PAUL SCHERRER INSTITUT

# The MUSE experiment and the Proton Radius

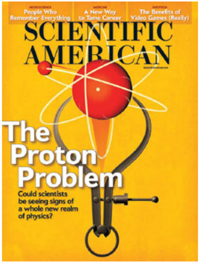
**Cristina Collicott**

SPIN 2016

# The Proton Radius Puzzle

**How big is the proton?**

- Easy question to ask, not so easy to answer!
- Currently an unanswered problem in physics

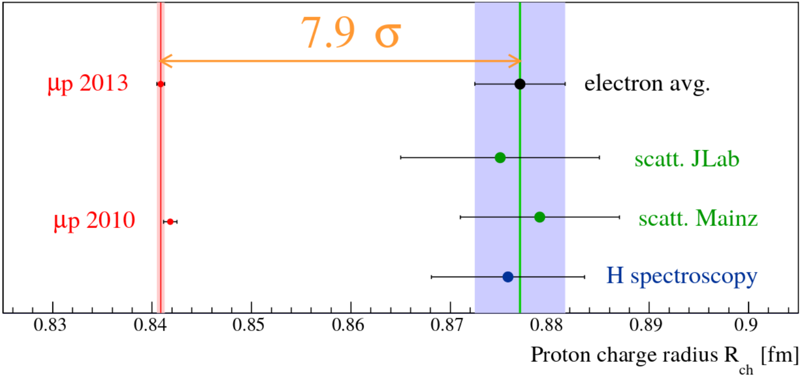




# The Proton Radius Puzzle

**What is the proton radius puzzle?**

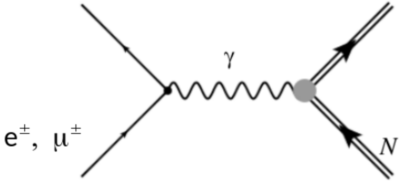
The proton charge radius, measured via muonic hydrogen spectroscopy, is 4% smaller than results from hydrogen spectroscopy and elastic electron proton scattering experiments.



# The Proton Radius Puzzle - scattering

**Rosenbluth scattering:**

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{(\text{point.})} \left( \frac{G_E^2(Q^2) + x G_M^2(Q^2)}{1+x} + 2x G_M^2(Q^2) \tan^2\frac{\theta}{2} \right)$$




**Sach's form factors**
($F_1$, $F_2$ Dirac and Pauli FFs)

$$G_E(Q^2) = F_1(Q^2) - xF_2(Q^2)$$
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$$x = \left(\frac{hq}{2Mc}\right)^2$$

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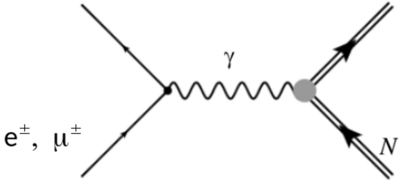


**Derivative in the $Q^2 \to 0$ limit**

$$< r_E^2 >= -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2\to 0}$$

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**We expect identical results for experiments with ep and $\mu$p scattering...**

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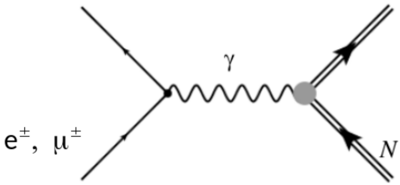


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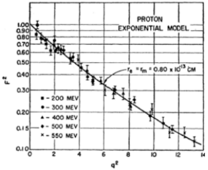
**Derivative in the $Q^2 \to 0$ limit**

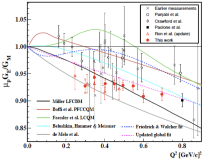
$$< r_E^2 >= -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

