Progress on Proton Charge Radius Measurements

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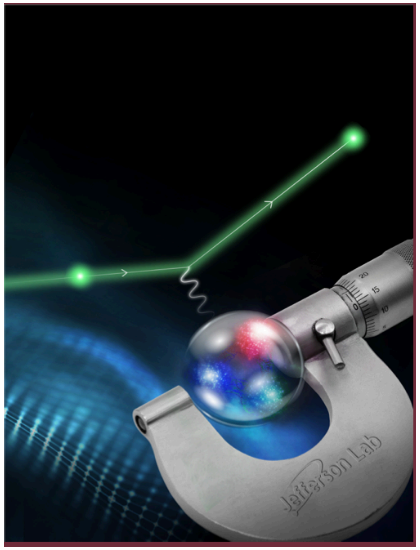
Outline

- methods of proton radius measurement
- the proton radius puzzle
- PRad experiment and the results
- new experiments
- summary and outlook

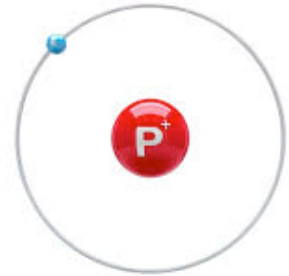
PRoton Radius

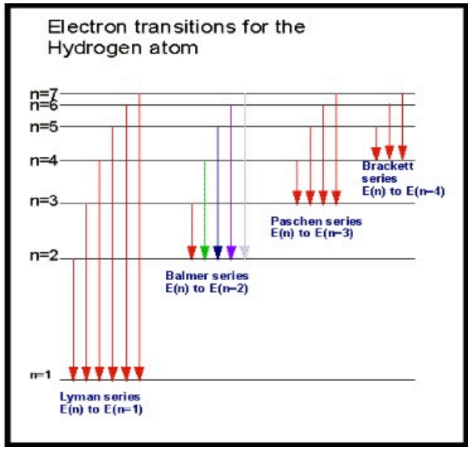


Proton Charge Radius

One of the most fundamental quantities in physics:

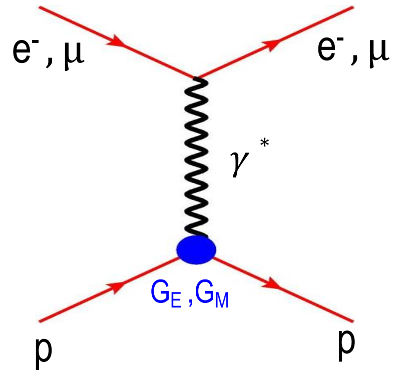
- atomic physics:
  - ✓ precision atomic spectroscopy (QED, Lamb shifts, Rydberg constant R_∞);
  - ✓ r_p is strongly correlated to R_∞
- nuclear physics:
  - ✓ QCD, test of nuclear/particle models
- connects atomic and subatomic physics.





Methods to measure the proton rms charge radius (r_p):

- Hydrogen spectroscopy (lepton-proton bound state, Atomic Physics):
  - ordinary hydrogen
  - muonic hydrogen
- Lepton-proton elastic scattering (nuclear physics):
  - ep- elastic scattering (Mainz-A1, PRad, …)
  - μp- elastic scattering (MUSE, AMBER …)

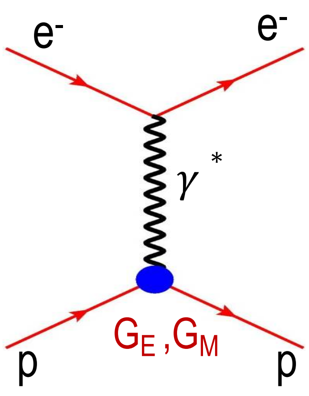


Proton Radius from ep→ep Scattering Experiments

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

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

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

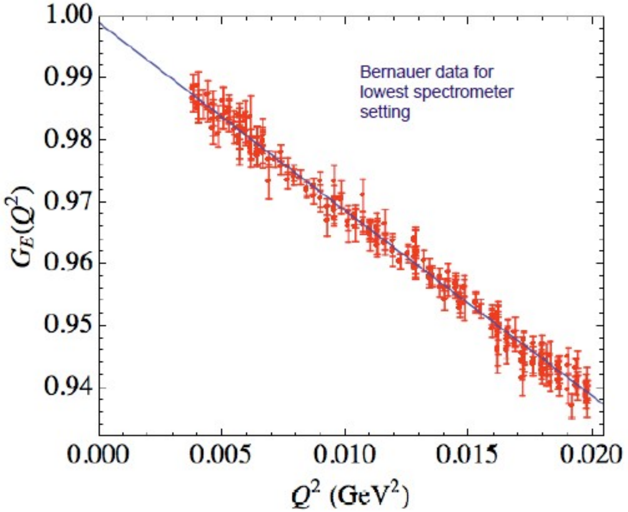


- Structureless proton:

