The Proton Charge Radius Puzzle: an Overview

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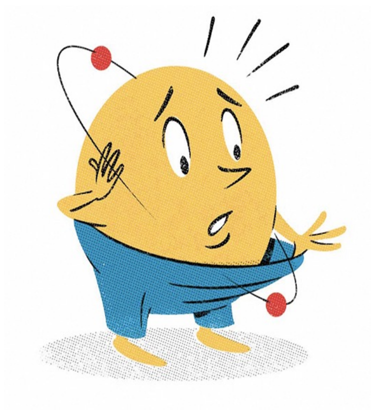
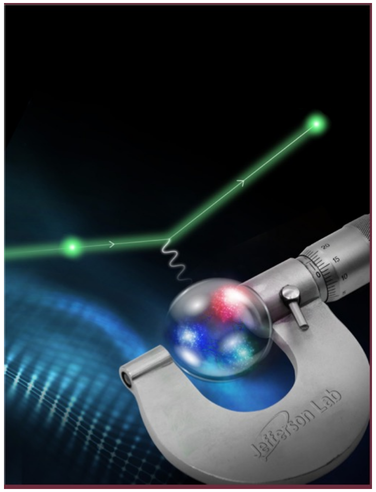
for the PRad collaboration

Outline

- introduction, the Proton
- the Puzzle, recent history
- today's status
- current and planed new experiments
- summary and outlook

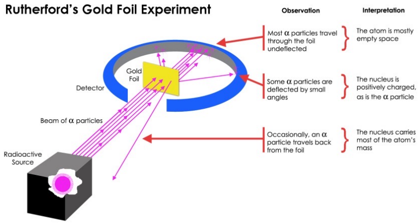


New York Times



The Subject of this Talk: the Proton

- 1919 Rutherford postulated the existence of the Proton through the scattering experiments
- Proton is the primary, stable building block of all visible matter in the Universe



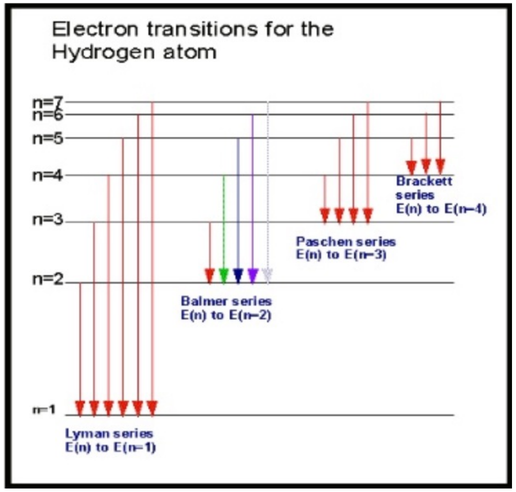
- Proton is one of the best testing laboratory in Physics:
  - atomic physics:
    - ✓ precision atomic spectroscopy (bound state QED, Lamb shifts)
    - ✓ correlated with the Rydberg constant R_∞
  - nuclear physics:
    - ✓ QCD, test of nuclear/particle models
  - connects atomic and subatomic physics

- 1933 Otto Stern: discovery of the Proton's anomalous magnetic moment:
  - it is not a Dirac point-like particle
  - it has some structure
- 1956 R. Hofstadter measured the size of the Proton

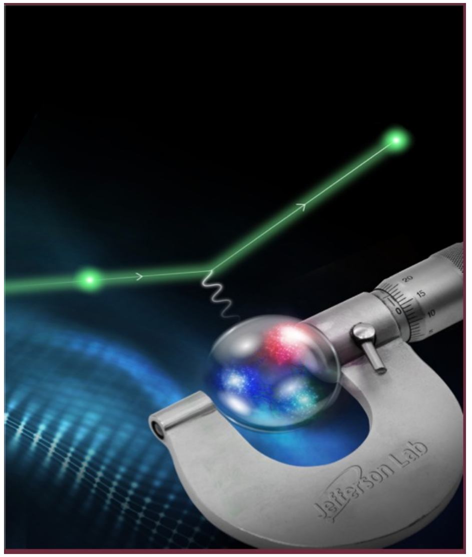
Methods to Measure the Proton Charge Radius

- Two different experimental methods:

1) Hydrogen spectroscopy (lepton-proton bound states, Atomic Physics, Lamb shift):
   - regular hydrogen
   - muonic hydrogen



2) Lepton-proton elastic scattering (Nuclear Physics):
   - ep- scattering (like MAMI, PRad …)
   - μp- scattering (like MUSE, AMBER …)



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2) \right)$$

With relativisticly correct definition of the Proton charge radius:

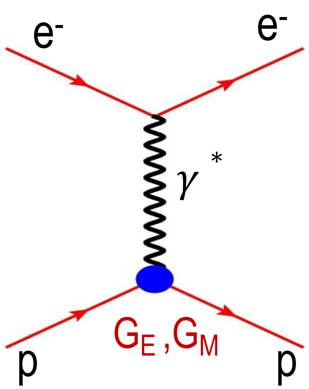
$$\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

Proton Radius from ep→ep Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

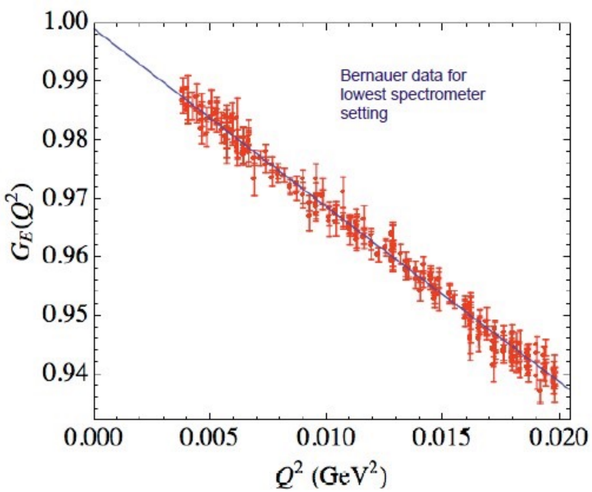
$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



- Structureless proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2 \left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- G_E and G_M can be extracted using Rosenbluth separation
- for extremely low Q^2, the cross section is dominated by G_E



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

- Taylor expansion of G_E at low Q^2

derivative at $Q^2 = 0$:

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

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

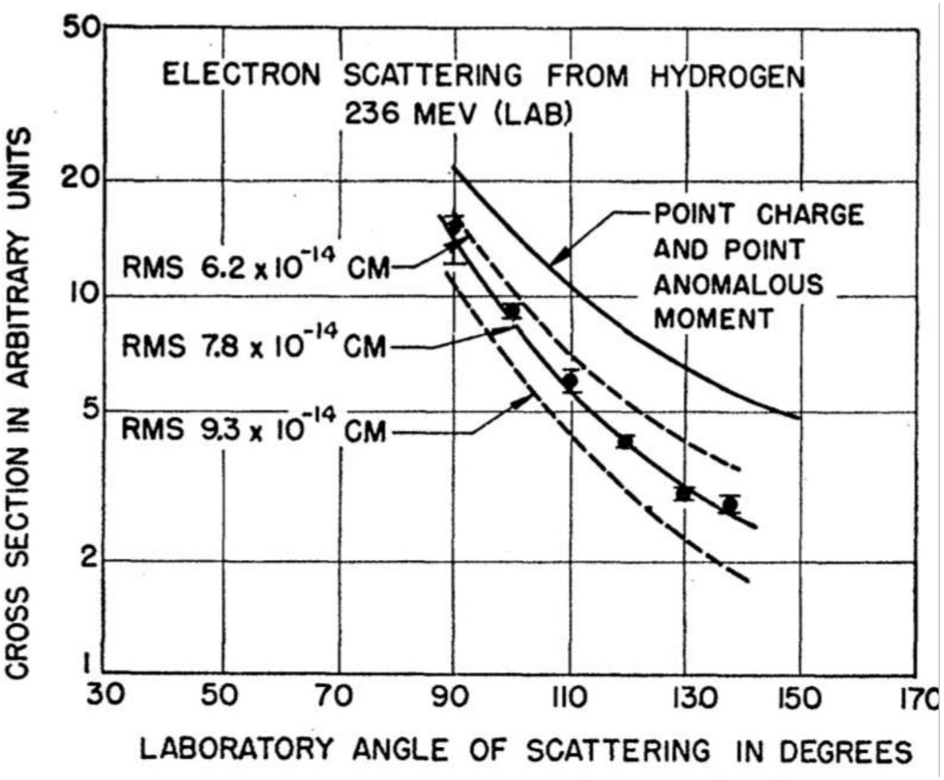
The First Measurement of the Proton Charge Radius (ep-scattering)

- First scuttering experiment by R. Hofstadter in 1956
  - ✓ Nobel prize in Physics (1961):
  - ✓ "… for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons …"

- The Proton rms charge radius in 1956 was measured to be:
  - ✓ 7.8 10^{-14} cm (0.78 fm)

    Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

- Over 60 years of experimentation!
  - ✓ started from 0.78 fm
  - ✓ reached to 0.895 fm (by 2014)
  - ✓ the current value 0.84 fm (from 2018)



Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).

Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

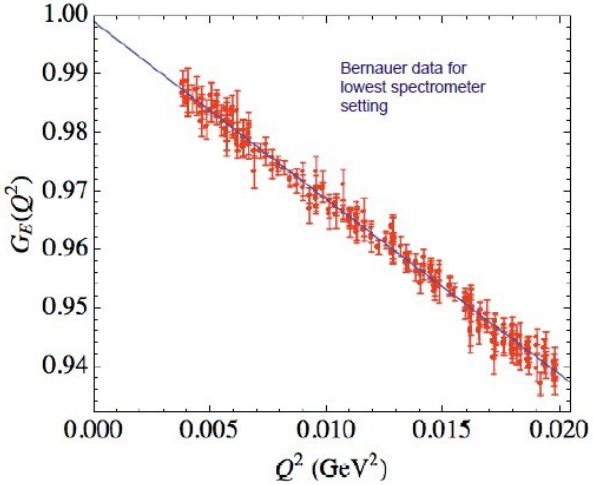
The Latest High Precision ep-scuttering Experiment:

(MAMI A1, Mainz, 2010)

- Magnetic spectrometer experiment (3 mag. spectrometers)
- Sub-GeV beam energies (E_e ~ 180 – 850 MeV)
- Luminosity monitored with second spectrometer
- Wide range of scattering angles
- $Q^2 = 0.004 – 1.0 (GeV/c)^2$
- Large amount of overlapping data sets (~ 1400 groups)
- Very low statistical error $\leq 0.2\%$
- Result: **r_p = 0.8791 ± 0.0079 fm**

Full agreement with the previous experiments

Three spectrometer facility of the A1 collaboration:



