The MUSE experiment at PSI: Status and Plans

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(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 NSF

The Proton Radius Puzzle

July 2010

April 2013

July 2013

January 2014

The Proton Radius Puzzle

What exactly is the puzzle ?

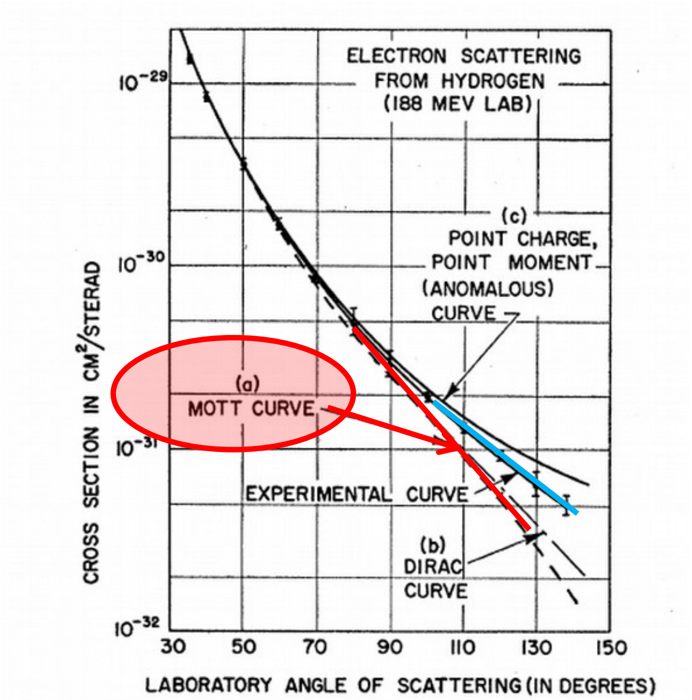
How do you measure proton radius?

- Scattering experiments

(Hofstadter @ Stanford: 1950s -electron scattering)

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

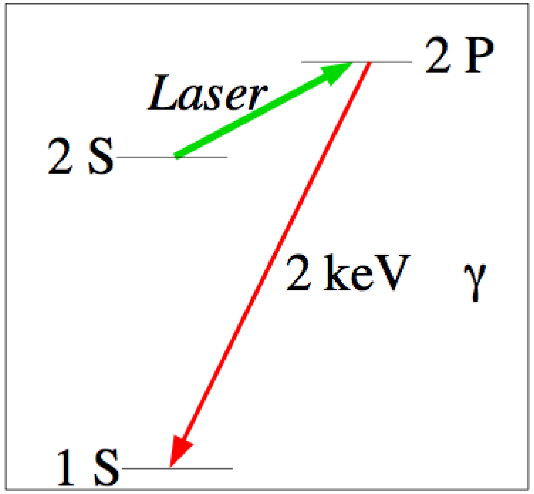
$$\langle r_E^2 \rangle = -6 \left.\frac{dG(Q^2)}{dQ^2}\right|_{Q^2=0}$$



- Atomic Energy Levels

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

- Lamb Shift: Finite size of proton changes hydrogen energy levels
- Extract from hydrogen spectroscopy



Electron Scattering Measurements

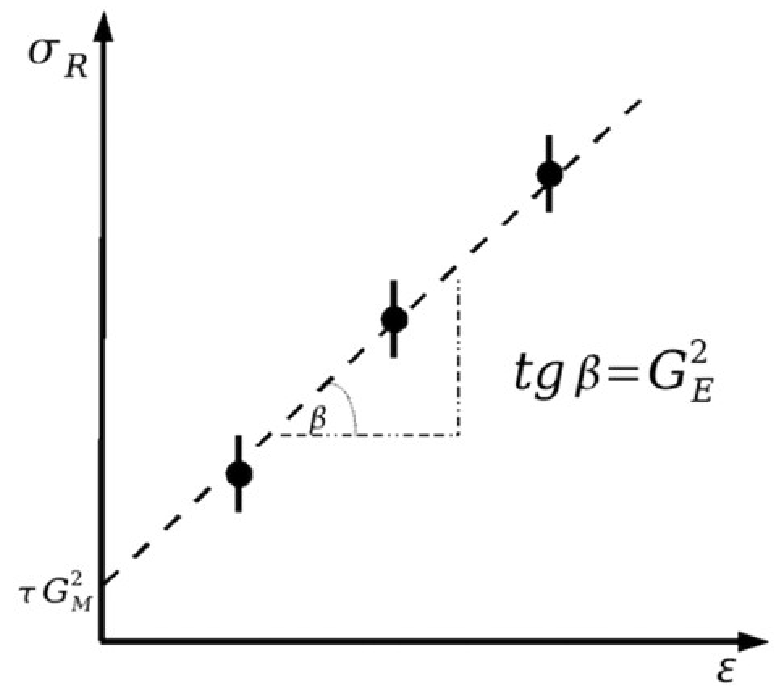
- Cross section for ep scattering (Born approximation)

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

τG_M^2: current density; εG_E^2: charge distr.

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

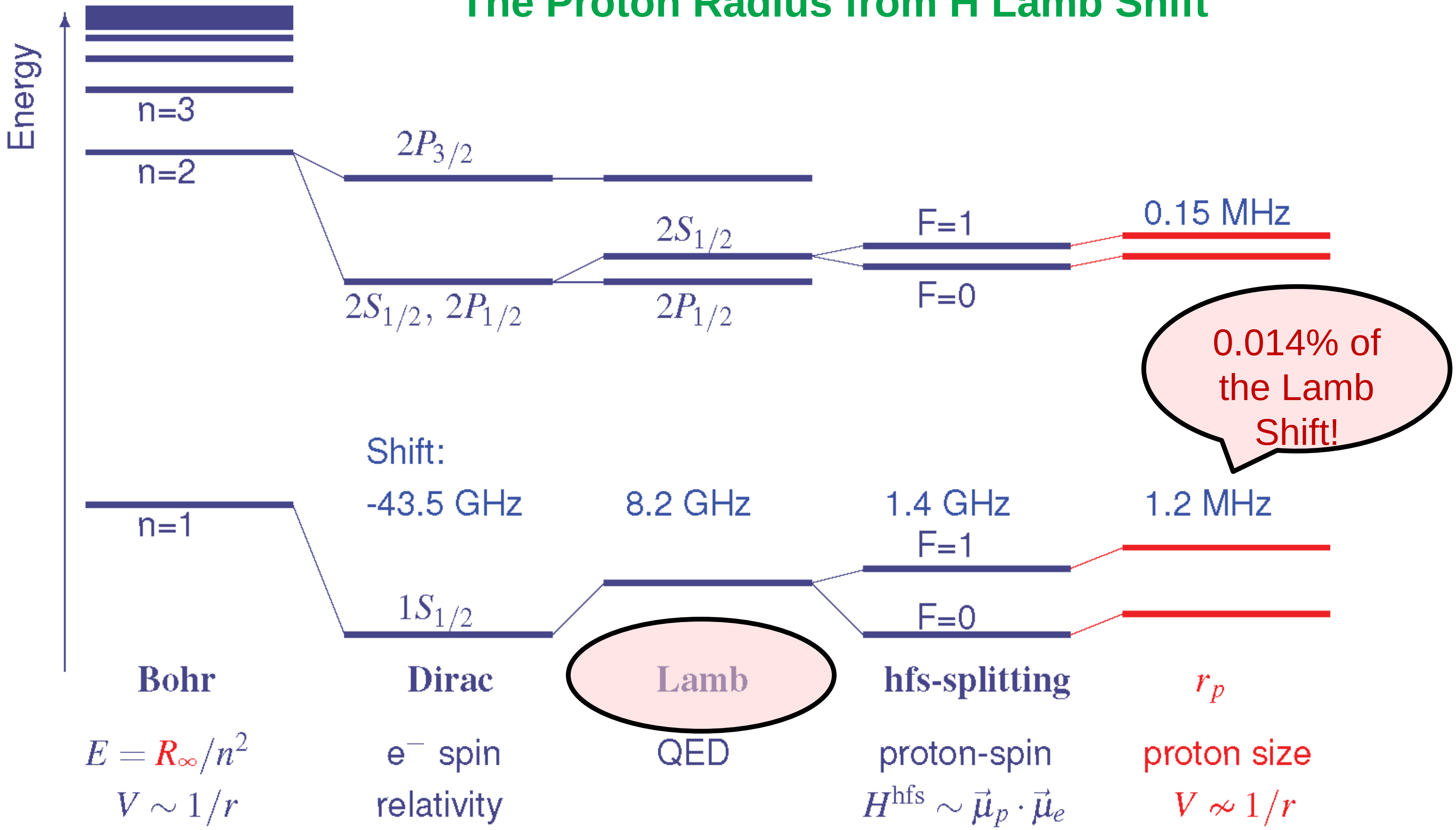
- Classical **Rosenbluth separation**
  - measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed
  - linear fit to get intercept and slope
- Note: G_M is suppressed at low Q^2 → G_E dominates cross section at low Q^2



