. Myers, Phys. Rev. A 98, 010101(R)
3) Optical trapping of anti-hydrogen
P. Crivelli and N. Kolachevsky, Hyp. Int. 241, 60 (2020)

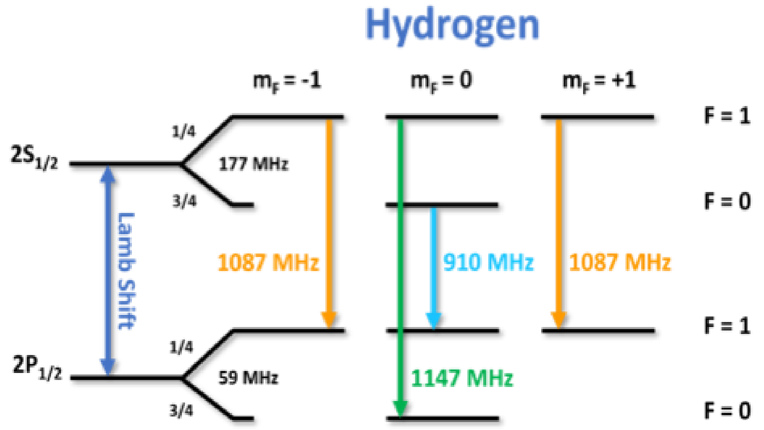
SEE TALK NICK SCHWEGLER GROUP KIENZLER

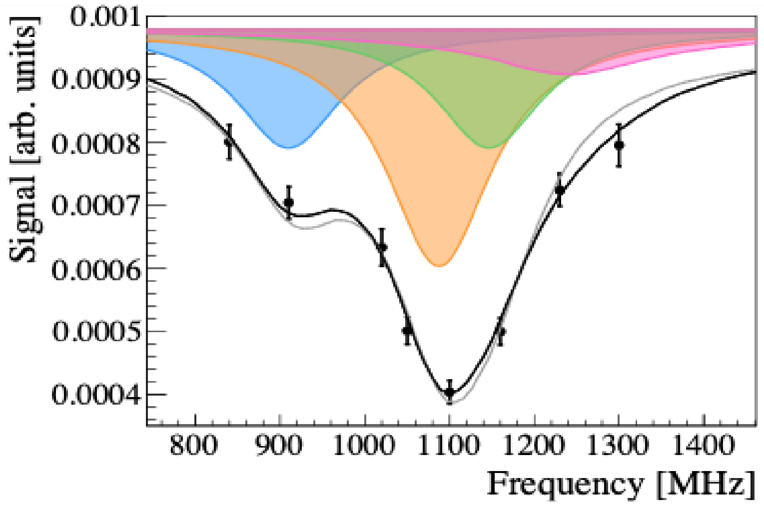
GBAR: Byproduct measurement – Antihydrogen Lamb shift setup

P. Crivelli, D. Cooke, and M. W. Heiss, PRD 94 (2016), 052008.
G. Janka, ETHZ PhD thesis (2022)

Byproduct measurement (Lorentz/CPT test), not perturbing GBAR program



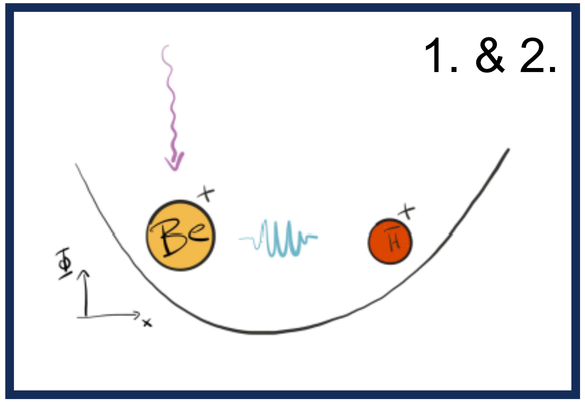


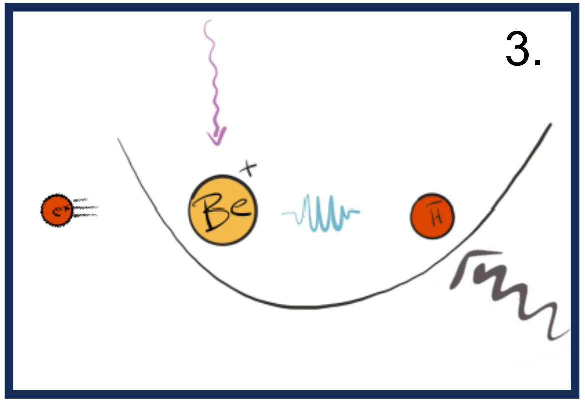


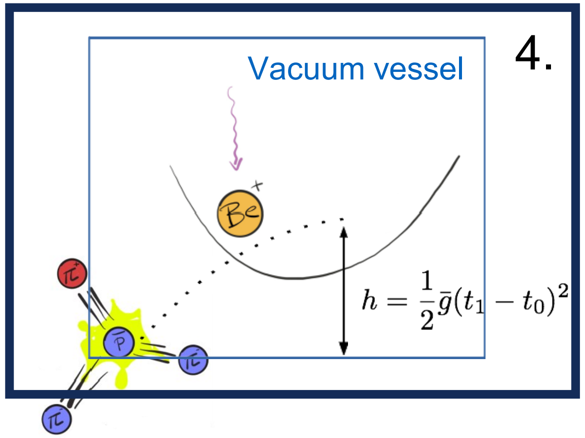
- Successful commissioning of setup at PSI
- Setup moved to CERN
- Installed at GBAR and transition of hydrogen already detected