**We expect identical results for experiments with ep and $\mu$p scattering...**

# The Proton Radius Puzzle: electron scattering



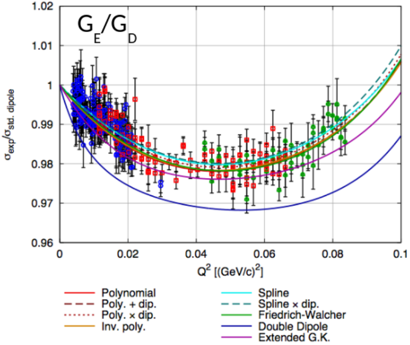

Chambers and Hofstadter, Phys Rev 103, 14 (1956)

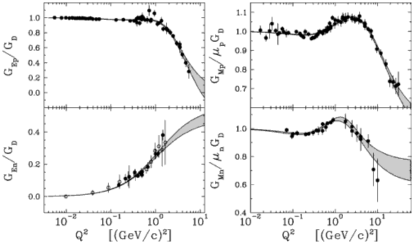



Zhan et al., PLB705, 59 (2011)

**Significant experimental interest in the Form Factors!**

Bernauer et al., PRL 105, (2010)

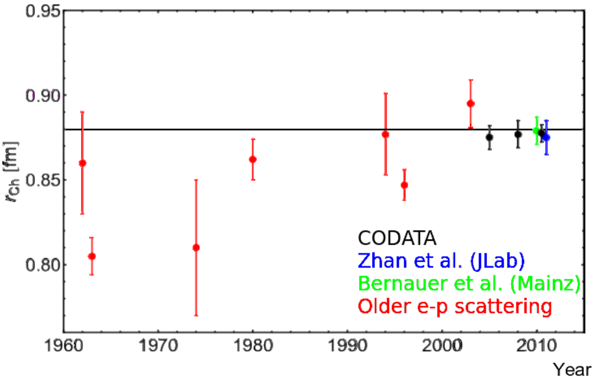



Kelly, Phys. Rev. C70, (2004)

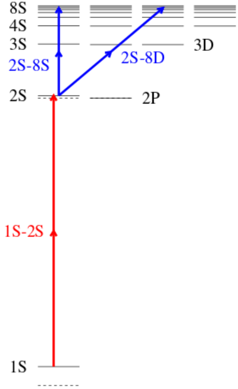
# The Proton Radius Puzzle: electron scattering

Electron scattering experiments give a fairly consistent extraction of the proton radius of approximately 0.88 fm.



# The Proton Radius Puzzle: H spectroscopy

Radius can also be studied from a spectroscopy approach:




**Two Unknowns → Two transitions!**

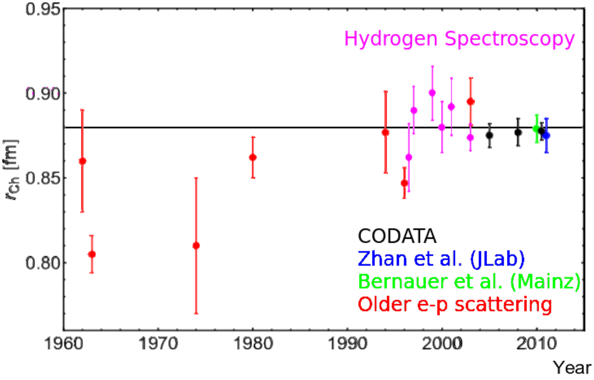
- Rydberg constant: $R_\infty$
- Lamb Shift: $L_{1S}$ $(< r_p^2 >)$