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

Hydrogen Spectroscopy Measurements

The Proton Radius from H Lamb Shift



comparing measurements with QED calculations that include corrections for finite size of proton provide indirect but very precise value for $\langle r_E^2 \rangle$

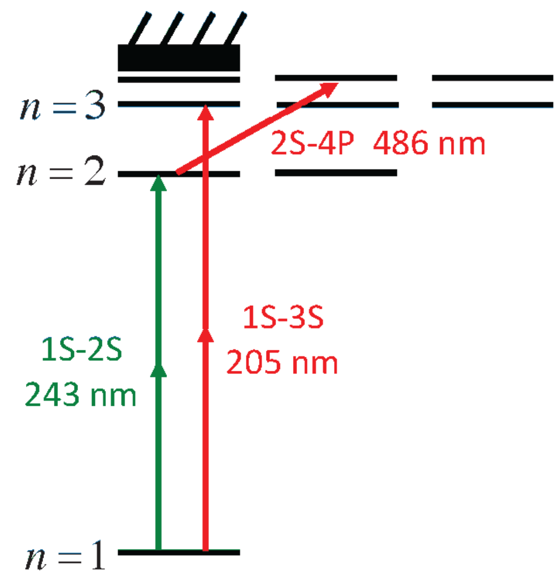
Hydrogen Atom Spectroscopy

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

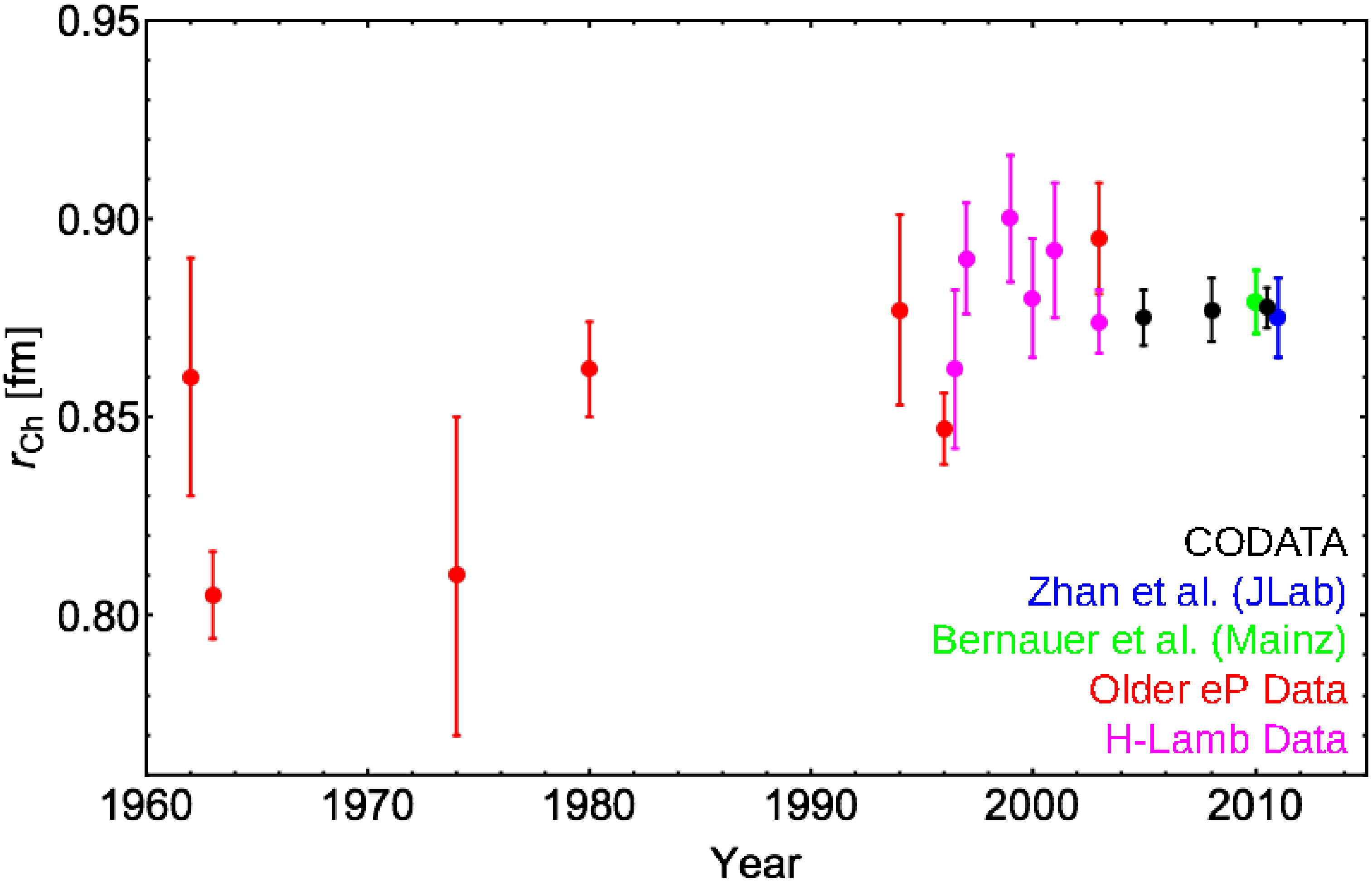
$$\text{Lamb shift}: \quad L_{1S}(r_p) = 8171.636(4) + 1.5645 \langle r_p^2 \rangle \text{ MHz}$$

- 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).

