The MUSE experiment at PSI: Status and Plans

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University of Michigan
(for the MUSE collaboration)
(27-August-2019)

The Proton Radius Puzzle

- What is the problem ?
- How do we solve it: MUSE ?

This work is supported by

The Proton Radius Puzzle

July 2010

The Proton Radius Puzzle

July 2010

April 2013

The Proton Radius Puzzle

July 2010

April 2013

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The Proton Radius Puzzle

July 2010

April 2013

July 2013

January 2014

The Proton Radius Puzzle

The Proton Radius Puzzle

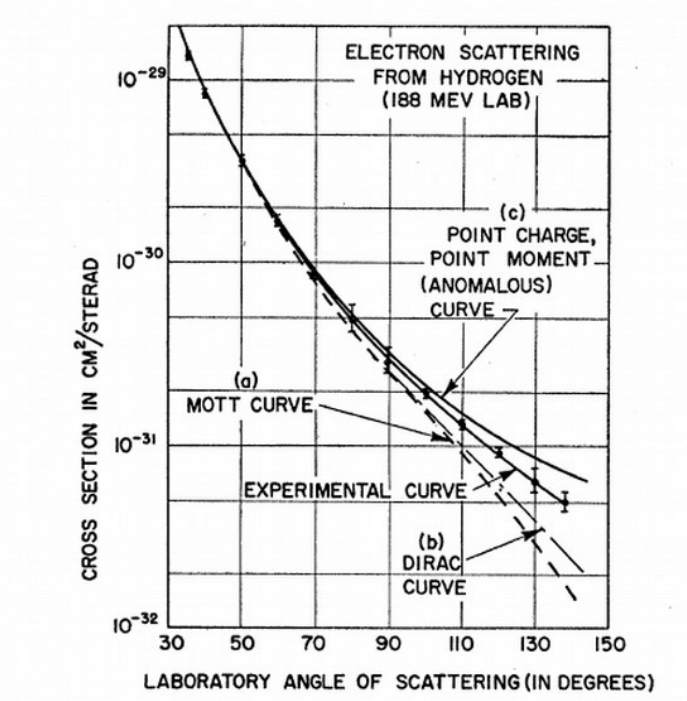
What exactly is the puzzle ?

How do you measure proton radius?

- Scattering experiments

  (Hofstadter @ Stanford: 1950s -electron scattering)

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{point} \times \left(G(Q^2)\right)^2$$



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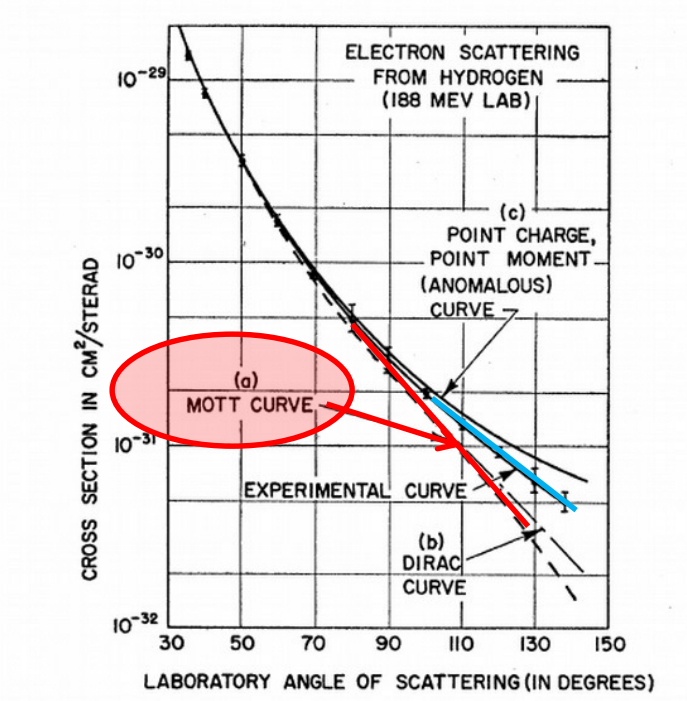
$$\left\langle r_E^2 \right\rangle = -6 \left.\frac{dG(Q^2)}{dQ^2}\right|_{Q^2=0}$$



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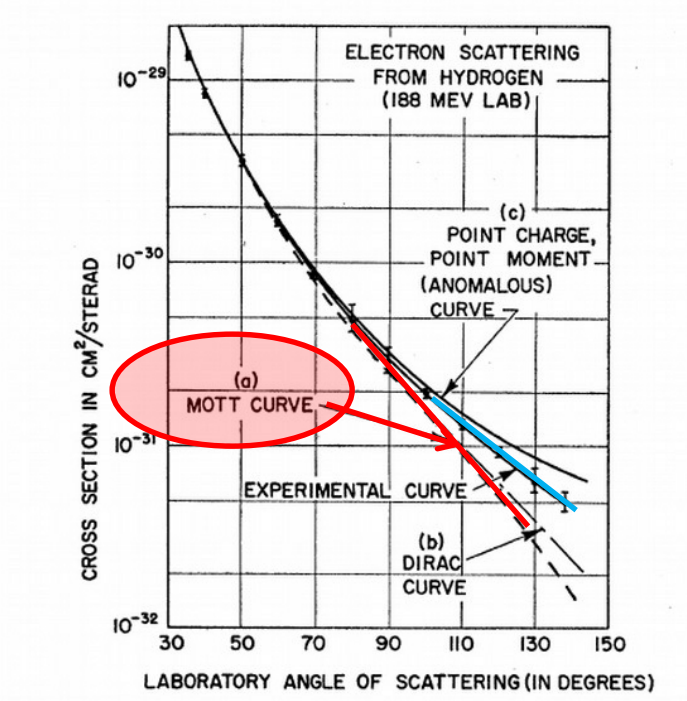


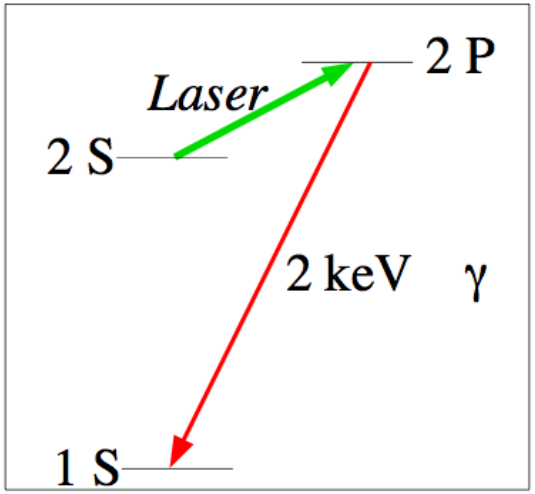
- Atomic Energy Levels

$$\Delta E_1 = \frac{2\pi\alpha}{3} \left|\phi^2(0)\right| \left\langle r_E^2 \right\rangle$$

  - Lamb Shift: Finite size of proton changes hydrogen energy level

    (only affects s states significantly, not p states)

  - Extract from hydrogen spectroscopy



Electron Scattering Measurements

- Cross section for ep scattering (Born approximation)

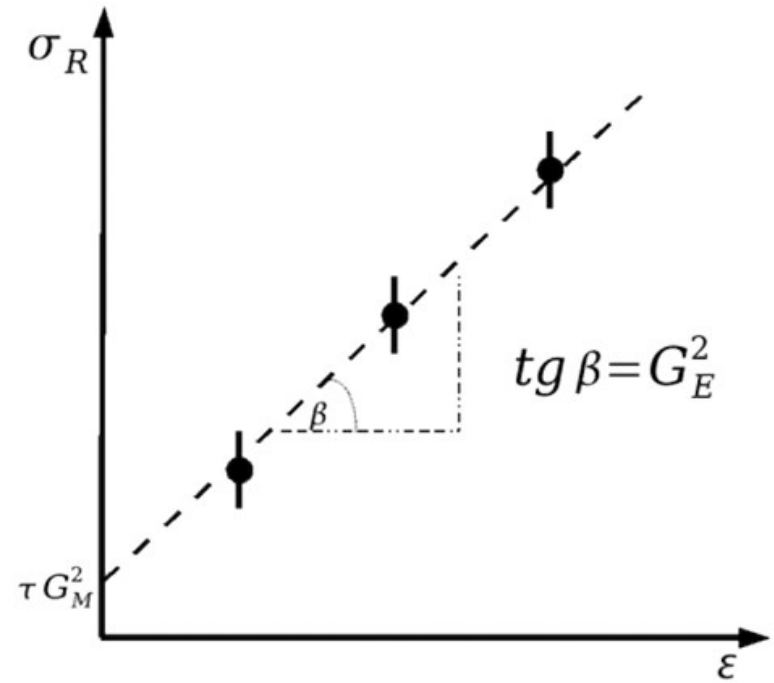
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{Mott} \frac{1}{\varepsilon(1+\tau)} \overbrace{\left[\tau G_M^2 + \varepsilon G_E^2\right]}^{\sigma_R}; \quad \text{with } \tau = \frac{Q^2}{4M^2} \; ; \; \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

current density

charge distr.

$$G_E^2(0) = 1; \quad G_M^2(0) = \mu_p$$

- Classical **Rosenbluth separation**
  - measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed
  - linear fit to get intercept and slope
- Note: G_M is suppressed at low Q^2
  → G_E dominates cross section at low Q^2