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

$$L_{1S}(r_p) = 8171.636(4) + 1.5645 < r_p^2 > \text{MHz}$$

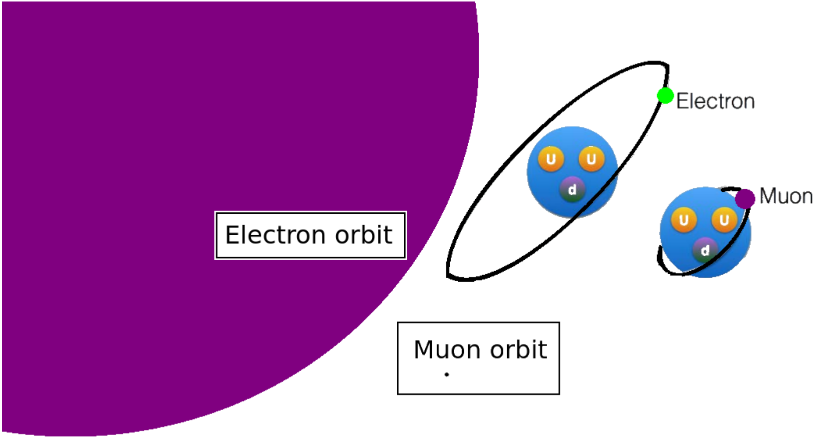
# The Proton Radius Puzzle: H spectroscopy

Radius can also be studied from a spectroscopy approach:
Again we find a radius consistent with 0.88 fm.



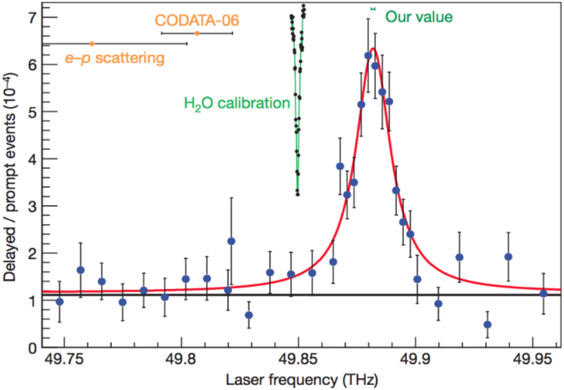
# The Proton Radius Puzzle: Muonic Hydrogen

**Why is muonic Hydrogen interesting?**



# The Proton Radius Puzzle: $\mu$H spectroscopy

## 2S $\rightarrow$ 2P Lamb Shift




Pohl et al., Nature 466 (2010)
A. Antognini et al., Science 339 (2013)

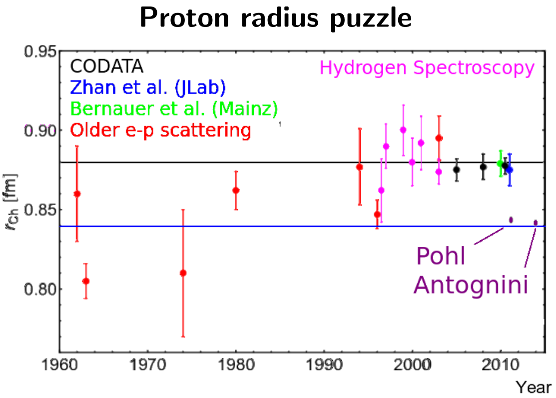
**Pohl (2010):**

$r_p = 0.84184 \pm 0.00067$ fm

**Antognini (2013):**

$r_p = 0.84087 \pm 0.00039$ fm

# The Proton Radius Puzzle: $\mu$H spectroscopy




Hydrogen: $r_p = 0.88$ fm

$\mu$-Hydrogen: $r_p = 0.84$ fm

**Pohl (2010):**

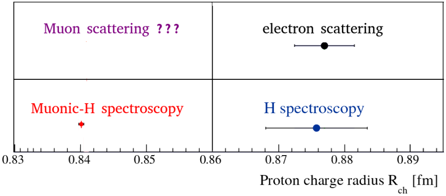
$$r_p = 0.84184 \pm 0.00067 \text{ fm}$$

**Antognini (2013):**

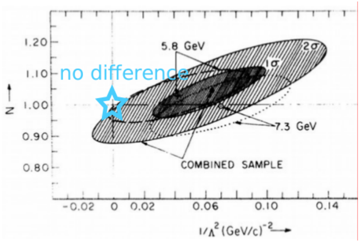
$$r_p = 0.84087 \pm 0.00039 \text{ fm}$$