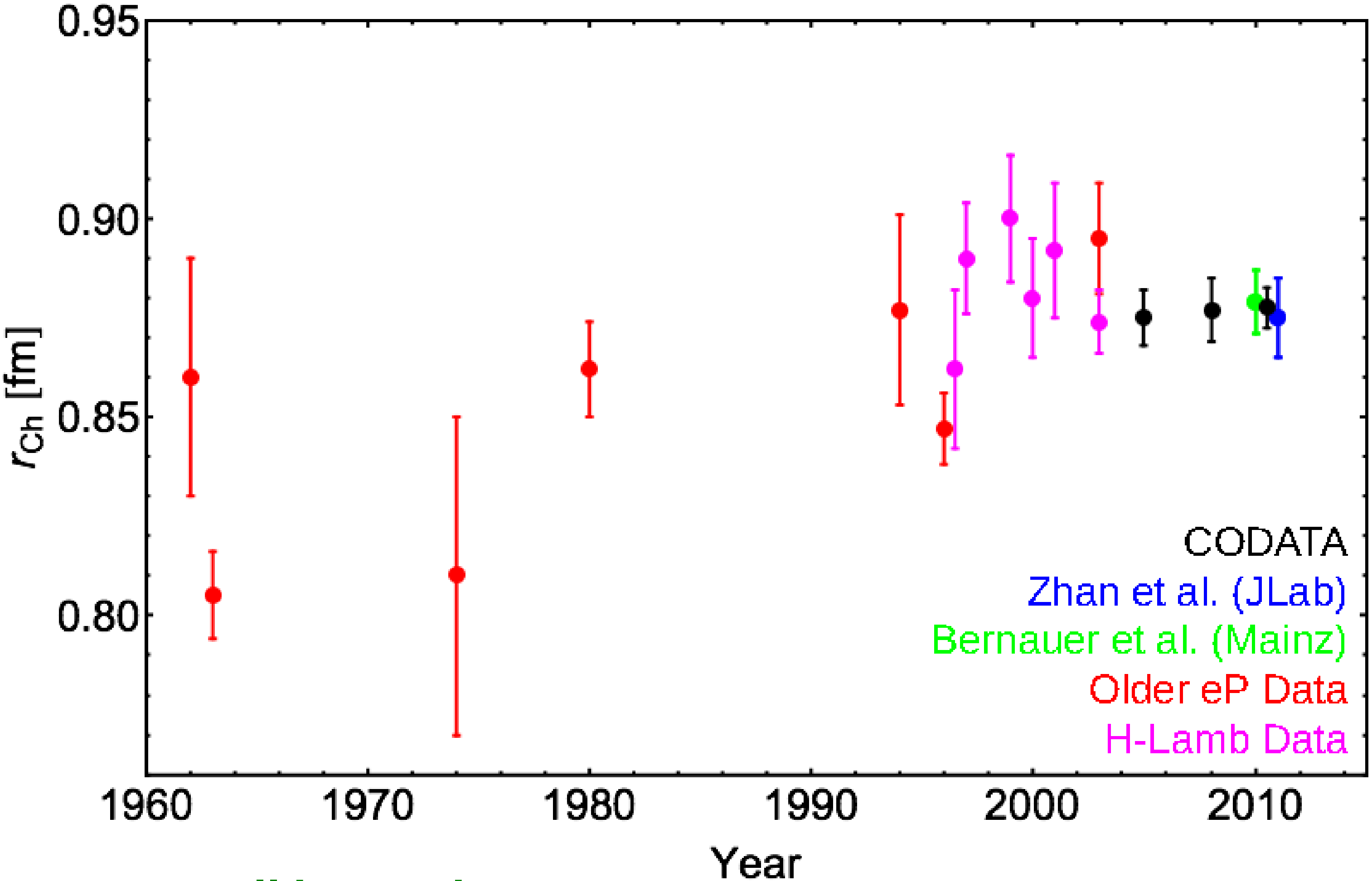


The Proton Radius from H Lamb Shift and ep



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

The Proton Radius from H Lamb Shift and ep



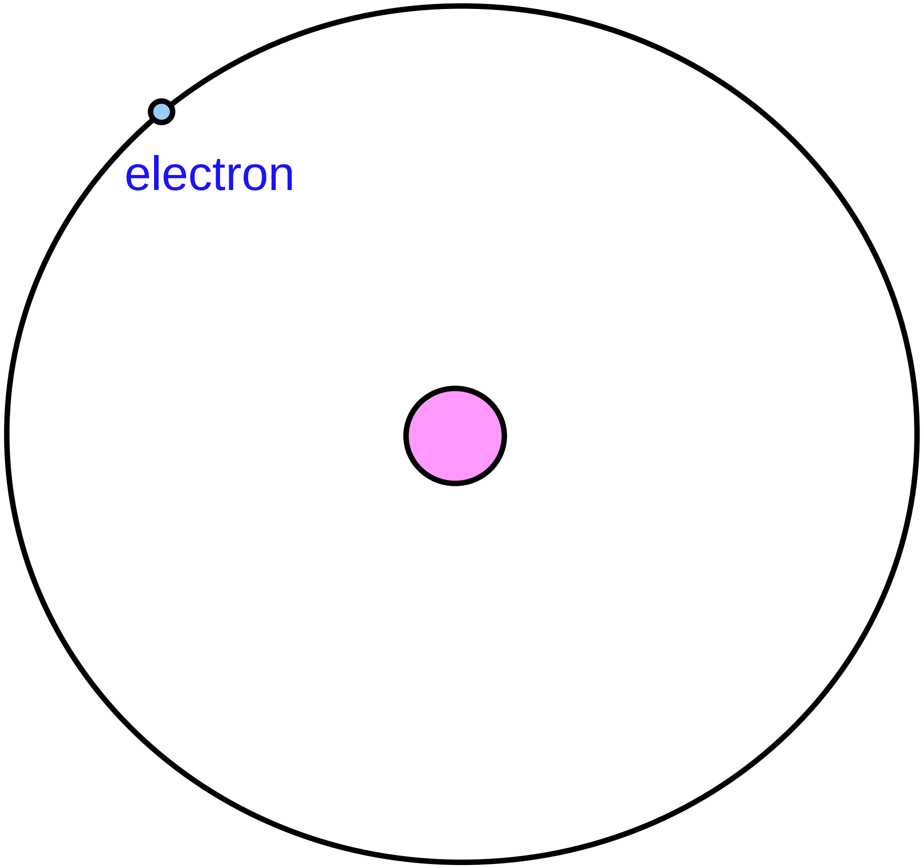
All is good:
scattering data and H-atom data agree very well

But can we do better?
use Muonic Hydrogen

Why Measure with μH ?

Regular hydrogen:

electron e^{-} + proton p



Muonic hydrogen:

muon μ^{-} + proton p

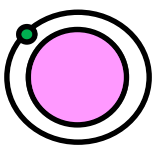
muon mass $m_{\mu} = 207\ m_e$

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

Probability for μ^{-} to be inside proton:

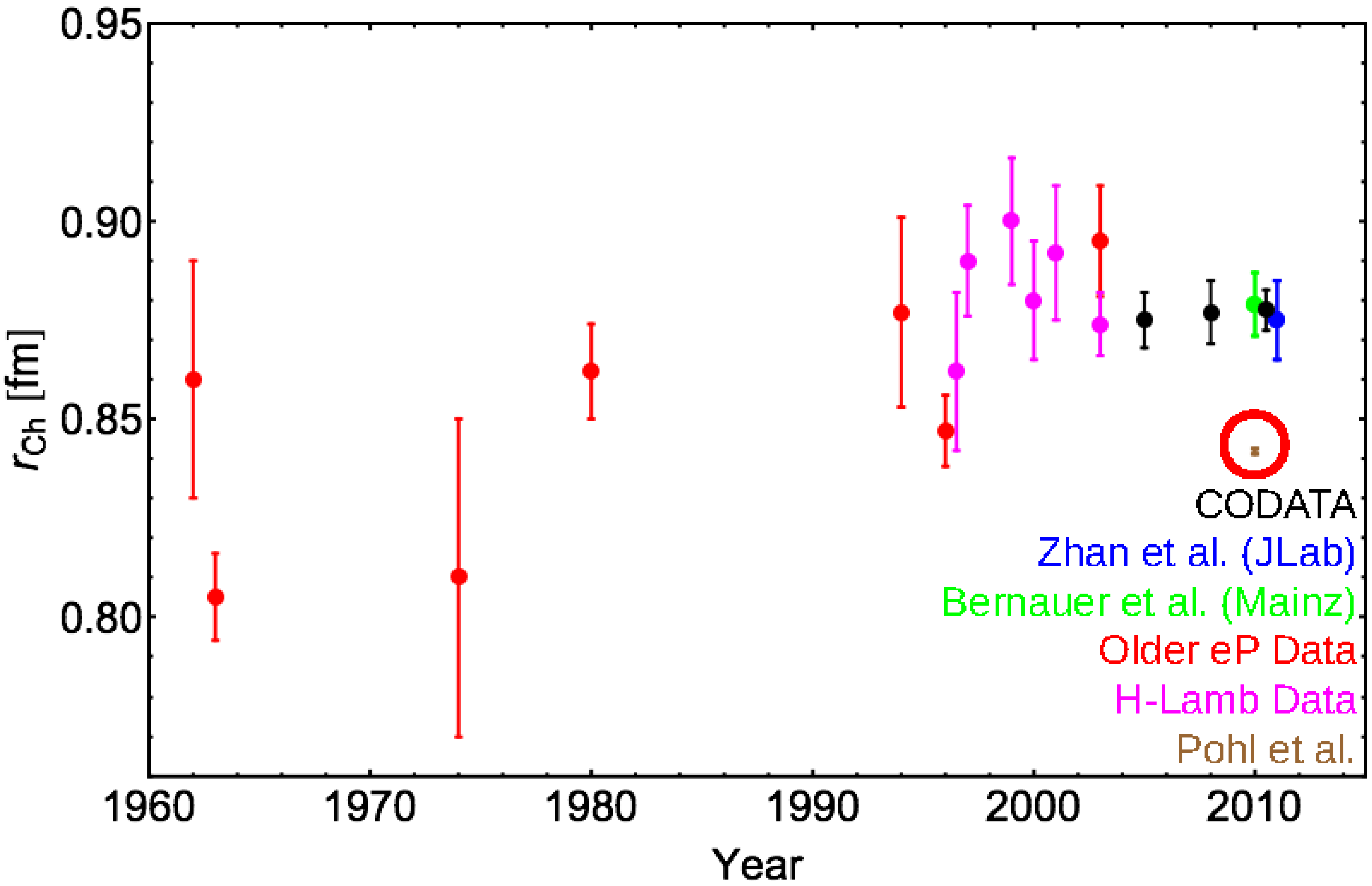
$$\cong \left(\frac{r_p}{a_{\mathbf{B}}}\right)^3 = \left(r_p \alpha\right)^3 m^3$$