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

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

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



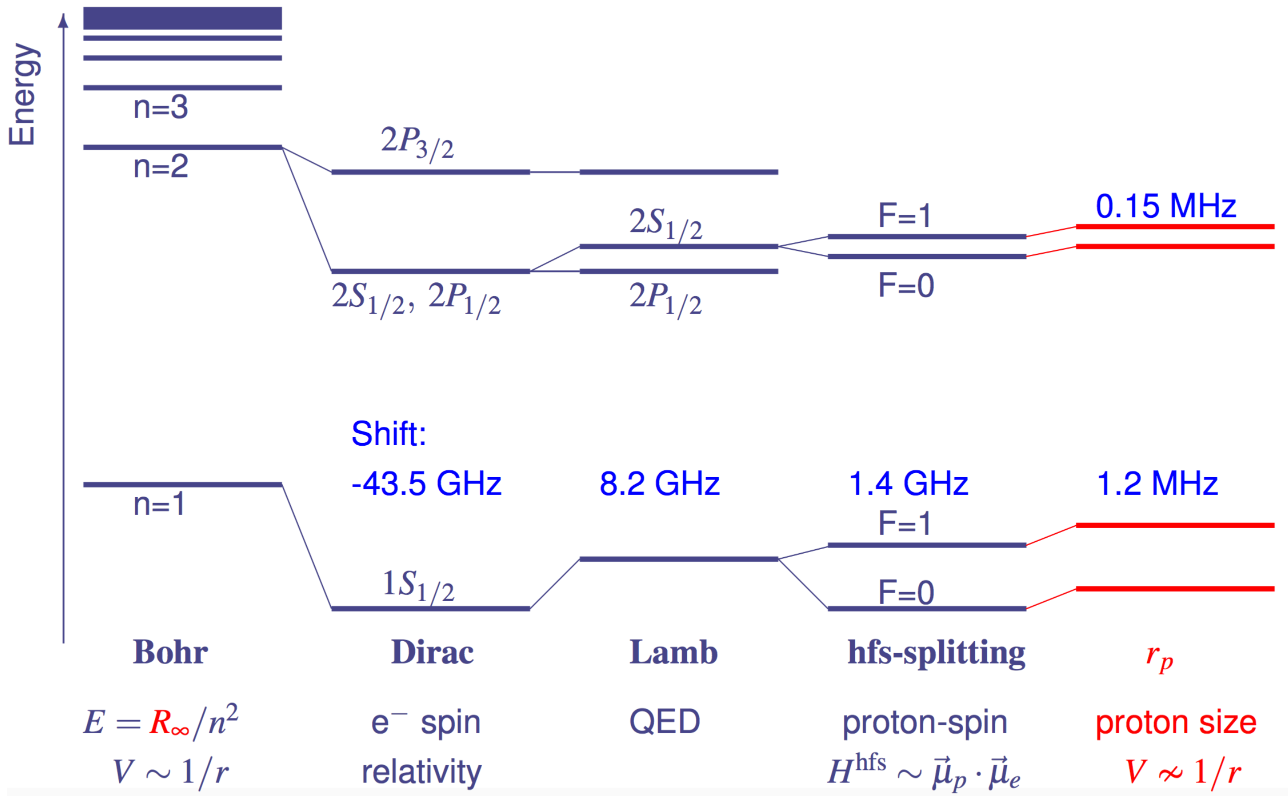
derivative at $Q^2 = 0$:

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

definition of the proton rms charge radius →

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

Proton Radius from Hydrogen Spectroscopy Experiments



- Difference between energy levels has been measured
  - ✓ with accuracy of 1.4 part in 10^{14}
  - ✓ using atomic cesium as a frequency standard
  - ✓ also yields the Rydberg constant, R_∞

- electron in S states is sometimes inside the proton.
  - ✓ S-states are shifted by the size of proton
  - ✓ shift is proportional to the size of the proton
- in P states electron is not inside the proton.
- P-S transitions better for proton radius measurement

The First Proton Charge Radius Measurements

- Robert Hofstadter, experiments in 1955-1956
  - ✓ ep-elastic scattering
  - ✓ E_e = 188 MeV electron beam
  - ✓ at Stanford University

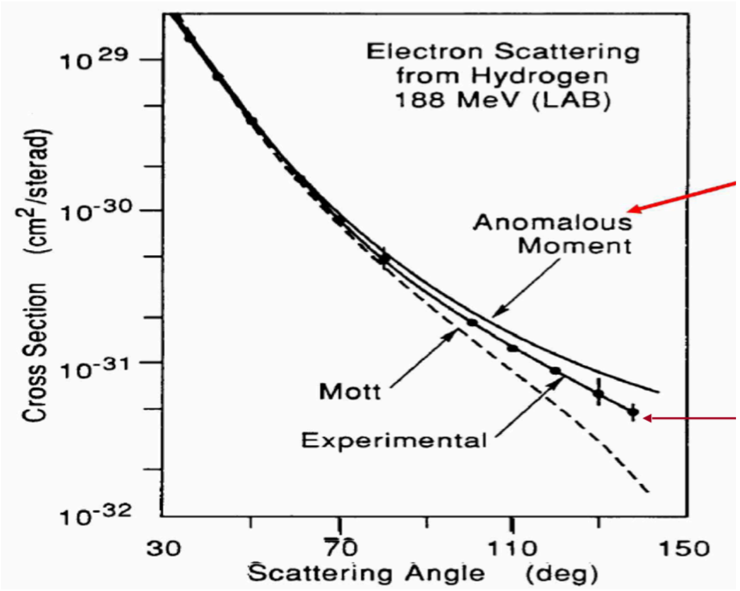
- Nobel prize in 1961:
  "*for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the* ***structure of nucleons***"

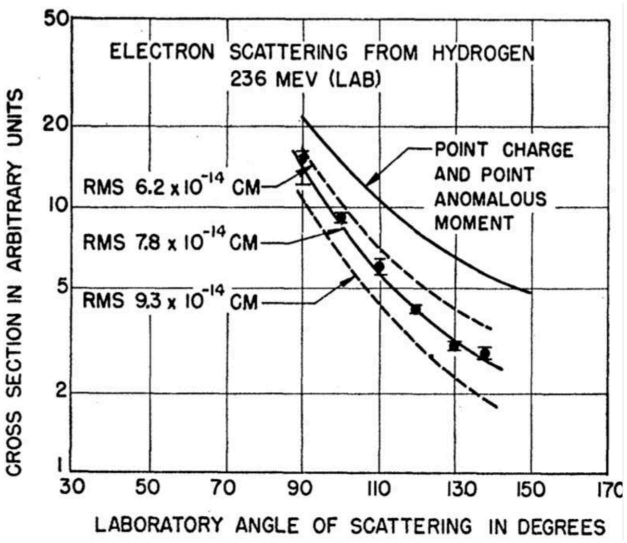
"***proton has a diameter of 0.74 ∓ 0.24 x 10^{-13} cm***"