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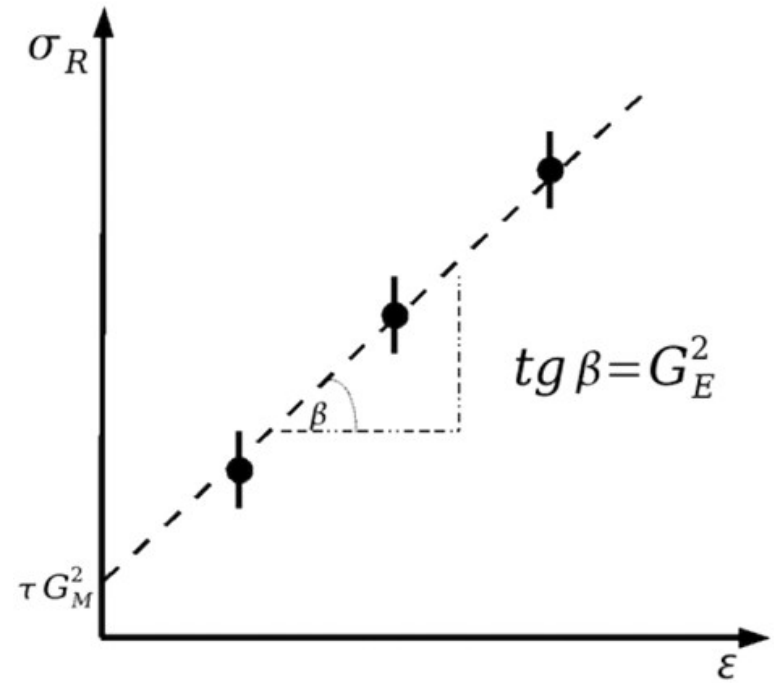
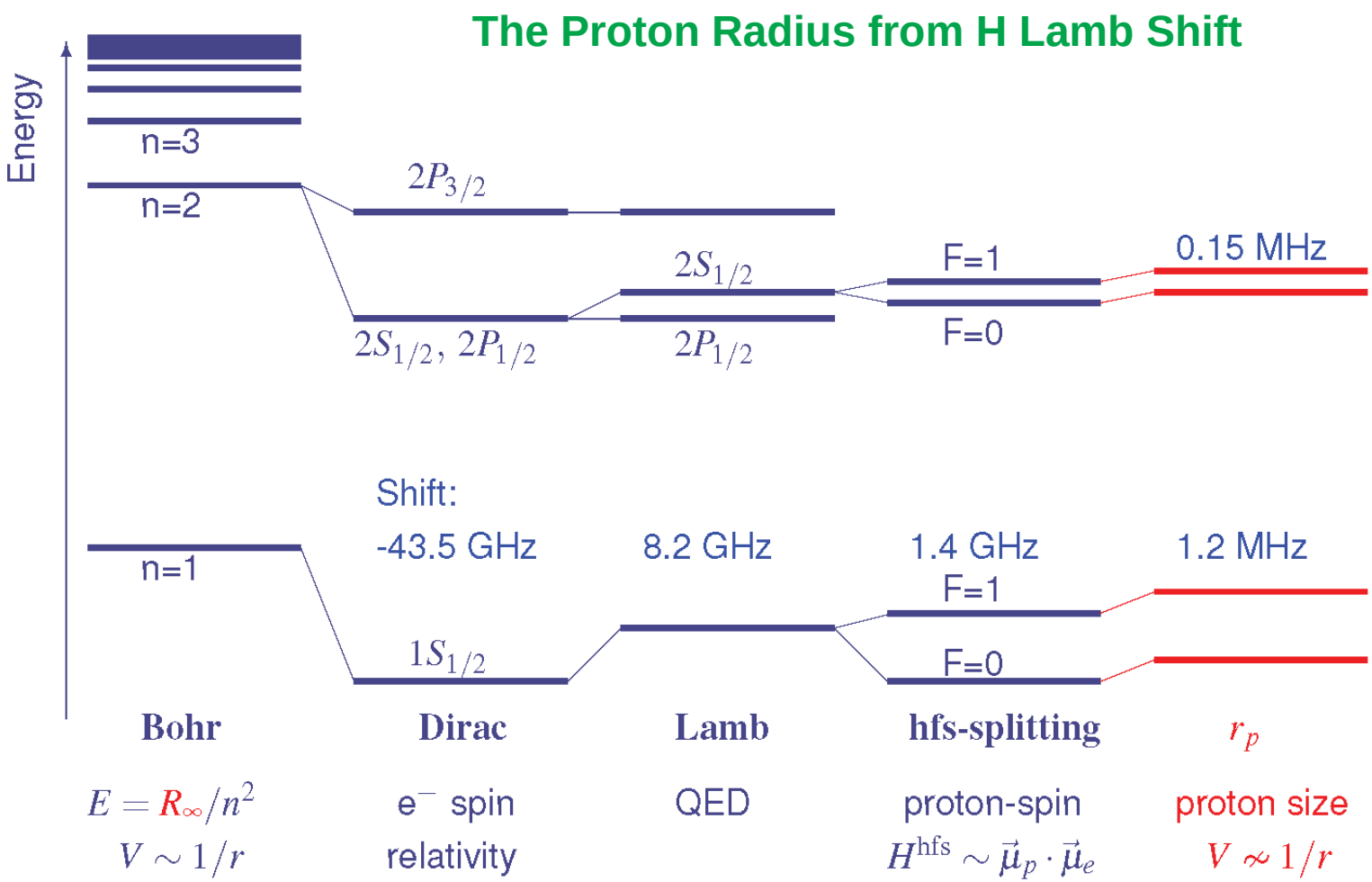


- Alternatively: direct fits of G_M (Q^2) and G_E (Q^2) to experimental cross section data

Hydrogen Spectroscopy Measurements



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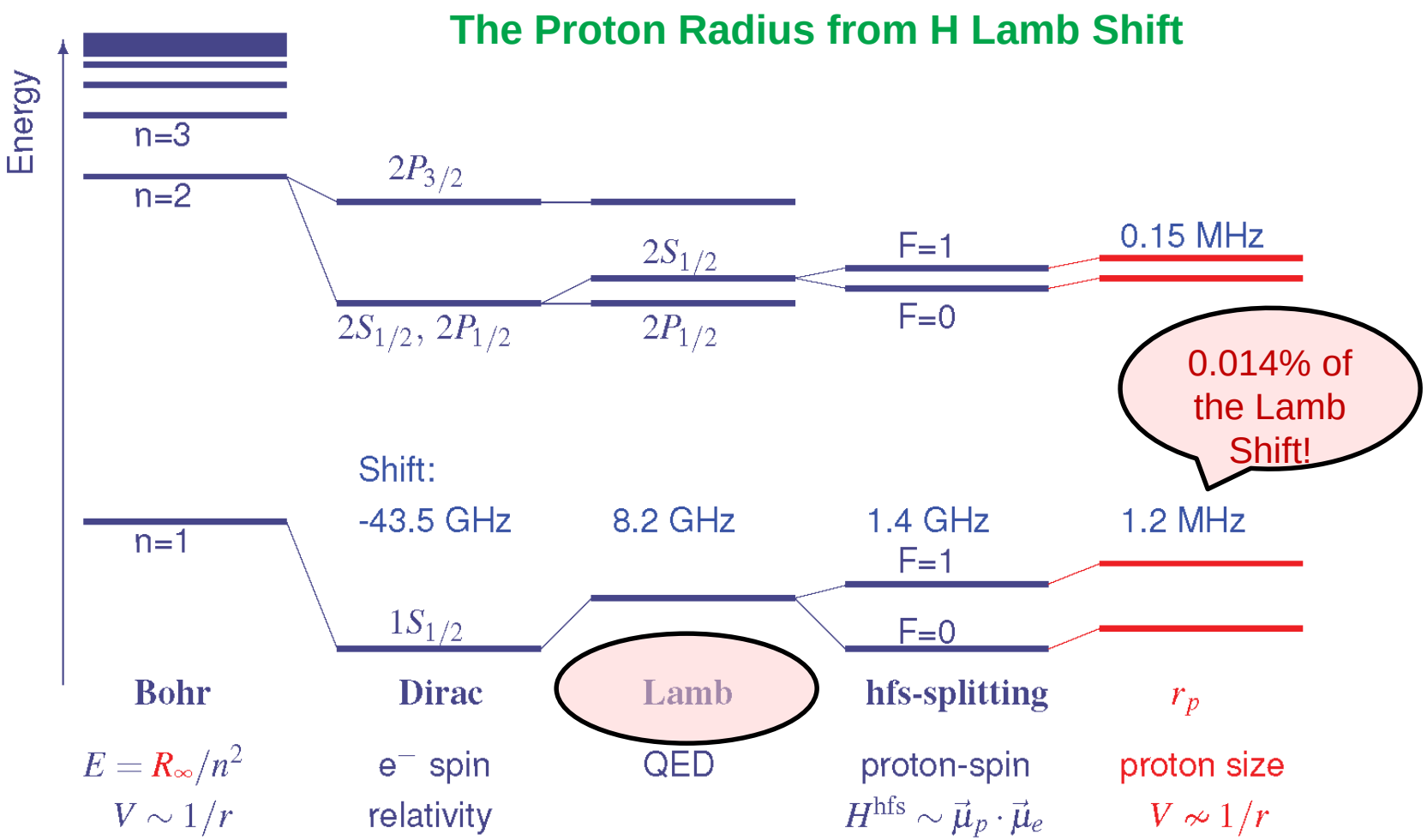

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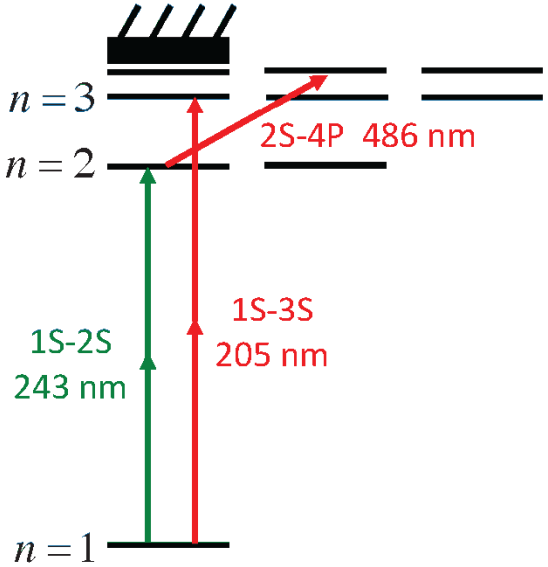
Hydrogen Atom Spectroscopy

$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

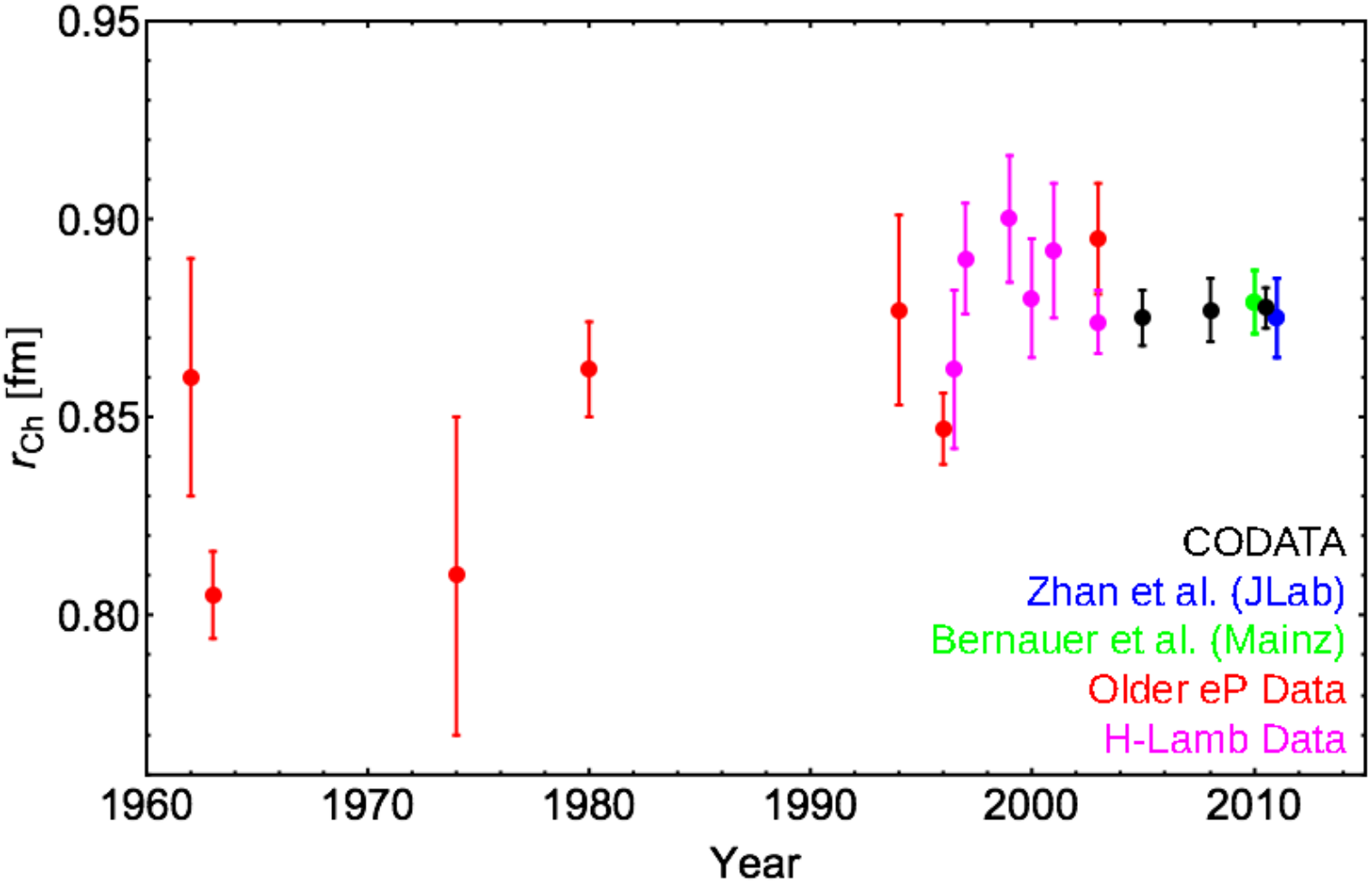
$$\text{Lamb shift}: \quad L_{1S}(r_p) = 8171.636(4) + 1.5645\,\langle r_p^2 \rangle \text{ MHz}$$