$\rightarrow 207^3 \approx 8$ *million*



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

The Proton Radius from H & μH Lamb Shift and ep

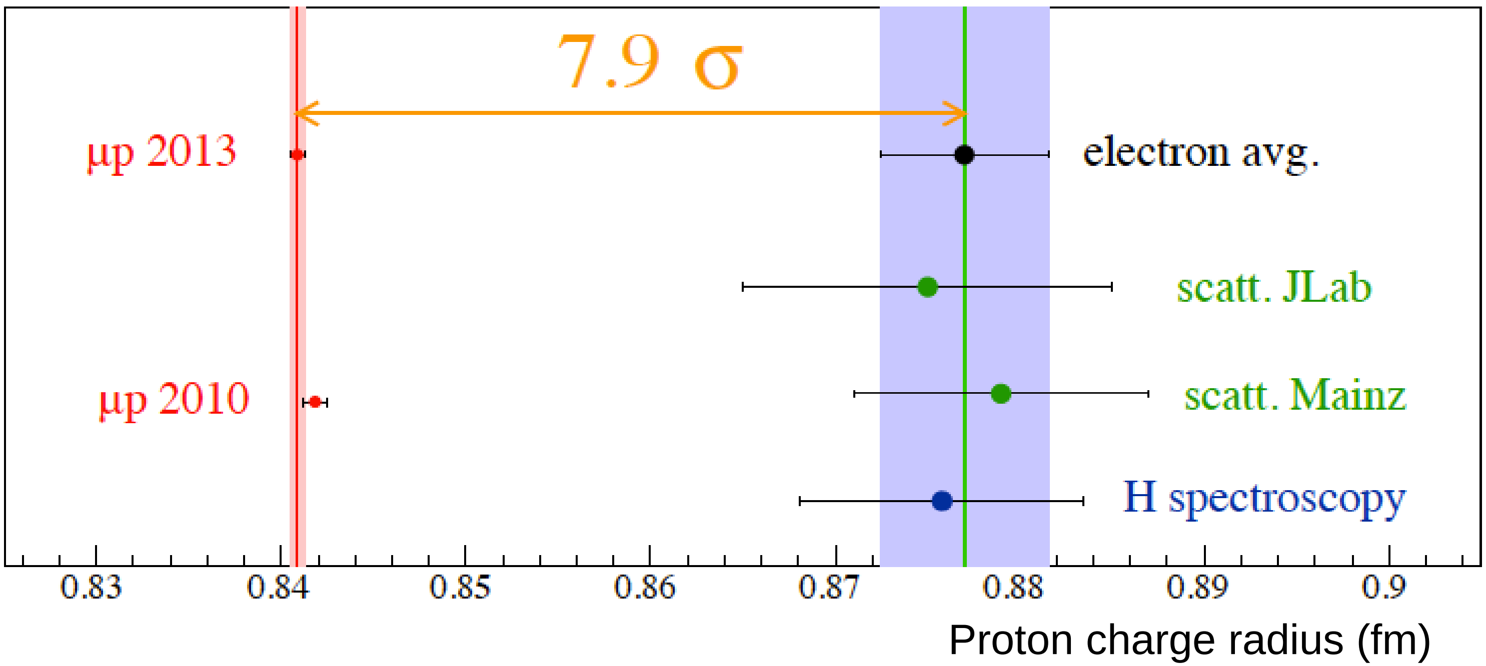


The Proton Radius Puzzle

Proton radius measured with

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

muonic hydrogen: **0.8409 ± 0.0004 fm**

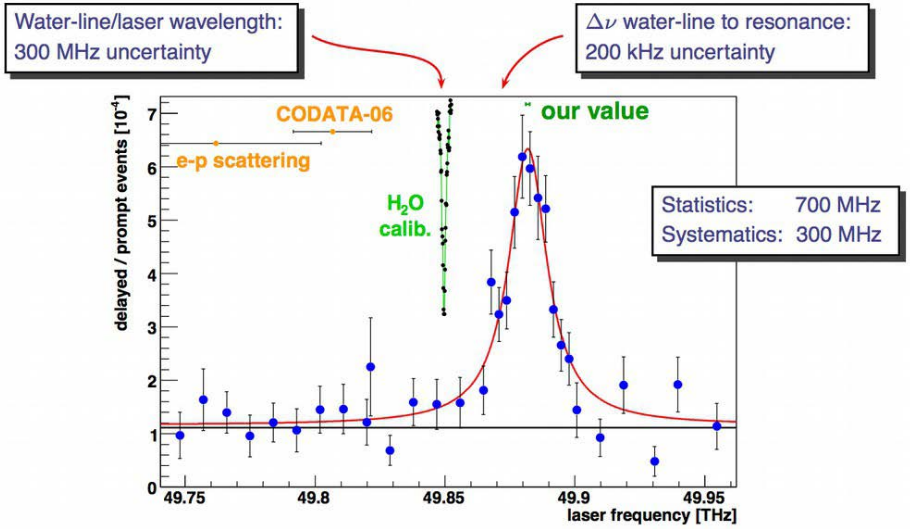


Radius from Muonic Hydrogen 4% below previous best value

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

Why do the muon and electron give different proton radii?

- Experimental error in μp measurement ?



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

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 ?
  - both scattering and H-spectroscopy are wrong?
  - Rydberg constant off by 5σ ?

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- Theory Error?

#	Contribution	Ref.	Our selection Value	Unc.	Pachucki [31–33] Value	Unc.	Borie [34] 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

Why do the muon and electron give different proton radii?

- Experimental error in μp measurement ?
  - seems unlikely
- Experimental error in ep measurements ?
  - both scattering and H-spectroscopy are wrong?
  - Rydberg constant off by 5σ ?
- Theory Error?
  - checked, rechecked, and checked again
  - …. is framework wrong?

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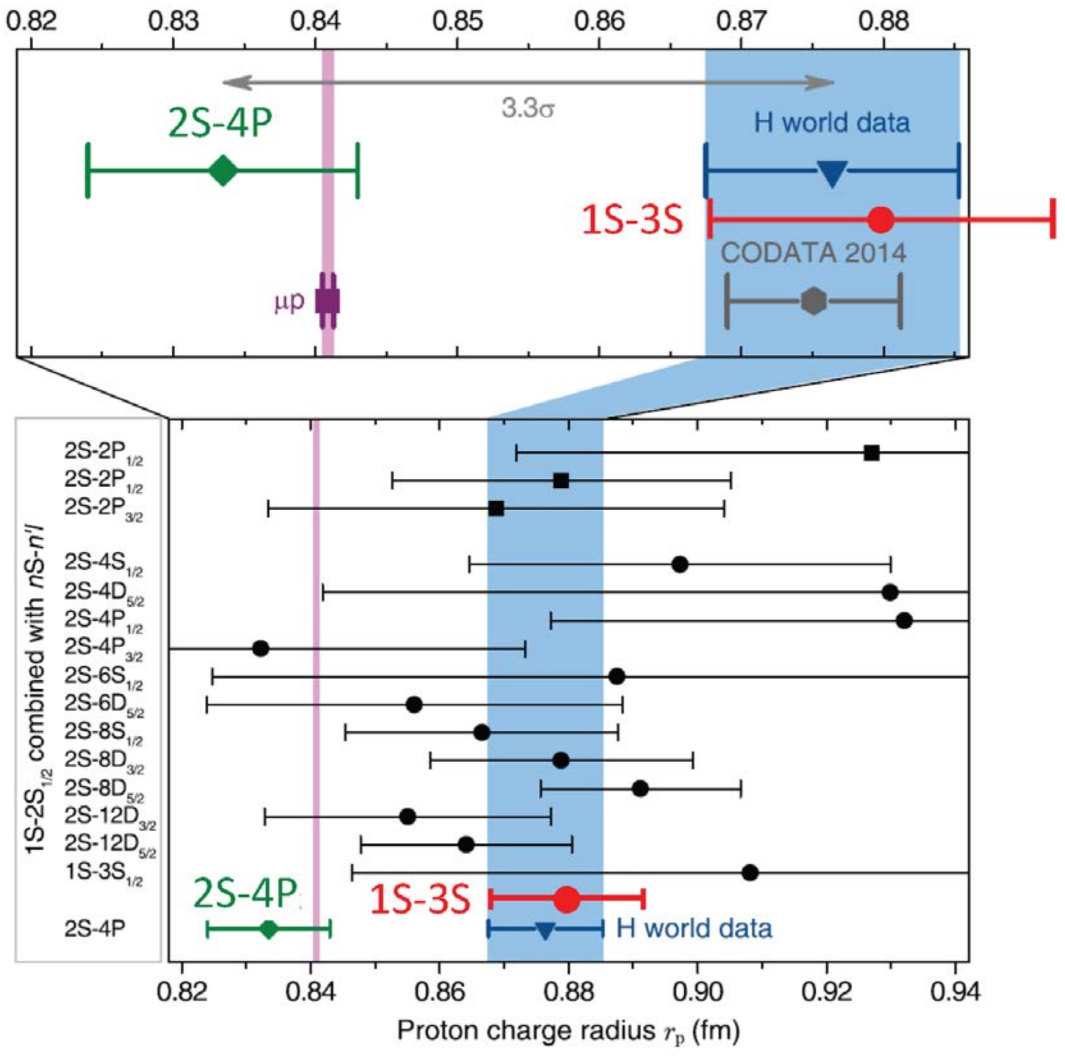
  - …. is framework wrong?
- Everybody is correct ? New Physics !
  - BSM Physics
    - violation of lepton universality
  - Novel Hadronic Physics
    - proton polarizability affects μ, but not e (effect $\propto m_l^4$)
    - two-photon exchange corrections (effects important at high Q^2)

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!