r_p = 0.74 fm with a 32% uncertainty

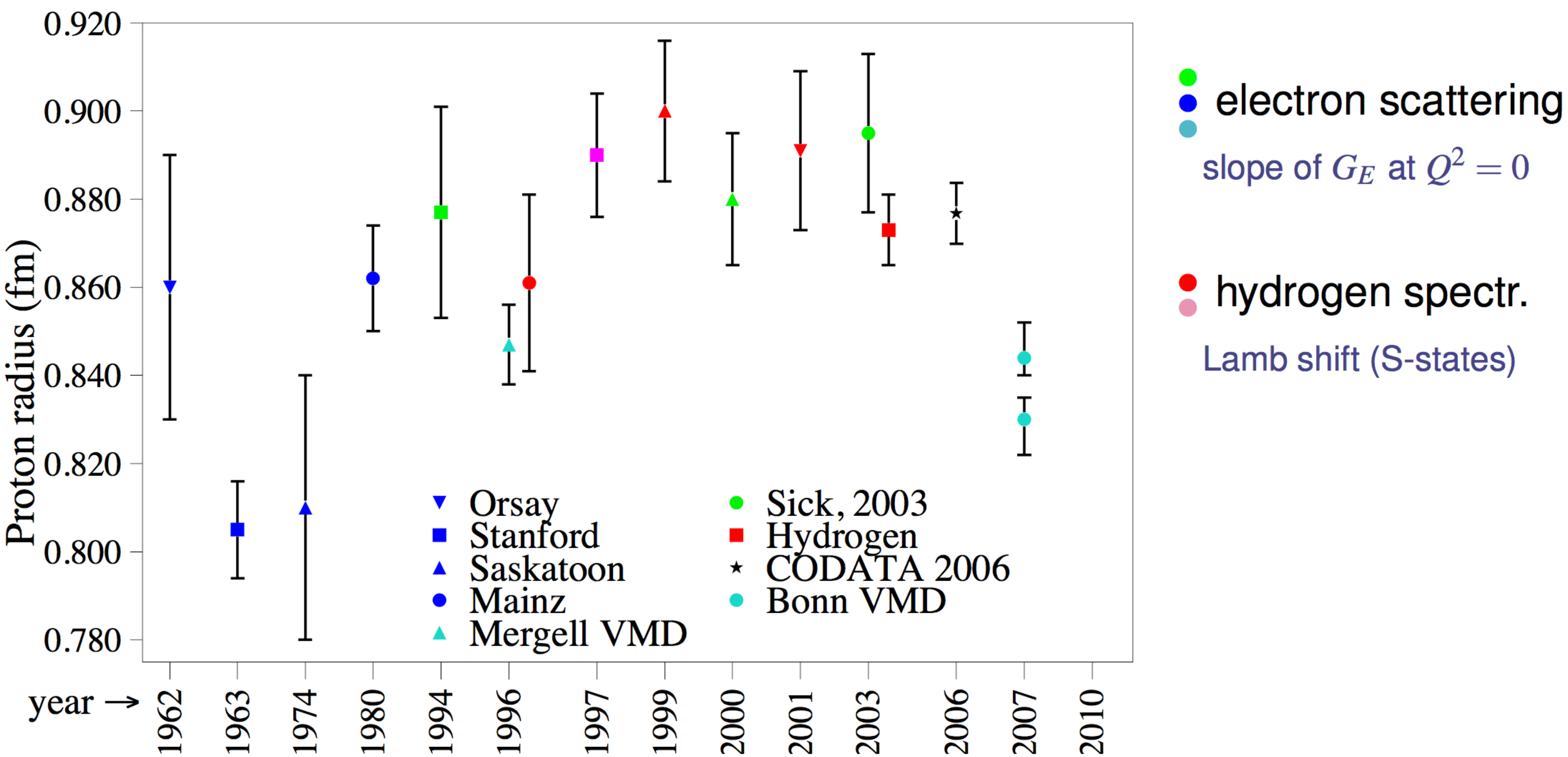
Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956)

- Over 50 years of experimentation!
  - ✓ started from 0.74 fm
  - ✓ ended to 0.895 fm by 2010.
  - ✓ where we are now ???





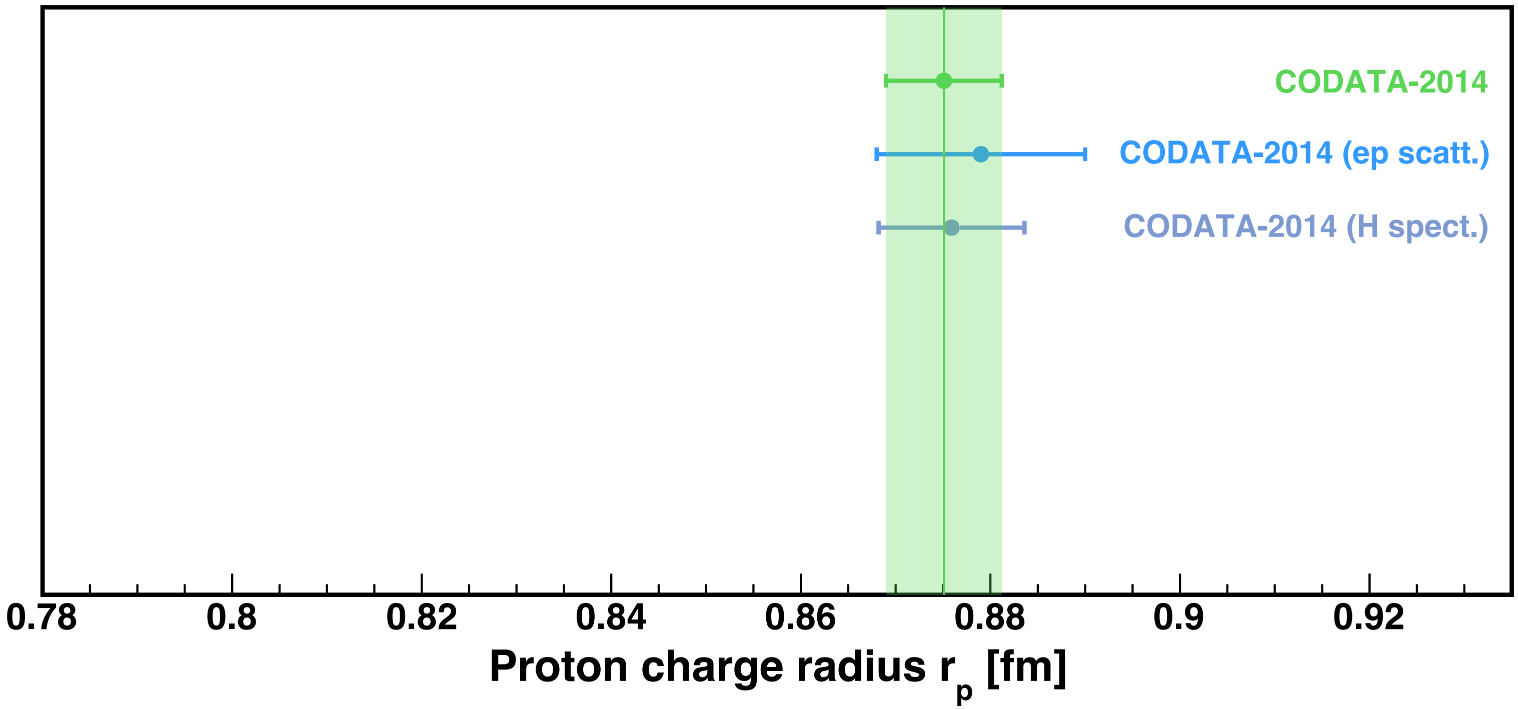
Proton Charge Radius vs. Time (before 2010)



from R. Pohl

e-p scattering:	0.895(18) fm (σ_r = 2%)
Hydrogen spectroscopy:	0.8760(78) fm (σ_r = 0.9%)

Proton Radius before the *Puzzle*



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 !

