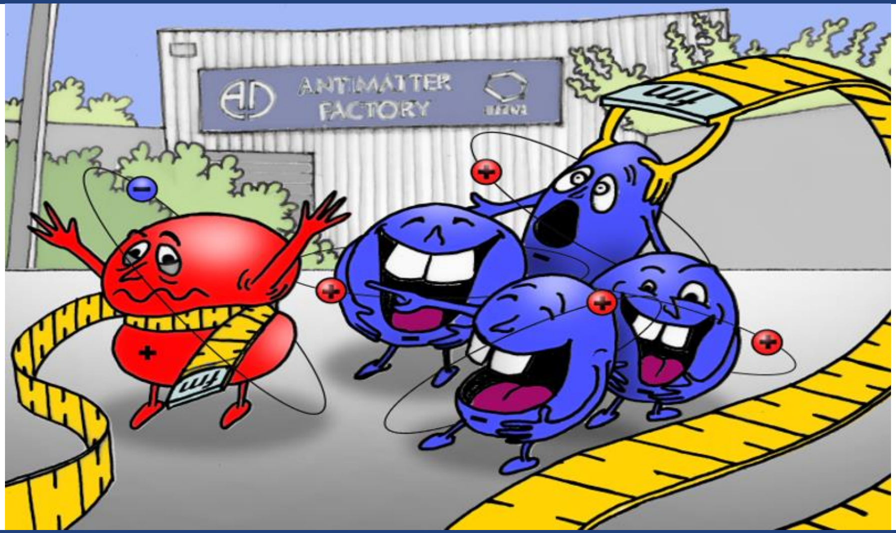


Progress towards measuring the Lamb Shift of Muonium and Antihydrogen

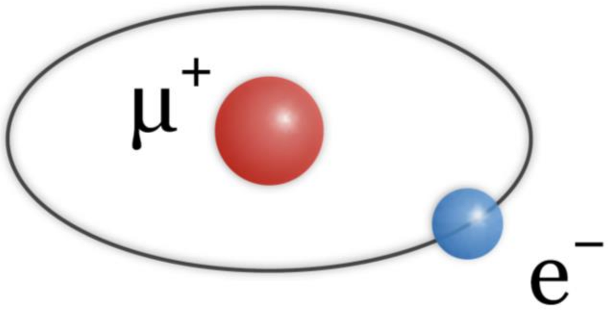
Gianluca Janka

PI: Prof. Paolo Crivelli

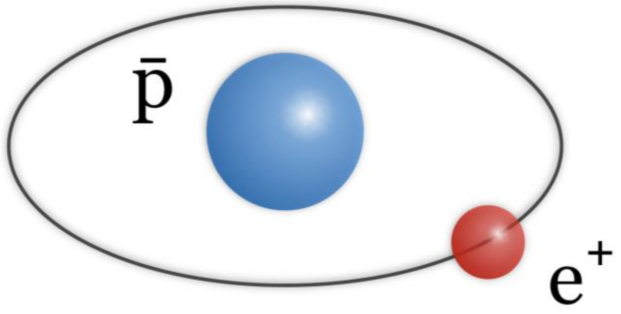
This work is supported by ETH Research Grant (ETH-46 17-1), ERC (818053-Mu-MASS) and SNF (grant 173597)

Introduction: Why measurements with Muonium or Antihydrogen?

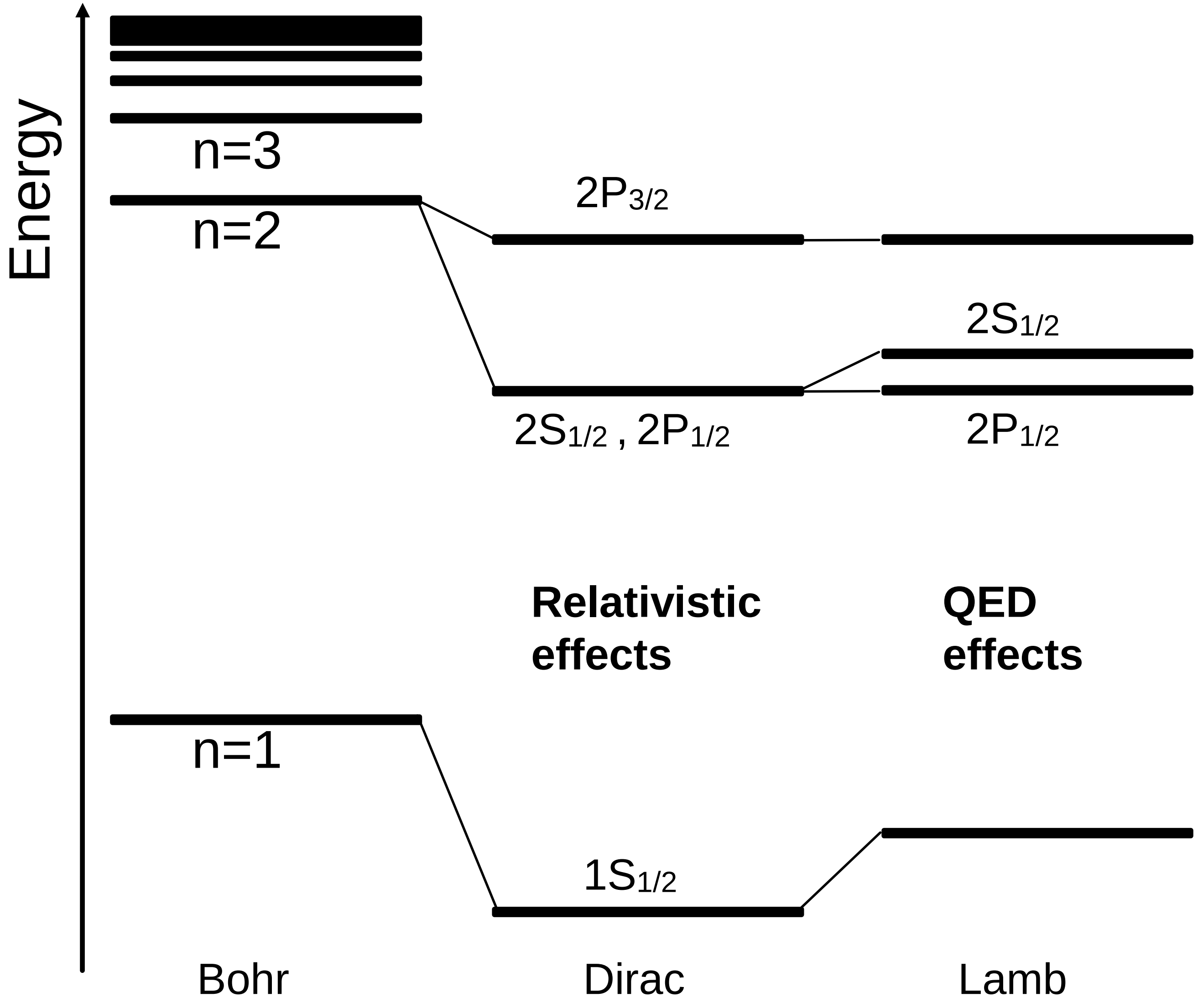
- **Muonium (Mu):**
  - made of electron and positive muon → has no internal structure
  - great system to test bound state QED and extract fundamental constants (e.g. muon mass, magnetic moment)
  - sensitive probe for existence of exotic dark-sector particles, new muonic forces, and hidden dimensions



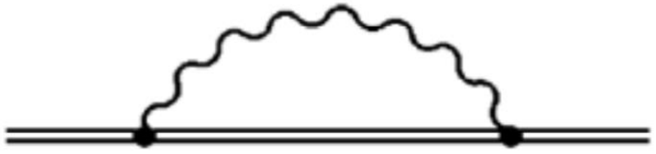
- **Antihydrogen ($\bar{H}$):**
  - made of antiproton and positron
  - measurements can be compared to its very well known counterpart Hydrogen
  - provides stringent tests of CPT symmetry, to give insight about matter-antimatter asymmetry observed in the Universe
  - good candidate for first direct test of Weak Equivalence Principle (WEP) for antimatter