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

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** (first muon proton scattering experiment)
    - plans at COMPASS (100 GeV SPS muon beam)

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

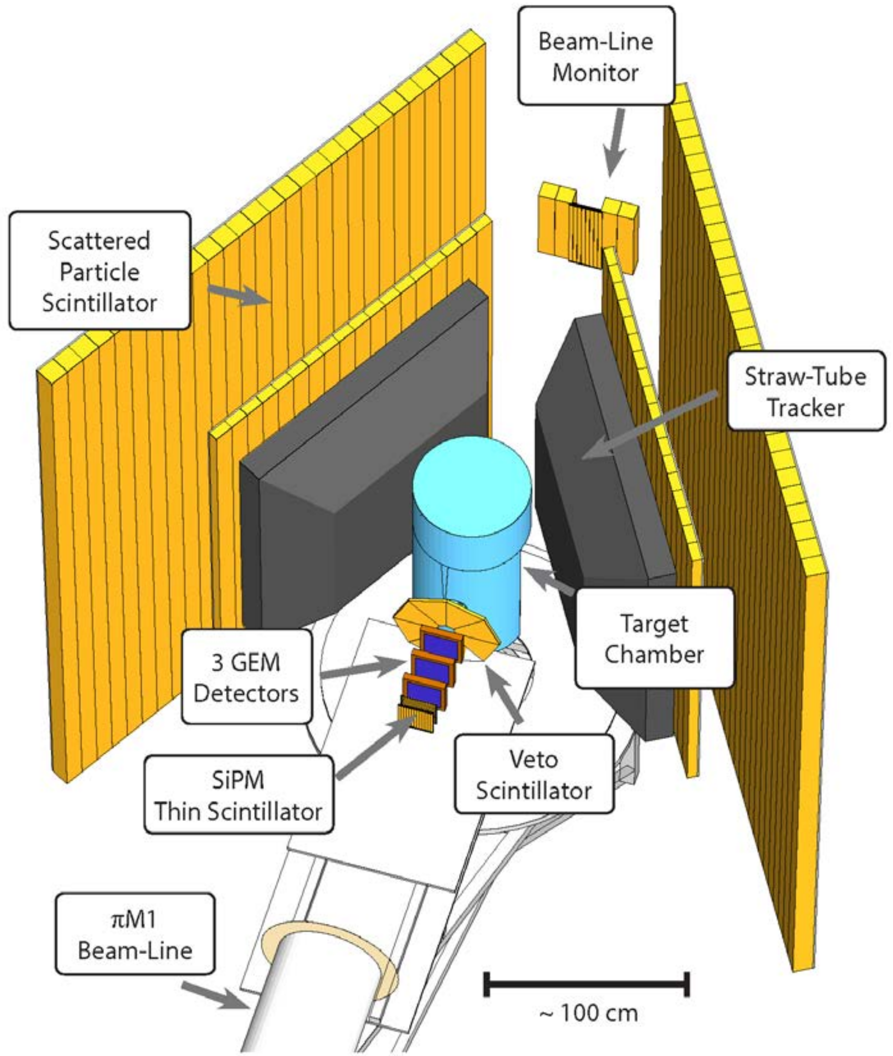
→ charge reversal: test two photon effects

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

→ momenta: 115 – 210 MeV/c → Rosenbluth separation of G_E and G_M
  - $Q^2 = 0.002 – 0.07\ GeV^2$

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



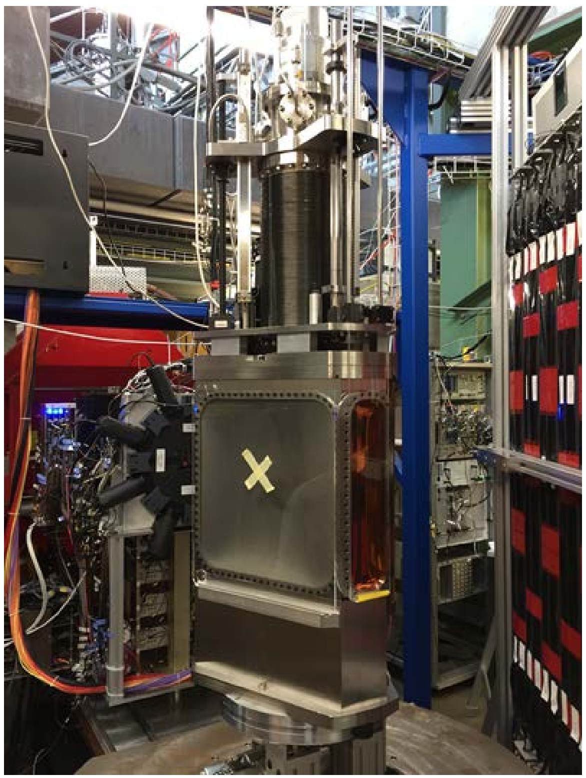
LH_2 Target (U-M)