# The Proton Radius Puzzle: What about muon scattering?

## $r_p$ from muonic-H and electronic-H

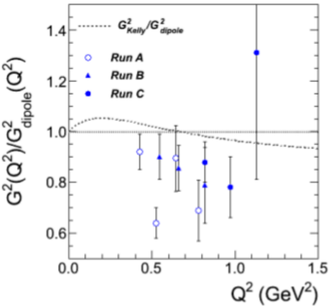



**$\mu$-p v. e-p elastic difference**
Kostoulas et al. PRL 32 (1974)




$\sigma(\mu - p)/\sigma(e - p) \approx 1.0 \pm 0.04$ ($\pm 8.6\%$ systematics)
A. Entenberg et al (1974)

**Form factors from elastic $\mu$-p**




Ellsworth et al. Phys. Rev. 165 (1968)

Previous scattering experiments confirm universality to 10% level.

**Insufficient precision to test proton radius issues!**

# Resolutions to the Puzzle

## Experimental problems?

**e-p problems**

- underestimated uncertainties
- incorrect radius extractions

**$\mu$-p problems**

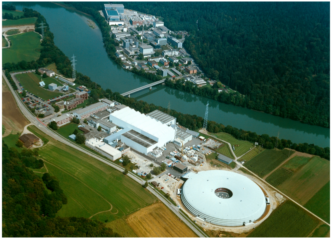
- 3-body effects

## New physics?

- Lepton non-universality
- New force / particle (dark photon?)
- Two-photon exchange
- ...

$\rightarrow$ **New (high-quality) data is needed to solve the puzzle.**

# MUSE - MUon Scattering Experiment



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PSI

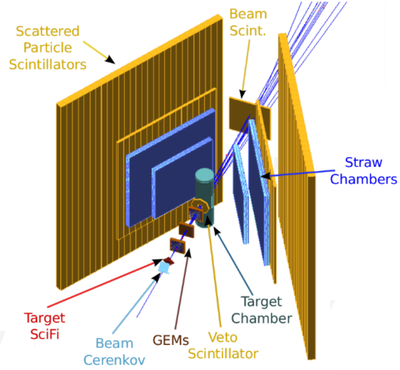
**World's most powerful proton beam!**

- Secondary e±, $\mu\pm$, $\pi\pm$ in $\pi$M1 beamline
- Planned momenta coverage: (115, 153, and 210) MeV/c.
- $Q^2$ range of $\approx$ 0.002 - 0.07 $GeV^2$
- Separate out particle species by timing relative to beam RF
- Cut as many pions as possible, trigger on e±, $\mu\pm$

# MUSE - MUon Scattering Experiment: Detector Overview

**Beamline:**

- Beam species ID/tracking via beam line detectors (SiPMs/GEMs).
- Vetos reject large $\pi$-induced background (beam line decays).



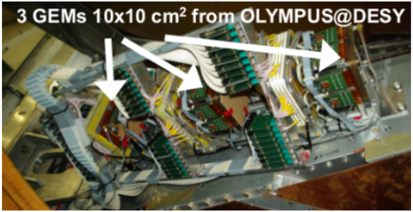

**Scattered particle detectors:**

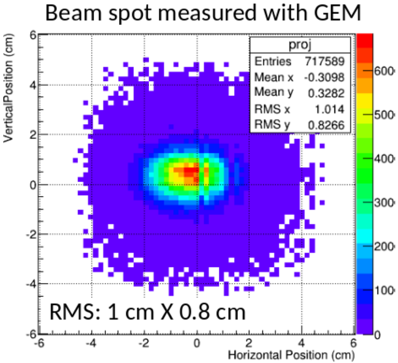
- Straw Tube Tracker detector (2850 channels).
- Scattered particle scintillators (184 channels).
- Scattering angle coverage: $20^\circ \rightarrow 100^\circ$.