- 2 measurements required to determine R_∞ and r_p
  - A **single** narrow transition: 1S-2S ($\Delta\nu$ = 1.3 Hz) measured with high accuracy.
  - Other transitions: natural width ~ MHz.

  Each measurement, combined with 1S-2S, yields a correlated pair (R_∞, r_p).



The Proton Radius from H Lamb Shift and ep



proton rms charge radius measured with electrons:
0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

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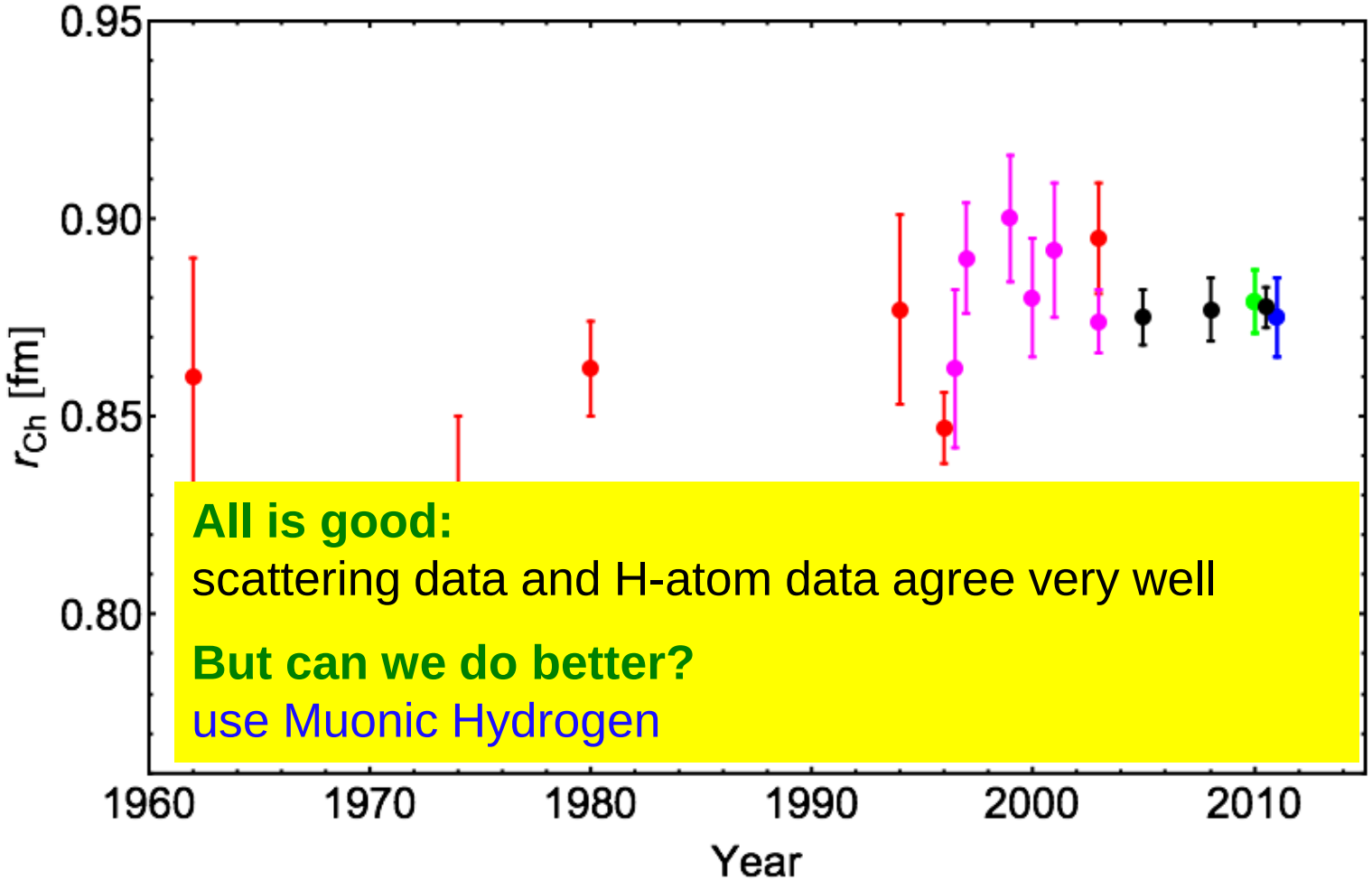

All is good:
scattering data and H-atom data agree very well

But can we do better?
use Muonic Hydrogen

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Why Measure with μH ?

Regular hydrogen:

electron e^- + proton p

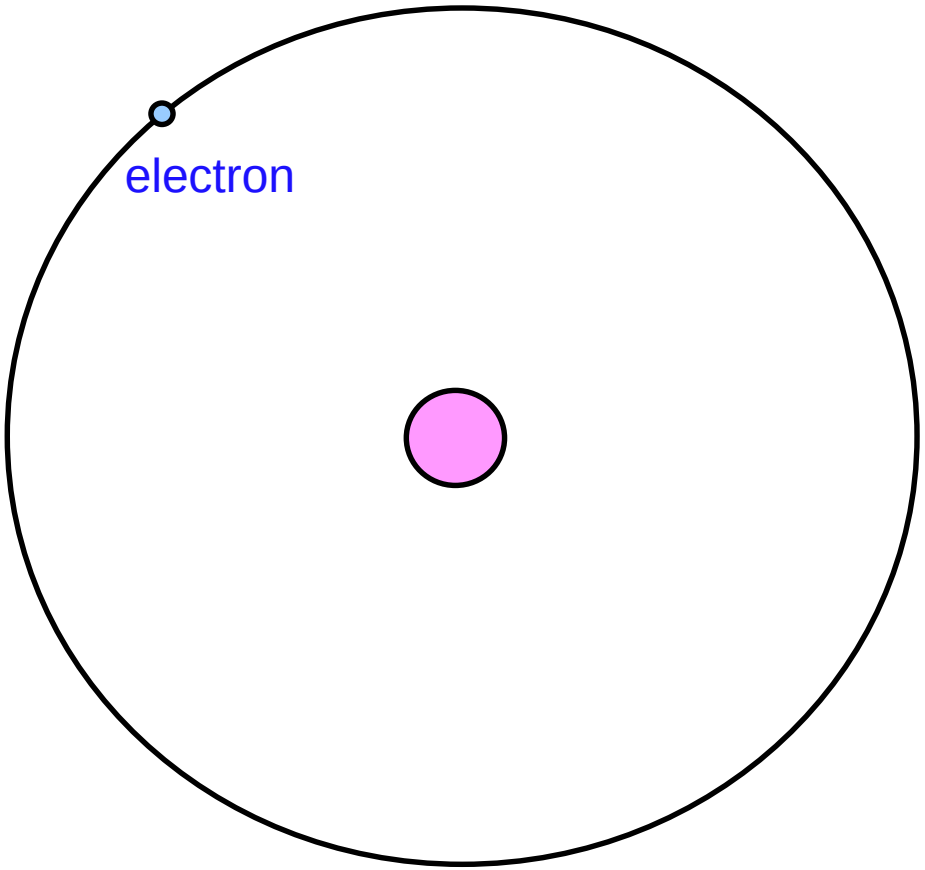


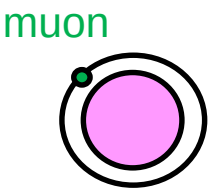
figure not to scale

Muonic hydrogen:

muon μ^- + proton p

muon mass $m_\mu = 207\ m_e$

Bohr radius $a_{B,\mu} = 1/207\ a_{B,e}$



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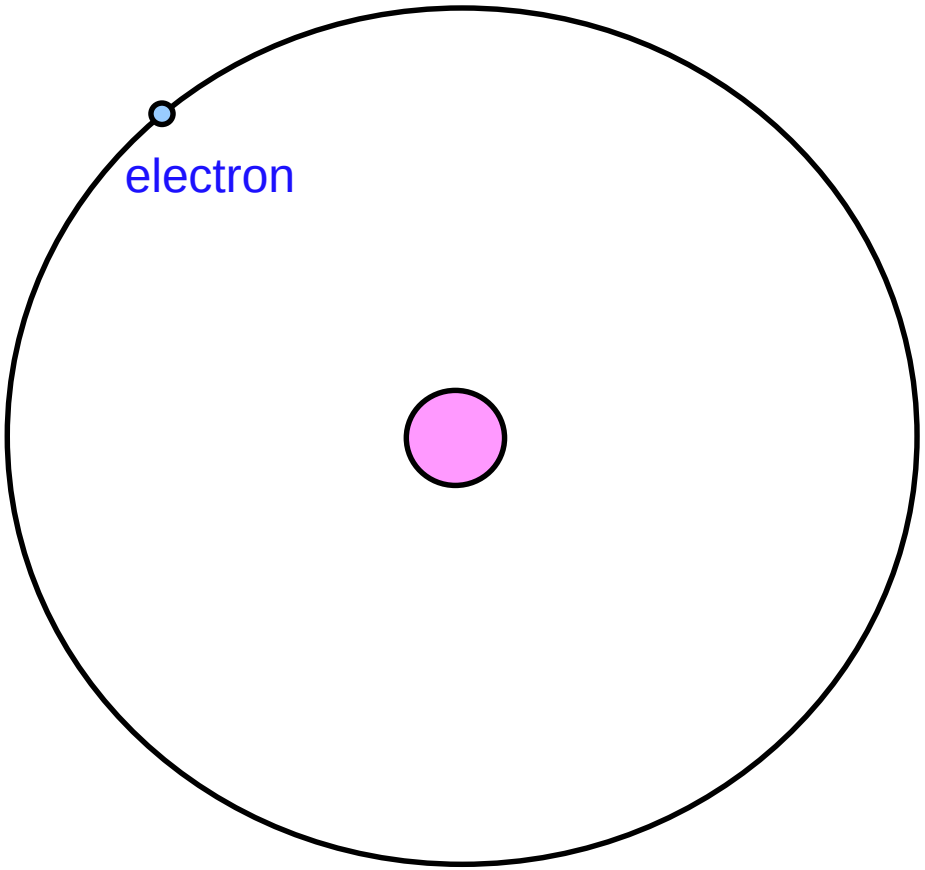