Mainz low Q^2 data set
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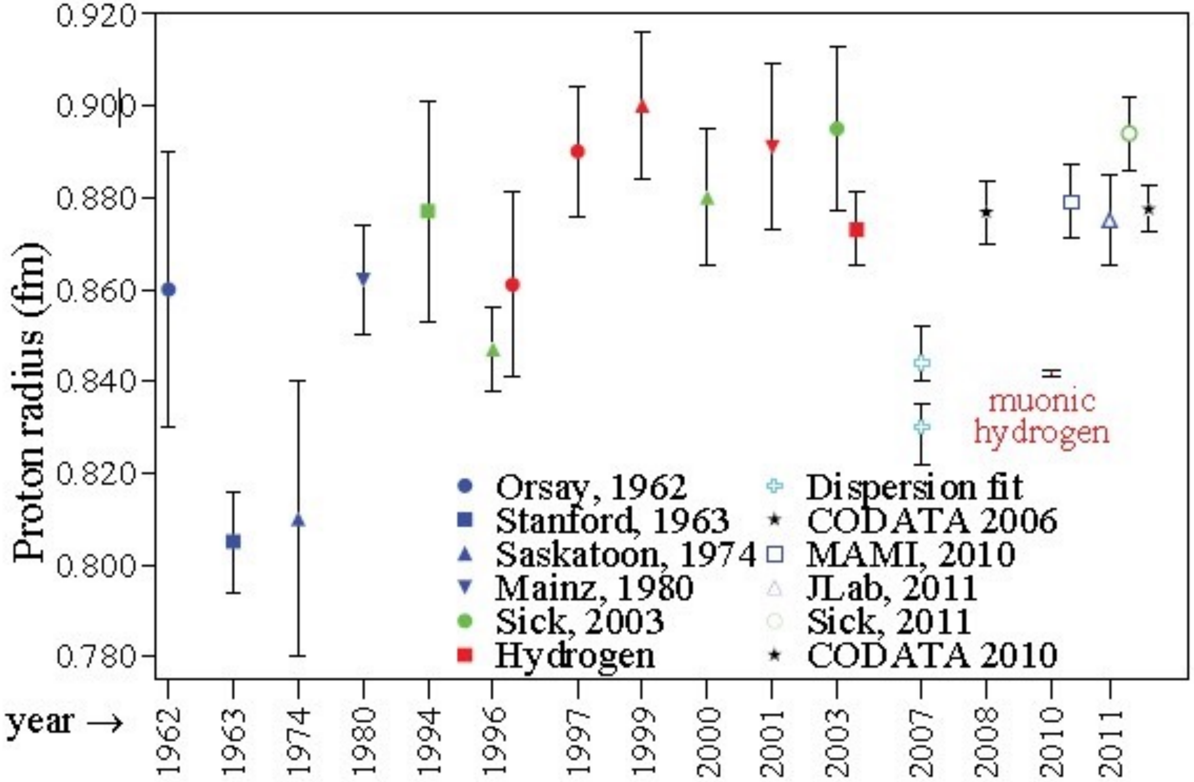
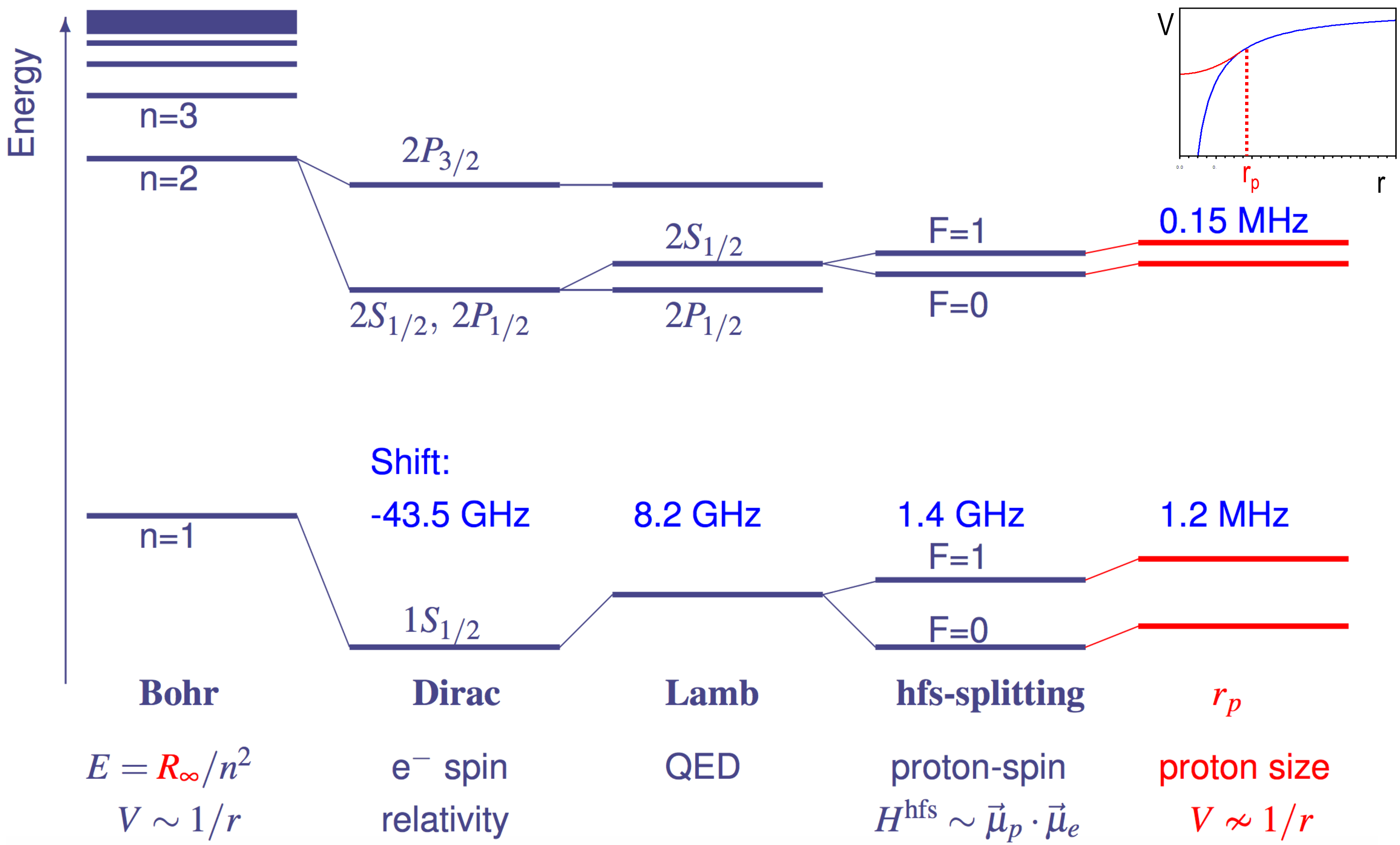
Proton Radius Extracted From e-p Scattering Experiments
(before 2012)



- More different analysis results than actual experiments
- Started with: $r_p \approx$ 0.78 fm in 1956
- Reached to: $r_p \approx$ 0.88 fm by 2011

Proton Radius from Hydrogen Spectroscopy



R. Pohl

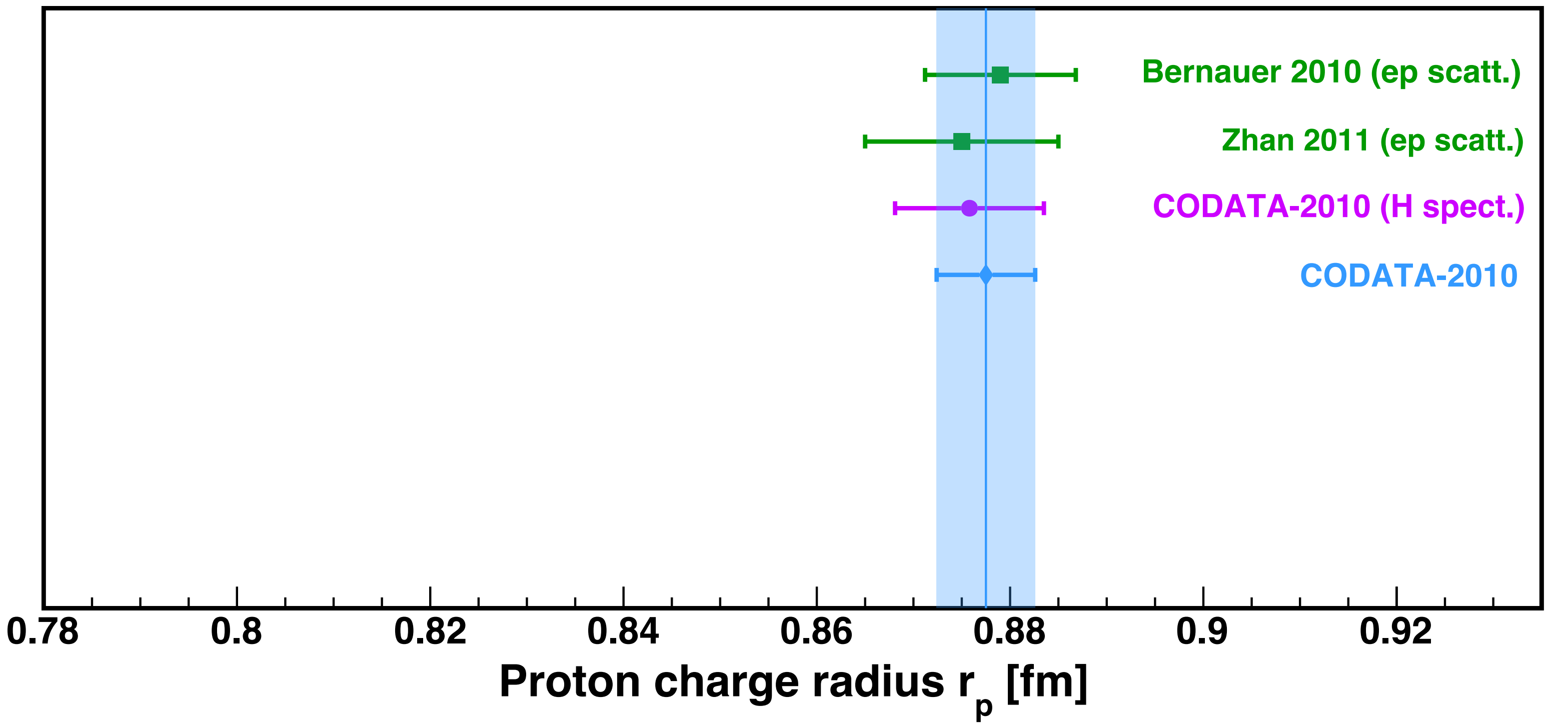
Hydrogen Spectroscopy and the Proton Radius

$$E_{n,l,j} = hcR_\infty \left(-\frac{1}{n^2} + f_{n,l,j}(\alpha, \frac{m_e}{m_p}, \ldots) + \delta_{l,0} \frac{k_N}{n^3} r_p^2 \right)$$

- Two hydrogen transitions are needed to extract the r_p and R_∞

Proton Radius Before Muonic Hydrogen Experiment

(before 2010)

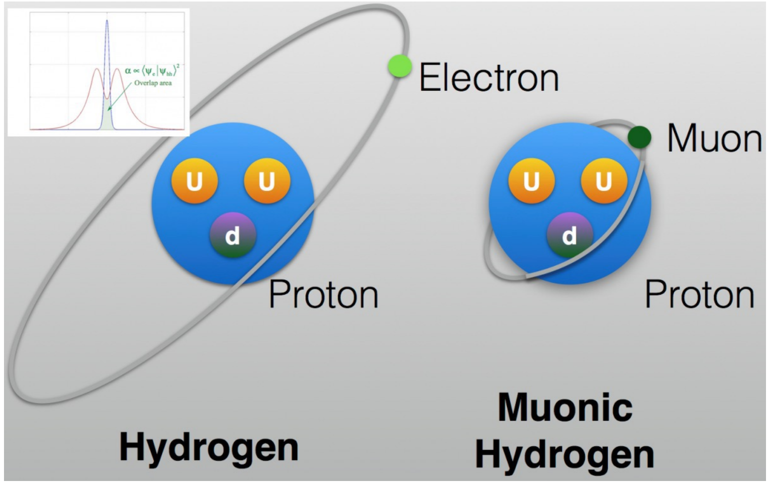


CODATA average:	0.8751 ± 0.0061 fm
ep-scattering average (CODATA):	0.879 ± 0.011 fm
Regular H-spectroscopy average (CODATA):	0.859 ± 0.0077 fm

Very good agreement between ep-scattering and H-spectroscopy results !

New Method: Muonic Hydrogen Precision Spectroscopy

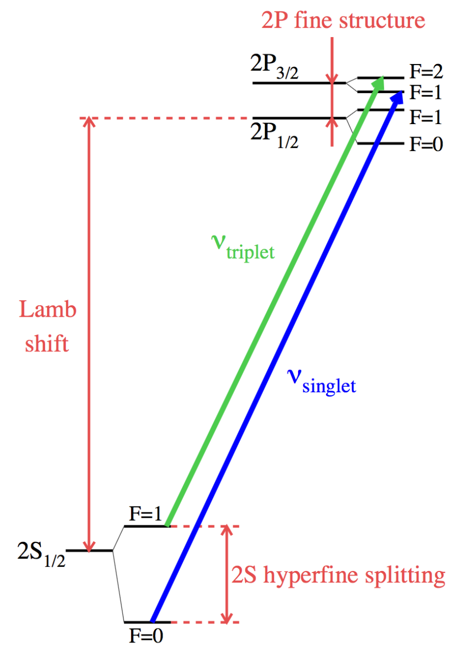
- muon is ~200 times heavier than electron,
  then muon is ~ 200 closer to the proton.



- Transition energy difference, ΔE:
  ΔE ~ (probability of the lepton be inside of proton)
  ~ $(\alpha\, r_p)^3 m_r^3$, with m_r - the reduced mass:
  $m_r = 186\, m_e$

  ✓ μH is ~ $8\text{x}10^6$ more sensitive to Proton Radius !!!

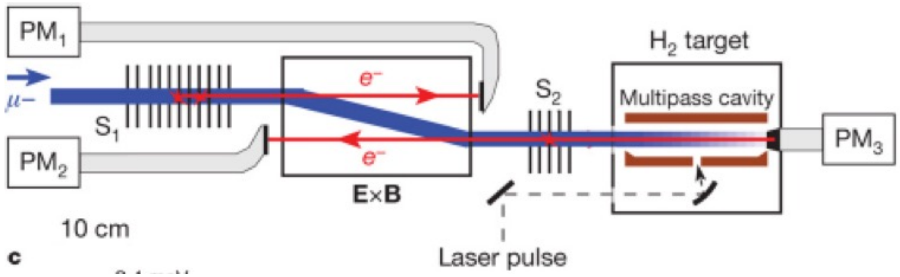
- Lamb shift in μH:
  $\Delta E = 206.0668(25) - 5.2275(10)\, R_p^2$ [meV]
  proton size is ~2% correction to μH Lamb shift
  vs. 0.015% for eH.