Introduction: Energy spectrum of hydrogen-like atoms

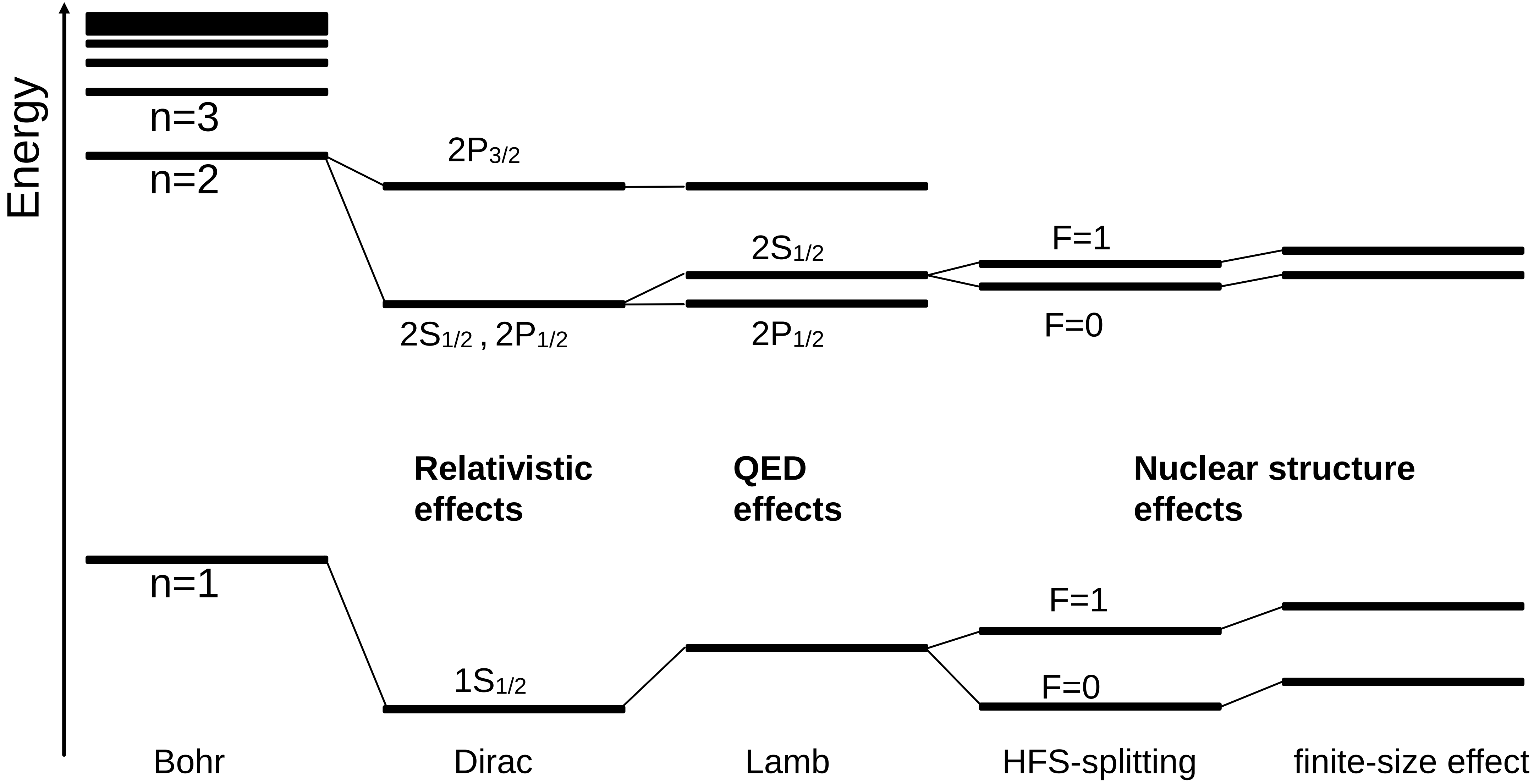


- Leading QED effect in conventional atoms is by the self energy contribution
- A virutal photon can be emitted and re-absorbed by the bound electron:



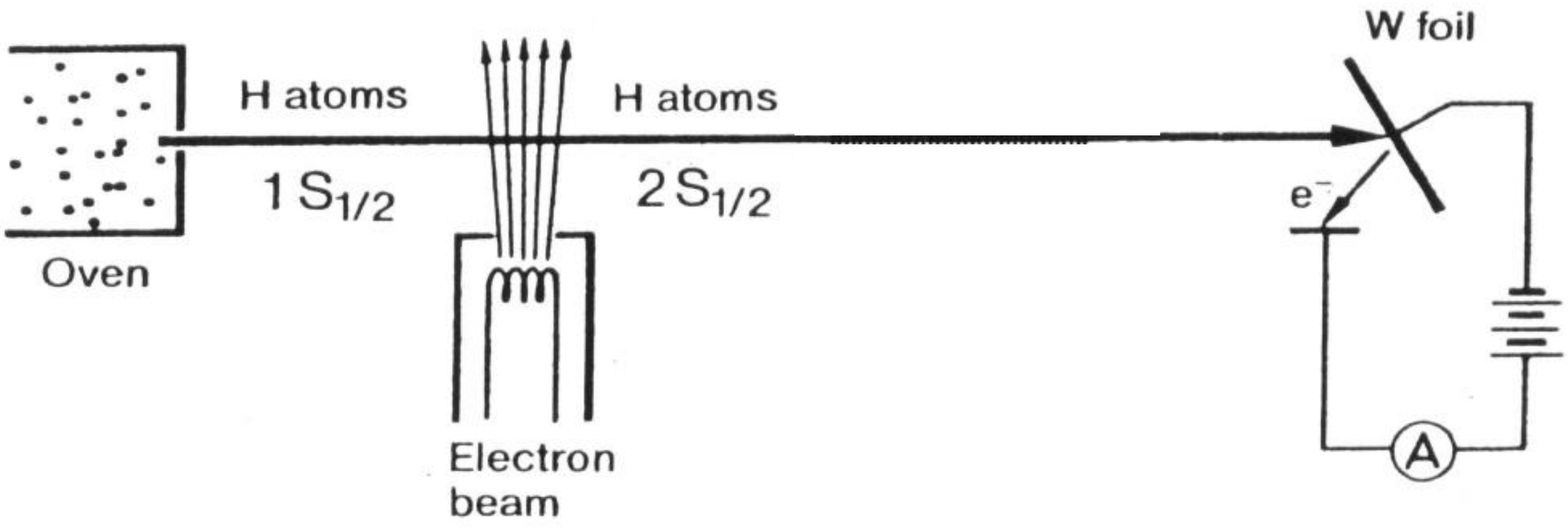
- This fluctuation of the EM-field can be pictured as perturbing the electron orbit and therefore shifting the energy levels

Introduction: Energy spectrum of hydrogen-like atoms



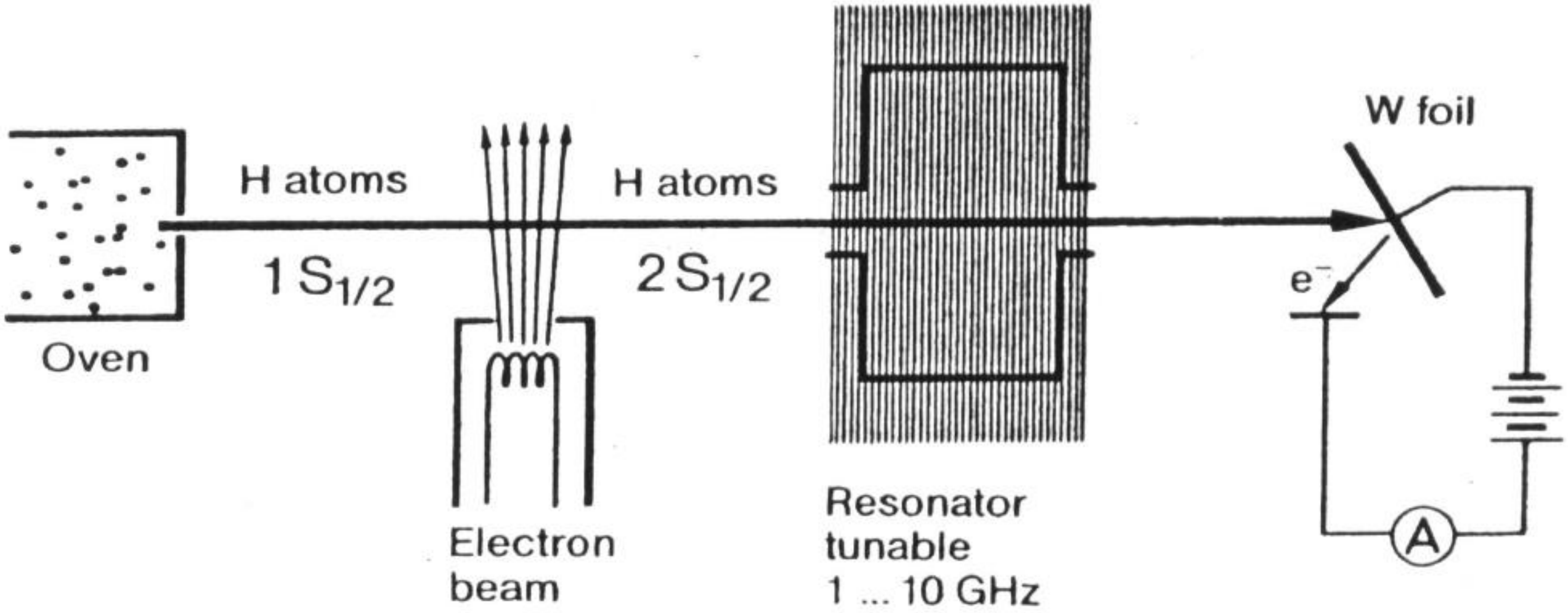
Introduction: Lamb's experiment (1947)