GOAL: 100ppm measurement

GBAR: Main goal & principle of the experiment







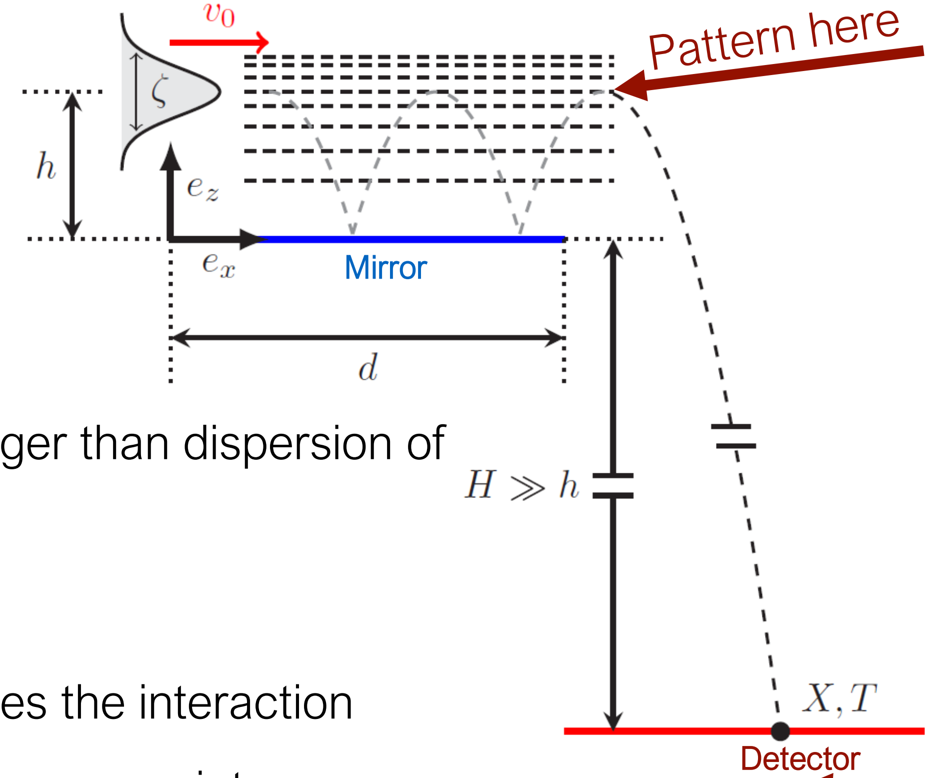
1. Produce $\bar{\mathrm{H}}^+$ and trap in Paul trap, pre-filled with Be^+ ions
2. Sympathetically cool anti-ions to 10uK, cool Be^+ with 313nm laser
3. Photo-detach excess positron with 1640nm laser
4. Measure time of flight and annihilation position of $\bar{\mathrm{H}}$ with Micromegas

GOAL: first step $\frac{\Delta\bar{g}}{\bar{g}} \leq 1\%$, later to 10^{-6} with «quantum free fall»

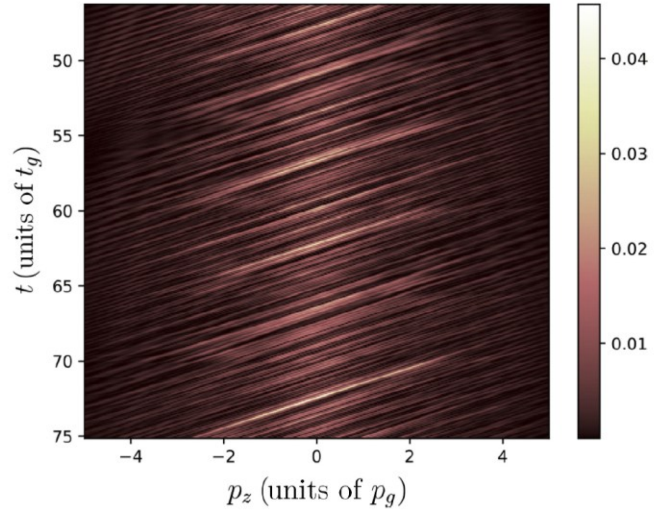
“Quantum free fall” of Anti-hydrogen

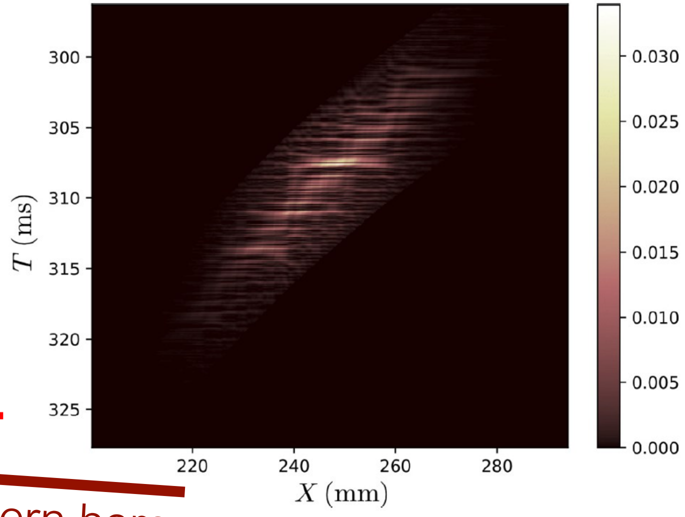
Crepin et al. Phys. Rev. A 99, 042119 (2019)

- **Parabolas:** classical motion with rebounds above the mirror
- **dashed horizontal lines:** paths through different quantum states which interfere in the detection pattern



Pattern here





Pattern here

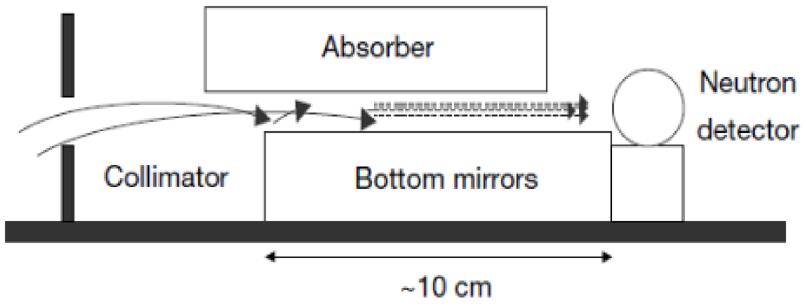
- Height of free fall must be much larger than dispersion of wave packet

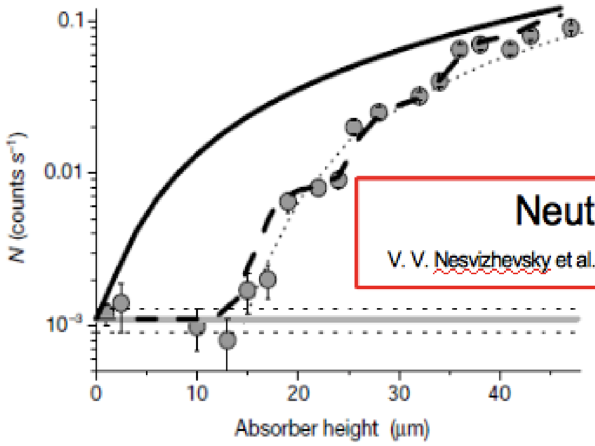
→ free fall considered to be classical

→ acts as diffraction process, translates the interaction time and momentum after interference zone into space and time positions of annihilation event

Neutron quantum gravitational states (QGS)