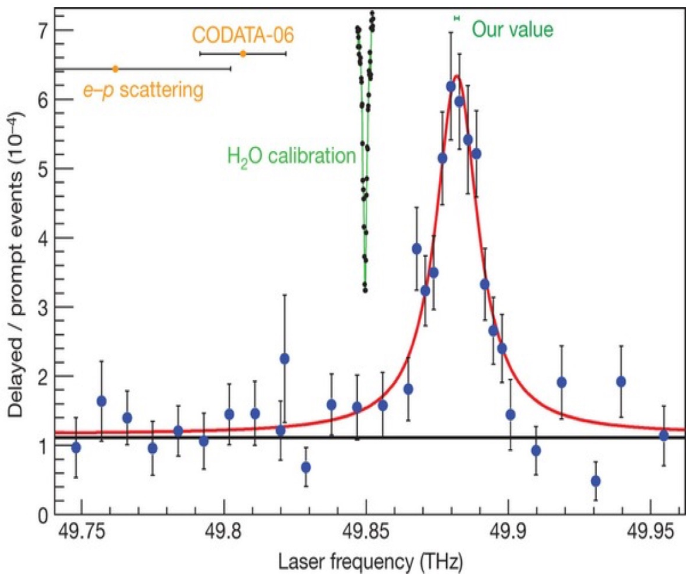


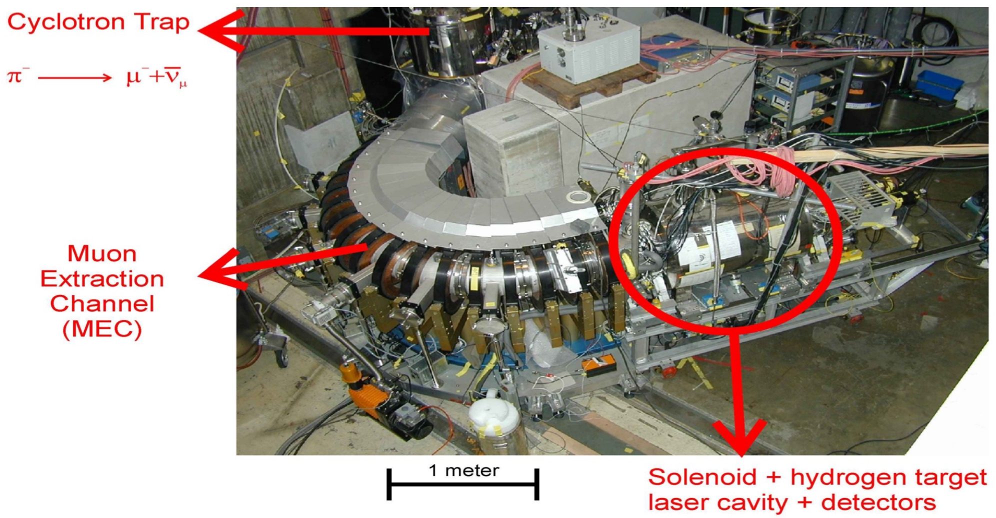
- Two experiments performed at PSI (CREMA collaboration) for proton radius in 2010 and 2013 with ~10 times higher precision (≤ 0.1%) compered to all previous experiments.

Muonic Hydrogen Experiments in 2010 and 2013

- most of μH atoms are formed with n~ 14
- 99% of them de-excite to 1S state
- 1% ends in metastable 2S state
- 6 μm laser pulse induces a 2S → 2P transition
- 2P state decay to 1S ground state (1.9 KeV X-rays, used in coincidence with the laser)
- the proton radius, R_p is extracted from the laser frequency spectrum.

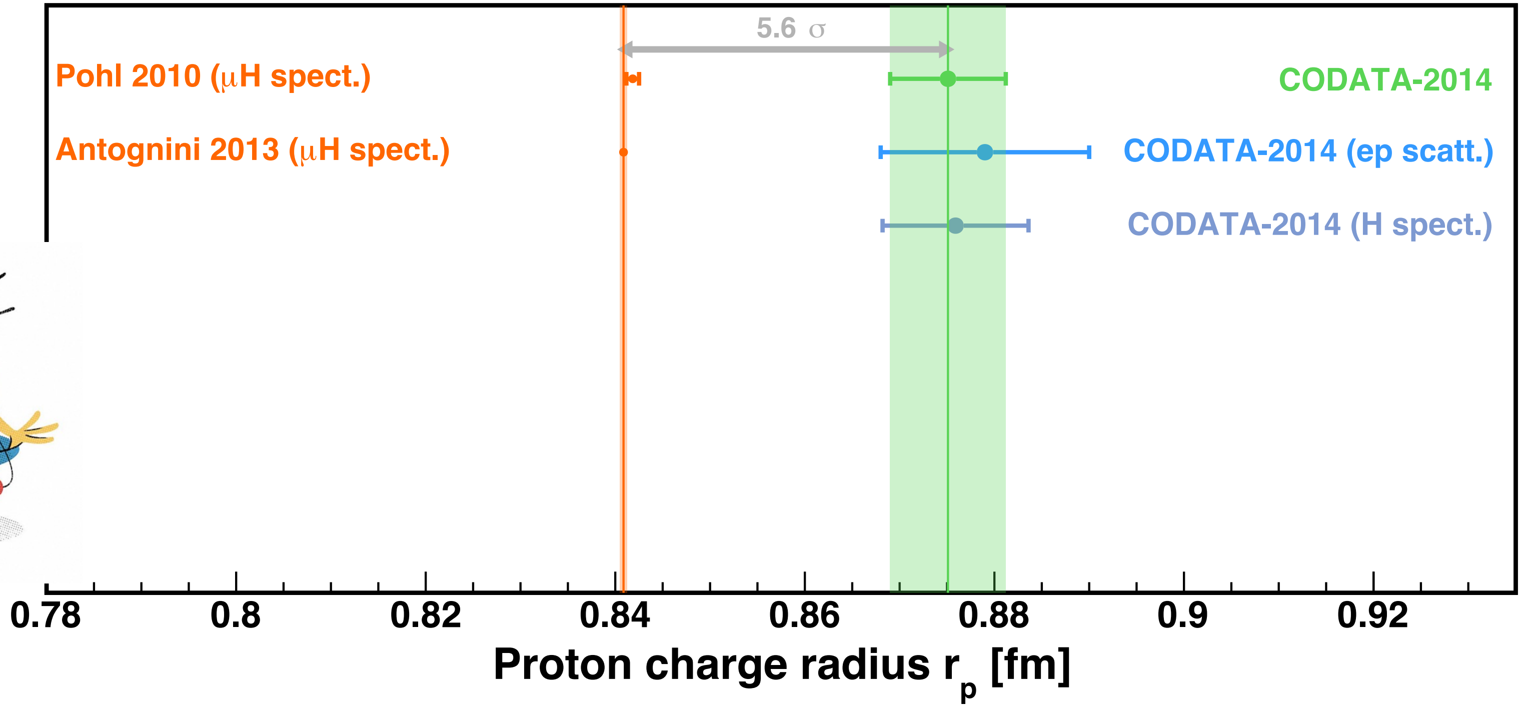


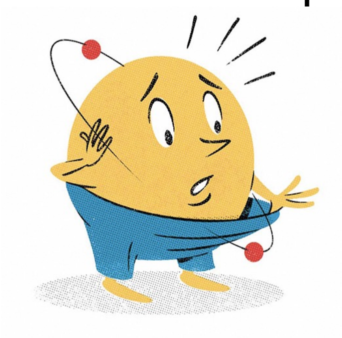




R. Pohl, et al., Nature 466, 213 (2010): 0.8409 ± 0.0004 fm
A. Antognini, et al., Science 339, 417 (2013): 0.84184 ± 0.00067 fm

The Proton Radius Puzzle: in 2010-2013





New York Times

Regular hydrogen average (CODATA): 0.8751 ± 0.0061 fm

Muonic hydrogen (CREMA coll. 2013): 0.8409 ± 0.0004 fm

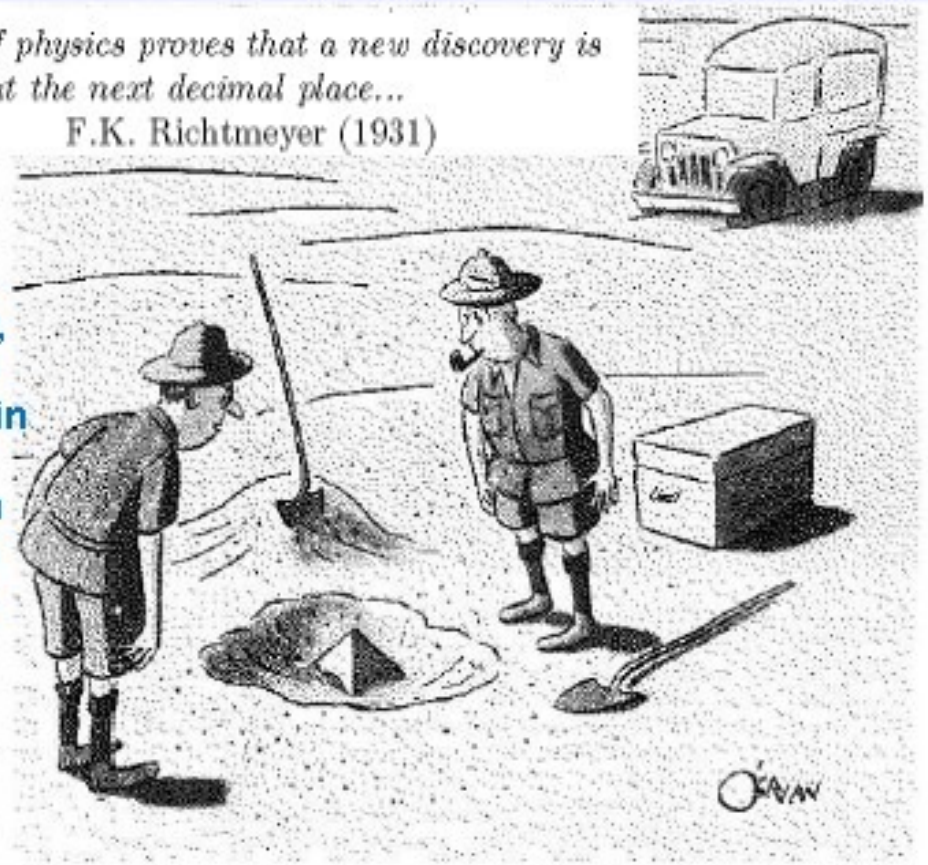
Muonic hydrogen (CREMA coll. 2010): 0.84184 ± 0.00067 fm

The Proton Radius Puzzle: an Archeological View

The proton radius puzzle

The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place...
F.K. Richtmeyer (1931)

Carlson & Rislow, PRD86: it may be possible to explain both g-2 and muonic hydrogen with new physics but seems highly fine tuned!



"This could be the discovery of the century. Depending, of course, on how far down it goes."

from T. Thomas

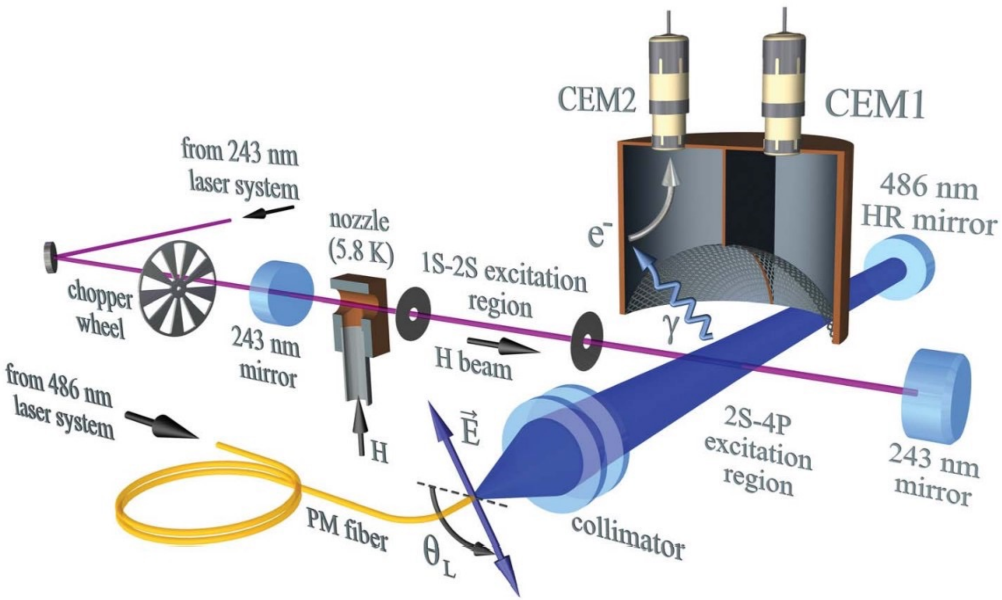
Possible Resolutions to the Proton Radius Puzzle

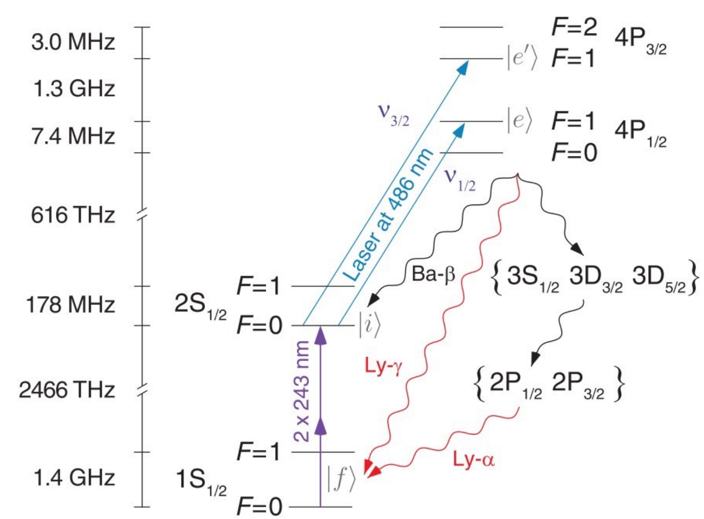
- Some initial open questions about QED calculations:
  - additional corrections to muonic-hydrogen. — Not found
  - missing contributions to electronic-hydrogen. — Not found
  - higher moments in electric form factor; — Not significant
  - …
- Is the ep-interaction the same as μp-interaction (the lepton universality principle)?
- New Physics (forces) beyond the Standard Model (SM)? — Not found yet
  - ✓ many models, discussions, suggestions …
- Potential solutions: need new high precision, high accuracy experiments:
  - ✓ ep-scattering experiments:
    - reaching extremely low Q^2 range (10^{-4} Gev/c^2)
    - possibly with new independent methods — PRad at JLab
    - measure absolute cross sections in ONE experimental setting!
    - MUSE at PSI, ISR at Mainz, ULQ^2 in Japan …
  - ✓ ordinary hydrogen spectroscopy experiments:
    - York University Canada, LKB in Paris, Garching group in Munic, …