Liquid hydrogen target

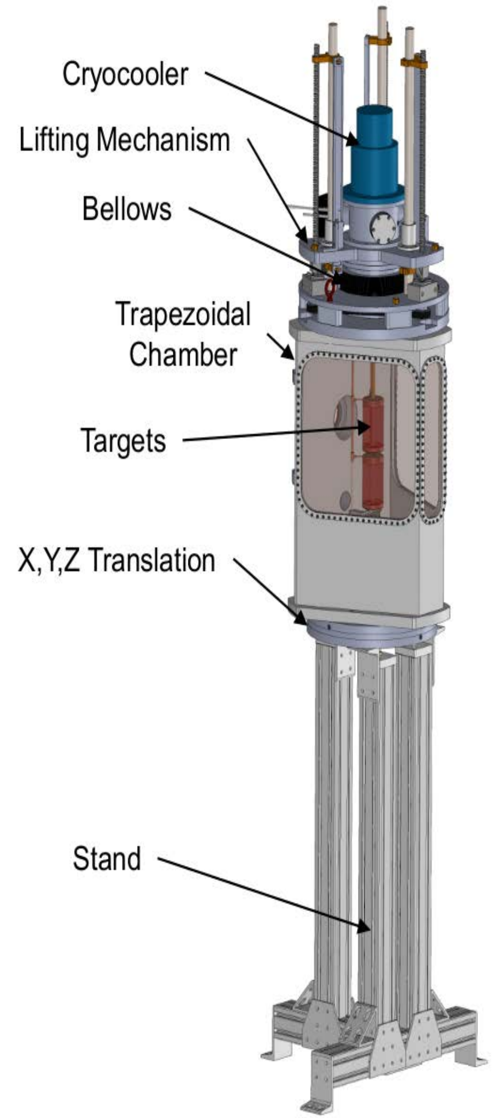
→ 280 ml Kapton cylinder

→ full and empty targets

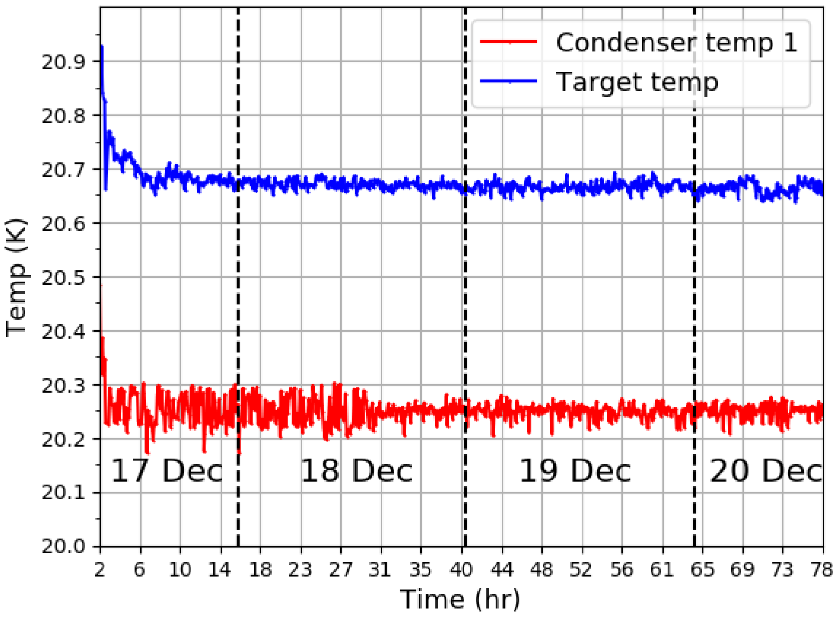
Target chamber in PiM1

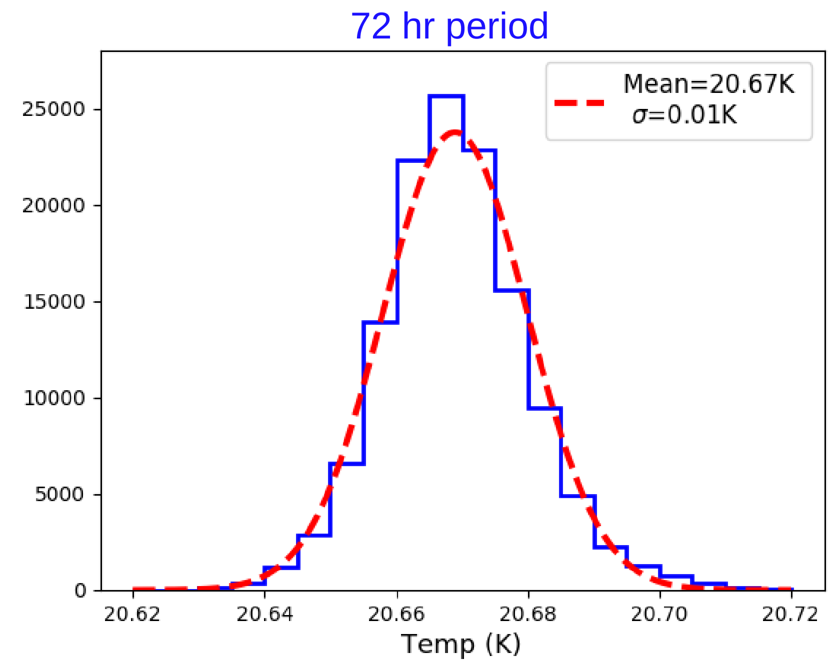


Target system



Target Performance

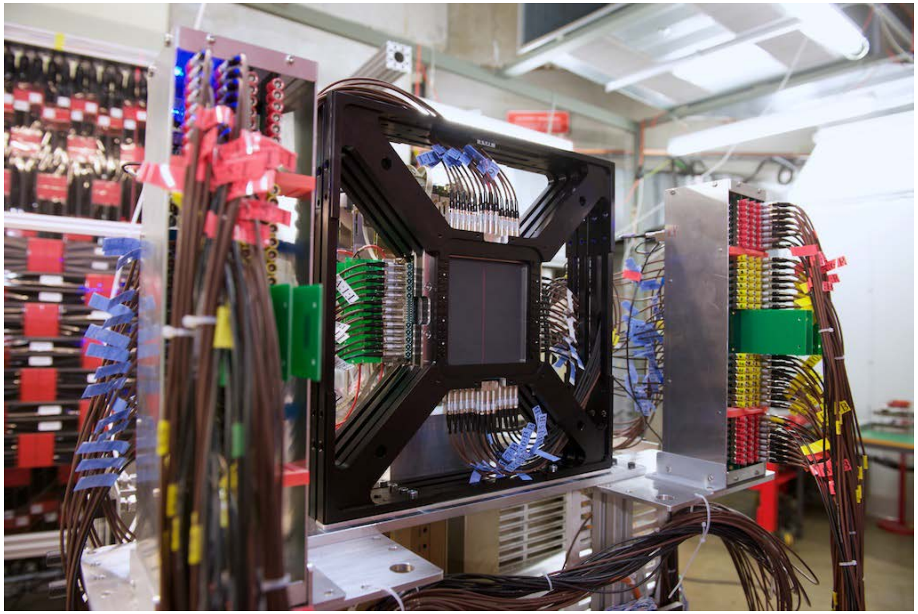




- Target Temperature: 20.67 ± 0.01 K
  - corresponds to a pressure of ~1.1 bar
- Target density: 0.070 g/cm^3 (stable to 0.02%)
  - once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached

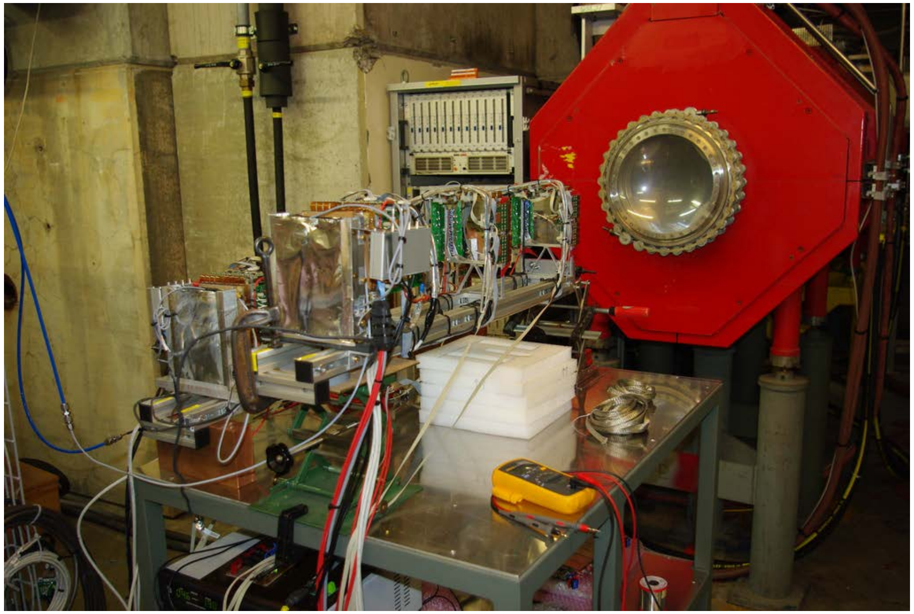
Detector Components

Beam hodoscope
(TAU, Rutgers, USC)



Time resolution 70ps at 99.8% efficiency!

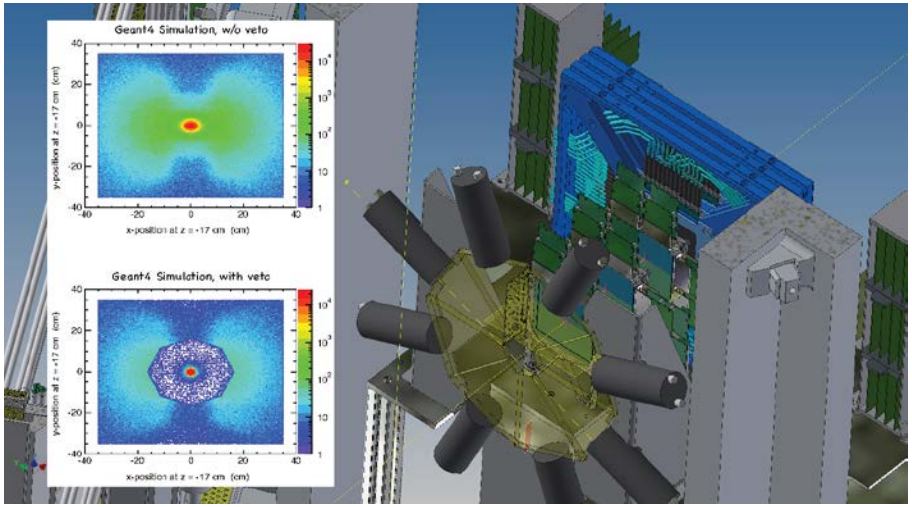
GEM telescope
(HU)



Measure trajectory of each incoming particle

Detector Components

Beam veto detector
(USC)



Significantly reduces trigger rate from background events

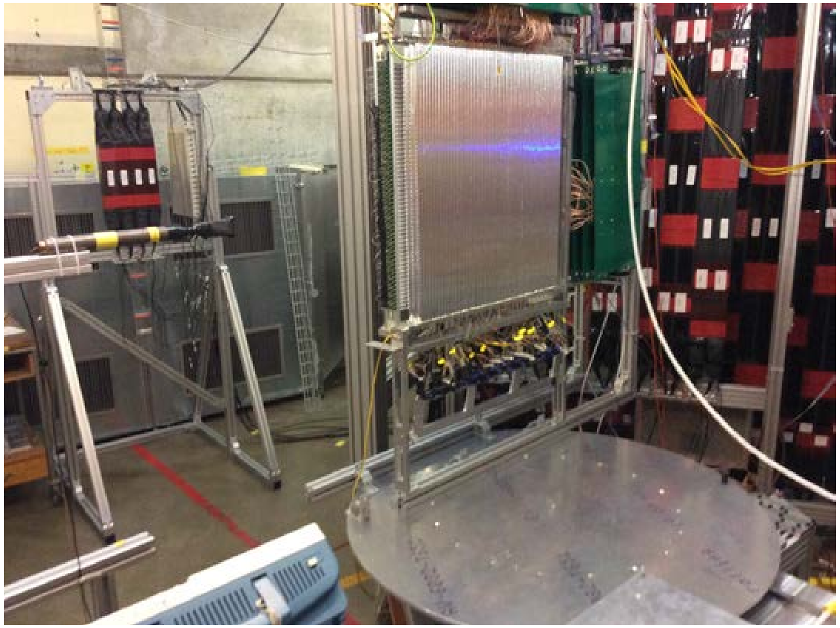
Beam Monitor
(TAU, Rutgers, USC)

Determination of particle flux downstream of target, Moller/Bhabha veto, ToF

Detector Components

Strawtube tracker

(HUJI)



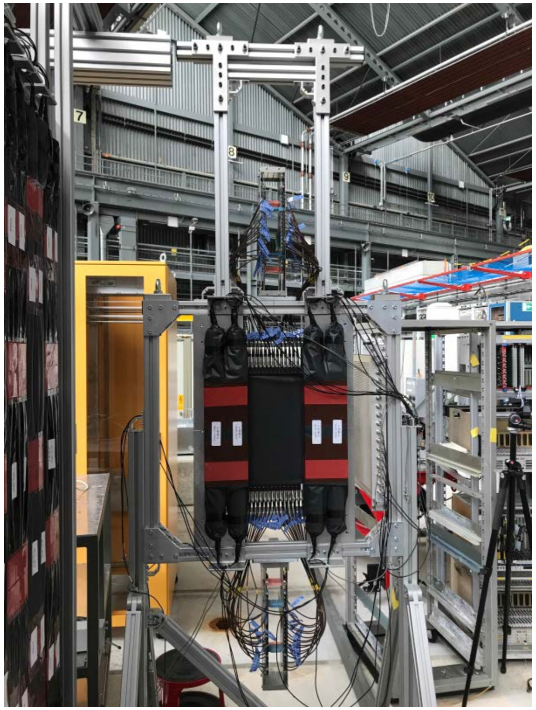
text

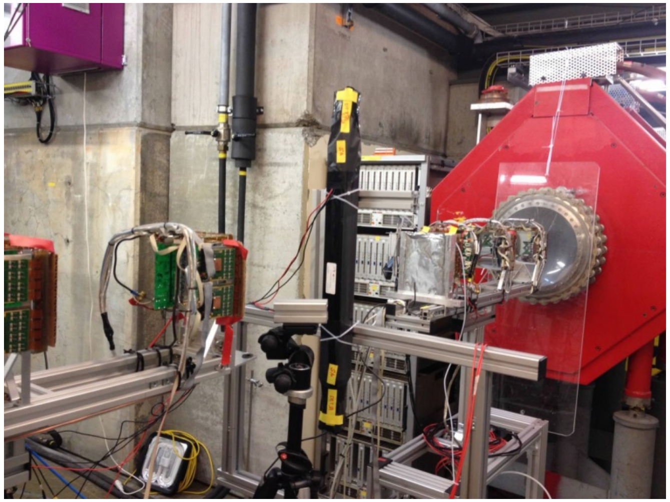
Scintillator wall

(USC)

Better time resolution (50ps) than design requirement!