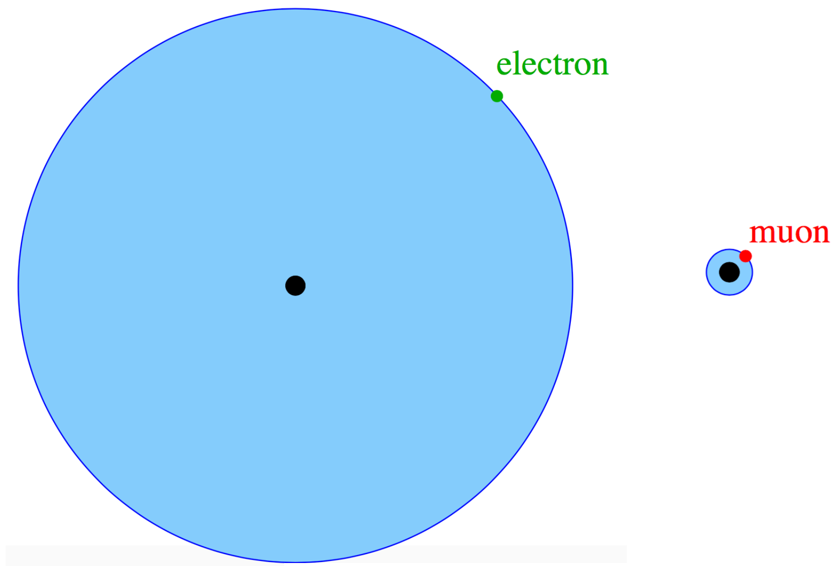
New method: Muonic Hydrogen Precision Spectroscopy

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

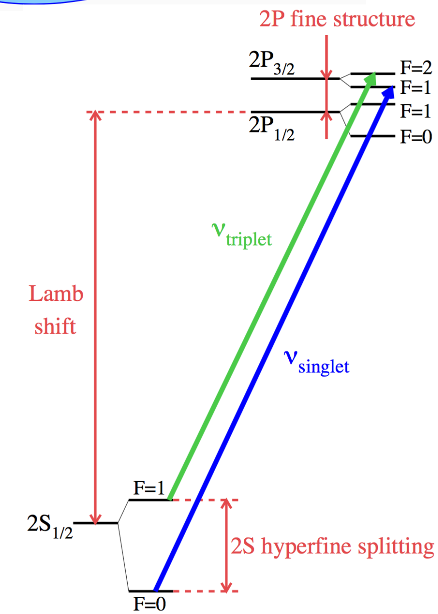
- Transition energy difference, ΔE:

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

  ✓ μ is ~ 8×10^6 more sensitive to the Proton Radius !!!



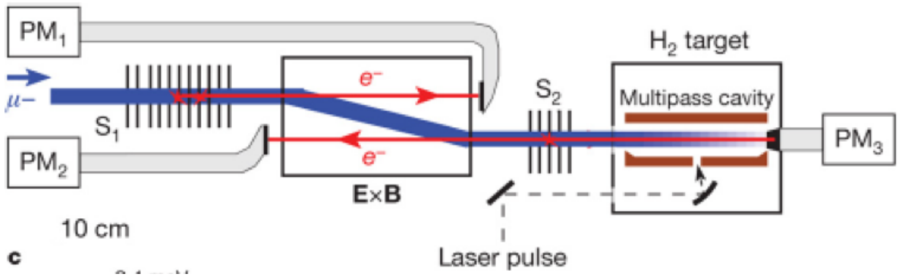
- Lamb shift in μH:
  $\Delta E = 206.0668(25) - 5.2275(10)\, R_p^2$ meV
  proton size is ~2% correction to μH Lamb shift.