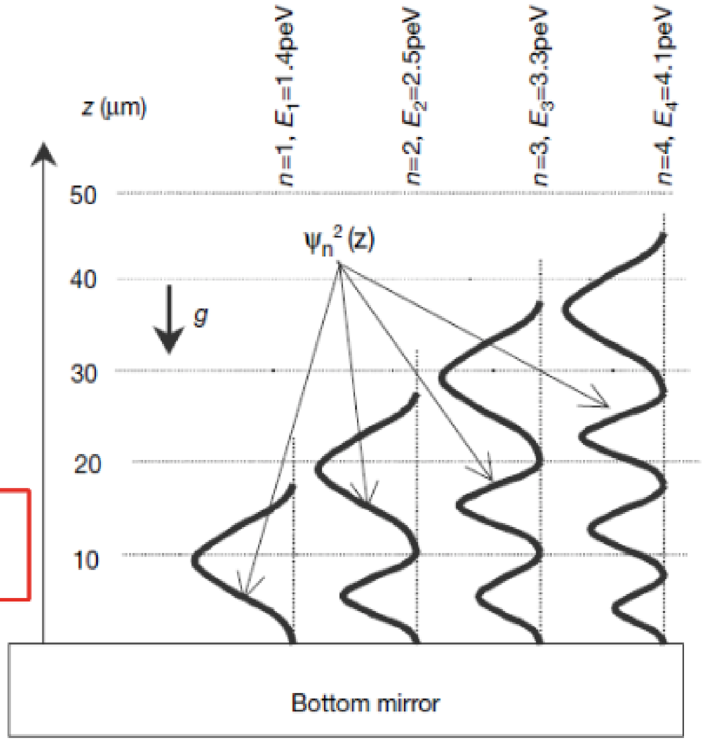
Nesvizhevsky, V., Börner, H., Petukhov, A. et al., Nature 415, 297–299 (2002)





Neutrons

V. V. Nesvizhevsky et al., Nature 415, 297 (2002).



$$E_n \cong \sqrt[3]{\left(\frac{9\cdot m}{8}\right)\cdot\left(\pi\cdot\hbar\cdot g\cdot\left(n-\frac{1}{4}\right)\right)^2}$$

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2\cdot m^2\cdot g}}$$

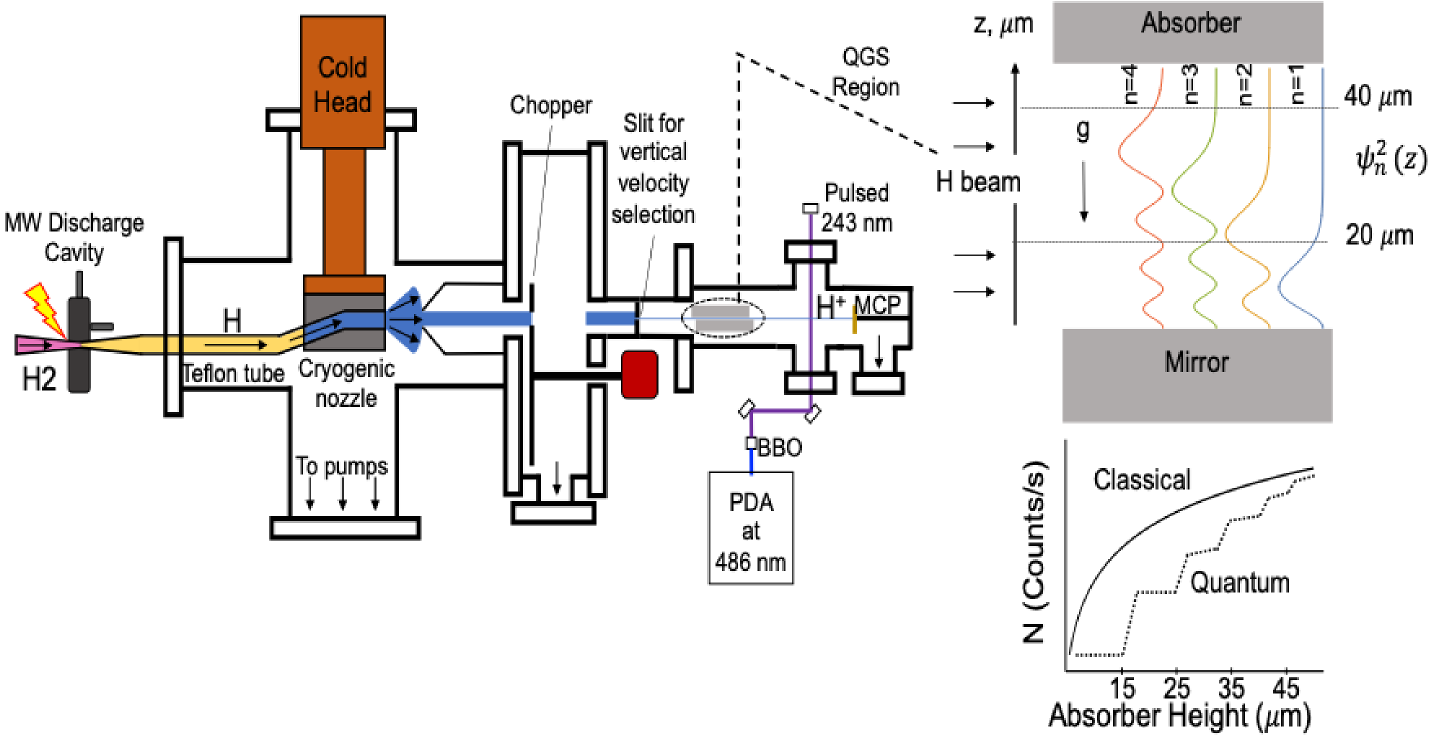
Hydrogen quantum gravitational states (QGS)

G. Dufour, et al., *Advances in High Energy Physics, vol. 2015, Article ID 379642, 16 pages, 2015*,

- At ETHZ cryogenic hydrogen beam developed for Mu-MASS / GBAR
- Detecting H through 1S-2S excitation and photo-ionization

  → Beam characterization ongoing; flux of atoms below 50m/s observed

  → feasibility to measure QGS and quantum free fall under investigation (possible test of short-range forces)



FOR NEW PHYSICS SEARCHES WITH NEUTRONS SEE TALKS OF
FLORIAN PIEGSA, GEORG BISON

Summary

- Exotic Atoms are great systems to look for new physics
  - Searching for new bosons/forces
  - Probing Standard Model Extension

Not limited to only exotic atoms shown in this talk; other systems where accurate calculations can be performed have great potential as well!