# MUSE - MUon Scattering Experiment: Beamline

**Scintillating SiPM Detector Array** (Tel Aviv, Rutgers, PSI)
→ Thin, fast, scintillators, double-ended SiPM readout

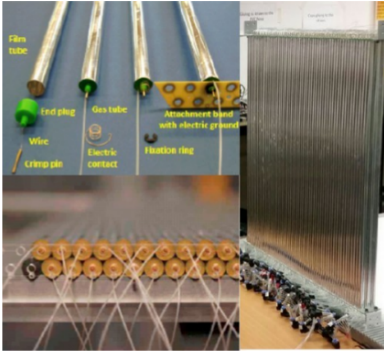
**GEM Chambers** (Hampton)
→ Inherited from OLYMPUS
→ $< 10$ mr resolution



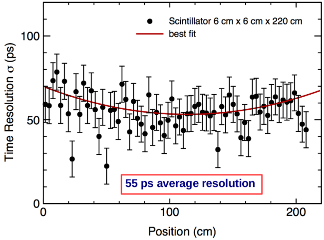
# MUSE - MUon Scattering Experiment: Scattering Det.

**Straw Tube Tracker** (HUJI, Temple)
→ Position/angular res. 140$\mu$m/1mr
→ Same design tested with PANDA

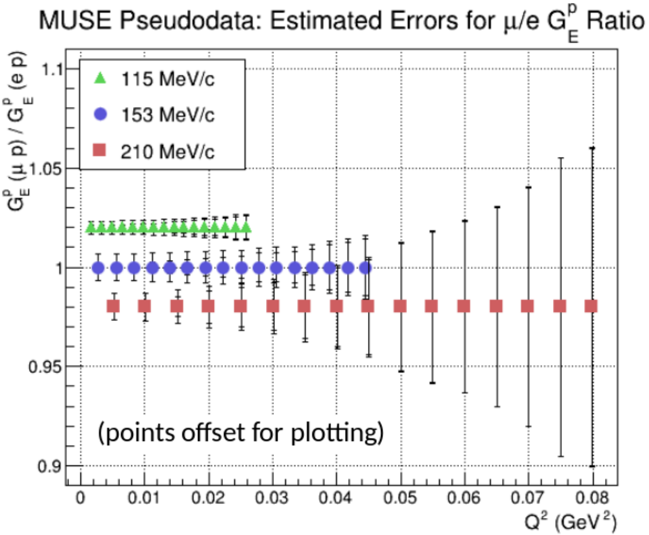




**Scintillator Walls** (USC)
→ 92 bars, double-ended readout
→ 100 cm/200 cm front/back bars



# MUSE - MUon Scattering Experiment: Projections



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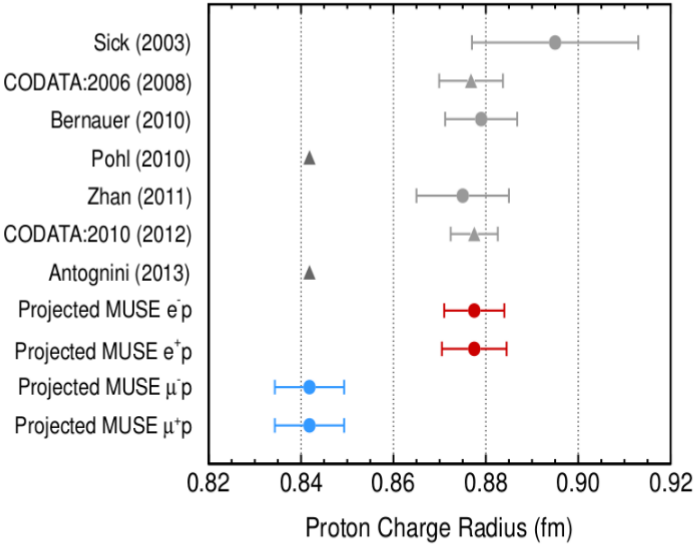
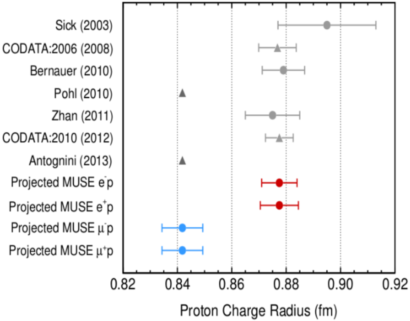