- Basic idea: produce a beam of hydrogen atoms in the metastable 2S state, $\tau_{2S} \simeq 10^8\,\text{ns} = 100\,\text{ms}$, by bombarding ground state atoms with electrons
  - The atoms in the 2S impinging on a metal surface release their electrons that can be detected with an electrometer while this process does not occur for the atoms in the ground state (1S)

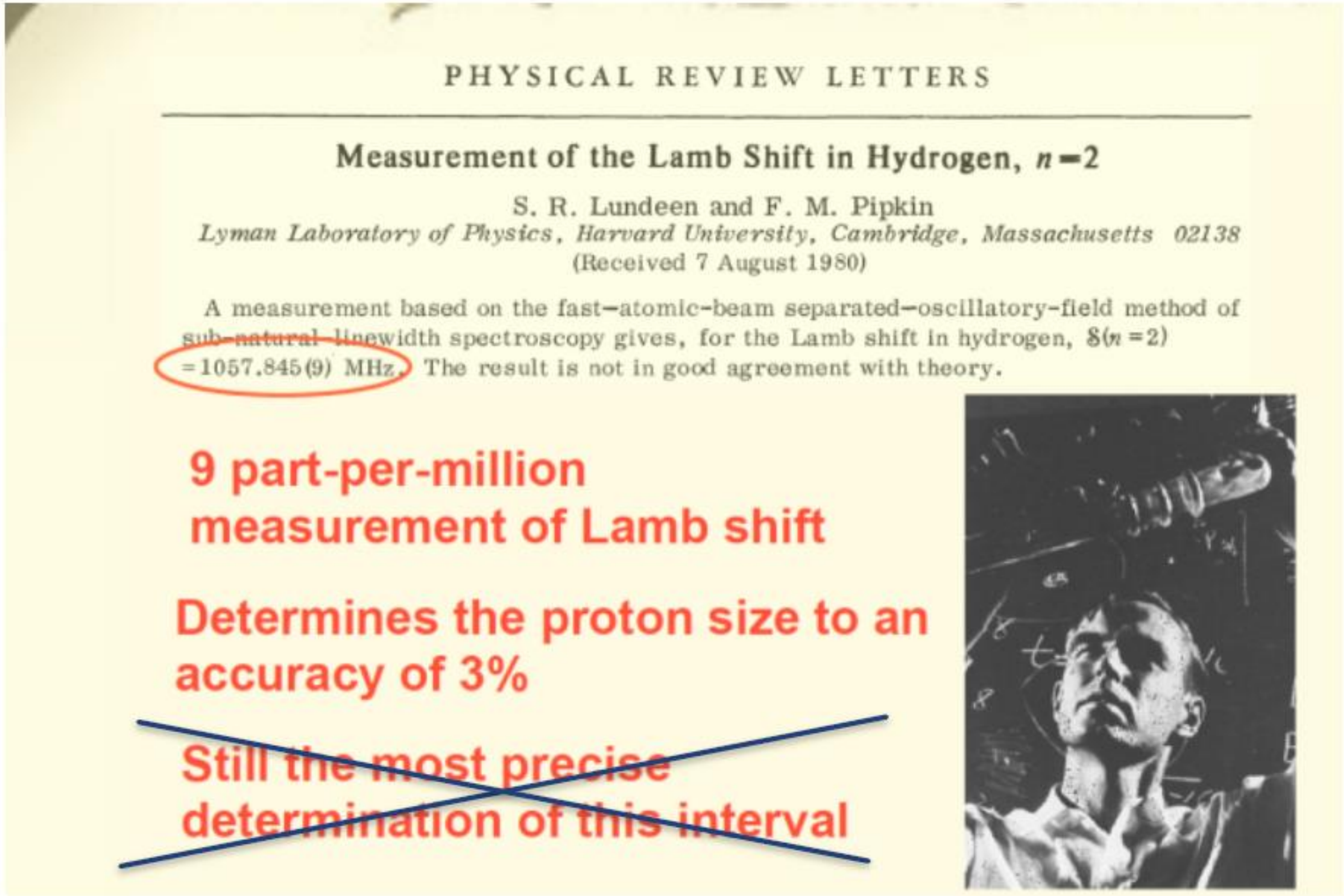


Introduction: Lamb's experiment (1947)

- Applying an RF field at the resonance frequency one can induce transition from the 2S to the 2P state
  - The 2P state, $\tau_{2P} \simeq 1\,\mathrm{ns}$, decays quickly to the ground state and therefore the signal in the electrometer will decrease