SEE TALKS OF:
Simon Scheidegger
Nick Schwegler

THANK YOU FOR YOUR ATTENTION

Acknowledgments

IPA ETH zürich MU-MASS

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PAUL SCHERRER INSTITUT PSI

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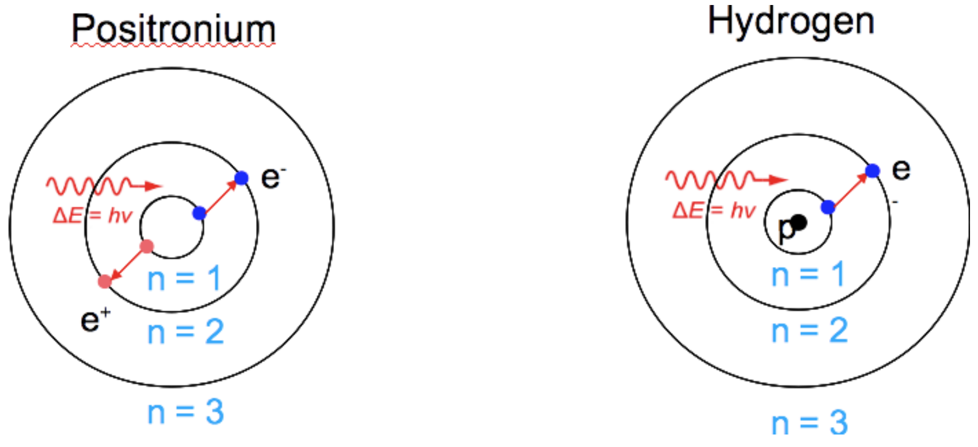
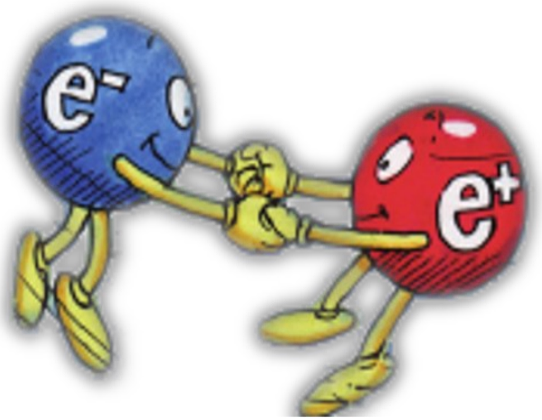
Backup Slides

The Positronium

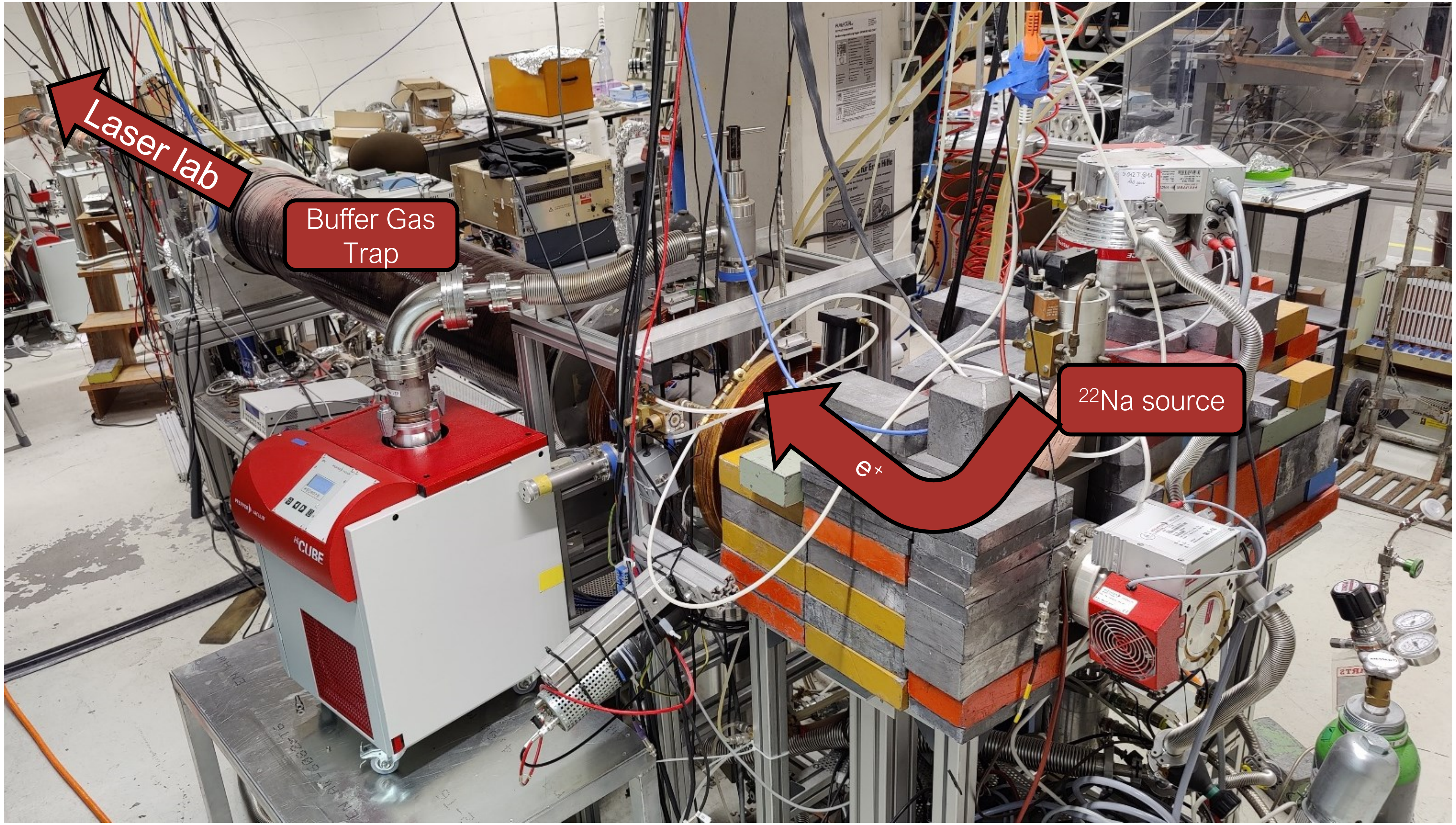


Classically: can be considered as an hydrogen-like atom, but with two particles of equal mass orbiting a common center.