New Ordinary Hydrogen Spectroscopy Experiment
(Garching group at PSI in 2017)

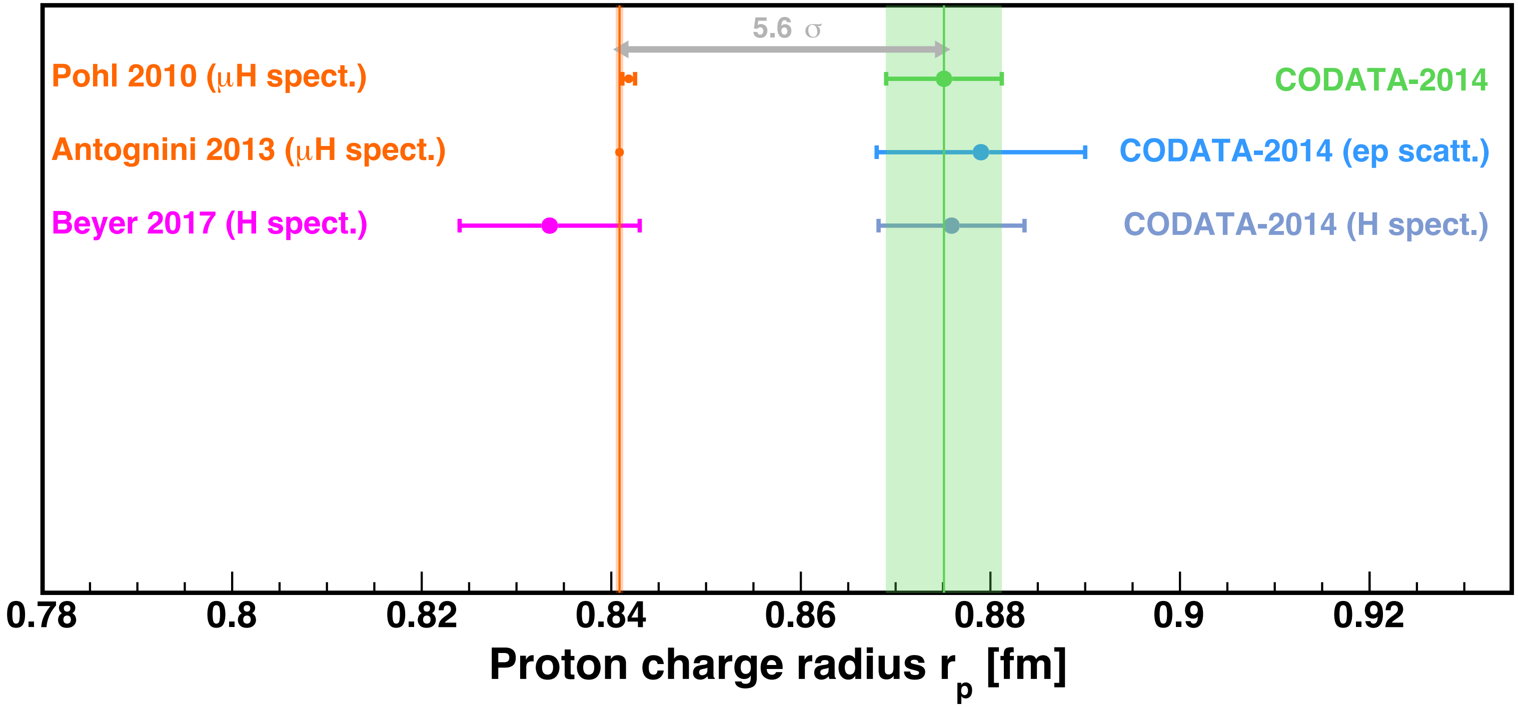
- 2S → 4P transition is measured in cryo-cooled ordinary atomic Hydrogen
- A. Beyer et al. Science 358, 79-86 (2017)

- $r_p = 0.8335 \pm 0.0095$ fm in good agreement with the muonic hydrogen results !!!





The Proton Radius Puzzle: 2017



Regular hydrogen average (CODATA): 0.8751 ± 0.0061 fm

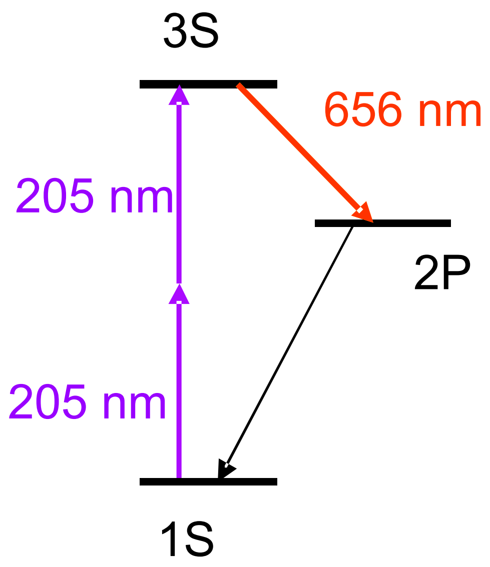
Muonic hydrogen (CREMA coll. 2013): 0.8409 ± 0.0004 fm

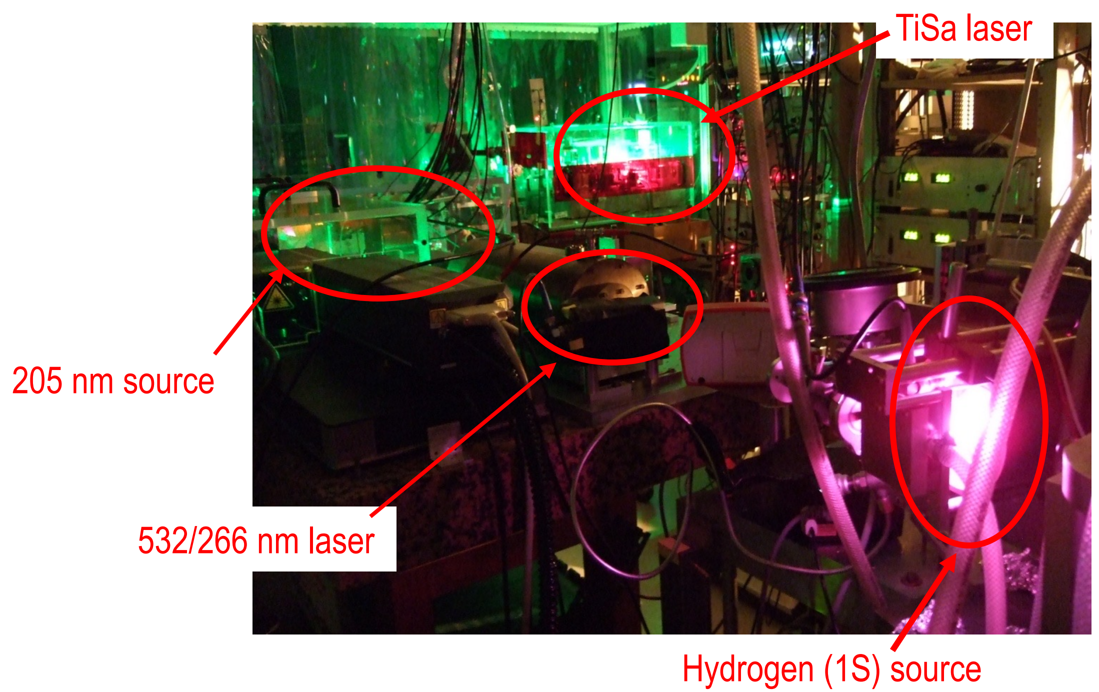
Regular H-spectr. (2S → 4P, Garching, PSI): 0.8335 ± 0.0095 fm

The Next Ordinary Hydrogen Spectroscopy Experiment
(LKB, Paris, 2018)

- 1S → 3S two photon spectrometry using ordinary hydrogen
- H. Fleurbaey et al. Phys. Rev. Lett., 120, 183001 (2018)

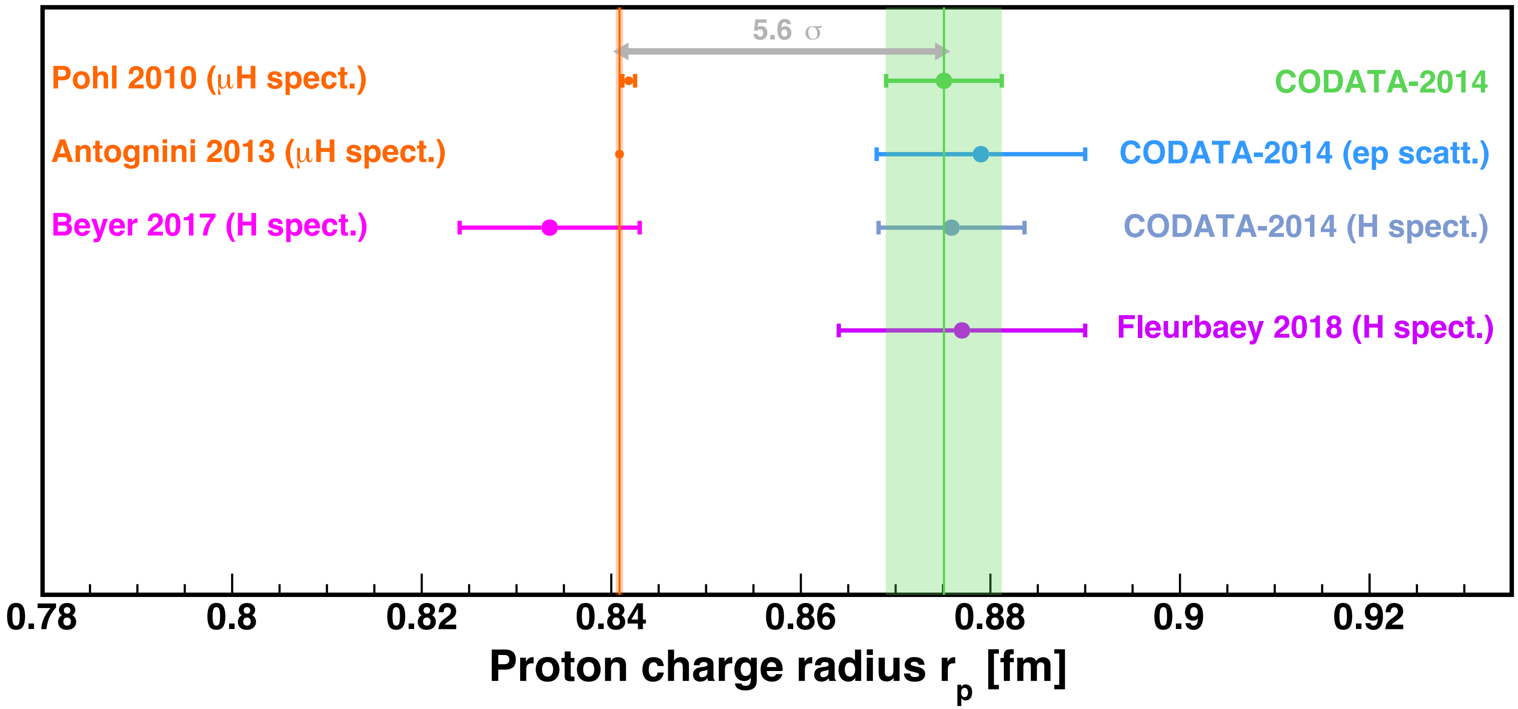
- $r_p = 0.877 \pm 0.013$ fm brings back to the larger radius !!!