Introduction: Most precise determination of the Hydrogen Lamb shift

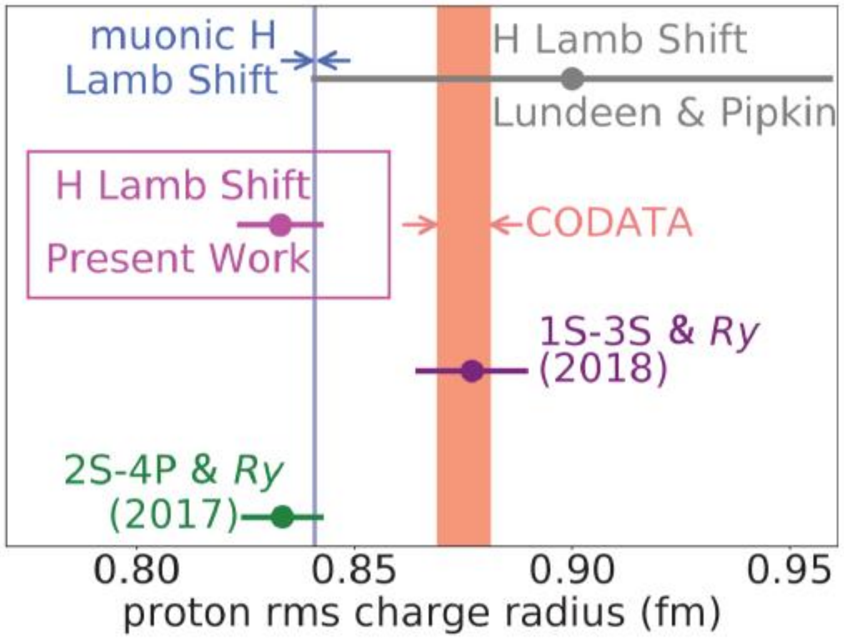

PHYSICAL REVIEW LETTERS

Measurement of the Lamb Shift in Hydrogen, $n=2$

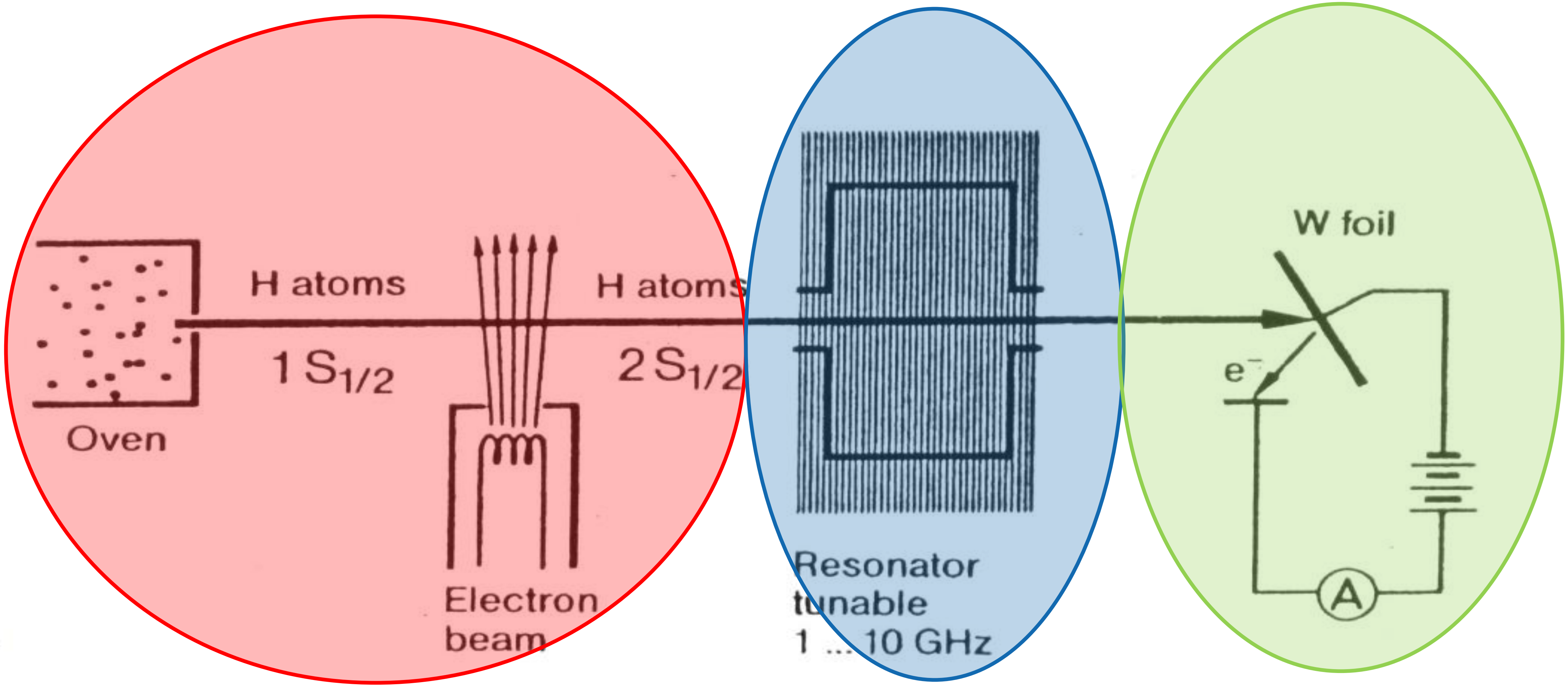
S. R. Lundeen and F. M. Pipkin
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 7 August 1980)

A measurement based on the fast-atomic-beam separated-oscillatory-field method of sub-natural-linewidth spectroscopy gives, for the Lamb shift in hydrogen, $\mathcal{S}(n=2) = 1057.845(9)$ MHz. The result is not in good agreement with theory.

N. Bezginov, T. Valdez, M. Horbatsch, A. Marsman, A. C. Vutha, **E. A. Hessels, Science 365, 1007–1012 (2019)**



Ingredients needed for a successful Lamb shift measurement

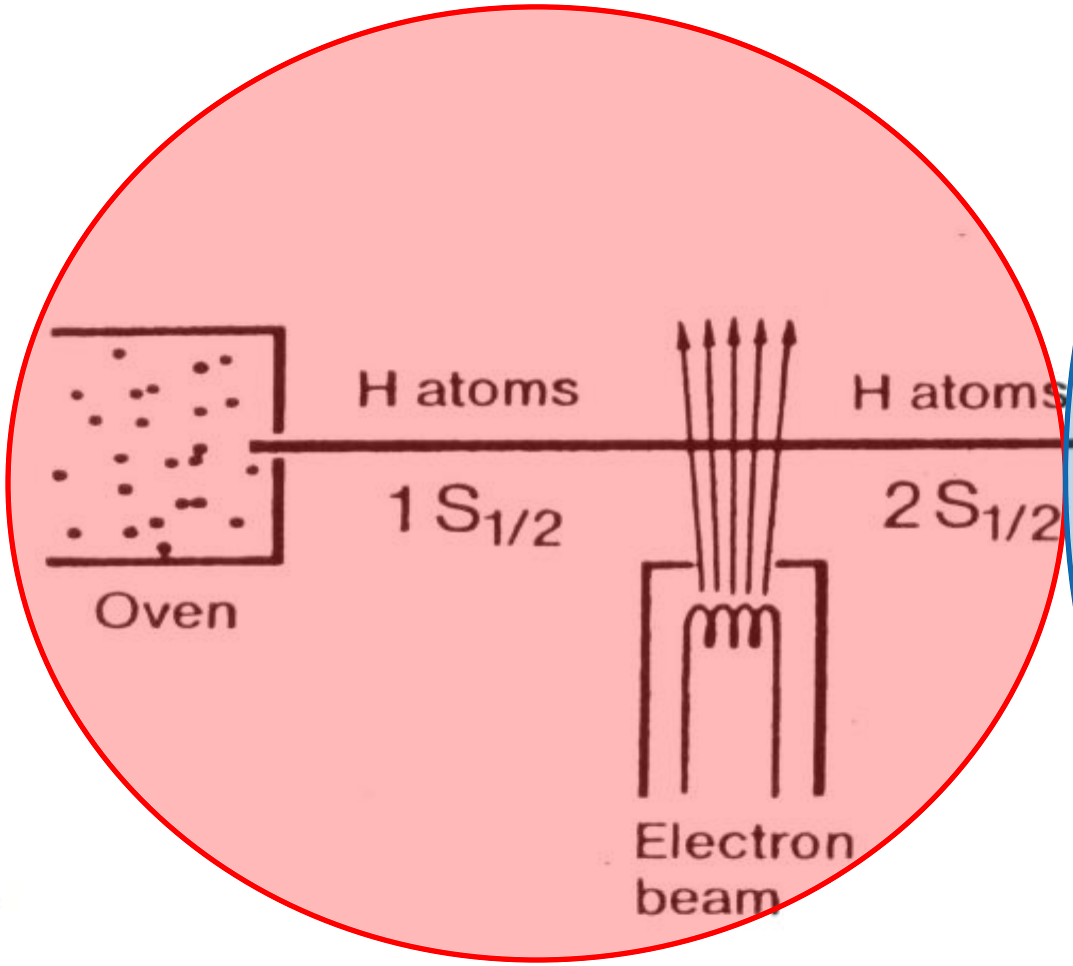


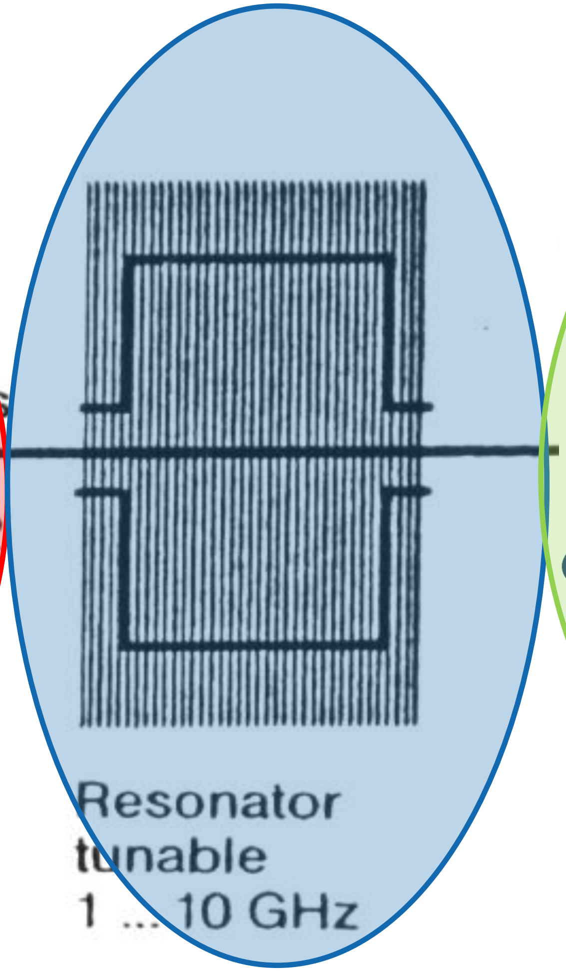
Well characterized particle beam in metastable 2S state