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muon μ^- + proton p

muon mass $m_\mu = 207\ m_e$

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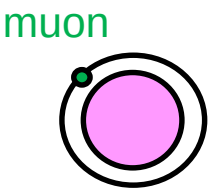
Probability for μ^- to be inside proton:

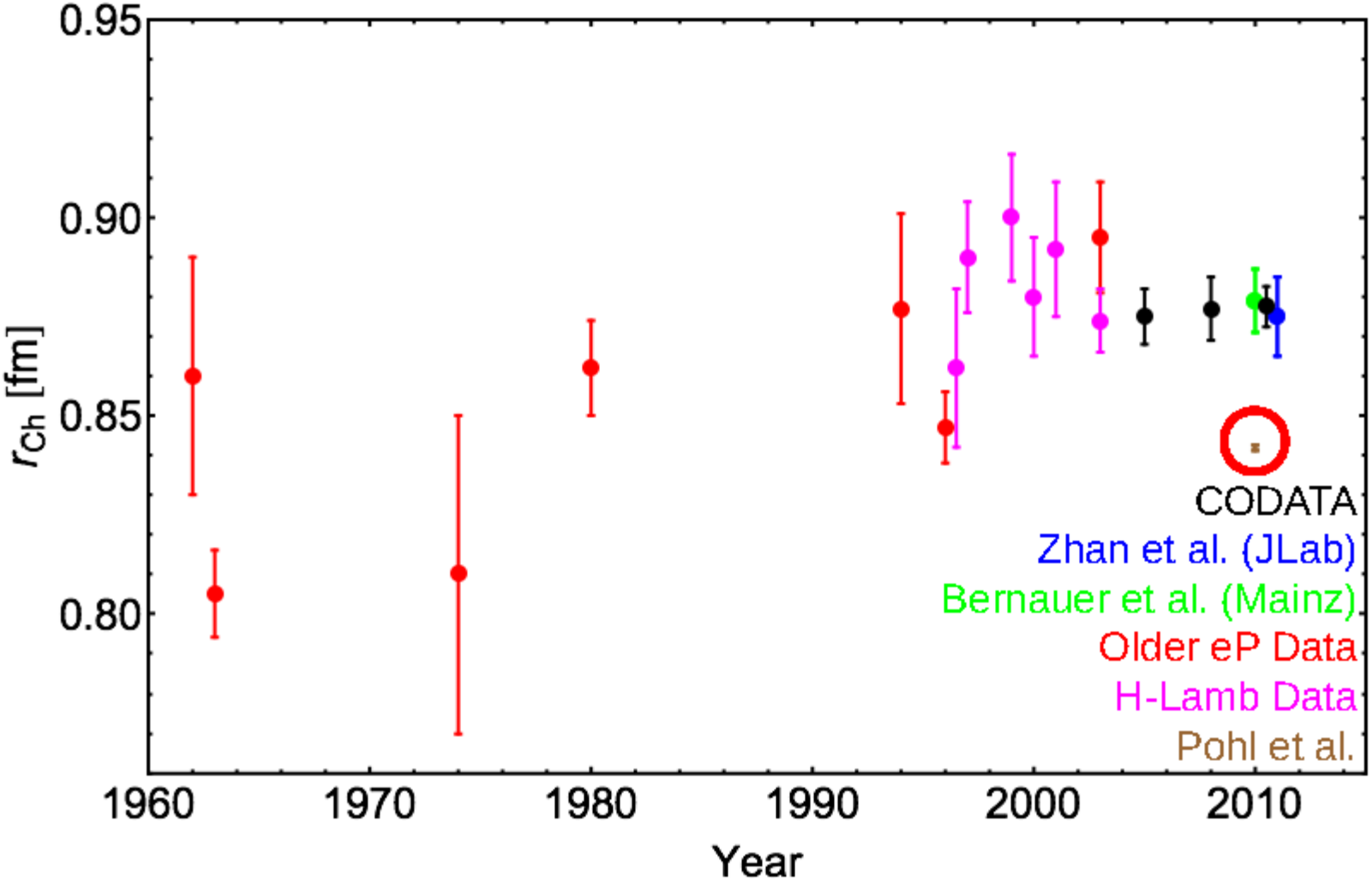
$$\cong \left(\frac{r_p}{a_B}\right)^3 = \left(r_p \alpha\right)^3 m^3$$

$\rightarrow 207^3 \approx 8$ million



muon is **much** more sensitive to proton radius

The Proton Radius from H & μH Lamb Shift and ep

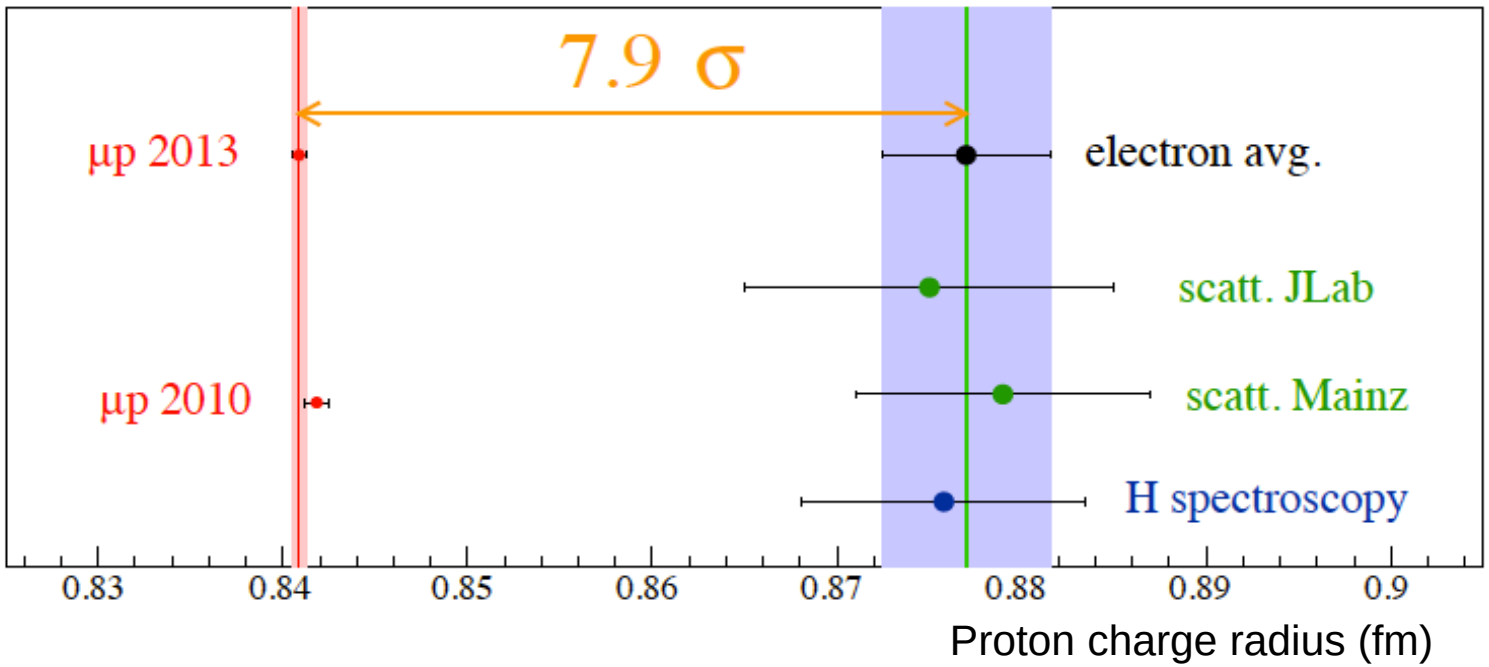


The Proton Radius Puzzle

Proton radius measured with

atomic physics and electron scattering: **0.8751 ± 0.0061 fm**

muonic hydrogen: **0.8409 ± 0.0004 fm**



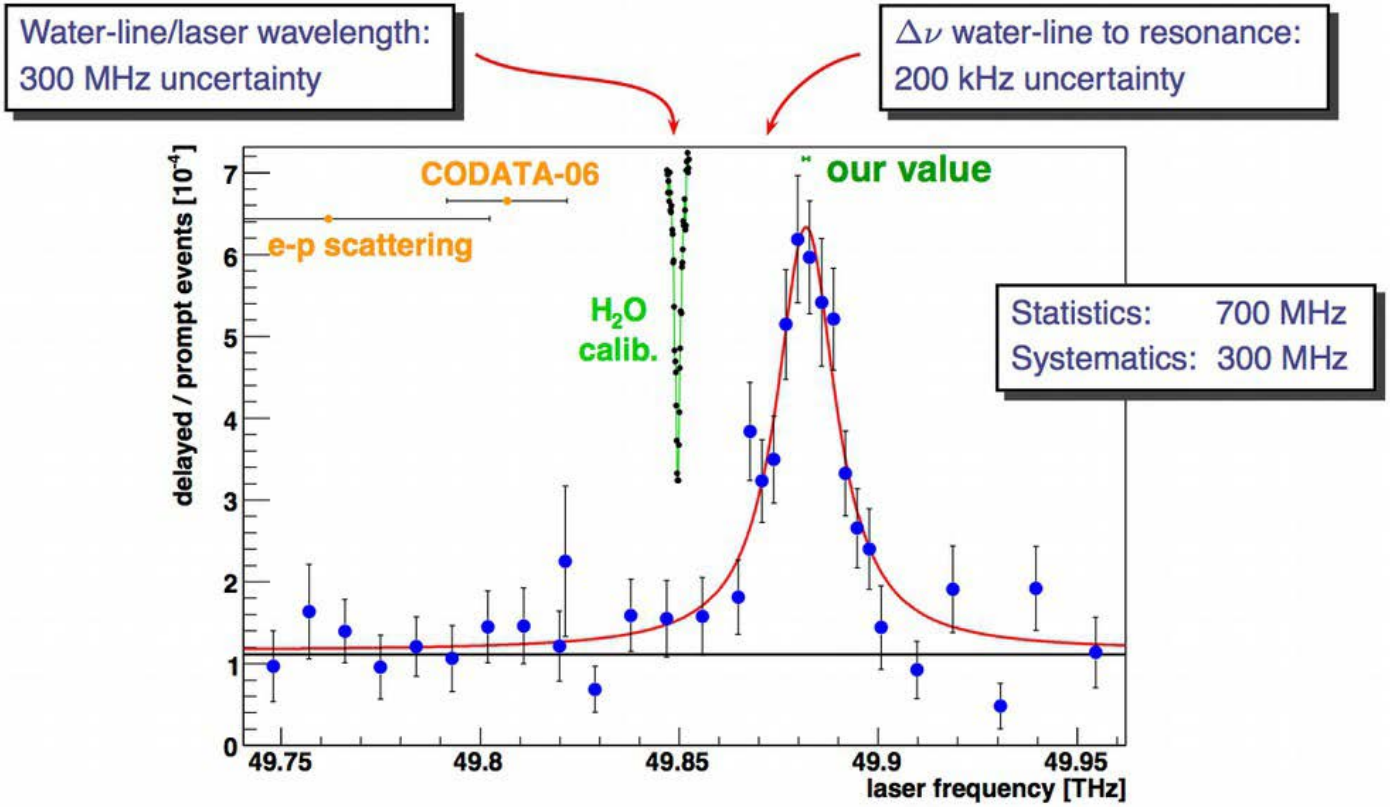
Radius from Muonic Hydrogen 4% below previous best value

→ 12% smaller (volume), 12% denser than previously believed

Why do the muon and electron give different proton radii?