from H. Fleurbaey

The Proton Radius Puzzle: 2018



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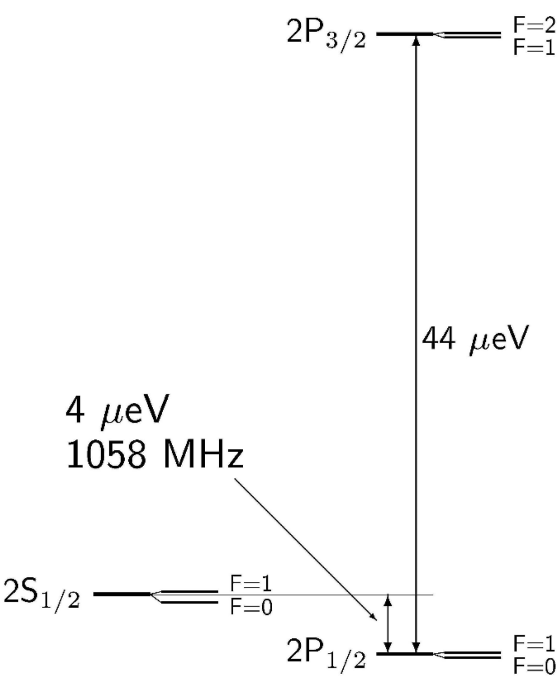
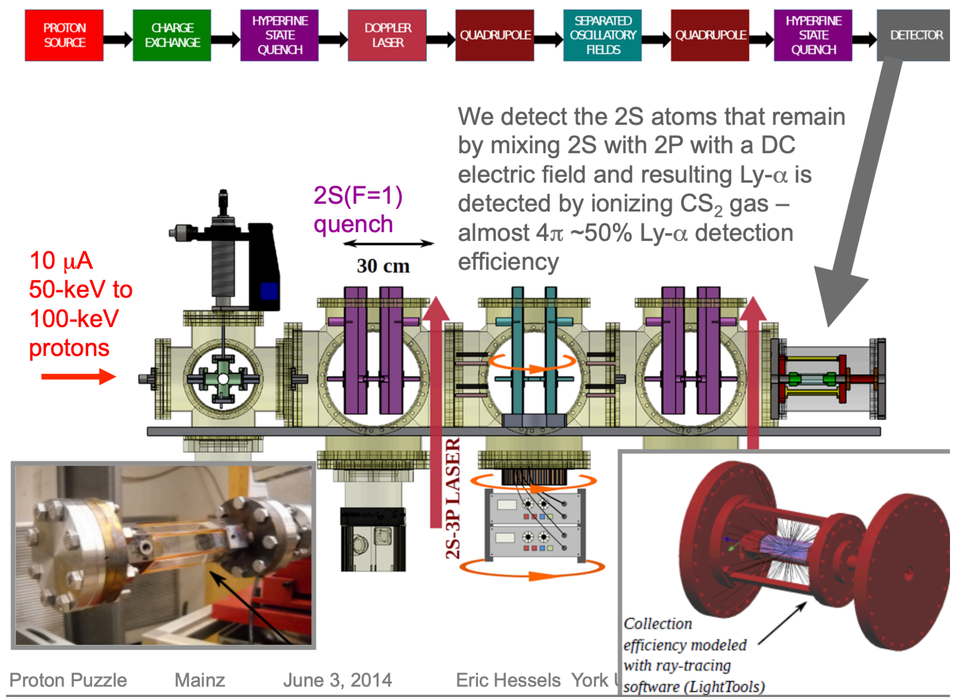
Muonic hydrogen (CREMA coll. 2013):	0.8409 ± 0.0004 fm
Regular H-spectr. (2S → 4P, Garching, PSI):	0.8335 ± 0.0095 fm
Regular H-spectr. (1S → 3S, LKB, Paris):	0.877 ± 0.013 fm

One More Ordinary Hydrogen Spectroscopy Experiment
(York Univ., Toronto, Canada. 2019)

- $2S_{1/2} \rightarrow 2P_{1/2}$ transition in ordinary hydrogen, no need for the Rydberg constant
- N. Bezginov et al. Science, v 365, 6457, 1007-1012, (2019)
- York University, Toronto, Canada

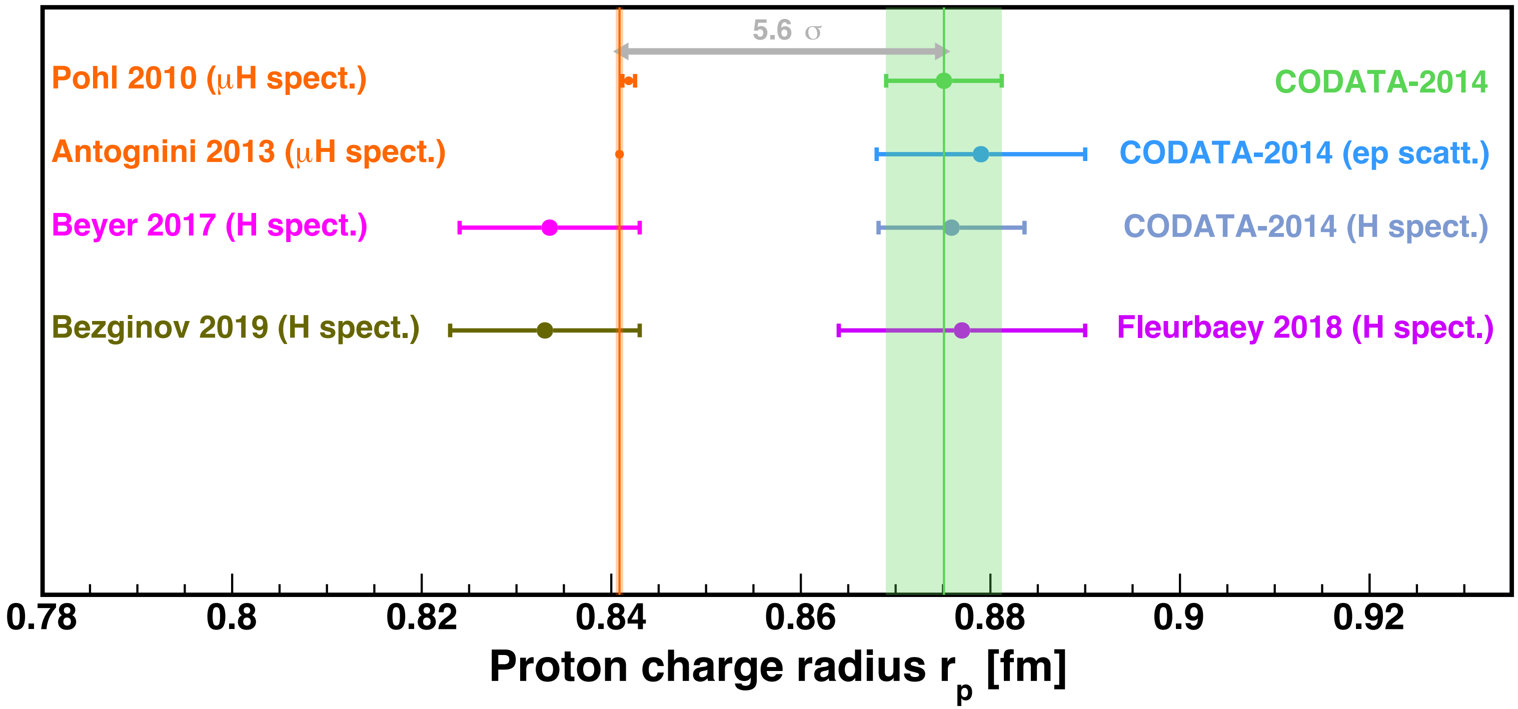
- r_p = 0.833 ± 0.010 fm in good agreement with the muonic hydrogen results !!!





The Proton Radius Puzzle: 2019

(3 months before the PRad publication)



Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013, PSI):	0.8409 ± 0.0004 fm
Regular H-spectr. (2S → 4P, Garching, PSI):	0.8335 ± 0.0095 fm
Regular H-spectr. (1S → 3S, LKB, Paris):	0.877 ± 0.013 fm
Regular H-spectr. ($2S_{1/2}$ → $2P_{1/2}$, York Un. Canada)	0.833 ± 0.010 fm

Back to Scuttering Experiments: PRad 2016 at JLab

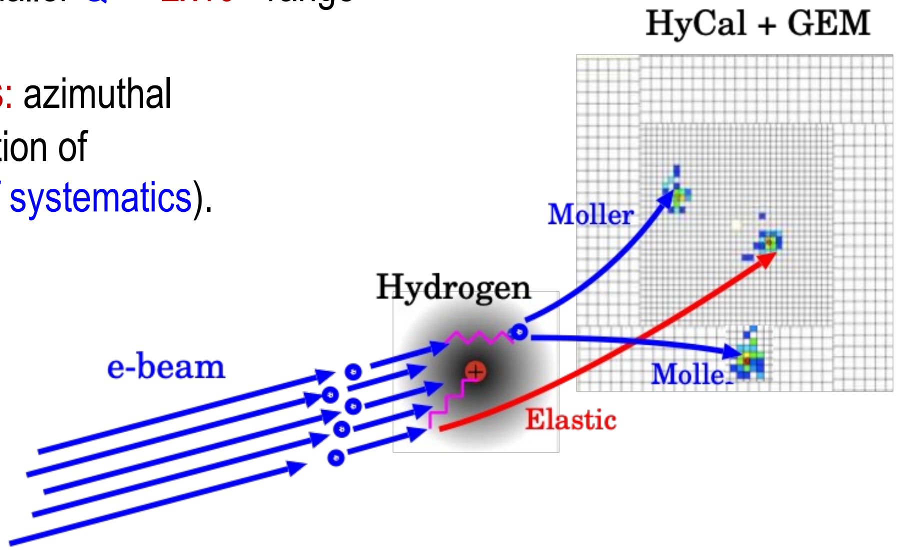
- Use large acceptance, high resolution electromagnetic calorimeter (together with a plain of GEM coordinate detectors):

  ✓ measure all angles in one experimental setting ($\vartheta_e = 0.6^0 - 7.0^0$) ($Q^2 = 2x10^{-4} \div 6x10^{-2}$) GeV/c^2;

  ✓ access to smaller angles ($\vartheta_e \approx 0.6^0$), and the smaller $Q^2 = 2x10^{-4}$ range

  ✓ calibrate with a well-known QED processes: azimuthal symmetry of the calorimeter, simultaneous detection of $ee \rightarrow ee$ Moller scattering (best known control of systematics).

- Use windowless cryogenic H_2 gas flow target to minimize experimental background.



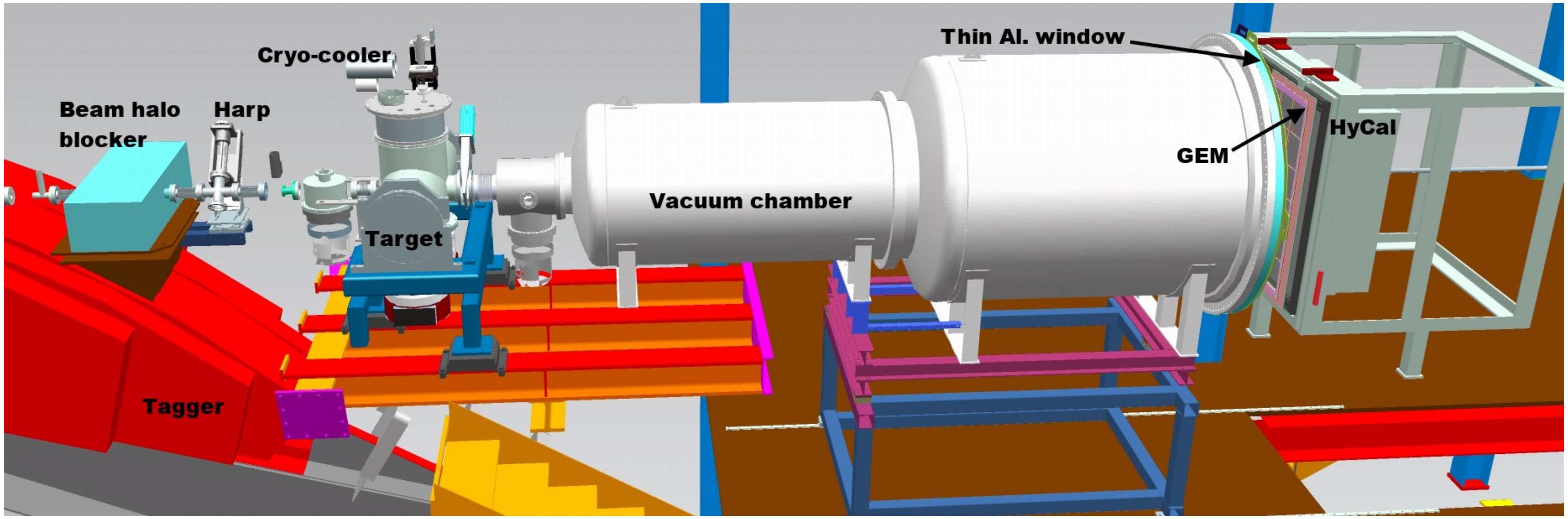
PRad result: $R_p = 0.831 \pm 0.007$ (stat.) ± 0.012 (syst.) fm