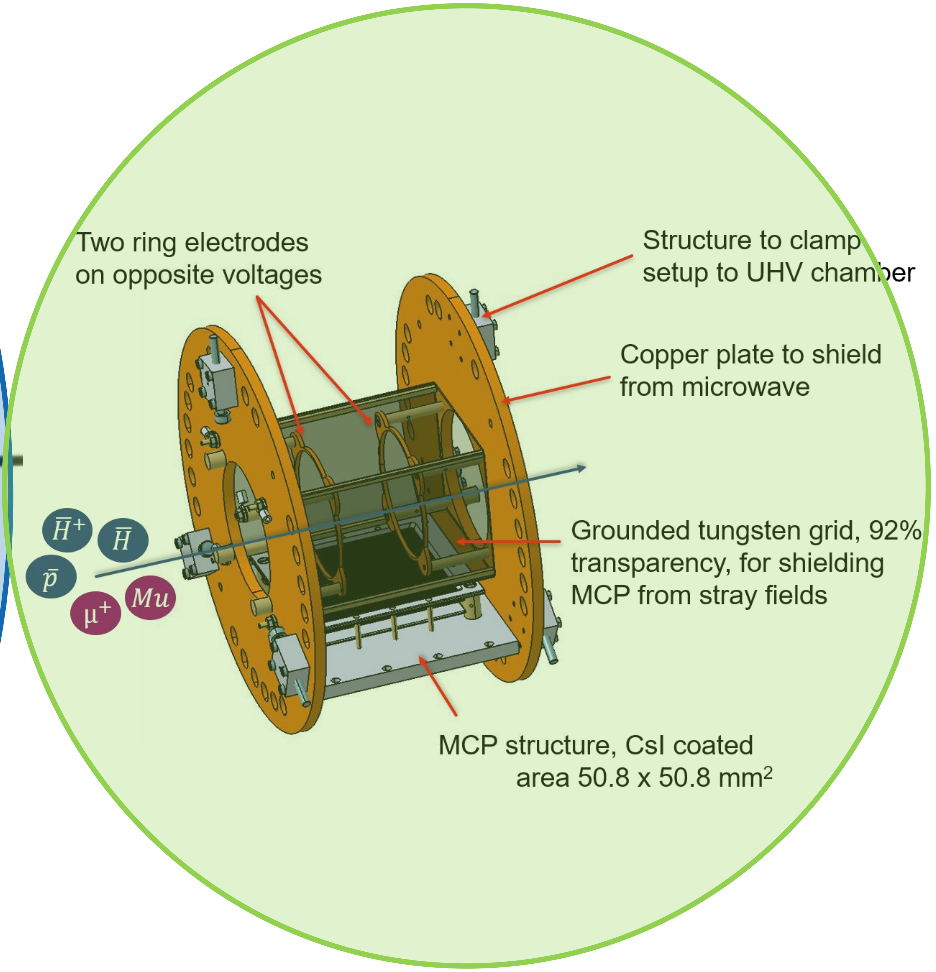
Device for applying powerful RF field to induce 2S-2P transition

Detection setup for determining 2S states surviving depending on RF frequency

Ingredients needed for a successful Lamb shift measurement





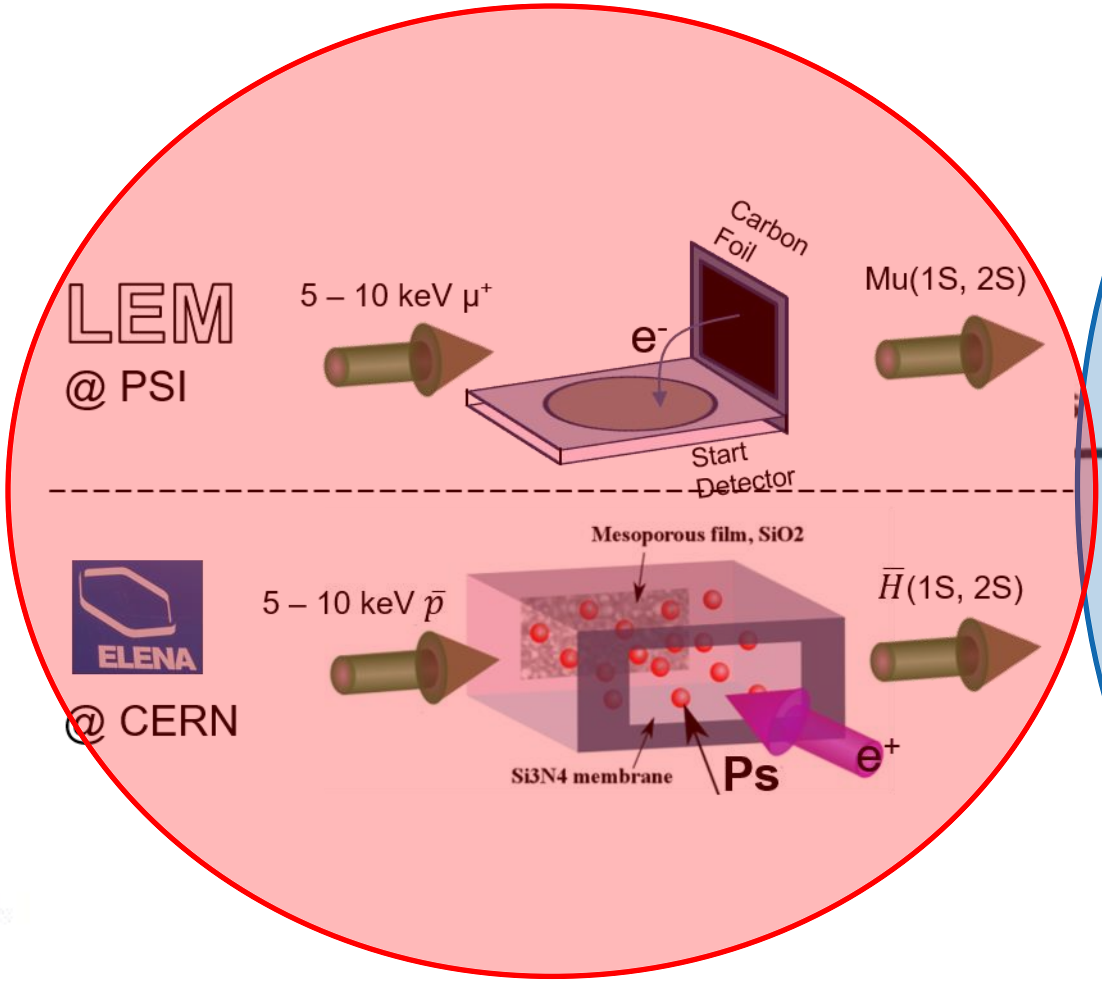


Well characterized particle beam in metastable 2S state

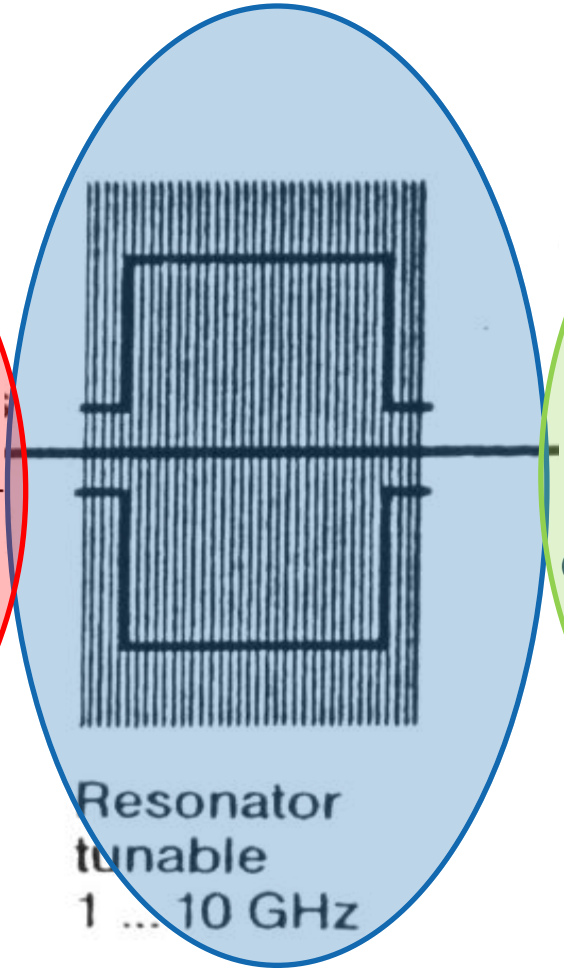
Device for applying powerful RF field to induce 2S-2P transition