Current status

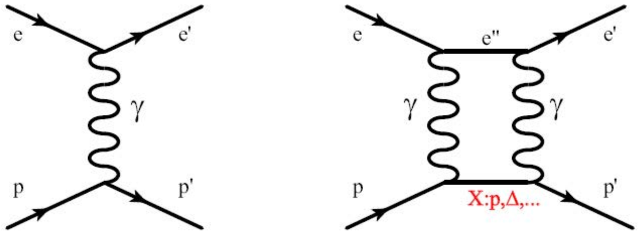




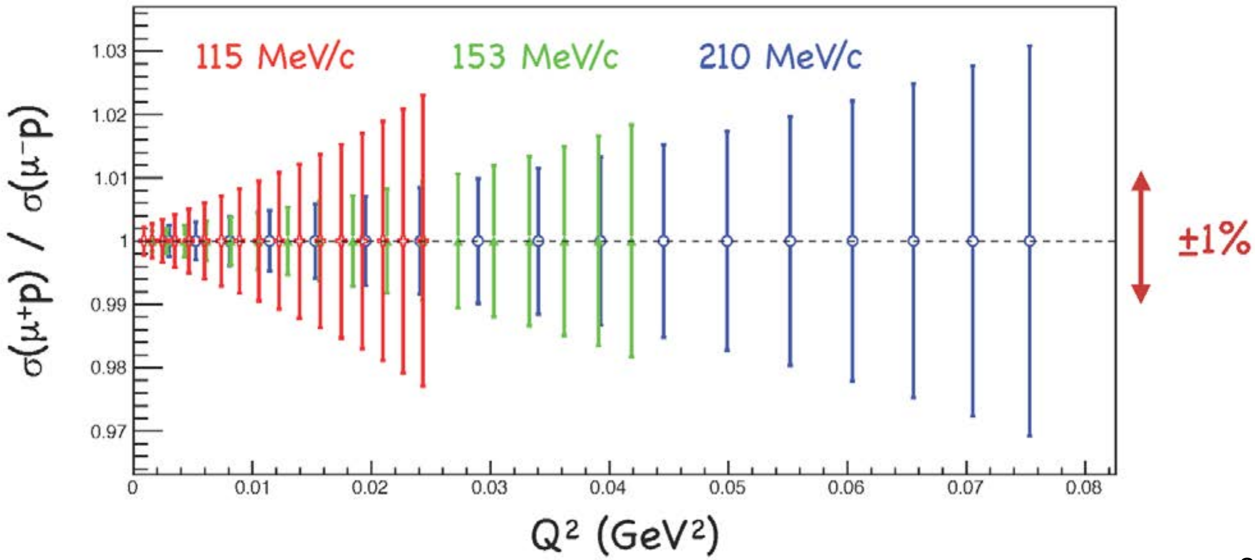
- 18 test runs (2012 – 2019) demonstrate simulation agreement & reliable performance
- Construction completed
  - commissioning almost complete
  - 12 month total data-taking in 2019 - 2021

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^-

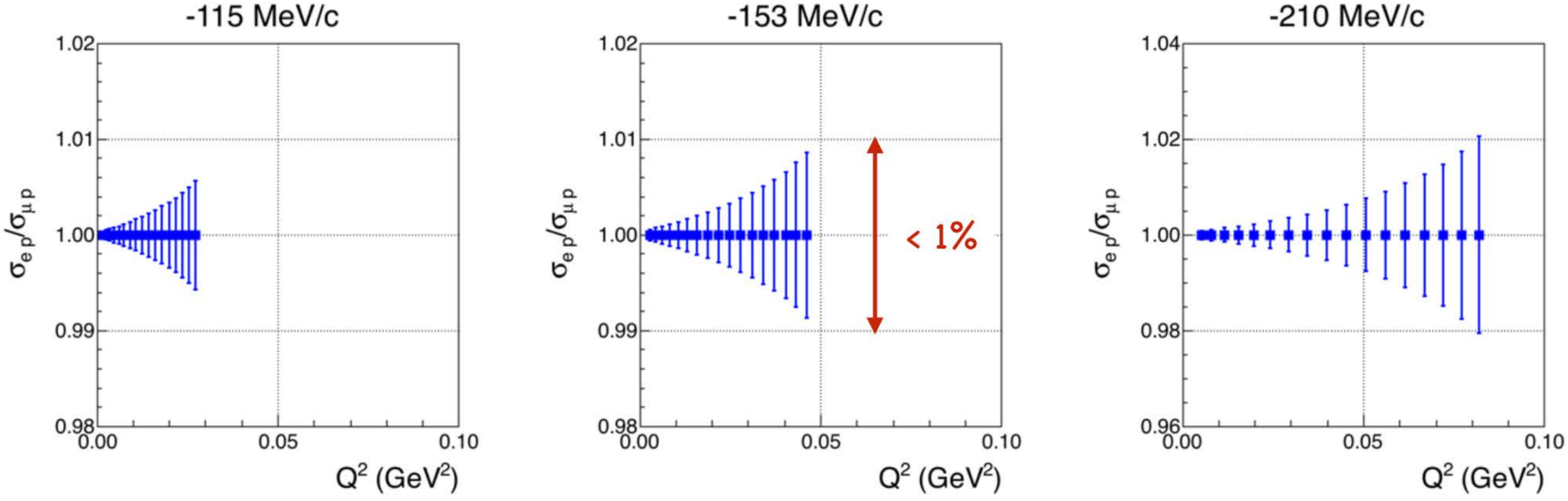


- Projected rel uncertainty in $\mu^+ p$ to $\mu^- p$ elastic cross sections. systematics: 0.2%



Comparison of ep to μp cross sections

- Projected relative statistical uncertainties in the ratio of ep to μp elastic **cross sections**.
- Systematics ≈ 0.5%



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

Projected sensitivity for MUSE

- absolute radius extraction uncertainty similar to current experiments

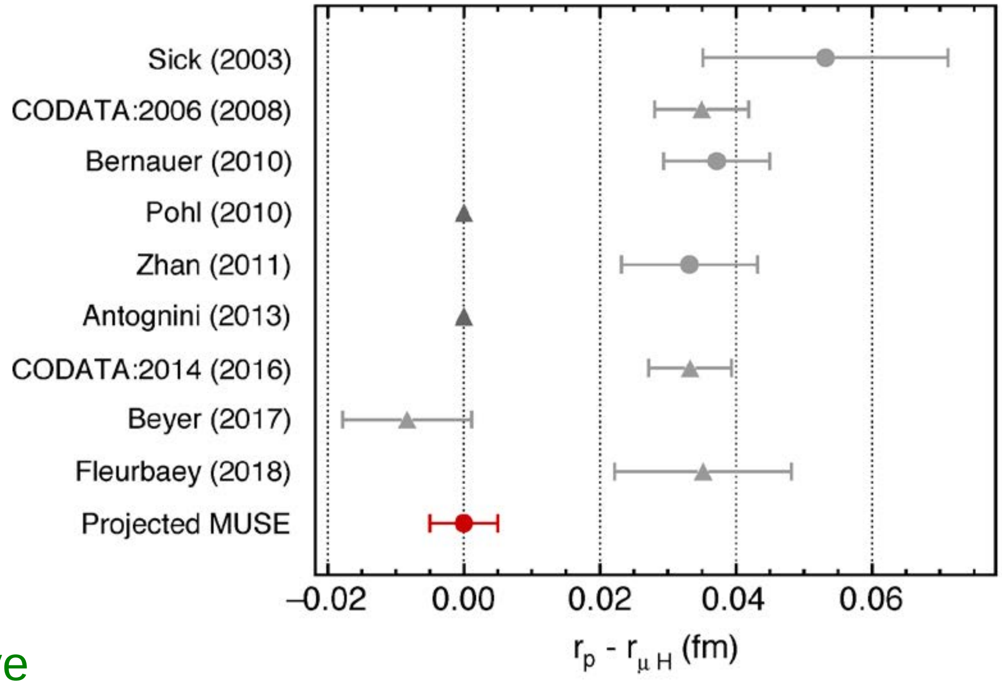
  $\sigma(r_e), \sigma(r_\mu) \approx 0.009$ fm