Why do the muon and electron give different proton radii?

- **Experimental error in μp measurement ?**



$$\Delta E(2P^{F=2}_{3/2} - 2S^{F=1}_{1/2}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ [meV]}$$

R. Pohl et al., Nature 466, 213 (2010):
0.84184 ± 0.00067 fm: 5σ off 2006 CODATA

Why do the muon and electron give different proton radii?

- **Experimental error in μp measurement ?**
  - seems unlikely
- **Experimental error in ep measurements ?**
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- **Theory Error?**

#	Contribution		Our selection		Pachucki [31–33]		Borie [34]	
		Ref.	Value	Unc.	Value	Unc.	Value	Unc.
1	NR One loop electron VP	[31, 32]			205.0074			
2	Relativistic correction (corrected)	[31–34]			0.0169			
3	Relativistic one loop VP	[34]	205.0282				205.0282	
4	NR two-loop electron VP	[14, 34]	1.5081		1.5079		1.5081	
5	Polarization insertion in two Coulomb lines	[31, 32, 34]	0.1509		0.1509		0.1510	
6	NR three-loop electron VP	[35]	0.00529					
7	Polarisation insertion in two and three Coulomb lines (corrected)	[35, 36]	0.00223					
8	Three-loop VP (total, uncorrected)				0.0076		0.00761	
9	Wichmann-Kroll	[34, 37, 38]	−0.00103				−0.00103	
10	Light by light electron loop contribution (Virtual Delbrück scattering)	[39]	0.00135	0.00135			0.00135	0.00015
11	Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	[31, 32]	−0.00500	0.0010	−0.006	0.001	−0.005	
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	[40–42]	−0.00150					
13	Mixed electron and muon loops	[43]	0.00007				0.00007	
14	Hadronic polarization $\alpha(Z\alpha)^4 m_r$	[44–46]	0.01077	0.00038	0.0113	0.0003	0.011	0.002
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	[45, 46]	0.000047					
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	[45, 46]	−0.000015					
17	Recoil contribution	[47]	0.05750		0.0575		0.0575	
18	Recoil finite size	[34]	0.01300	0.001			0.013	0.001
19	Recoil correction to VP	[34]	−0.00410				−0.0041	
20	Radiative corrections of order $\alpha^n(Z\alpha)^k m_r$	[19, 32]	−0.66770		−0.6677		−0.66788	
21	Muon Lamb shift 4th order	[34]	−0.00169				−0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m}{M} m_r$	[19, 32, 34, 39]	−0.04497		−0.045		−0.04497	
23	Recoil of order α^6	[32]	0.00030		0.0003			
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m_r$	[19, 31, 32]	−0.00960		−0.0099		−0.0096	
25	Nuclear structure correction of order $(Z\alpha)^5$ (Proton polarizability contribution)	[32, 34, 45, 48]	0.015	0.004	0.012	0.002	0.015	0.004
26	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[46]	0.00019					
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[46]	−0.00001					
	Sum		206.0573	0.0045	206.0432	0.0023	206.05856	0.0046

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  - **BSM Physics**
    - violation of lepton universality
  - **Novel Hadronic Physics**
    - proton polarizability affects μ, but not e (effect $\propto m_l^4$)
    - two-photon exchange corrections (effects important at high Q^2)

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Need More Data

The Quest for New Data

- Experiments include
  - → redoing atomic hydrogen
  - → light muonic atoms for radius comparison in heavier systems
  - → redoing electron scattering at lower Q^2
  - → Muon scattering!

- New data needed to test that the e and μ are really different, and the implications of novel hadronic physics
  - → BSM: compare ep to μp scattering
  - → Hadronic: enhanced 2γ exchange effects

The Quest for New Data

- Experiments include
  - → redoing atomic hydrogen
    - conflicting results: more careful systematics?
  - → light muonic atoms for radius comparison in heavier systems
    - puzzle seen in H & D, but not in He: (Z=1 radius puzzle?)
  - → redoing electron scattering at lower Q^2
    - many efforts
    - PRad (windowless H_2 gas flow target → removes major bkgds) is consistent with μp results!
  - → **Muon scattering!**
    - **MUSE** (2019-2021)
    - plans at COMPASS (100 GeV SPS muon beam: 2021-2023)

μp Scattering – The missing Piece

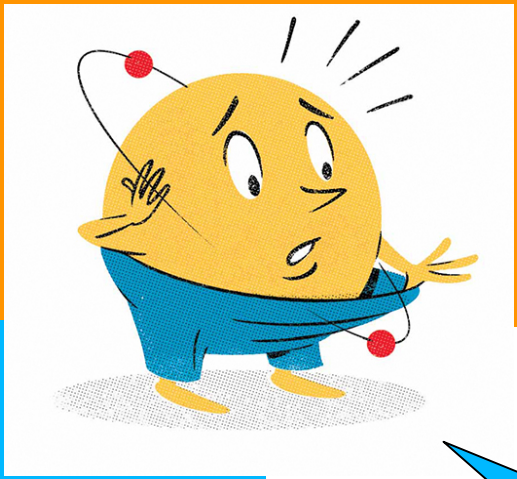
Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84087 ± 0.00039



Electron scattering

0.8770 ± 0.0060

Scattering

Muon scattering

???

MUon Scattering Experiment (MUSE) at PSI

Direct comparison of μp and ep scattering!

→ beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on LH_2 target
- separate particles by TOF, charge by magnets

→ charge reversal: test two photon effects

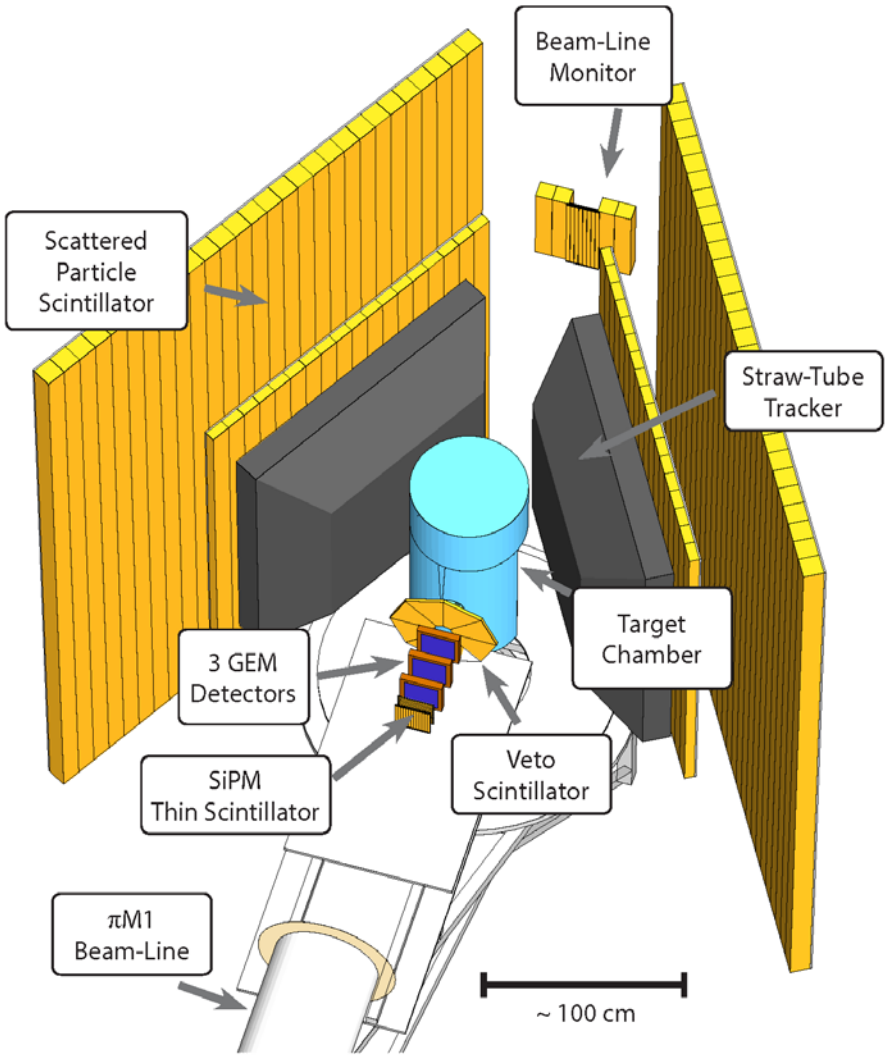
→ absolute cross sections for ep and μp
- use ratio to cancel systematics

→ momenta: 115 – 210 MeV/c; $Q^2 = 0.002 – 0.07\ GeV^2$

→ extract G_E and G_M from fits to experimental cross section data

MUSE: an unusual Scattering Experiment

- Secondary beam → identify and track beam particles
- Low beam flux (3 MHz) → large acceptance, non-magnetic spectrometer
- Mixed beam → PID in trigger