Detection setup for determining 2S states surviving depending on RF frequency

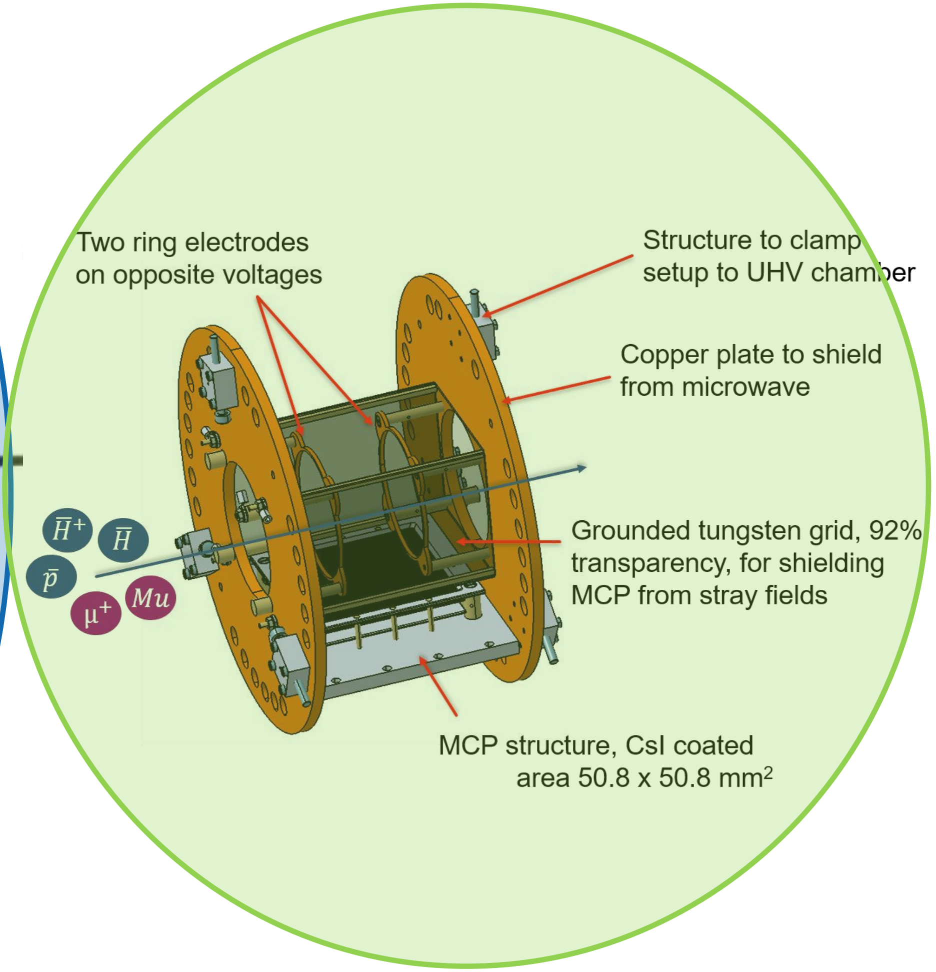
Ingredients needed for a successful Lamb shift measurement



Well characterized particle beam in metastable 2S state



Device for applying powerful RF field to induce 2S-2P transition

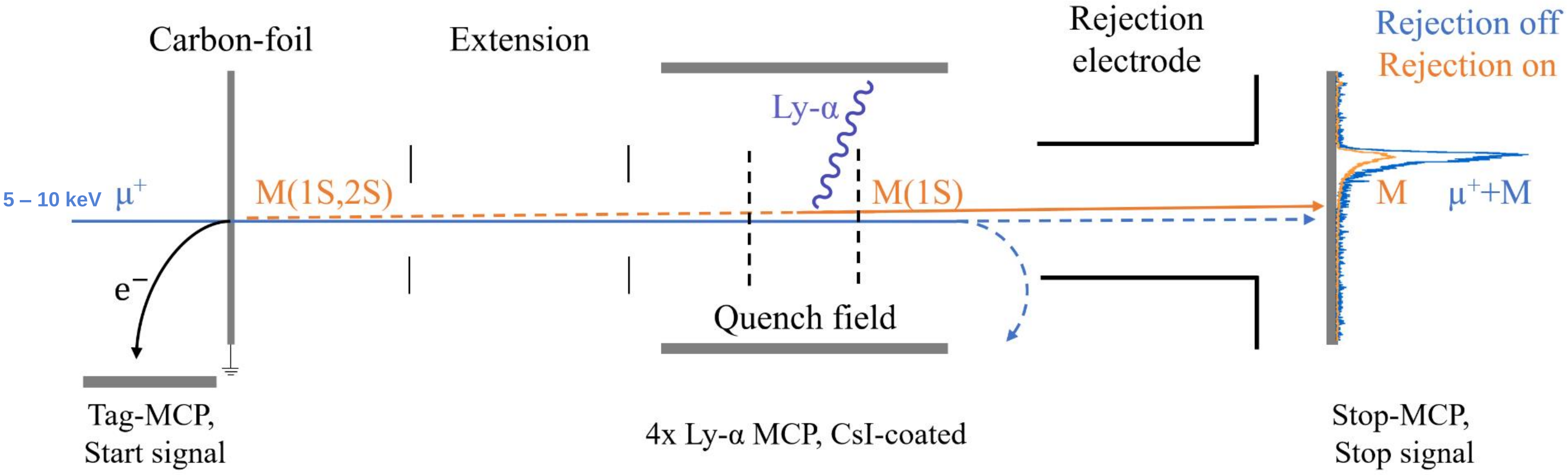


Detection setup for determining 2S states surviving depending on RF frequency

Mu-Lamb: Setup of Mu-Mass Beamtime Dec. 2019

First steps for Mu-Lamb:

Production of Mu(2S) beam at Low-Energy Muon Facility (LEM) beamline at PSI and testing the Ly-a detection setup