- 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

current discrepancy: $r_e - r_\mu \approx 0.034$ fm

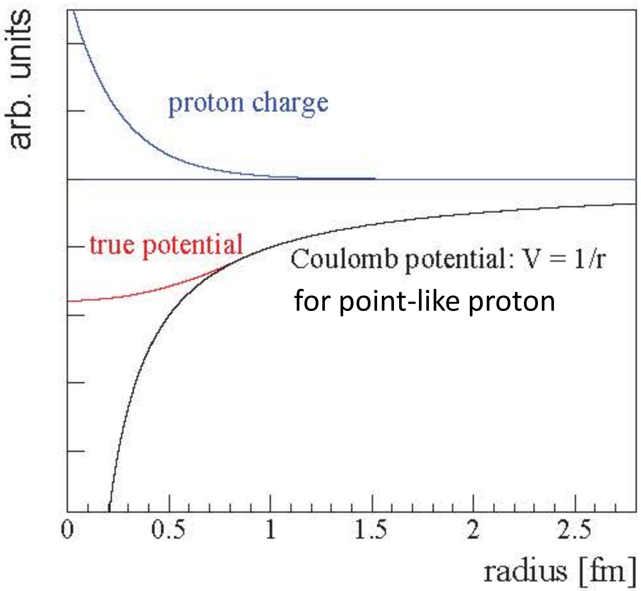


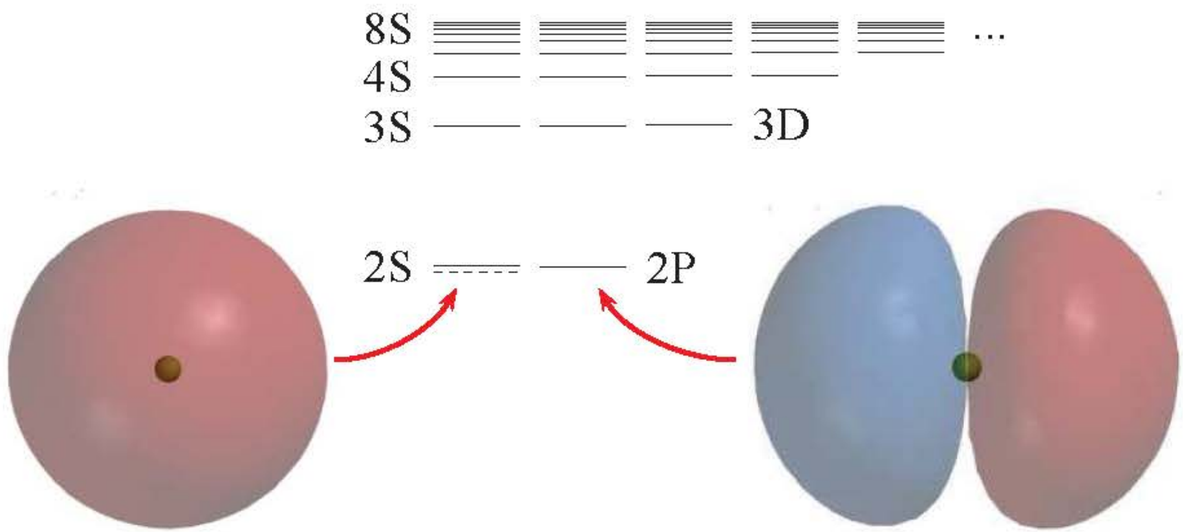
Summary

- We are still (possibly more) puzzled!
- Proton radius puzzle
  - discrepancy between muonic and electronic measurements remains a serious problem
  - Need new data
- Except 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

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

size of the proton

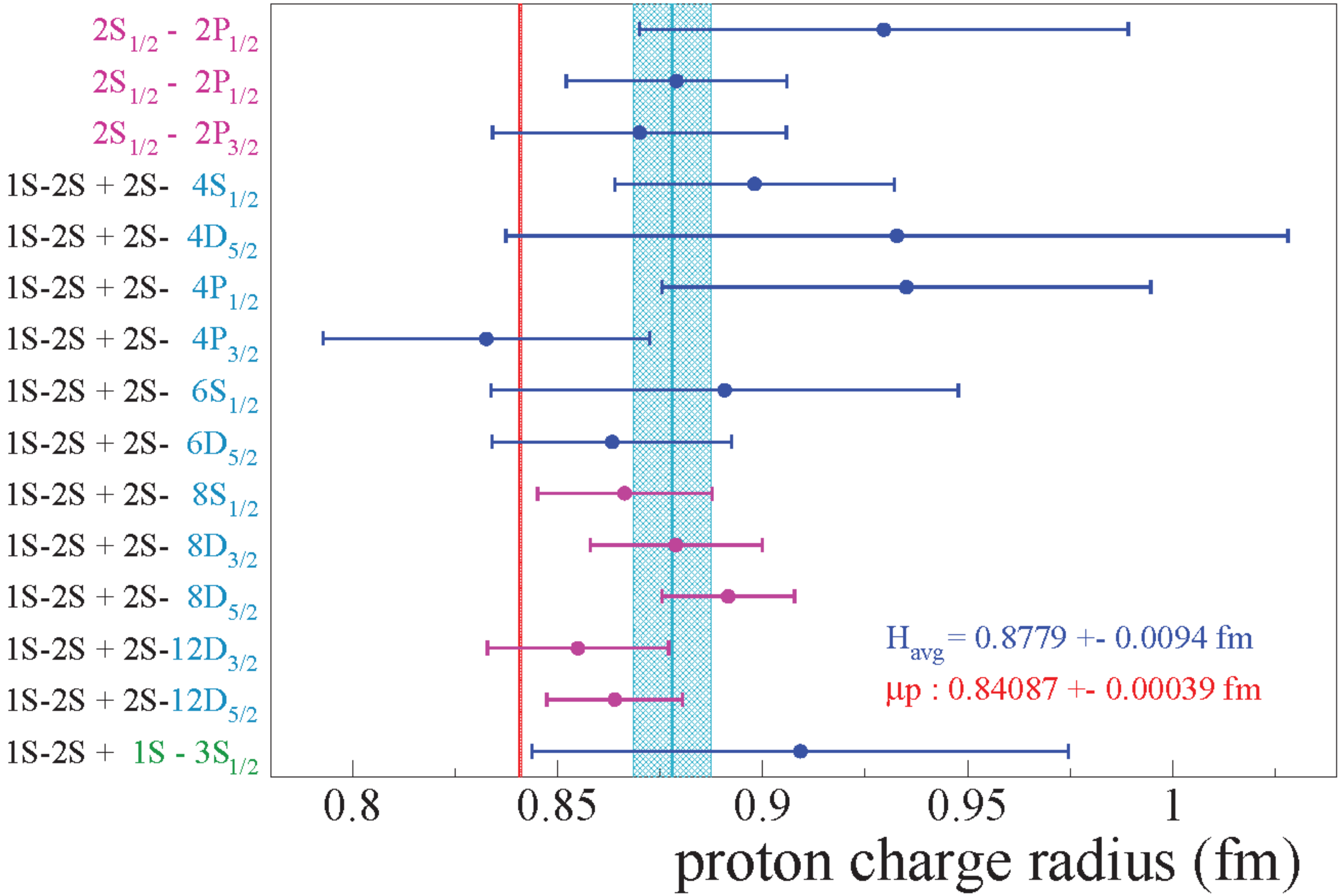
P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

Pictures: R. Pohl

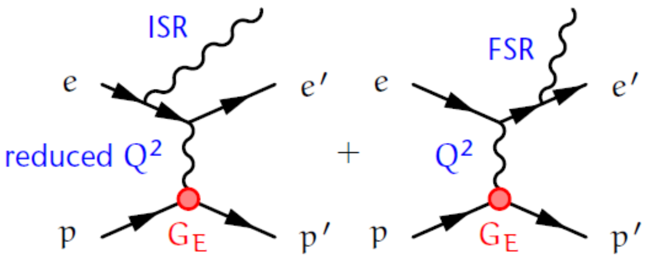
Hydrogen Atom Spectroscopy



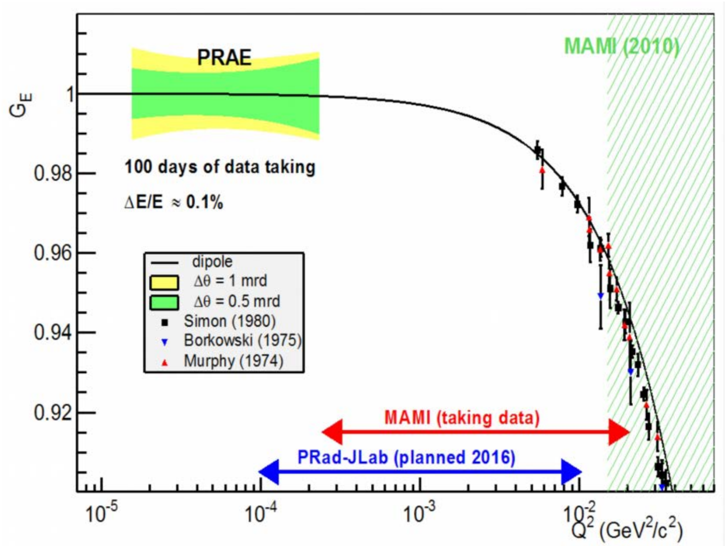
Redoing electron scattering at lower Q^2

- 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

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