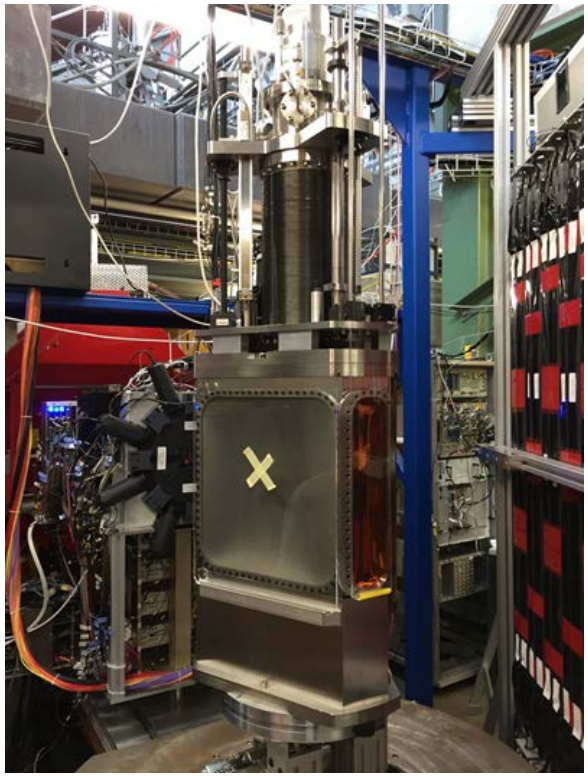
LH_2 Target (U-M)

Liquid hydrogen target

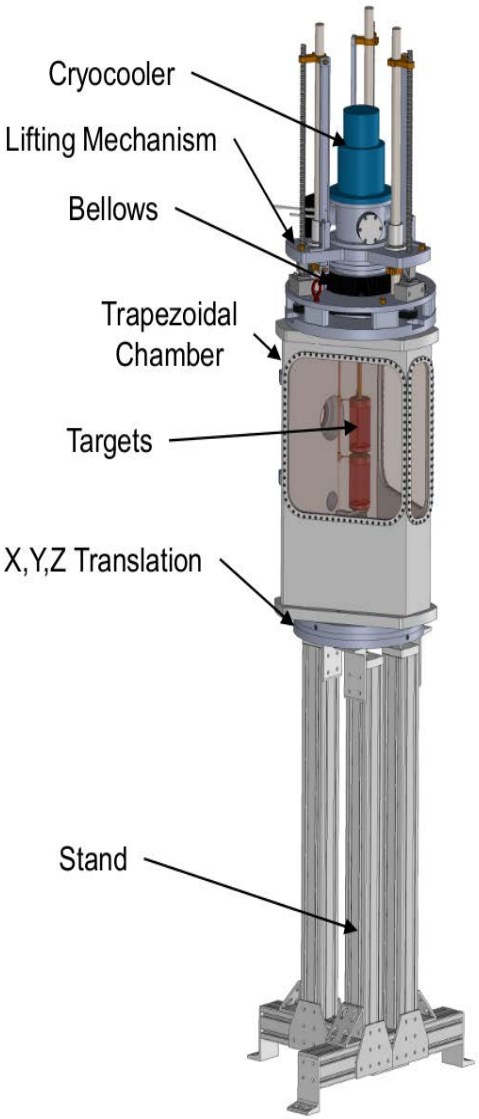
→ 280 ml Kapton cylinder

→ full and empty targets

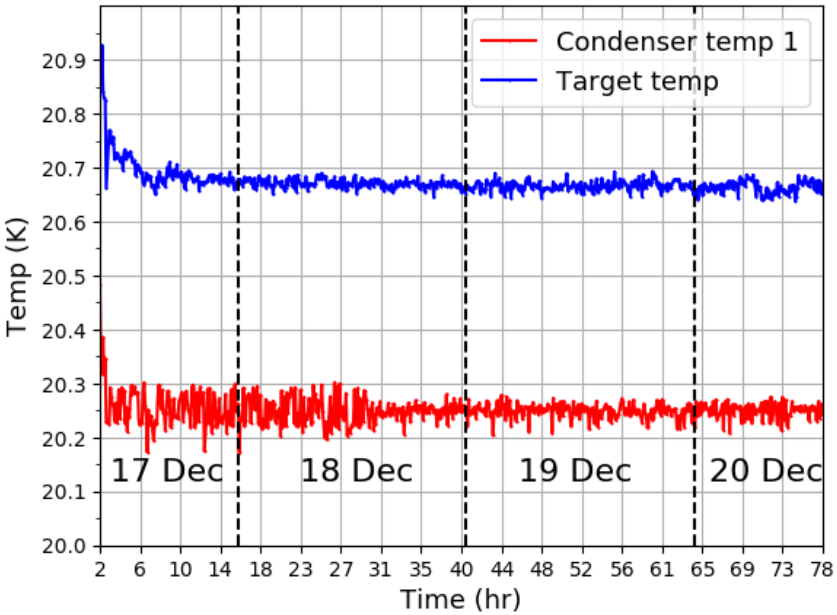
Target chamber in PiM1

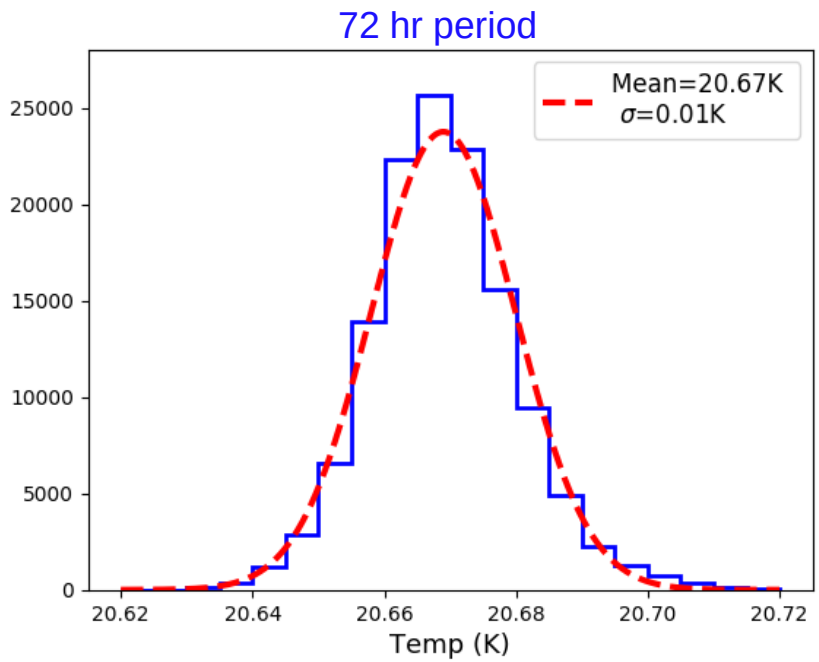


Target system



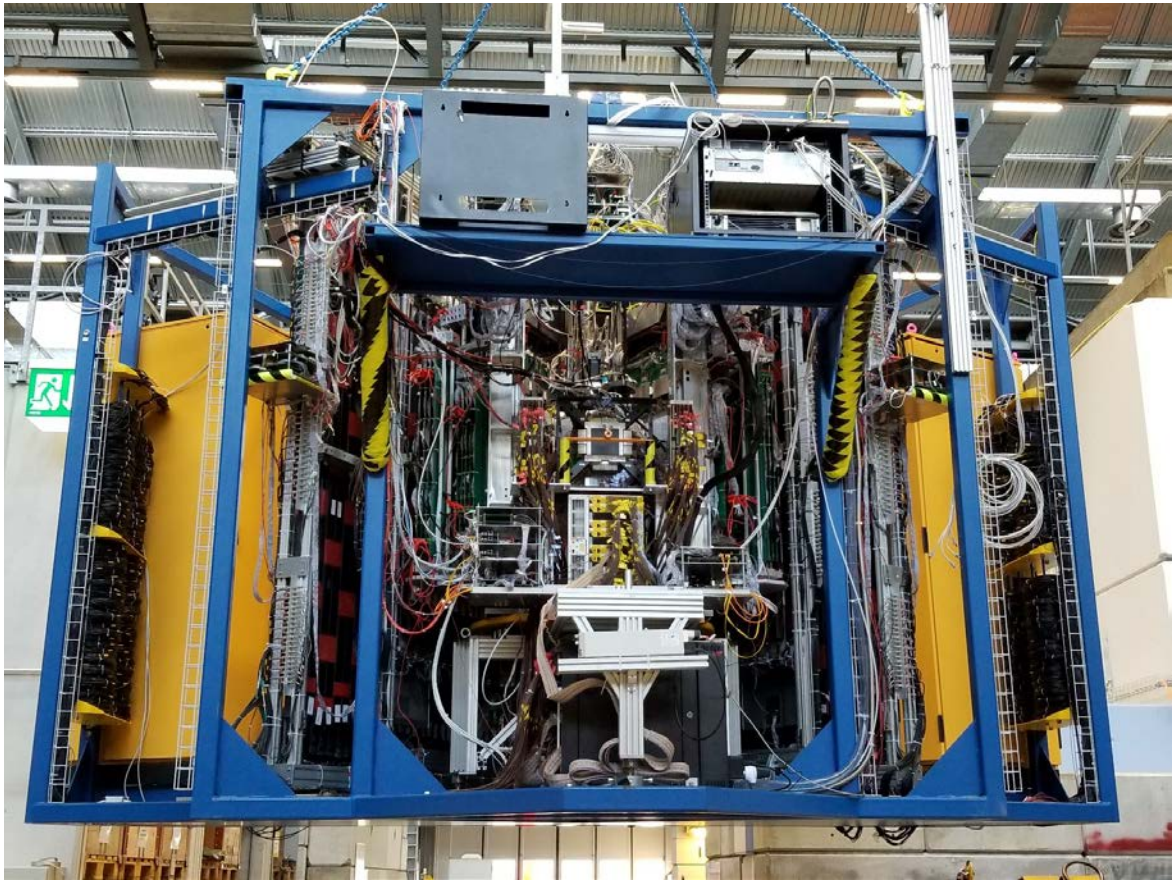
Target Performance





- Target Temperature: 20.67 ± 0.01 K
  - corresponds to a pressure of ~1.1 bar
- Target density: 0.070 g/cm^3 (stable to 0.02%)
  - once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached