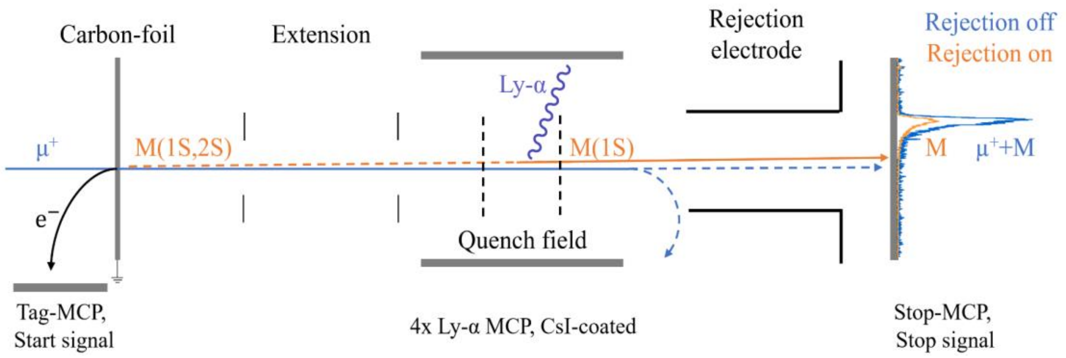


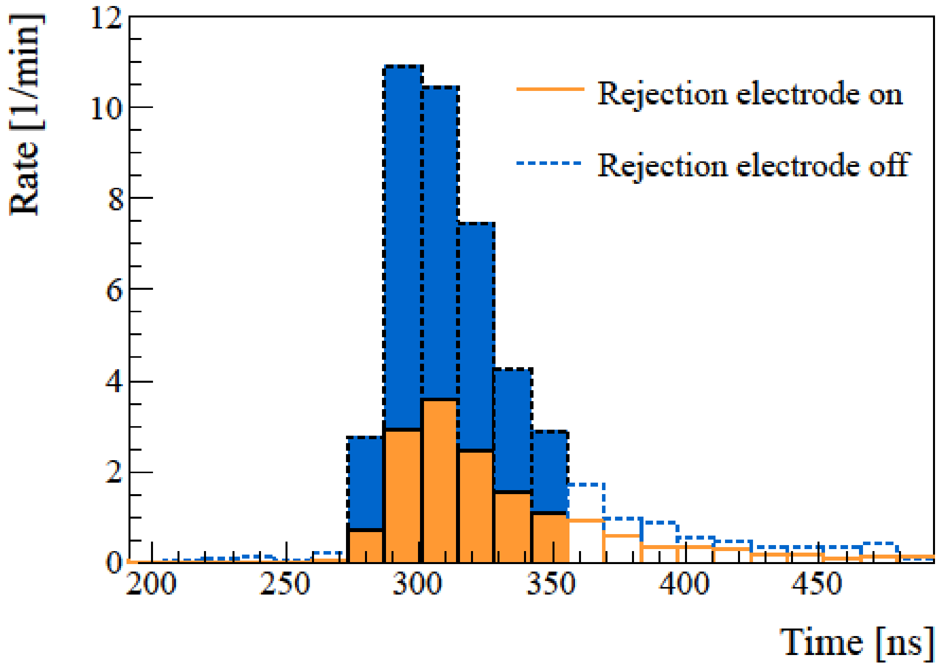
For detailed GBAR Antihydrogen Lamb shift setup please see:

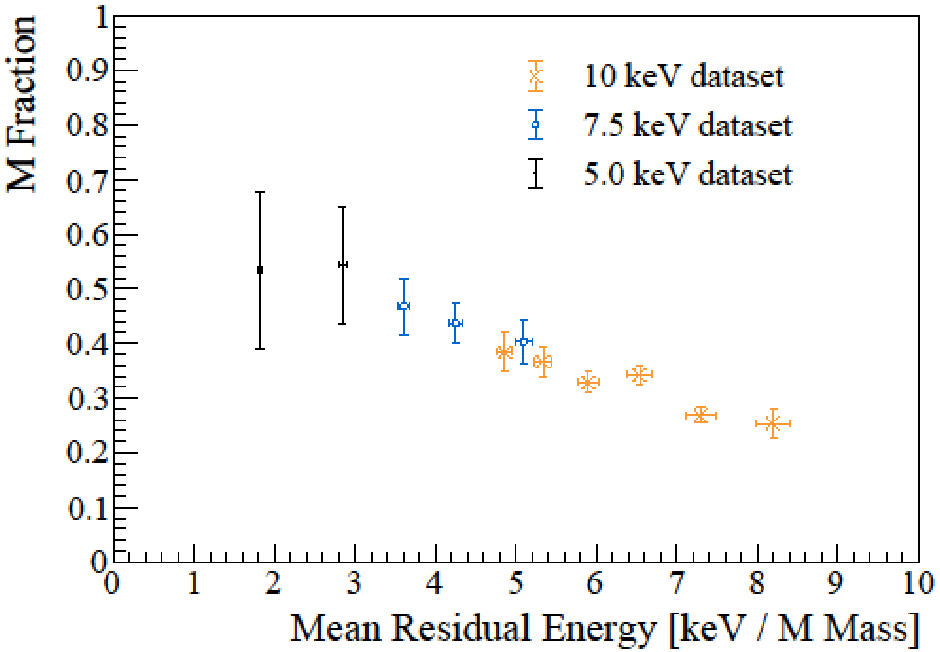
my PhD Seminar talk from March 2018 (https://indico.cern.ch/event/696534/) or P. Crivelli, D. Cooke, M. Heiss, "Antiproton charge radius", Phys. Rev. D 94, 052008 (2016)

Mu-Lamb: Muonium Formation

- Coincidence signal between Tag- and Stop-MCP to detect particle's passage
- Rate ratio between measurements with rejection electrode on & off → Muonium formation fraction







Mu-Lamb: Muonium 2S Formation & beam characterization

- Triple coincidence signal between Tag-, Ly-a and Stop-MCP to detect particle's passage and Ly-a emission
- Rate difference between measurements with quenching field on & off → Mu(2S) formation

M(2S) formation fraction

Triple coincidence rate, Mu(2S)

$$f_{2S/M} = \frac{R_T}{R_D \cdot \varepsilon_{QG} \cdot \varepsilon_{MCP}},$$

Double coincidence rate, Mu

combined quenching and geometrical efficiency

Ly-a detection efficiency of MCP

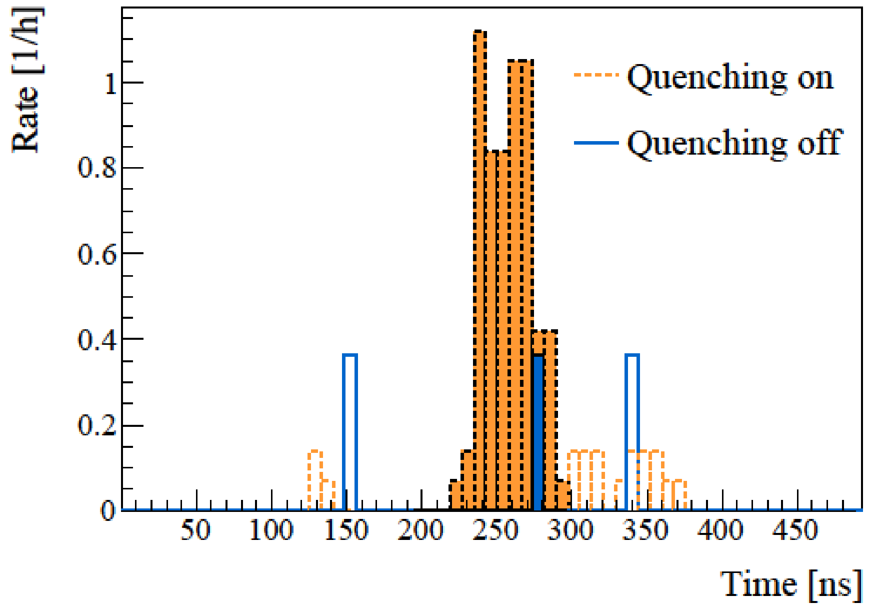


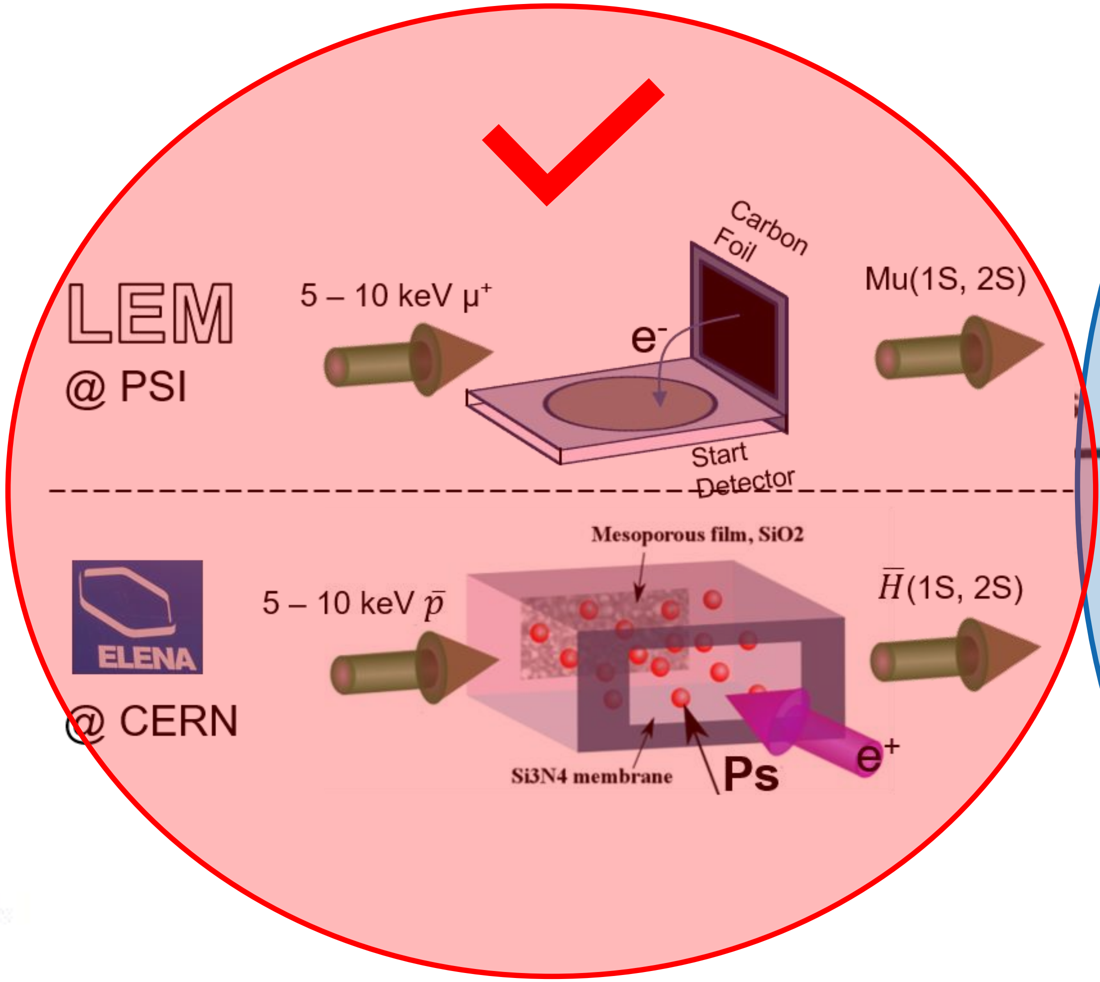
Table 1 Summary of values extracted from different incident energies E_{inc}. MPE is the Most Probable Energy for M that traversed the foil and reached the Stop-MCP