PRad Experimental Setup in Hall B at JLab

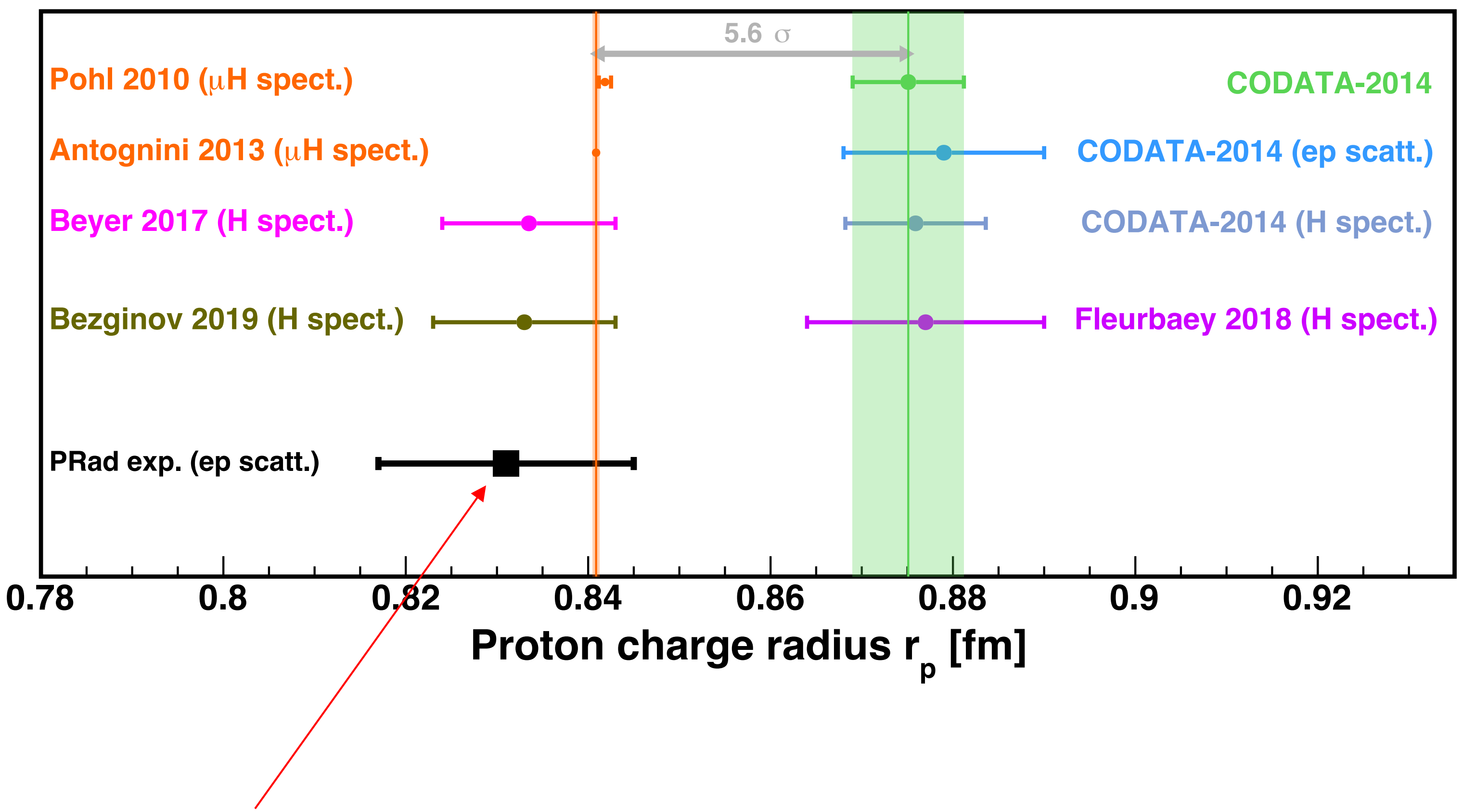
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo "cleanup")
  - Harp 2H00 I

e - beam

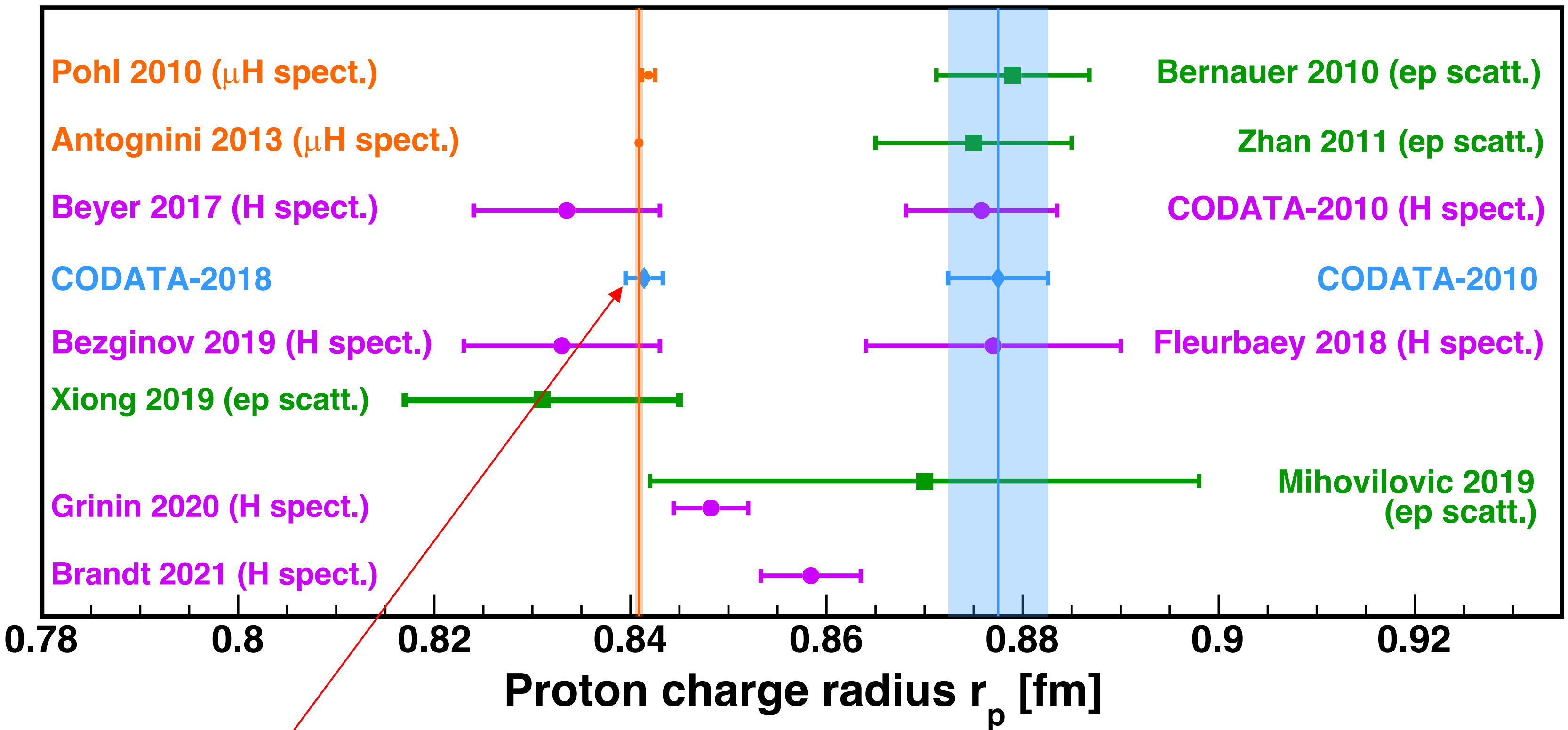


The PRad Final Result on the Radius



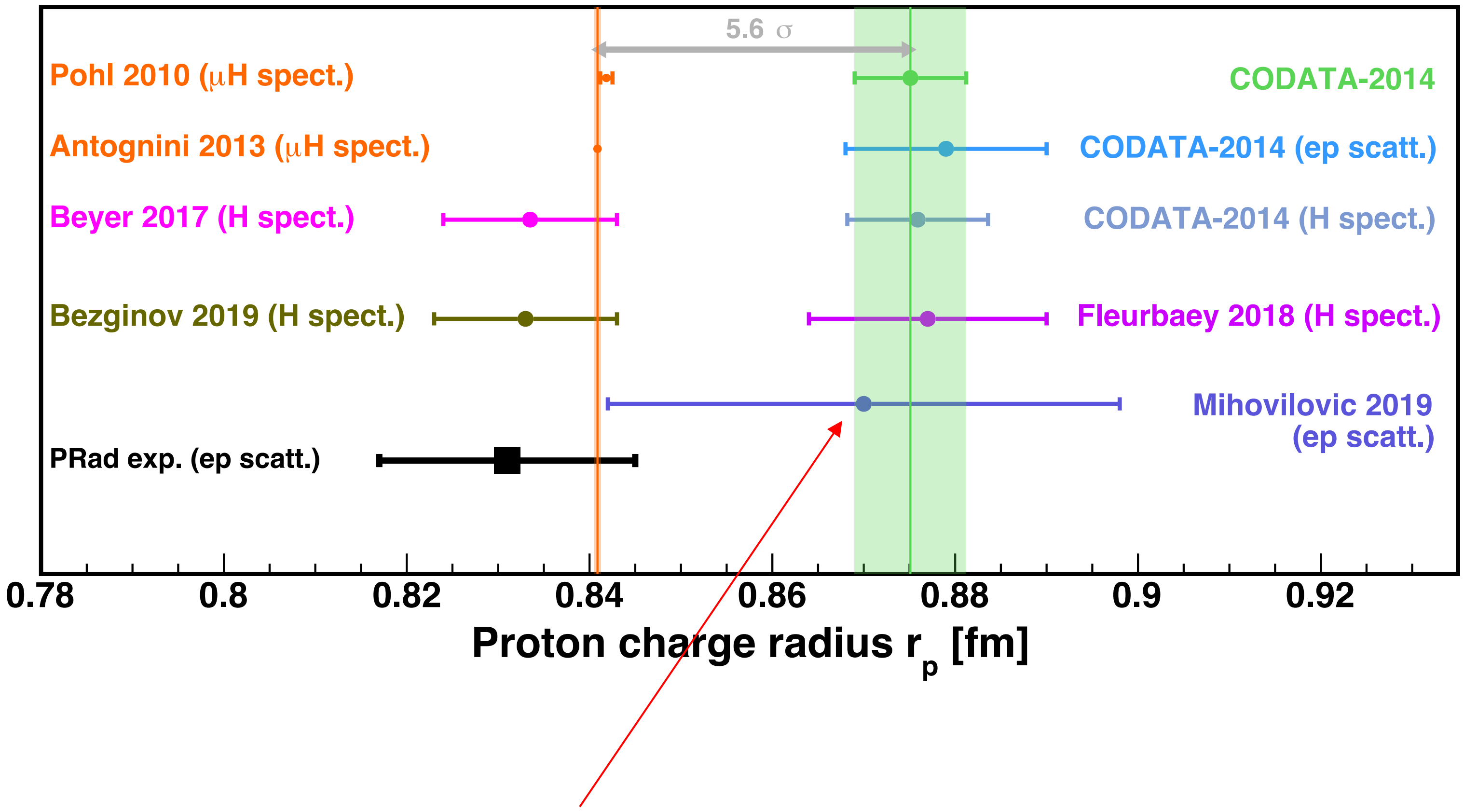
PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm

CODATA New Recommendation for the Proton Charge Radius (2018)



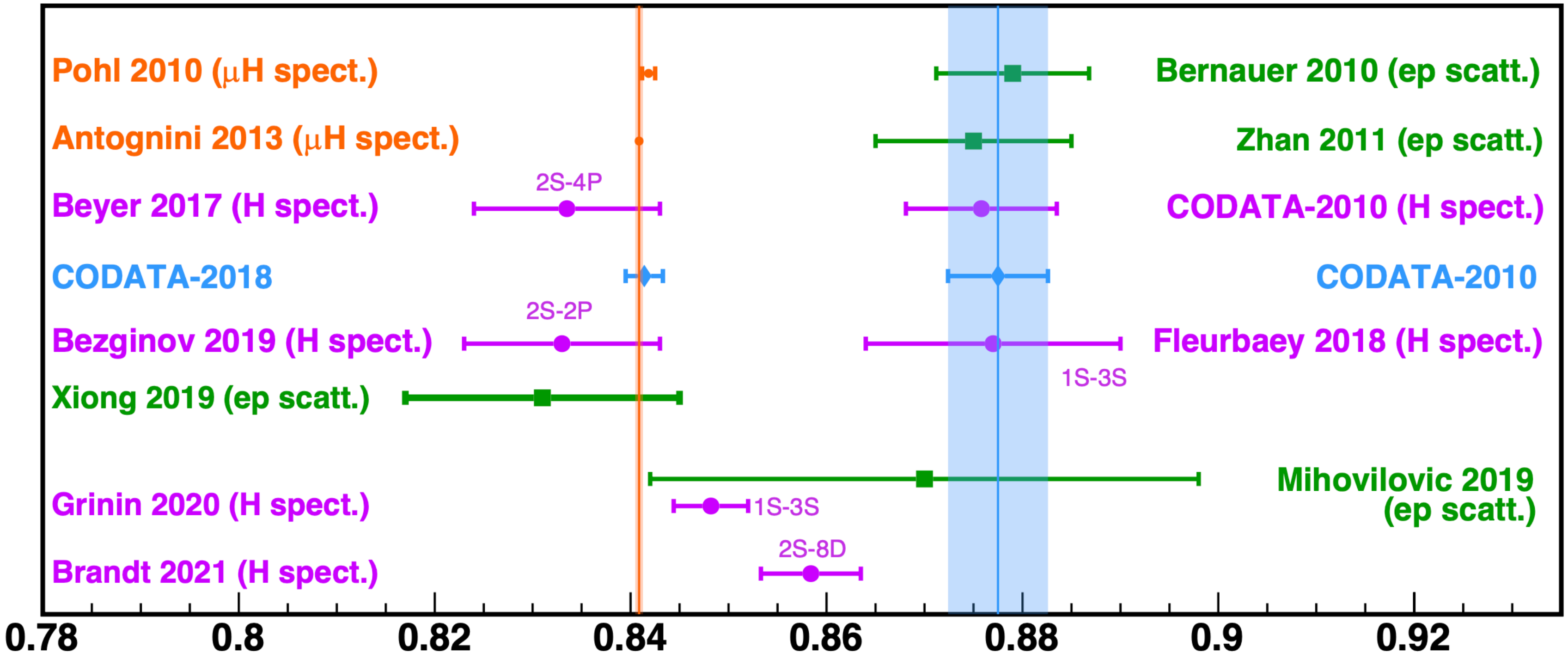
CODATA Recommended value on Proton Charge Radius from 2018

The PRad Final Result on the Radius with the Mainz ISR



MAMI Mainz new ep scuttering experiment with initial state radiation

Recent New Hydrogen Spectroscopy Results



What is Next? Or the Current Open Questions

- Arguably, the "Puzzle" is still not fully resolved! New high accuracy experiments are needed.
- Difference between PRad and all other ep scattering experiments is on 3σ level only.