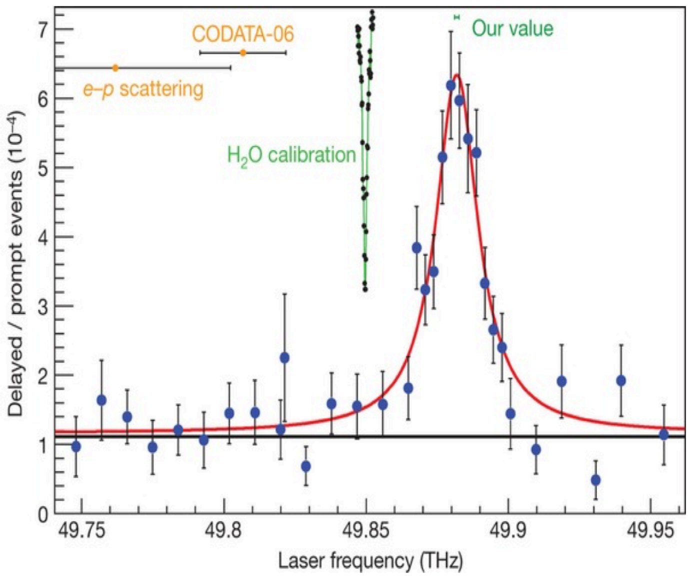


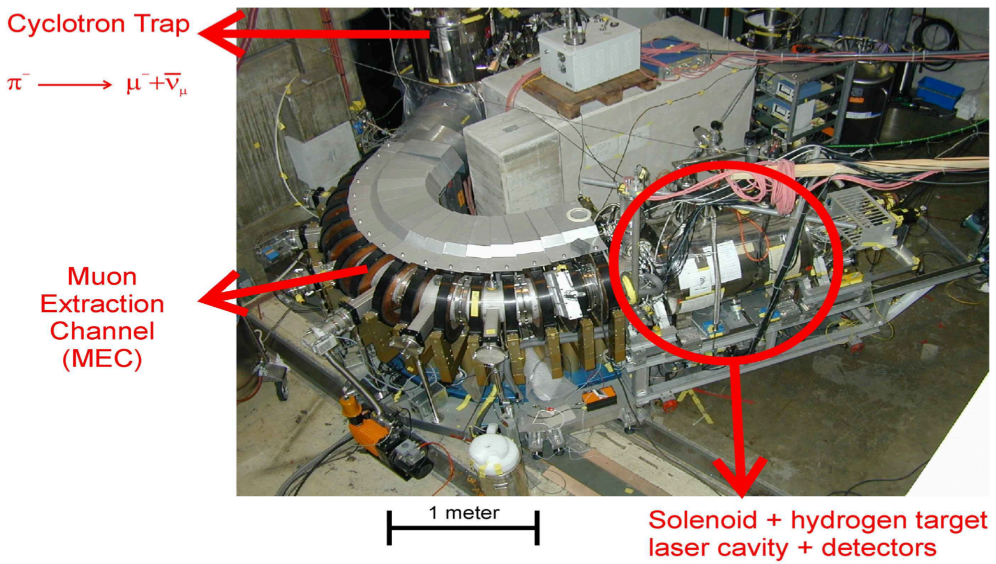
- Two experiments performed at PSI (CREMA collaboration) for proton radius in 2010 and 2013 with ~10 times higher precision (≤ 0.1%) compered to all previous experiments.

Muonic Hydrogen Experiments

- 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.





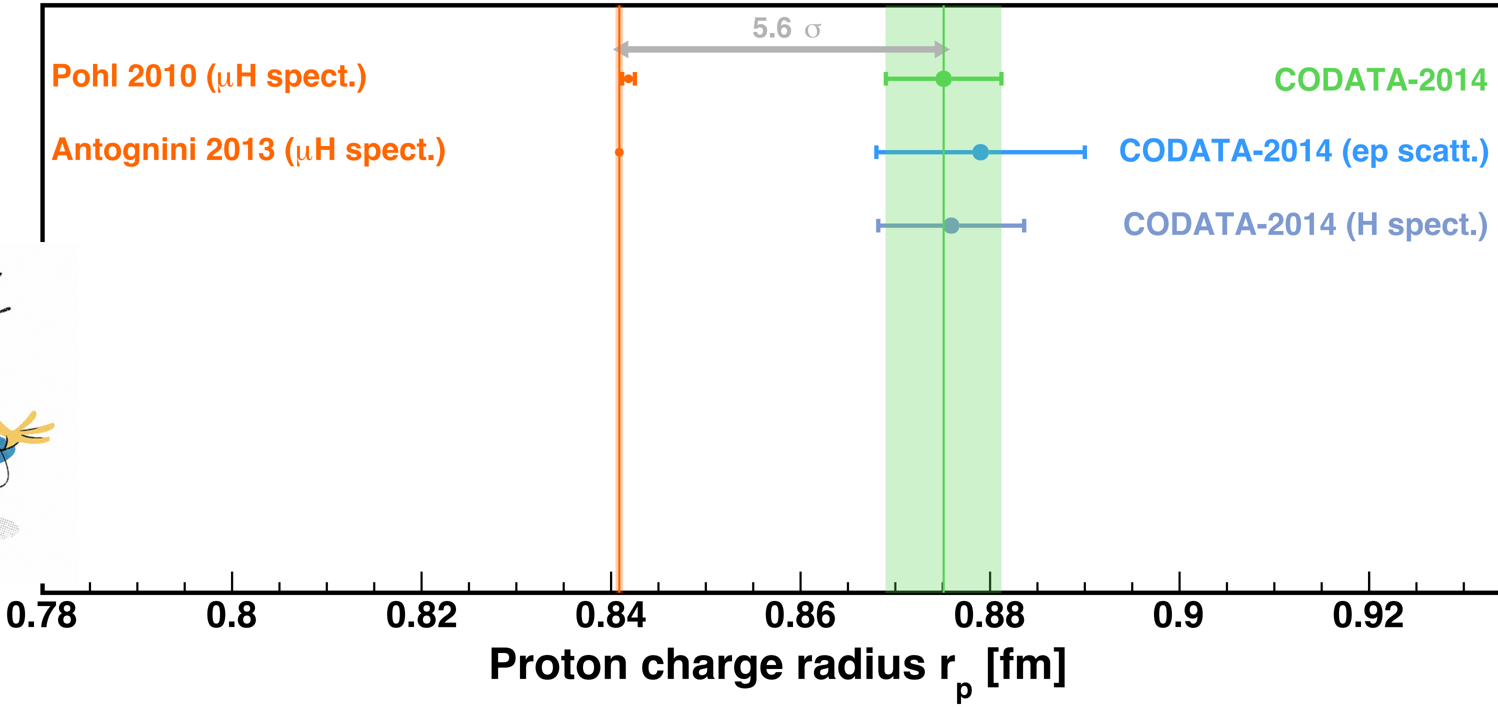


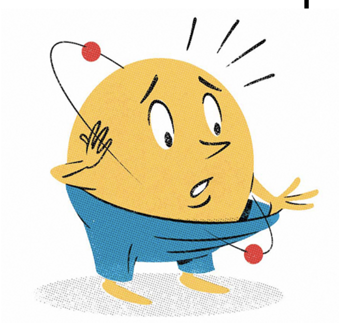
from R. Pohl

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*





The 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

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? — 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, AMBER at CERN …
    - ✓ ordinary hydrogen spectroscopy experiments:
      - York University in Canada, LKB in Paris, France, CREMA in Germany …