E_{inc} (keV)	MPE (keV)	f_{M/μ^+} (%)	$f_{2S/M}$ (%)	R_{μ^+} (kHz)	R_{2S} (Hz)
5.0	2.7 ± 0.1	56.8 ± 9.0	–	1.45	$83^* \pm 21$
7.5	4.7 ± 0.2	43.2 ± 2.4	11 ± 4	2.07	100 ± 30
10.0	7.0 ± 0.3	31.8 ± 0.8	10 ± 3	2.84	90 ± 30

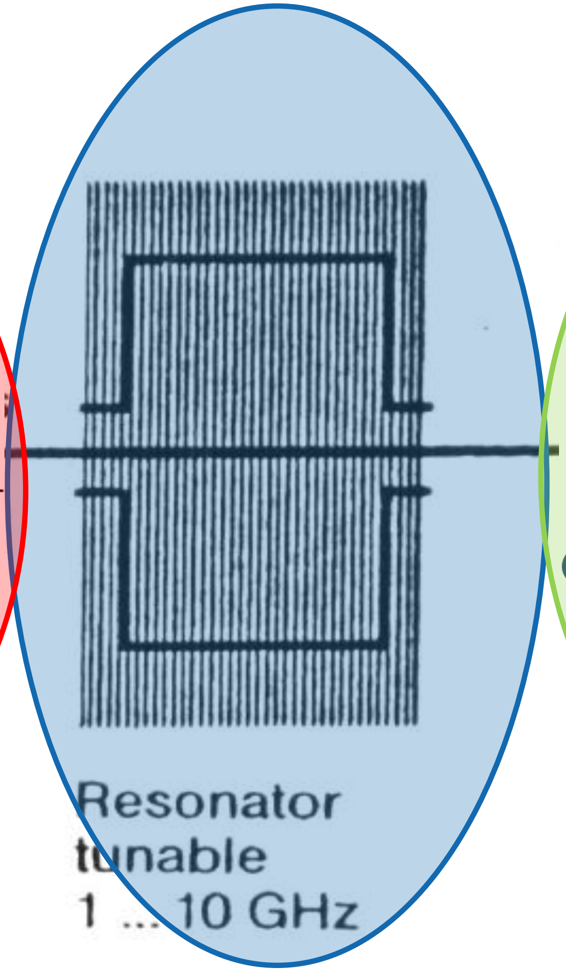
For R_{2S} at 5 keV, $f_{2S/M} = 10 \pm 2$ % was assumed (see text)

For more details, please see:
Janka, G. *et al*. *Eur. Phys. J. C* **80,** 804 (2020).
https://doi.org/10.1140/epjc/s10052-020-8400-1

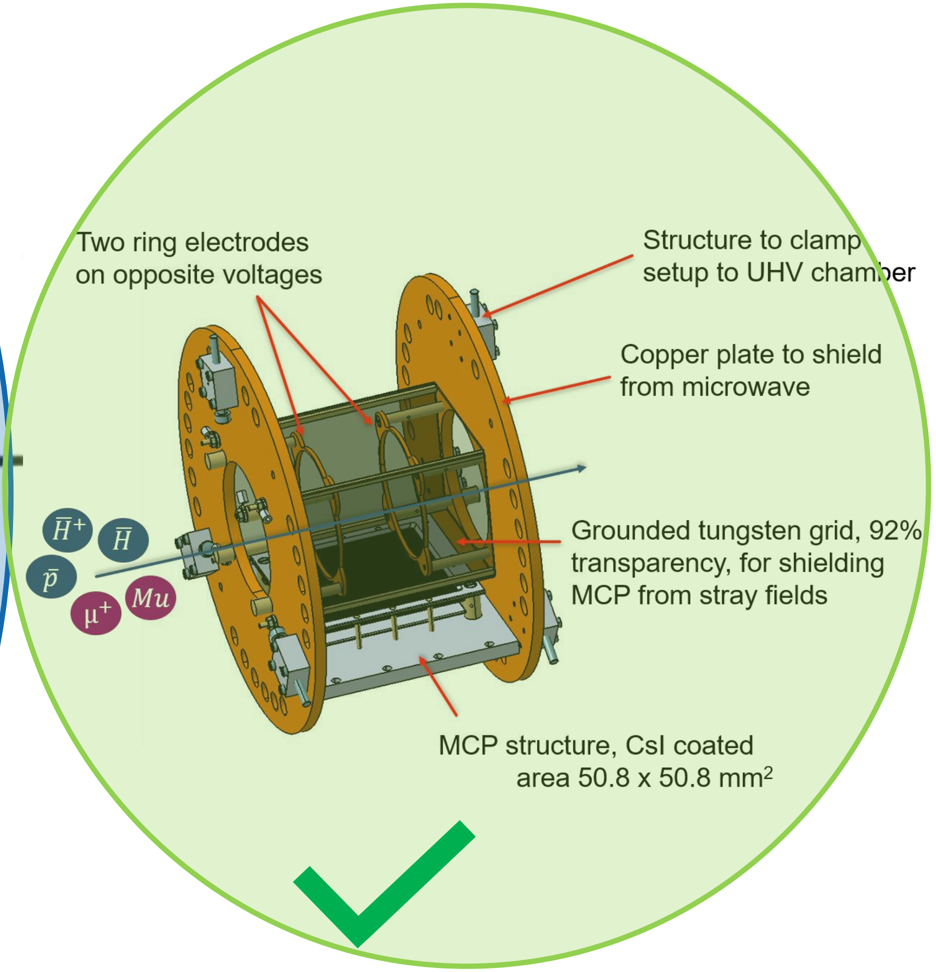
Ingredients needed for a successful Lamb shift measurement



Well characterized particle beam in metastable 2S state



Device for applying powerful RF field to induce 2S-2P transition



Detection setup for determining 2S states surviving depending on RF frequency

Current Status & Outlook

- **Mu-Lamb:**
  - First measurement of Mu creation efficiency through beamfoil technique over an energy range from 2 to 8 keV
  - Ly-a detection setup successfuly tested and production of intense metastable Muonium beam shown

    → Lamb shift to 100 kHz (current best 14 MHz, TRIUMF) feasible at the LEM beamline within a few days of beamtime

    → Test of bound state QED and new physics
  - Microwave as well as new Ly-a detection in construction (next beamtime December 2020 → stay tuned!)

- **GBAR:**
  - Current Ly-a detection setup will be shipped to CERN and installed permanently in the GBAR beamline (end of 2020)
  - First attemps for $\bar{H}$ Lamb shift measurements can be done when antiproton beam is back after LS2 (middle of 2021)
  - Goal: To measure the $\bar{H}$ Lamb shift at a level of 100ppm with roughly one month of data taking

    → stringent test of CPT symmetry, allows extraction of antiproton charge radius at level of 10%


QUESTIONS?
COMMENTS?
CONCERNS?