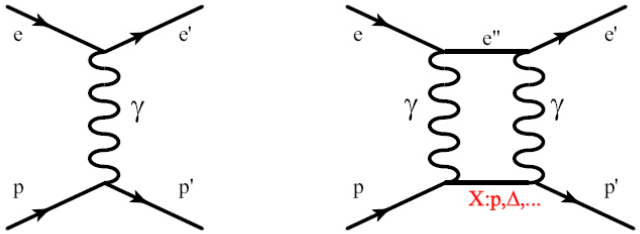
Current status



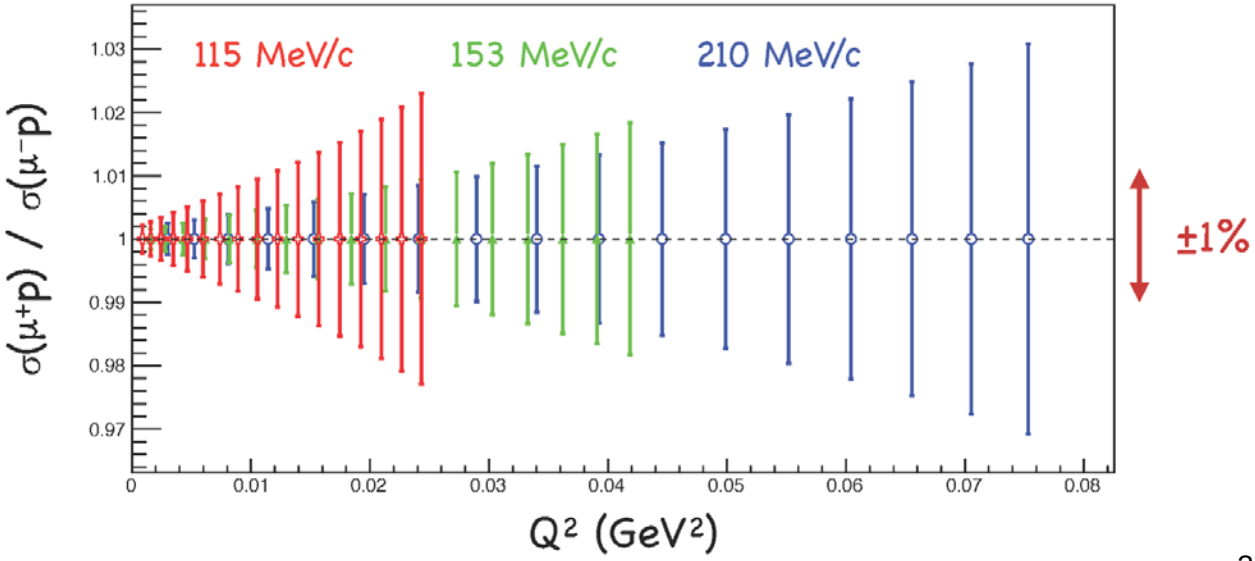
- 18 test runs (2012 – 2019) (beam studies, detector development, and commissioning) demonstrate simulation agreement & reliable performance
- Construction completed
  - commissioning almost complete
  - 12 months total data-taking in 2019 - 2021

Two-photon exchange at low Q^2

- High precision test of TPE for electron and muons at low Q^2
- TPE largest theor. uncertainty in low-energy proton structure
- expect sign change for e^+ and e^-

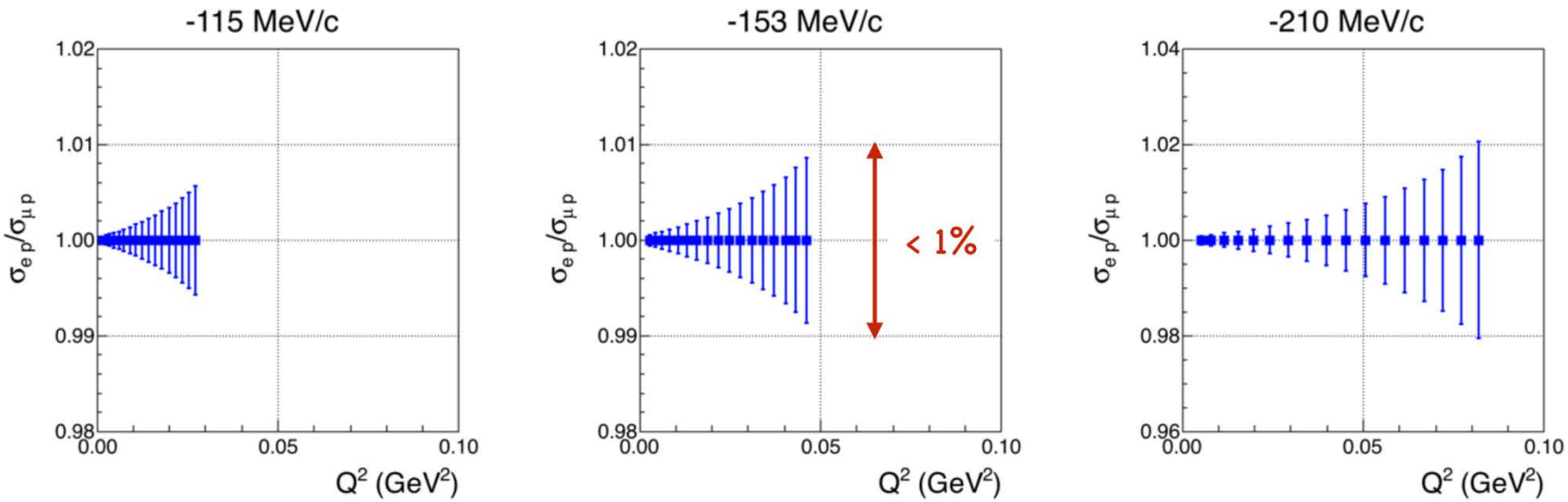


- projected relative uncertainty in μ^+p to μ^-p elastic cross sections
- systematics: 0.2%



Comparison of ep to μp cross sections

- projected relative statistical uncertainties in the ratio of ep to μp elastic **cross sections** (mass difference removed in ratio)
- systematics: 0.5%



- relative statistical uncertainties in the **form factors** are half as large

Projected sensitivity for MUSE

- absolute radius extraction uncertainty similar to current experiments

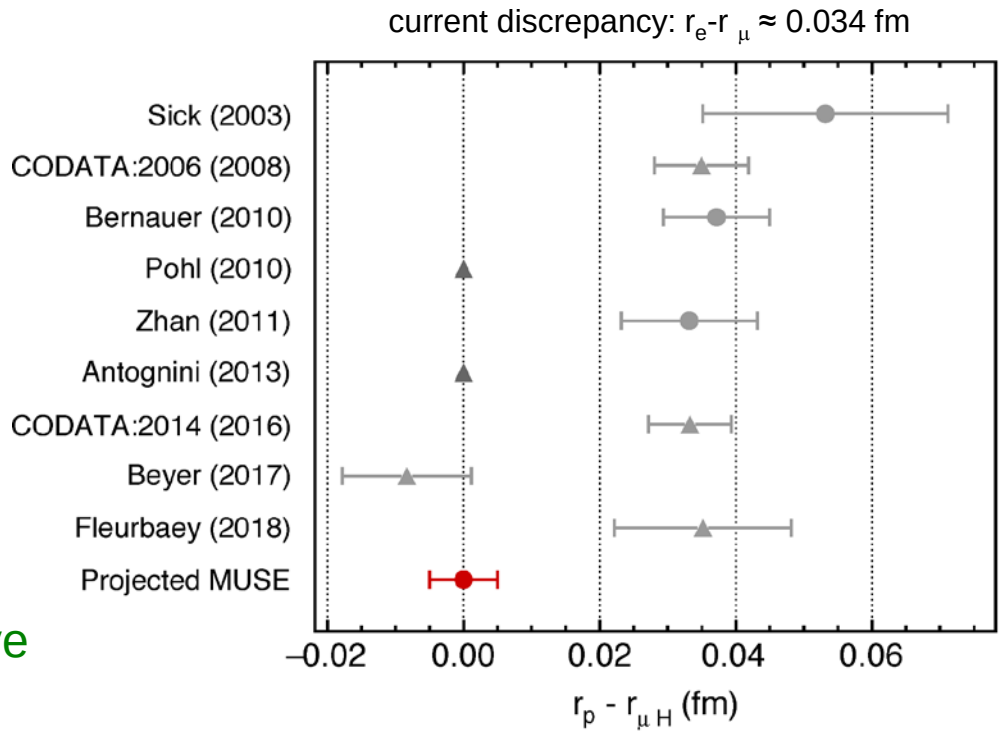
  $\sigma(r_e)$, $\sigma(r_\mu) \approx 0.009$ fm

- radius difference: common uncertainties cancel
  - comparison of μ to e, or μ^+ to μ^- insensitive to many syst. errors

  $\sigma(r_e - r_\mu) \approx 0.005$ fm

  → almost factor two more sensitive than absolute radius extraction

  → almost factor ten better than current discrepancy

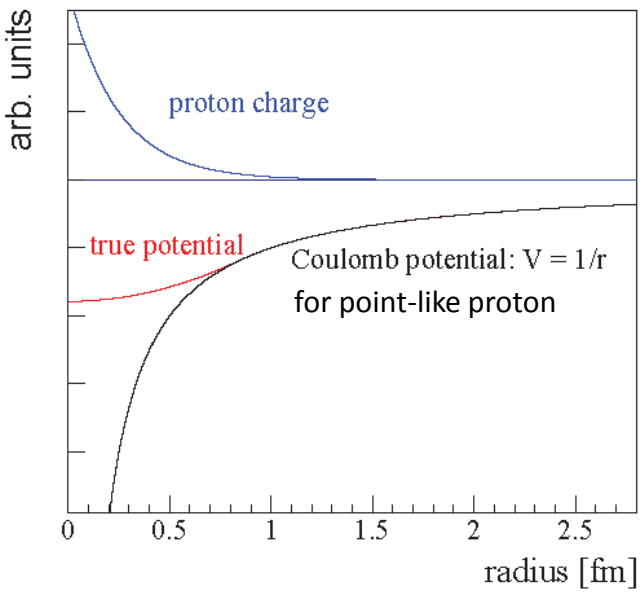


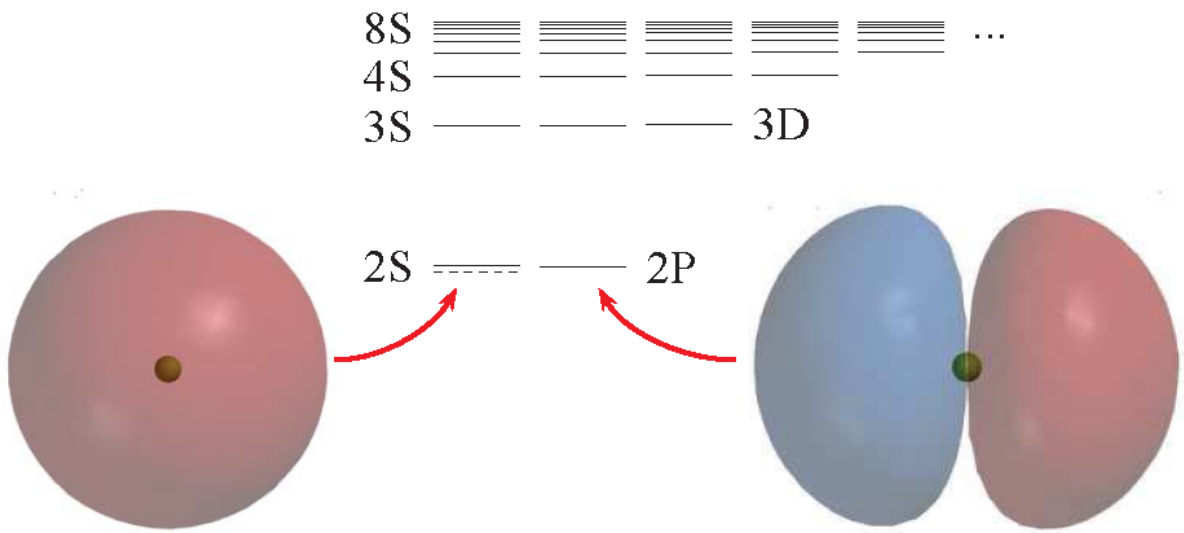
Summary

- We are still (possibly more) puzzled!
- Proton radius puzzle
  - discrepancy between muonic and electronic measurements remains a serious problem
  - need new data
- Expect new results in the coming years
- MUSE (w/ electron & muon scattering)
  - give first precise muon scattering results
  - will test existing values of radius
  - will test two photon exchange / proton polarizability
  - lepton universality