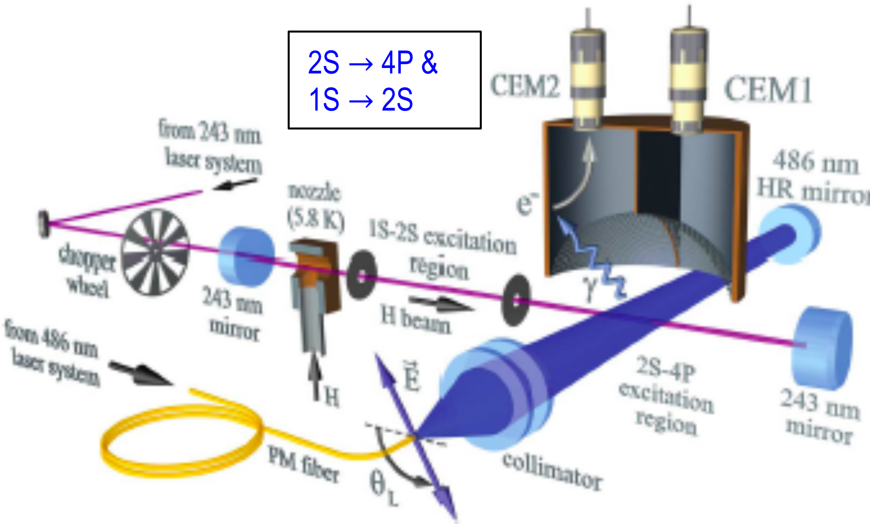
Two New Regular Hydrogen Spectroscopy Experiments

- Garching, Germany, regular hydrogen (2017):
  - ✓ cryogenic beam of H atoms (at 5.8 K)
  - ✓ 2S – 4P transition (also 1S - 2S used)

  $r_p = 0.8335(95)$ fm

  $R_\infty = 10\,973\,731.568\,076(96)\ m^{-1}$

  Beyer et al., Science 358, 79 (2017)

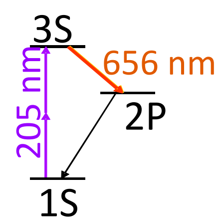


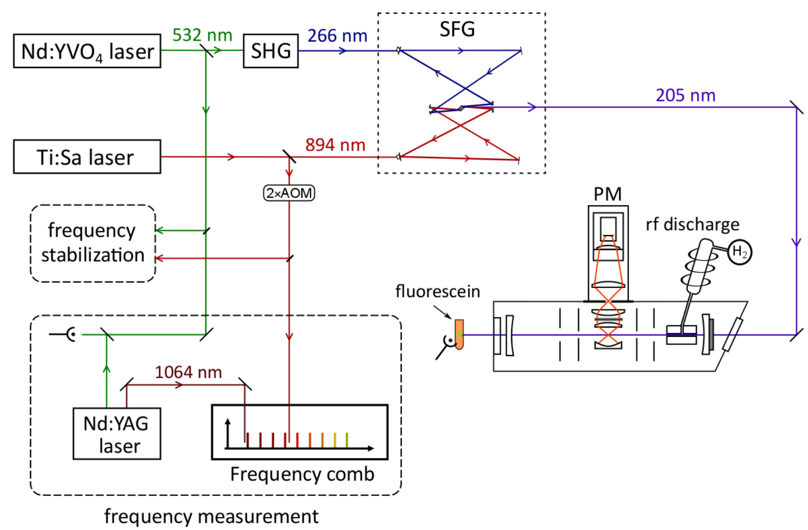
- Paris, France, regular hydrogen (2018):
  - ✓ room temperature H atomic beam
  - ✓ 1S – 3S two photon transition frequency
  - ✓ with 1S - 2S transition from Garching (2011)
  - ✓ second order Dopler effect ???

  $r_p = 0.877(13)$ fm

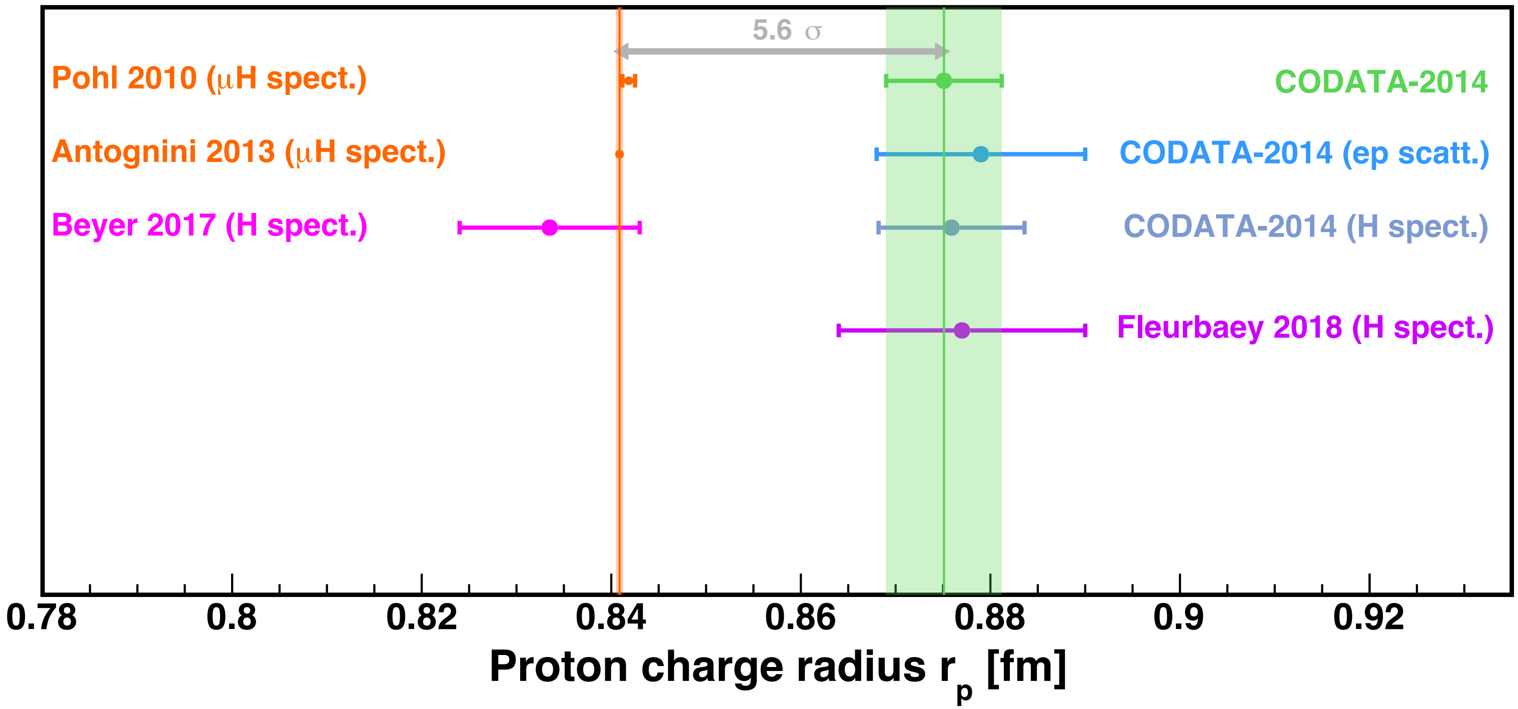
  $R_\infty = 10\,973\,731.568\,53(14)\ m^{-1}$