- Also, there is certain visible discrepancy between the very recent FF measurements.

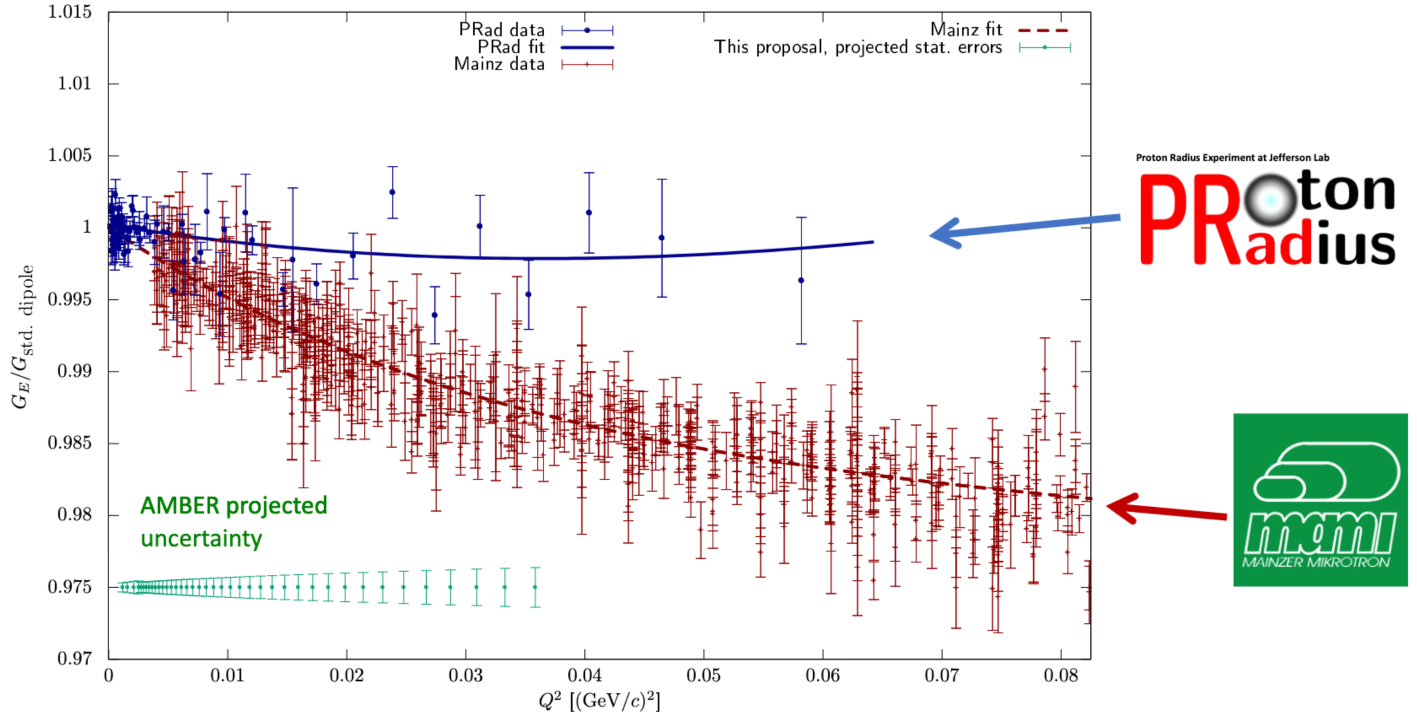
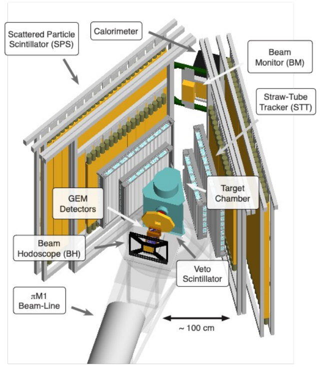


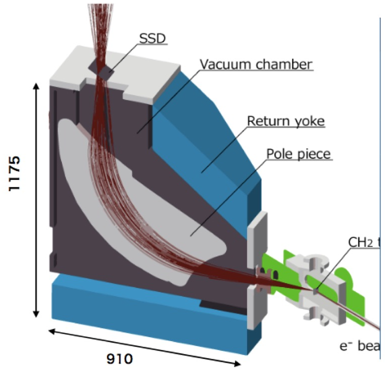
figure: J. Bernauer

New Scuttering Experiments in Progress

- MUSE at PSI: measure μp and ep scattering (Q^2 range $2x10^{-3} \div 10{-}2$ GeV^2):
  - test of lepton universality;
  - extraction of proton radius;
  - Check Tigran's talk on Wednesday afternoon.

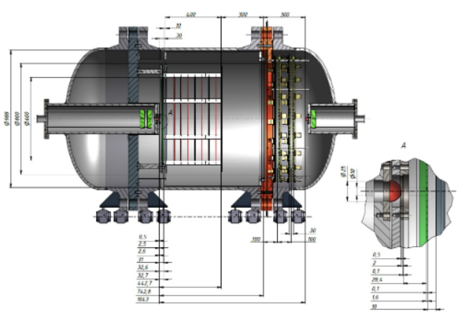


- ULQ^2 at Tohoku Univ. Japan (Q^2 ,10^{-4} – 10^{-3} GeV^2):
  - 20 ÷ 60 MeV electron beam;
  - extract the proton radius
  - in the data taking stage.



- High pressure hydrogen gas TPC detector at Mainz,
  - ep→ep scattering at moderate energies;
  - detection of recoil proton;
  - promising to reach $Q^2 = 10^{-5}$ GeV^2 range;
  - extraction of the proton radius;
  - In progress

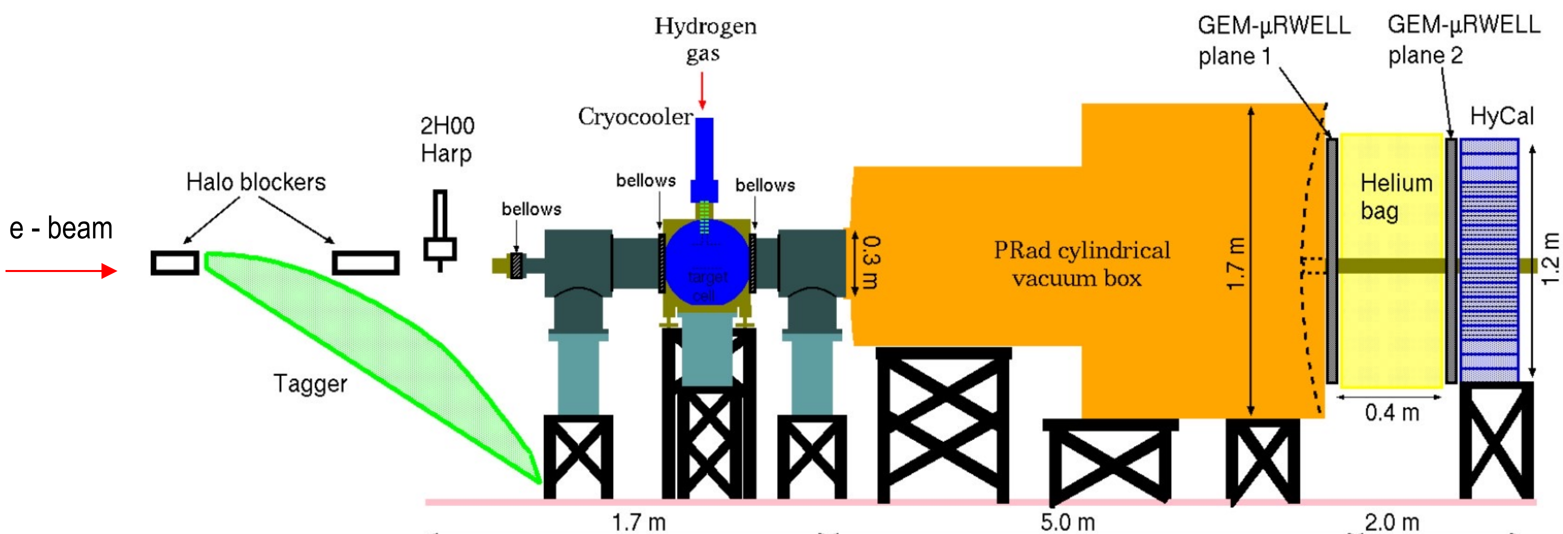
- The same high pressure hydrogen TPC detector at COMPASS (Q^2 range: 10^{-4} – 1 GeV^2):
  - $\mu p \to \mu p$ scattering at high energies;
  - detection of the recoil proton;
  - extract the proton radius;
  - in progress.



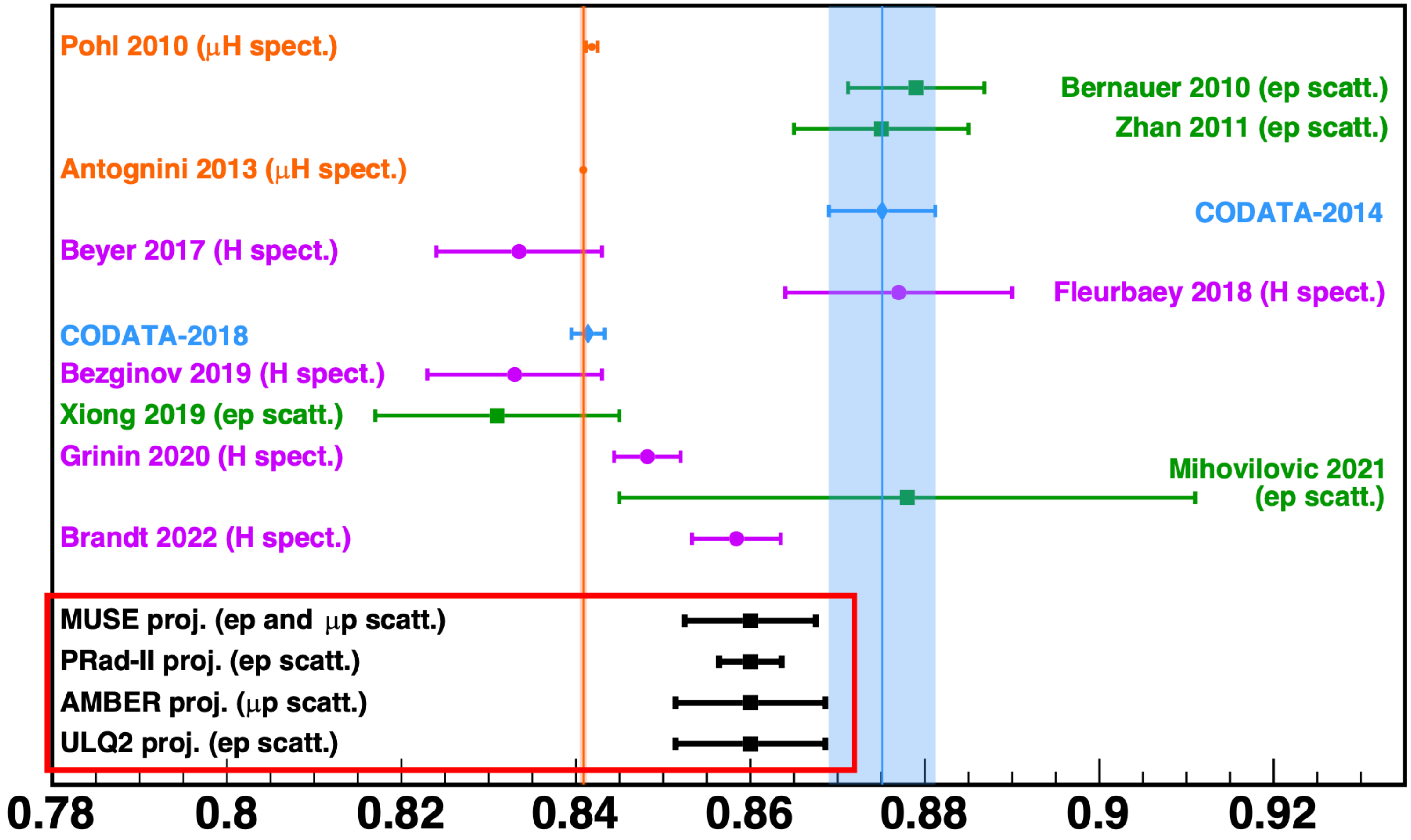
New PRad Experiment: PRad-II at JLab

- JLab "A" rated approved experiment (E12-20-004)
  - second GEM detector plane for tracking
  - new fADC based DAQ system for more statistics
  - new scintillator detectors to reach $Q^2 = 10^{-5}$ GeV^2 range
  - very accurate form factor measurement to resolve the current discrepancy between modern ep-scuttering experiments.
    ~ 4 times better extraction of the proton radius.

- Planned to run in Fall 2025 in Hall B at JLab



Future Lepton Scuttering Experiments
(projected to the middle value)



Summary and Outlook

- Many high precision spectroscopy and scuttering experiments in the past 15 years:
  - ✓ CODATA changed the values of the proton charge radius and the Rydberg constant
  - ✓ tensions between new Hydrogen spectroscopy results.
  - ✓ difference between PRad and all ep-scuttering experiments is 3 σ level only
  - ✓ significant, even visible difference between PRad and MAMI form factors

Is the Proton Radius Puzzle resolved ???

New high accuracy experiments in both sectors are needed to have a conclusive answer.