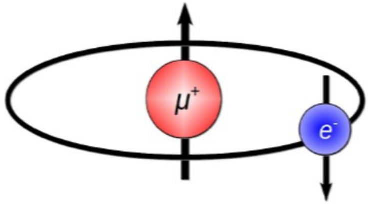
- Ps: electron – positron bound state
- Produced as para-Ps (S=0) or ortho-Ps (S=1)
- Very short lifetimes of 125ps (p-Ps) and 142ns (o-Ps)
- Main decay channel: p-Ps → 2γ, o-Ps → 3γ



Ps-Spectroscopy at ETH



The Muonium

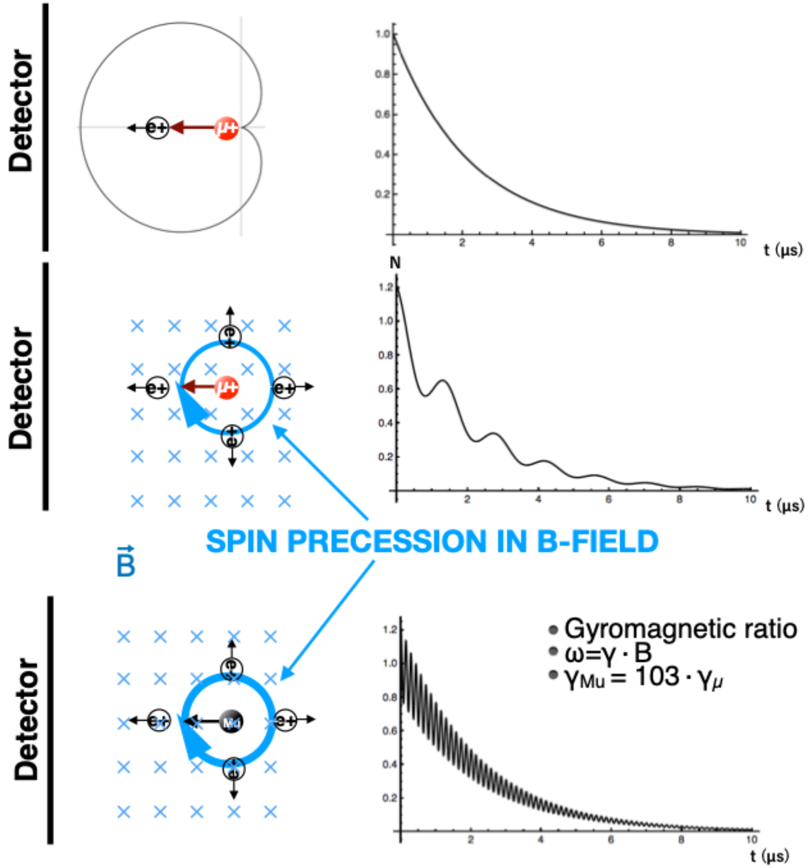


Actually M is not a real -onium atom (particle-antiparticle system).

The true muonium bound state would be $\mu^+\mu^-$ yet to be discovered…

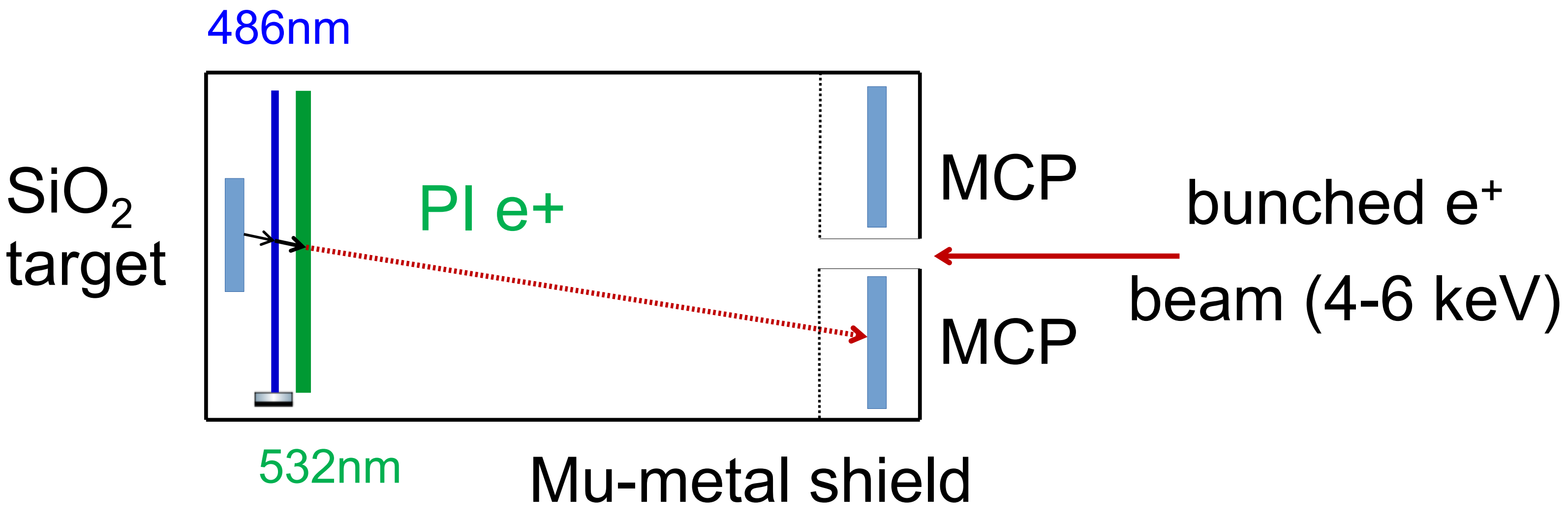
- M: positive muon-electron bound state
- Predicted in 1957 (Friedmann, Telegdi, Hughes)
- Unstable with lifetime of 2.2 μs.
- Main decay channel: μ^+ -> e^+ + $\bar{\nu}_\mu$ + ν_e

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



- Gyromagnetic ratio
- $\omega = \gamma \cdot B$
- $\gamma_{Mu} = 103 \cdot \gamma_\mu$