  Fleurbaey *et al.* PRL 120, 183001 (2018)





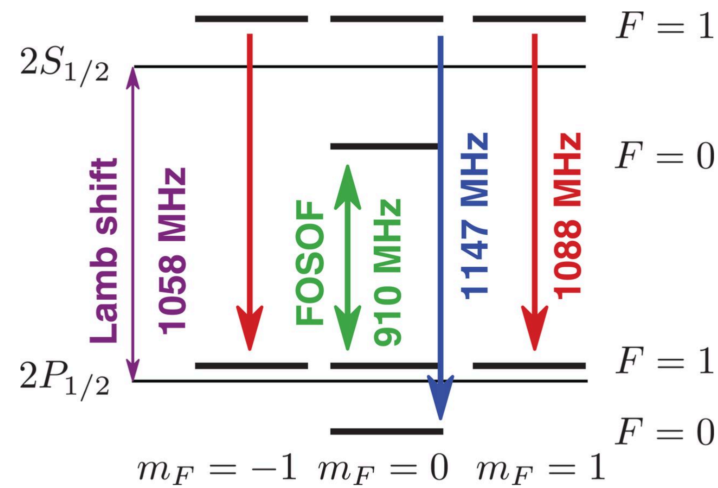
The *Proton Radius Puzzle* (in 2018)



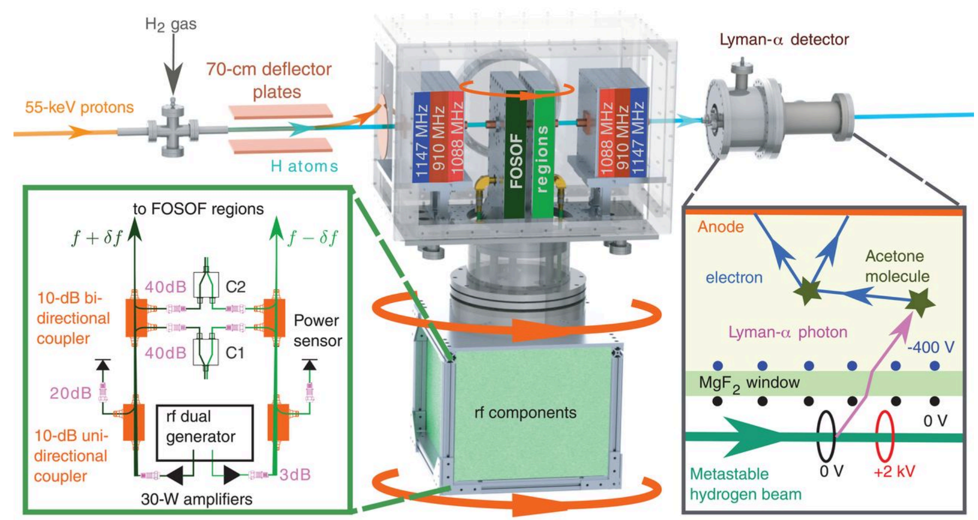
One More from Regular Hydrogen Spectroscopy
(York University, Canada)

- York University, Canada, regular hydrogen (2019):
  - ✓ room temperature H atomic beam
  - ✓ $2S_{1/2}$ (F=0) – $2P_{1/2}$ (F=1) transition frequency
  - ✓ Rydberg constant from other experiments
  - ✓ fast beam of hydrogen atoms (from proton beam)
  - ✓ two different radio frequencies