- Look forward for new experiments:
  - ✓ upcoming munic hydrogen spectroscopy experiment with 1S hyperfine splitting
  - ✓ first r_p measurements from muon scuttering experiments: MUSE and AMBER;
  - ✓ New ep-scuttering experiments: ULQ2 in Tohoku Japan, MAGIX and PRES in Mainz, PRad-II JLab

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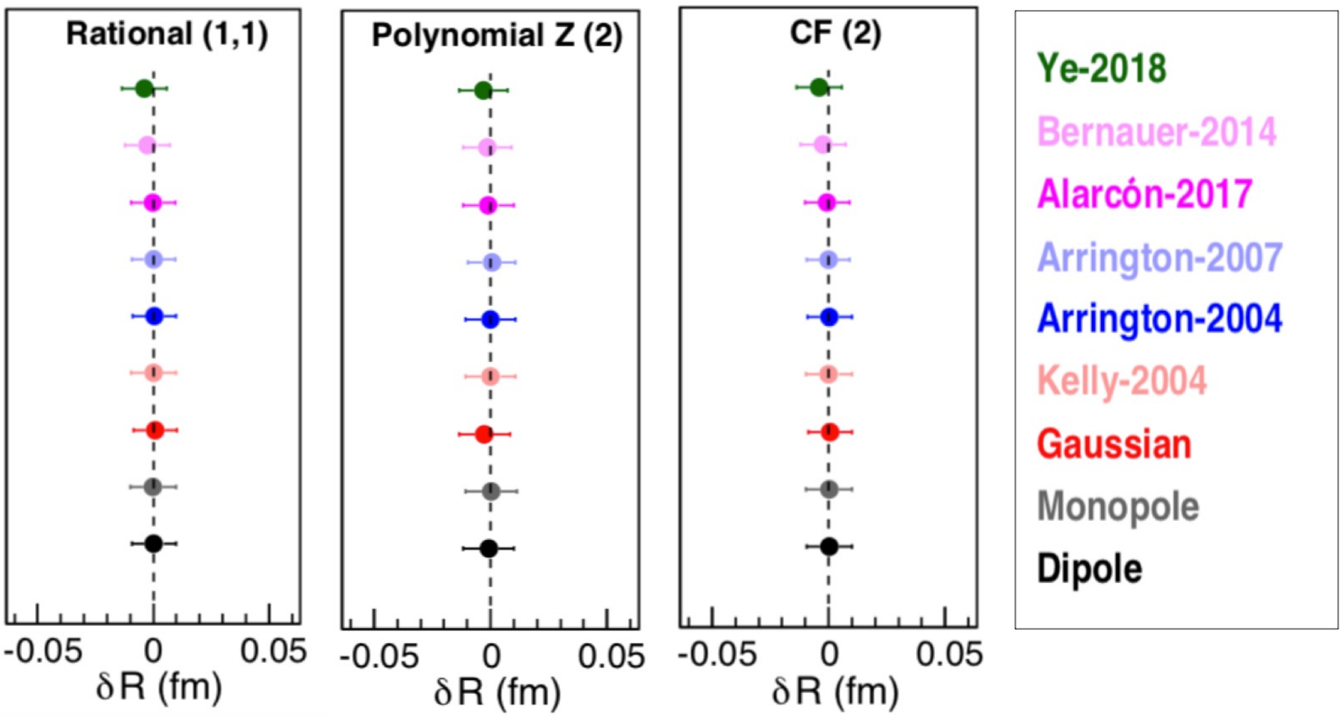
Thank you!

Recent Developments in Fitting Procedures



Rational (1,1)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order z transformation

$$p_0(1 + p_1 z + p_2 z^2)$$

$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

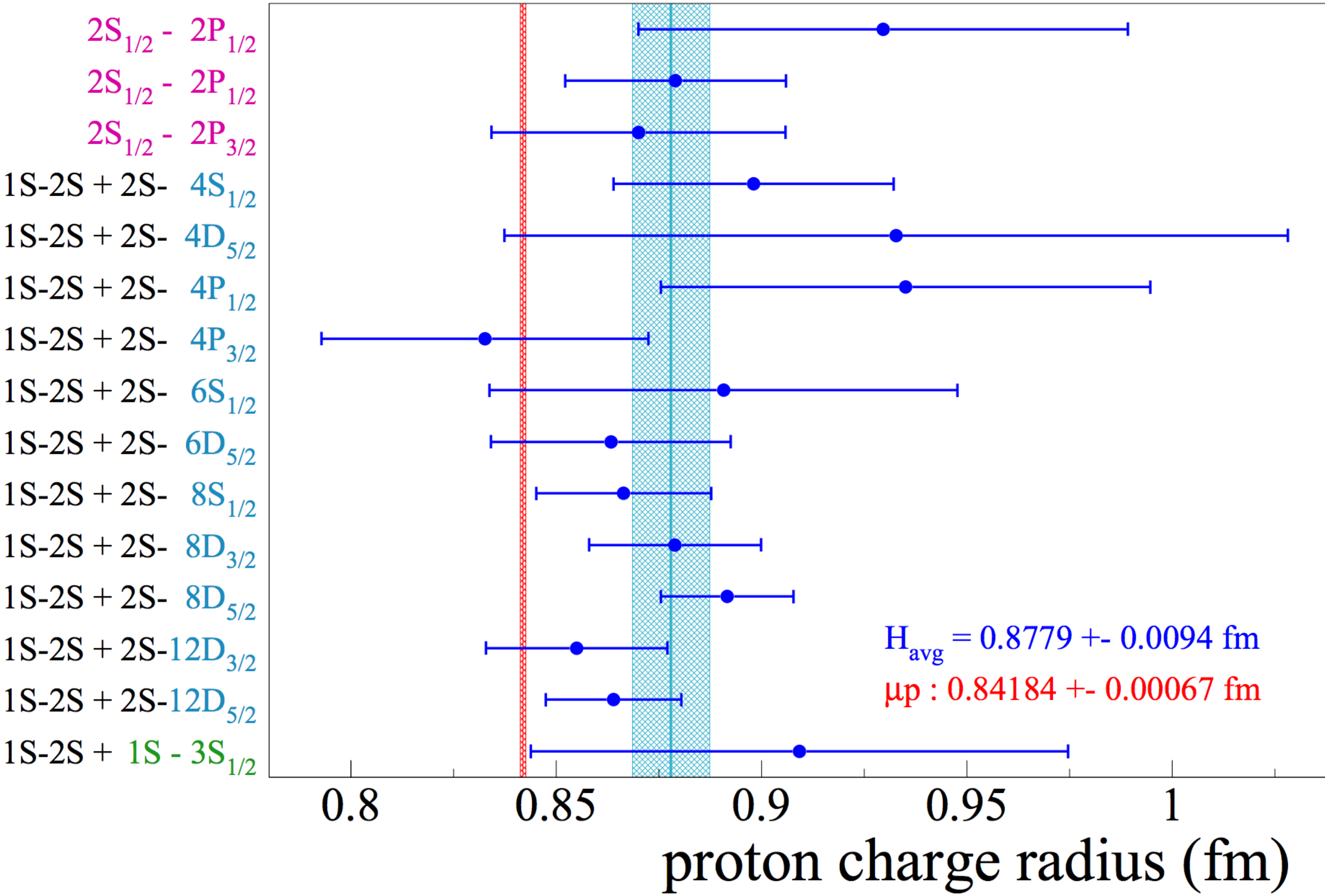
2nd order continuous faction

$$p_0 \frac{1}{1 + \frac{p_1 Q^2}{1 + p_2 Q^2}}$$

The robustness = root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{(\delta R)^2 + \sigma^2},$$

Proton Radius from Regular Hydrogen Spectroscopy
(before 2012)



The Latest High Precision ep-scuttering Experiment:

(MAMI A1, Mainz, 2010)

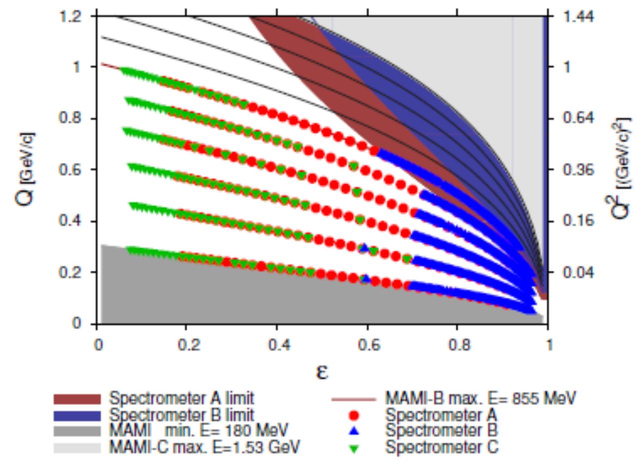
- Practically all ep-scattering experiments are performed with magnetic spectrometers and LH_2 targets!

  - ✓ high resolutions but, very SMALL angular and momentum acceptances:
    - need many different settings of angle (Θ_e) , energies (E) to cover a reasonable Q^2 fitting interval
    - normalization of each Q^2 bins
    - thair systematic uncertainties

  - ✓ limitation on minimum Q^2: 10^{-3} GeV/C^2
    - min. scattering angle: $\theta_e \approx 5^0$
    - typical beam energies ($E_e \sim 1$ GeV)

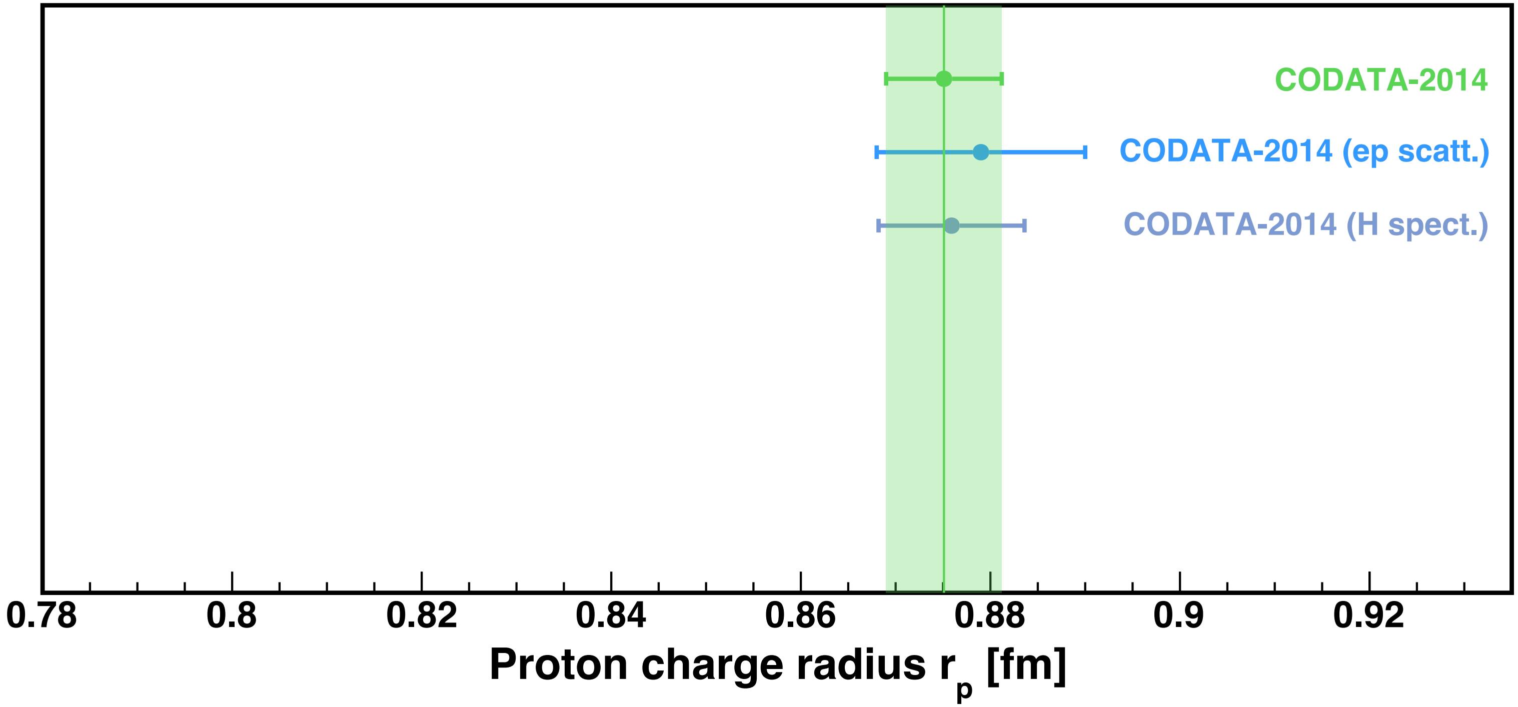
  - ✓ limits on accuracy of cross sections (dσ/dΩ): ~ 2 ÷ 3%
    - statistics is not a problem (<0.2%)
    - control of systematic uncertainties???
    - beam flux, target thickness, windows,
    - acceptances, detection efficiencies,
    - ...

Three spectrometer facility of the A1 collaboration:



Proton Radius Before Muonic Hydrogen Experiment

(before 2010)



CODATA average:	0.8751 ± 0.0061 fm
ep-scattering average (CODATA):	0.879 ± 0.011 fm
Regular H-spectroscopy average (CODATA):	0.859 ± 0.0077 fm

Very good agreement between ep-scattering and H-spectroscopy results !

The Main Beamline and Detection Elements