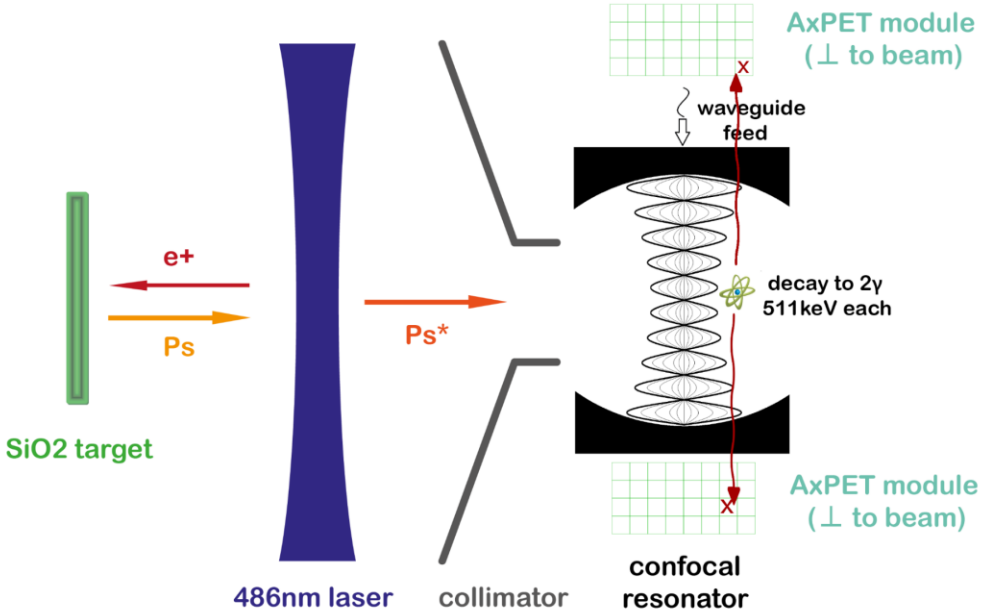
Ps-Spectroscopy at ETH: 1S-2S

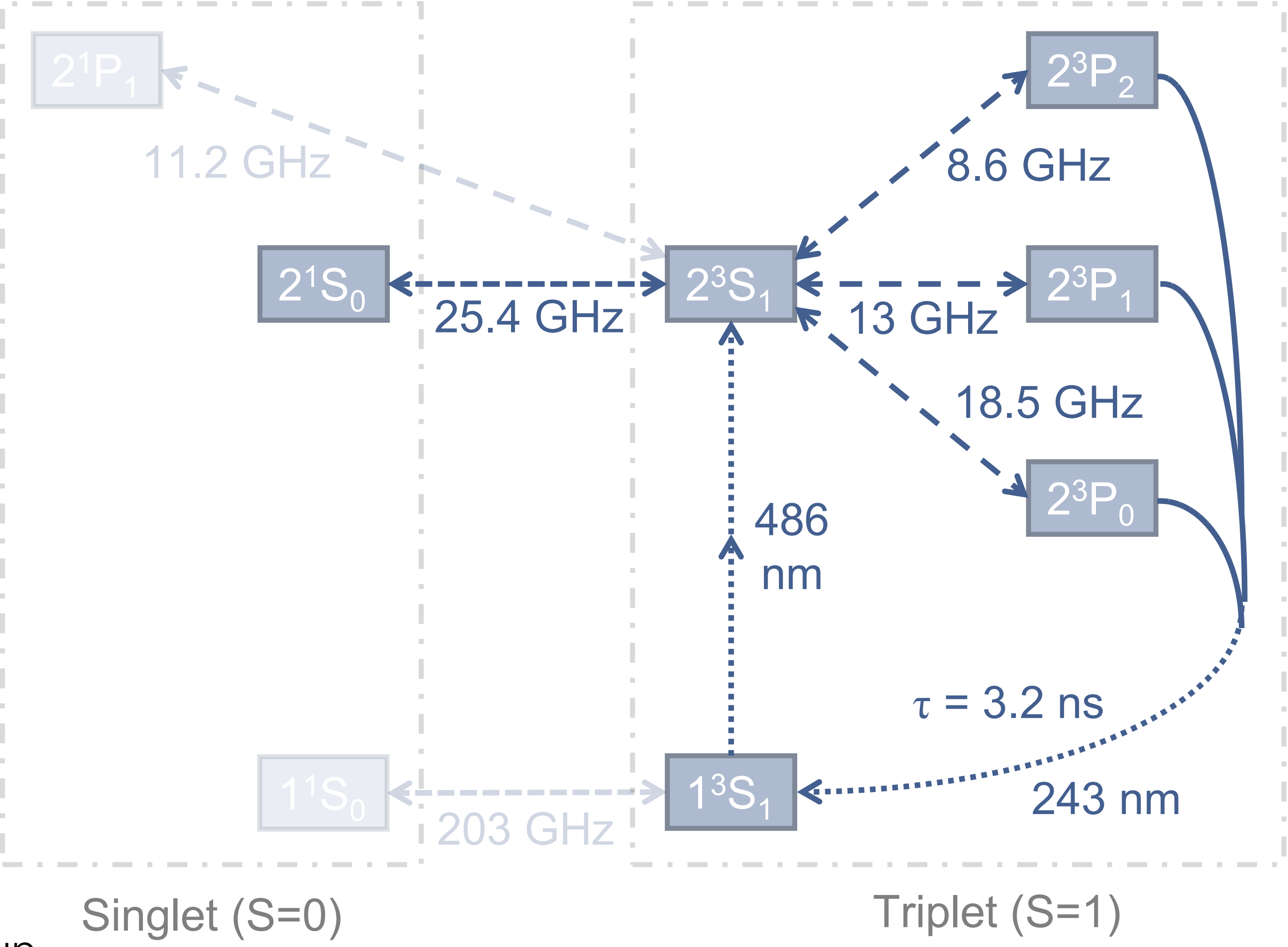


Multiple options for detecting 2S excitation:

- Direct photo-ionization in the exciting laser
- Delayed photo-ionization in separate laser (shown)
- 2S → Rydberg (e.g. 20P) and field ionization on MCP

Ps-Spectroscopy at ETH: 2S-HFS and 2S-FS





Detection signature:

either excess of 2γ 511 keV back-to-back (HFS) or 3γ (FS)