# Summary

**The proton radius puzzle is a high profile problem in physics!**
(still unresolved)

**MUSE** (MUon Scattering Experiment) will provide high quality e-p/$\mu$-p scattering data allowing for direct comparison of proton charge radius with reduced systematics.

**Up Next:** Discussion of PRad!



# Backups – What about the deuterium?

Science AAAS

RESEARCH ARTICLE

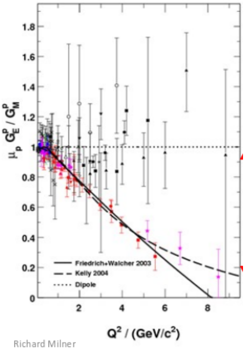
## Laser spectroscopy of muonic deuterium

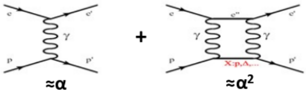
Randolf Pohl[1,2,*], François Nez[3], Luis M. P. Fernandes[4], Fernando D. Amaro[4], François Biraben[3], João M. R. Cardoso[4], Daniel S. Covita[5], Andreas Dax[6], Satish Dhawan[6], Marc Diepold[1], Adolf Giesen[7,8,†], Andrea L. Gouvea[4], Thomas Graf[7], Theodor W. Hänsch[1,9], Paul Indelicato[3], Lucile Julien[3], Paul Knowles[10,‡], Franz Kottmann[11], Eric-Olivier Le Bigot[3], Yi-Wei Liu[12], José A. M. Lopes[4,13], Livia Ludhova[10,§], Cristina M. B. Monteiro[4], Françoise Mulhauser[10,1,‖], Tobias Nebel[1,¶], Paul Rabinowitz[14], Joaquim M. F. dos Santos[4], Lukas A. Schaller[10], Karsten Schuhmann[11,8,15], Catherine Schwob[3], David Taqqu[15], João F. C. A. Veloso[5], Aldo Antognini[1,11,15], The CREMA Collaboration

**Quote:**

*We measured three 2S-2P transitions in $\mu d$ and obtain $r_d$ [$\cdots$] 7.5$\sigma$ smaller than the CODATA-2010 value $r_d$. The $\mu d$ value is also 3.5$\sigma$ smaller than the $r_d$ value from electronic deuterium spectroscopy.*

# Backups – What about TPE?




JLab (polarization transfer technique) showed a linear drop in the ratio of $G_E/G_M$ with $Q^2$ from unity.
→ **TPE to explain**

Compare $\mu+/\mu-$ and $e+/e-$ ratios:

- TPE opposite sign for switched polar.
- TPE dominates uncertainty of radiative corrections for $\mu$ (not e)
- Ratios ($\mu+/\mu-$ and $e+/e-$) $\cdots$ some systematics cancel ()

# Backups – Error Budget

**MUSE Error Budget**

Evie Downie

| | |
|---|---|
| Scintillator efficiency | 0.1% |
| Solid angle | 0.1% |
| Beam momentum offset | 0.1% |
| Theta offset | 0.2% |
| Multiple scattering | 0.15% |
| Muon decay in flight | 0.1% |
| Radiative corrections | 0.1% μ; 0.5% |
| Target wall subtraction | 0.3% |
| Beam PID mis-ID | 0.1% |

MUSE measuring relative cross sections

Point-to-point uncertainties, most important

Uncertainties mostly well controlled:
largest from angle and radiative corrections.

Have six settings and two independent detectors, consistency check