Backup slides

Finite-size shift of atomic energy levels





S states: max. at r=0

P states: zero at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

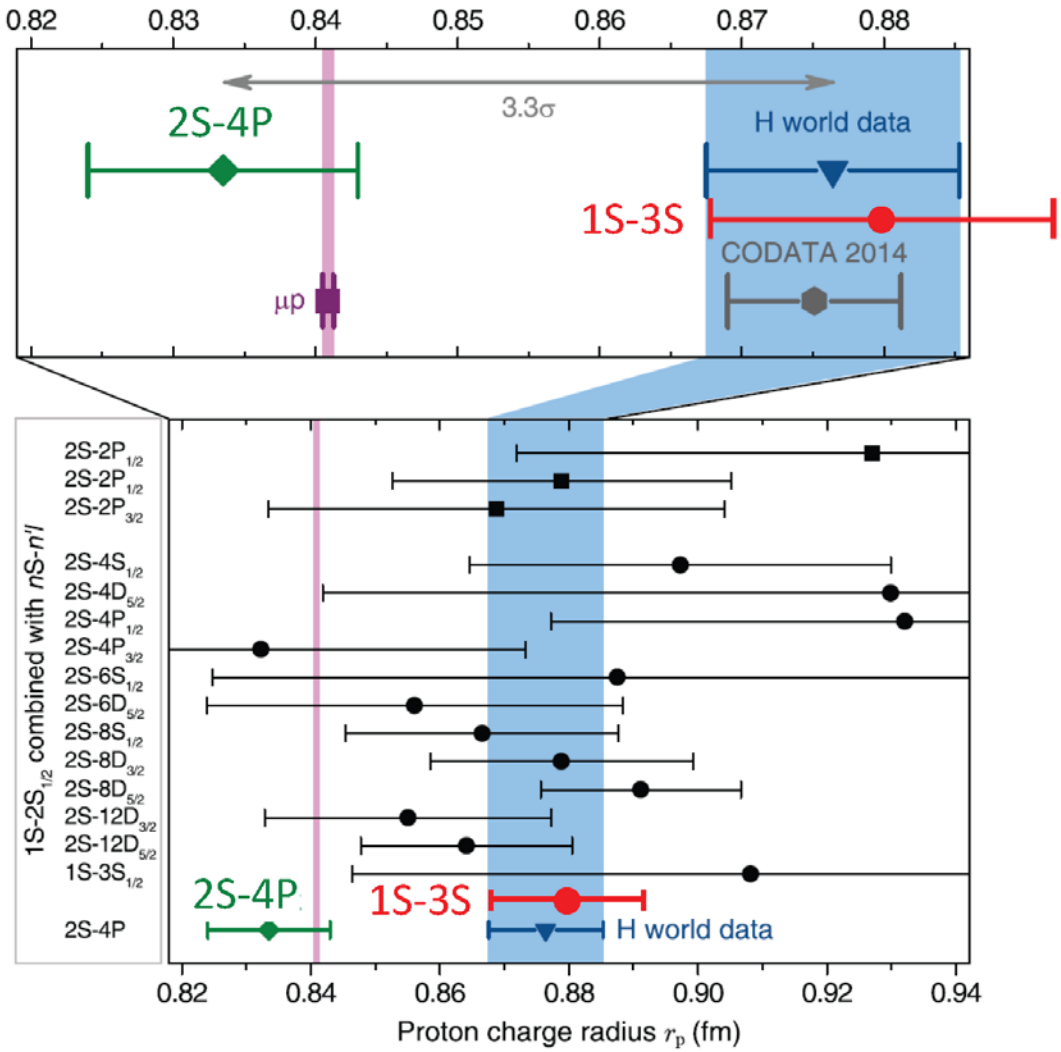
size of the proton

Electron is not inside the proton.

Orbital pictures from Wikipedia

Pictures: R. Pohl

Redoing Atomic Hydrogen



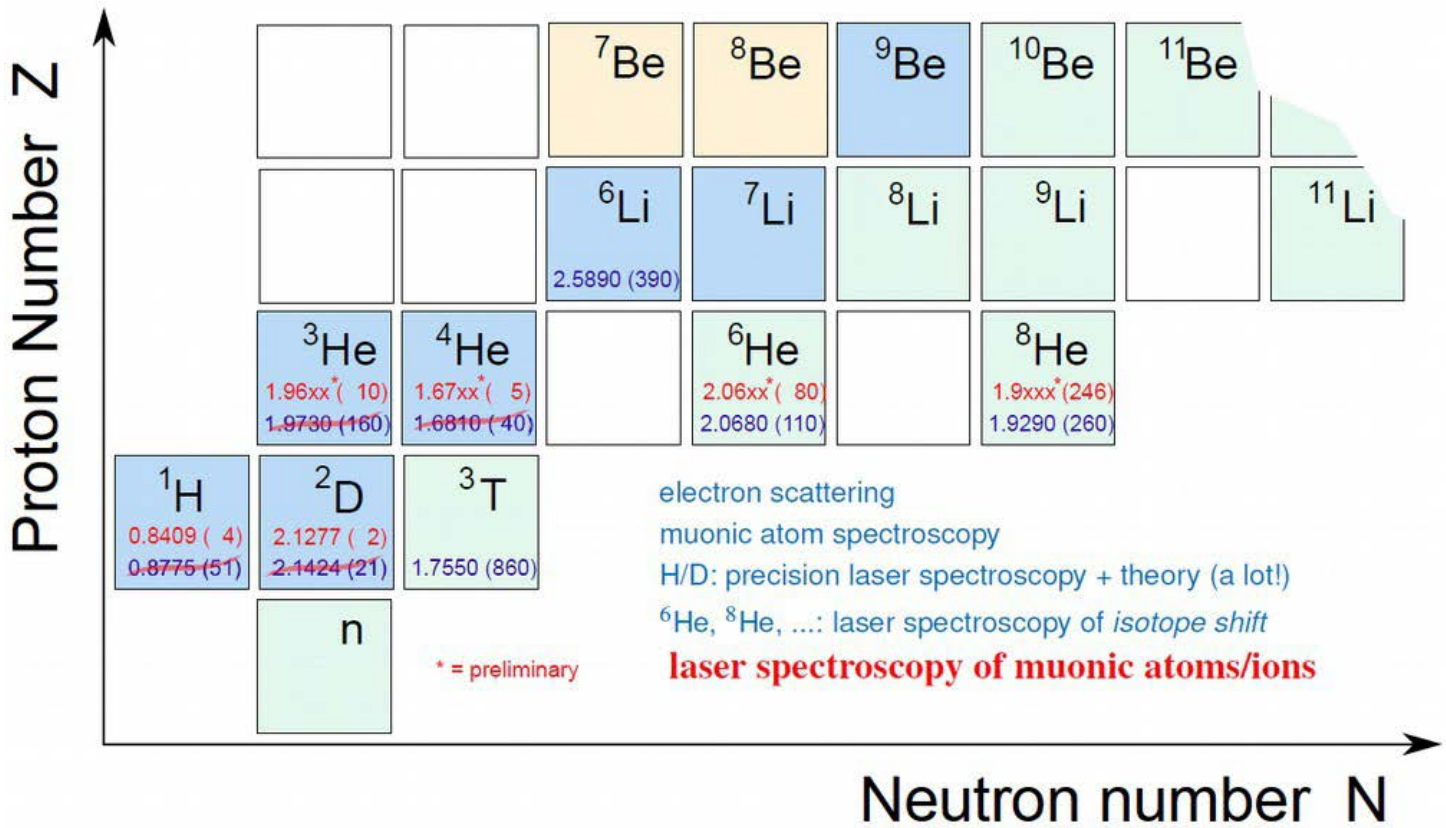
MPQ (Garching): NEW proton is small in regular hydrogen, too!

LKB (Paris): Prelim. No, it's not!

Systematics need to be carefully determined

μH and eH difference is only significant when results are averaged

Light Muonic Atoms

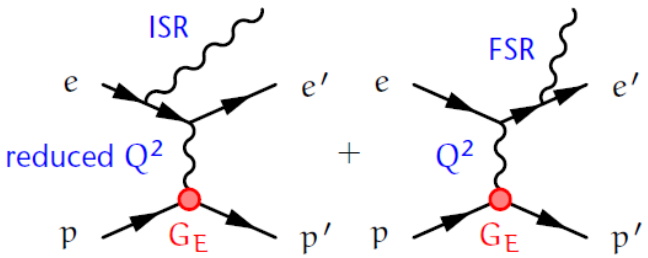


- CREMA Collaboration moved on to heavier atoms!
- Deuterium radius from μD agrees with μH
  - deuteron charge radius: r_d again 7σ away from CODATA
- Helium isotopes seem to agree (preliminary results)
- Puzzle seen in H & D (Z=1 radius puzzle?)

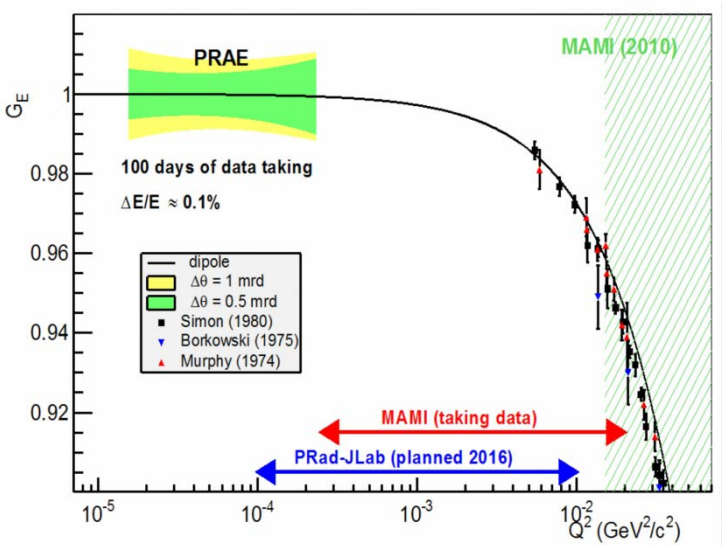
Pictures: R. Pohl

Redoing electron scattering at lower Q^2

- Jlab: PRad
  - low intensity beam in Hall B @ JLab into windowless gas target (1.3 billion H events)
  - Preliminary G_E slope favors smaller radius
- Mainz: ISR
  - exploit information in radiative tail
  - dominated by coherent sum of ISR and FSR
  - investigate G_E down to $Q^2 = 10^{-4}$ GeV^2/c^2
  - results not precise enough → upgrades underway



- LPSC, Grenoble: ProRad
  - New accelerator to be built in France
  - constrain Q^2-dependence of G_E and extrapolation to zero
  - non-magnetic spectrometer, frozen hydrogen wire / film target



MUon Scattering Experiment (MUSE) at PSI

58 MUSE collaborators from 25 institutions in 5 countries:

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