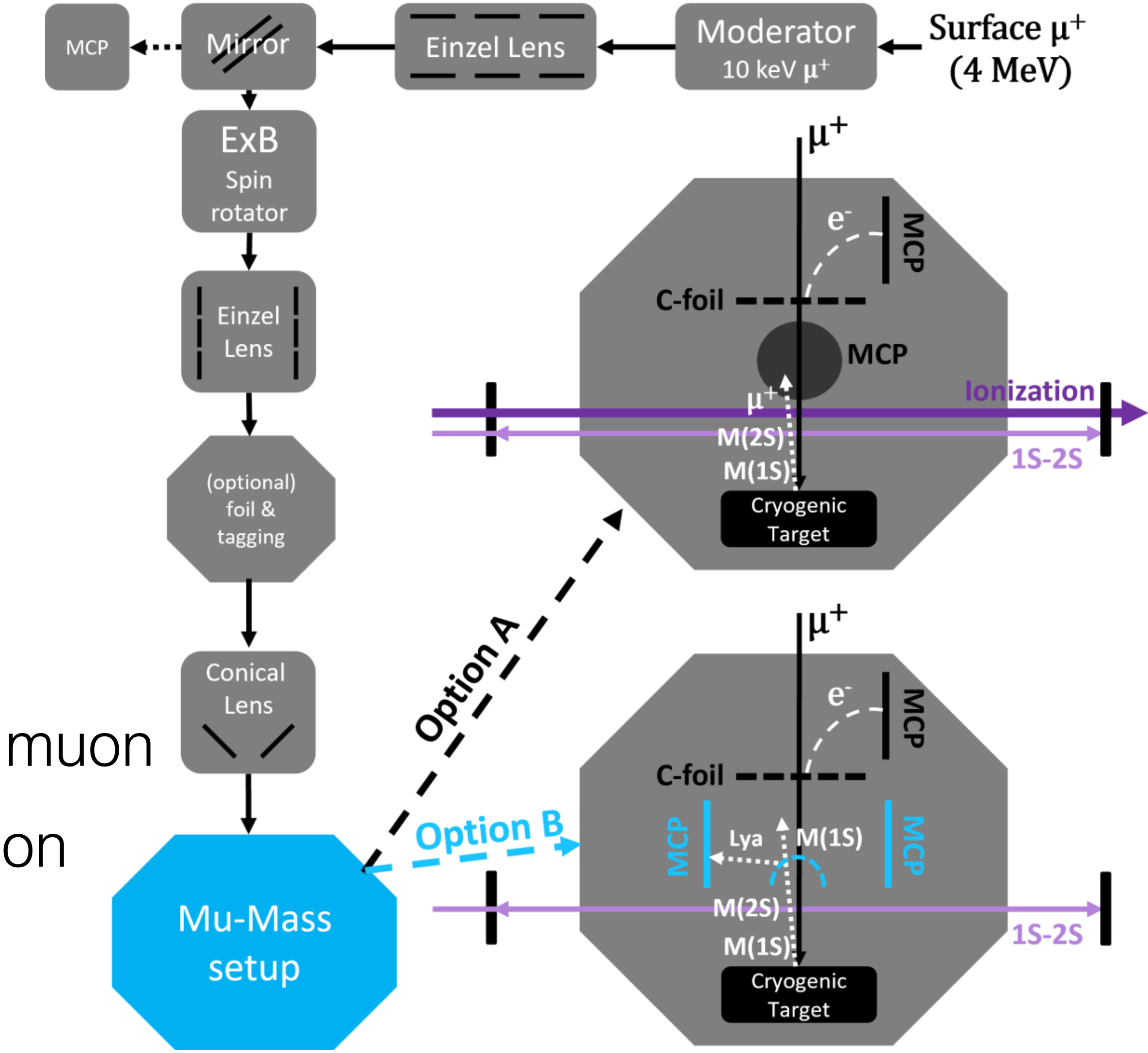
Status:

- HFS and FS measurements currently being set up
- 1S-2S measured in 2021 (Michael Heiss, PhD Thesis, https://doi.org/10.3929/ethz-b-000477081)

The Mu-MASS experiment at PSI: 1S-2S

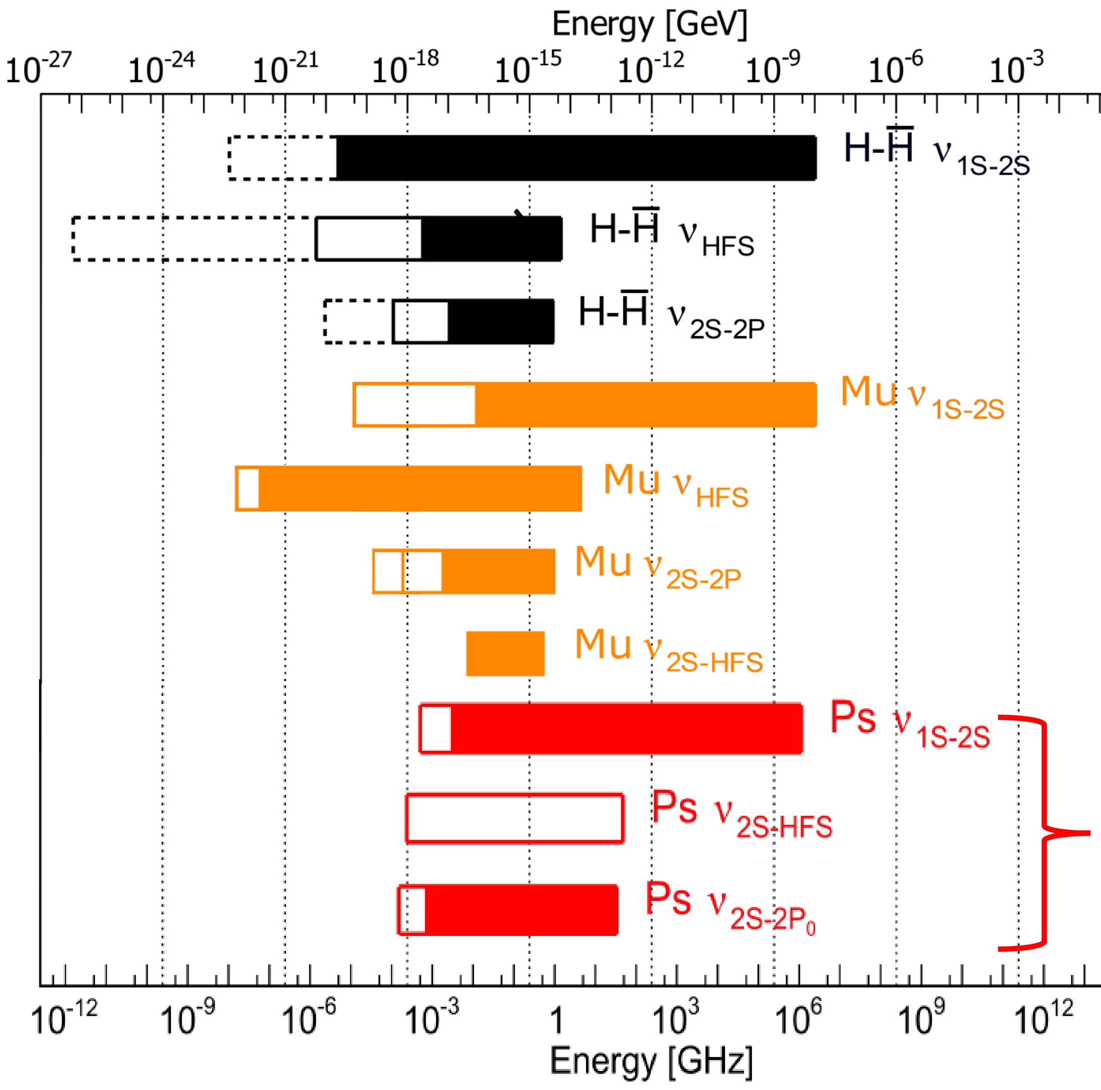
- Located at the LEM beamline at PSI
- Similar detection scheme as 1S-2S Ps

- Tagging incoming muon: carbon foil
- M-Formation: SiO_2 target
- Excitation: CW laser at 244nm
- Detection: Additional ionization laser (A) for muon or 2S quenching (B) for Lya photon (122nm)



Spectroscopy of Exotic Atoms as a sensitive test

- Left edge: absolute value
- Right edge: uncertainty
- Length of bar: sensitivity
- Filled bar: measured exp.
- Empty bar: proposed exp.



ALPHA collaboration. Nature, 541:506–510, 2016

ALPHA collaboration. Nature, 548(7665):66–69, 2017

E.Widmann et al. Hyperfine Interact., 215(1-3):1–8, 2013

ALPHA collaboration. Nature, 578(7795):375–380, 2020

P. Crivelli et al., Phys. Rev. D, 94:052008, 2016

V. Meyer, S. N. Bagayev, et al. Phys. Rev. Lett., 84:1136–1139, 2000

P. Crivelli. Hyperfine Interactions, 239(1), 2018

W. Liu, M. G. Boshier, et al.. Phys. Rev. Lett., 82:711–714, 1999

MUSEUM collaboration, arxiv.org/abs/2104.06663

B. Ohayon, G. Janka, P. Crivelli et al., PRL 128, 011802 (2022)

G. Janka PhD Thesis (2022)

M. S. Fee et al., Phys. Rev. Lett., 70(10):1397–1400, 1993

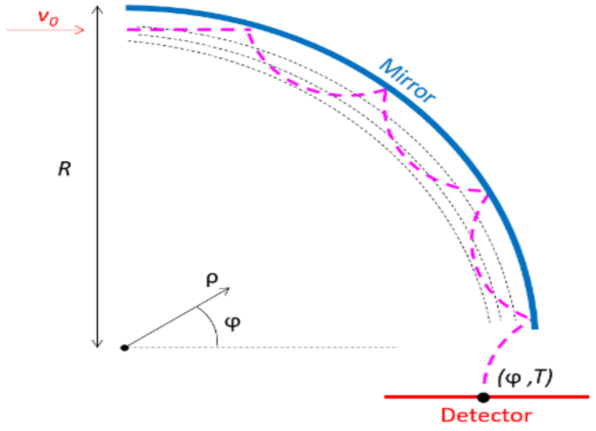
M. Heiss, PhD Thesis (2021), https://doi.org/10.3929/ethz-b-000477081

D. Hagena et al., Phys. Rev. Lett., 71(18):2887–2890, 1993

Bold: measurement
Regular: proposal

Hydrogen whispering gallery effect

Nesvizhevsky, V.V. & Voronin, Alexei.,
Comptes Rendus Physique. 12. 791–795. (2011)

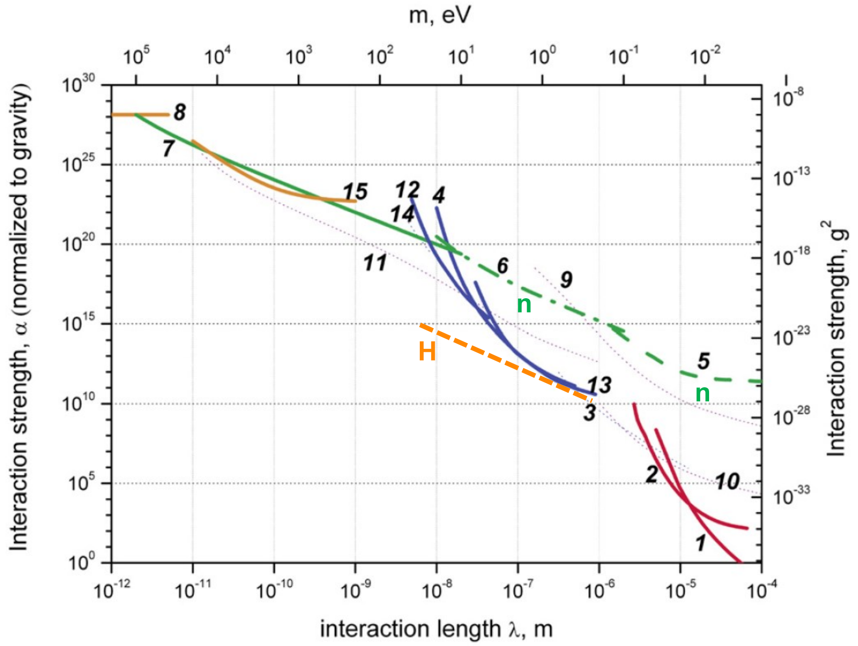


$$V(r) = \underbrace{m\frac{v^2}{R}r}_{centrifugal\ potential} + \underbrace{V_{CP}(r)}_{Casimir-Polder\ potential} + \underbrace{V_{hyp}(r)}_{hypothetical\ potential}$$

Yukawa distance

$$V_Y(r) = -\alpha\frac{e^{-r/\lambda}}{r}$$

coupling strength



2) Measurement of short range gravity with pendulums
A.A. Geraci, et al, Phys. Rev. D 78 (2008)

4) Measurement of Casimir and Van der Waals forces
R.S. Decca, et al, Eur. Phys. J. C 51 (2007)

5) Quantum Gravitational States of neutrons
Nesvizhevsky, V., Börner, H., Petukhov, A. et al., Nature 415, 297–299 (2002)

6) Whispering Gallery Effect of neutrons
Nesvizhevsky, V.V. & Voronin, Alexei., Comptes Rendus Physique. 12. 791–795. (2011)

H) Whispering Gallery Effect of hydrogen, projection
in collaboration with LKB (Serge Reynaud, Olivier Rousselle,...) and Grenoble (Valery Nesvizhevsky)

FOR NEW PHYSICS SEARCHES WITH NEUTRONS SEE TALKS OF FLORIAN PIEGSA, GEORG BISON

A more complete summary can be found in: I. Antoniadis et al., Comptes Rendus Physique, Volume 12, Issue 8, 2011