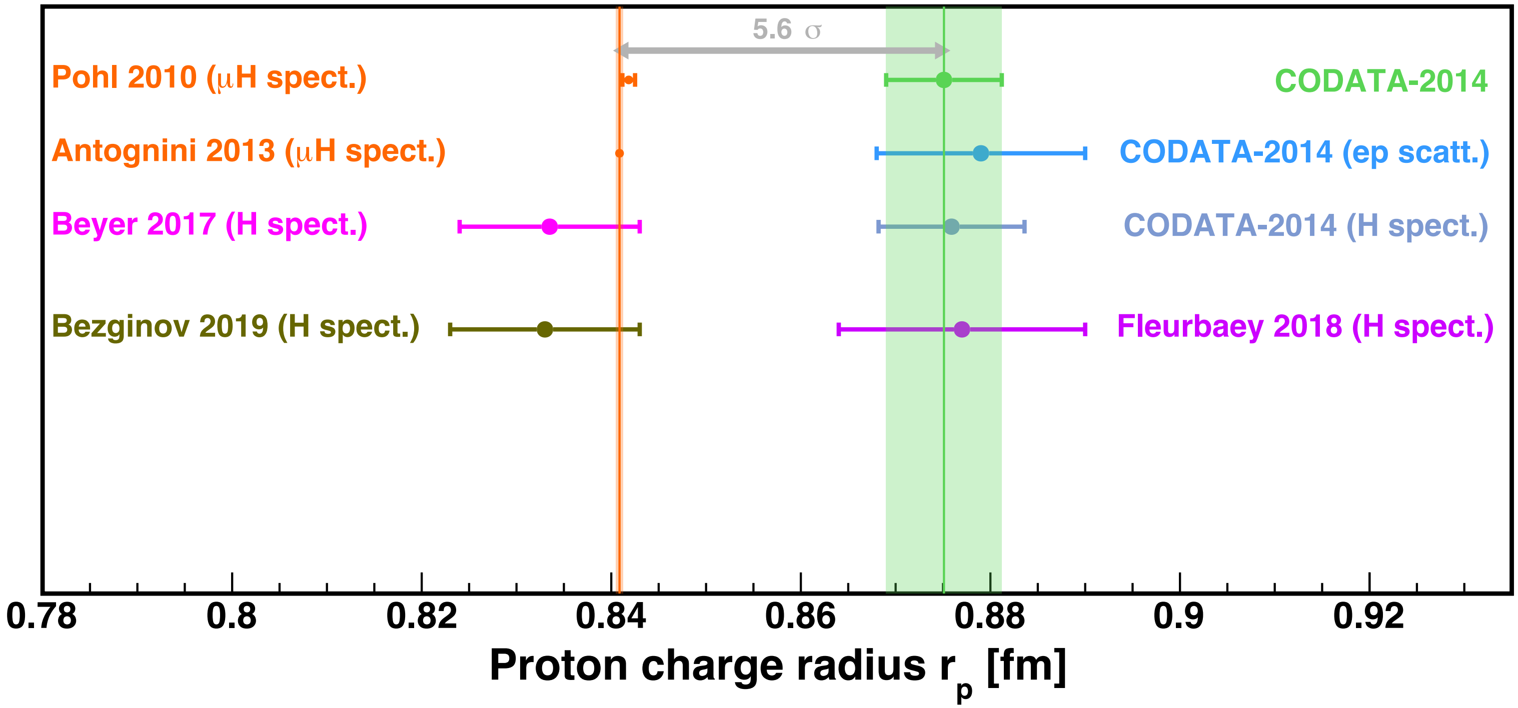
r_p = 0.833(10) fm



Bezginov *et al*., Science 365, 1007 (2019)



The Proton Radius Puzzle (in 2019)



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

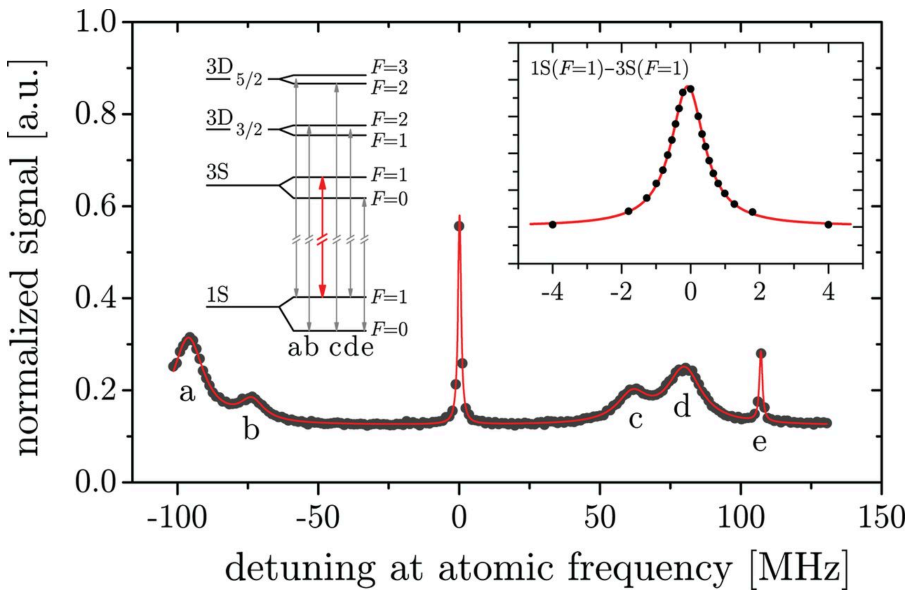
The Recent Regular Hydrogen Spectroscopy Experiment

- Garching, Munich, Germany, regular hydrogen (2020):

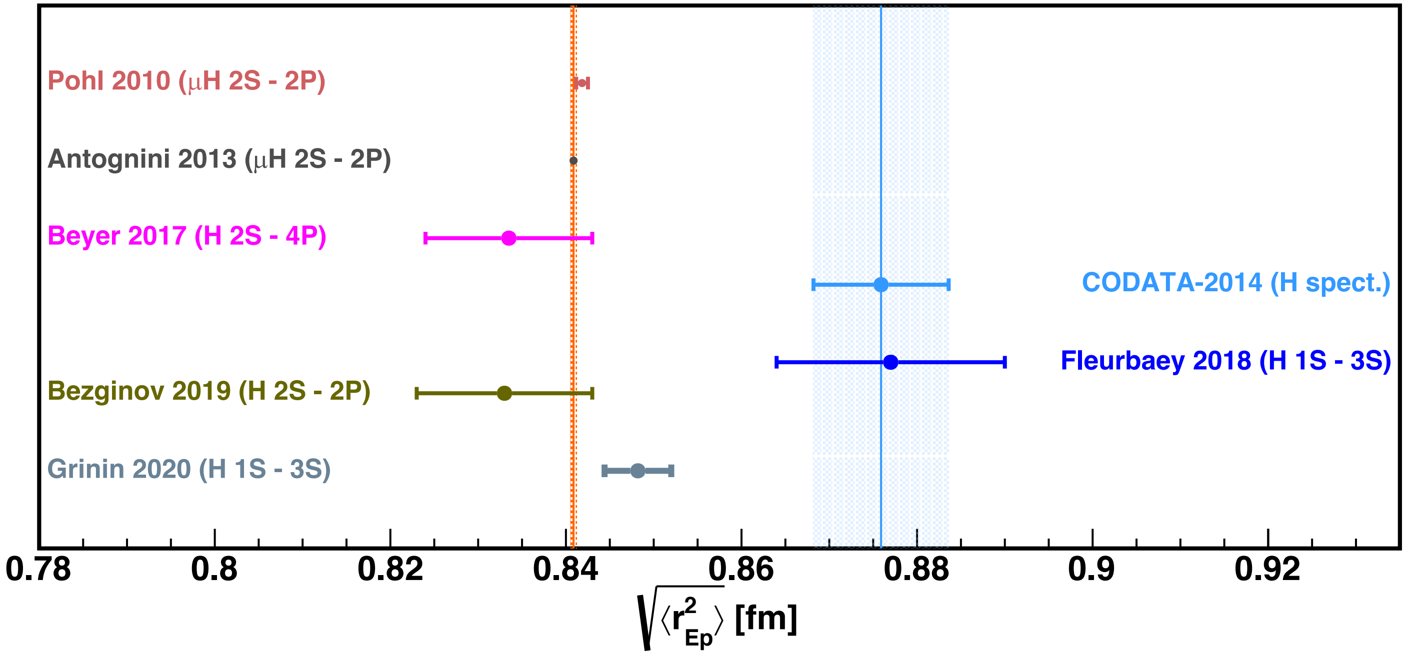
  - ✓ cold H atomic beam
  - ✓ 1S – 3S transition frequency (the same as Paris-2018)
  - ✓ two-photon direct frequency comb technique
  - ✓ 1S – 2S transition was also used from the same group

$$r_p = 0.8482(38)\ \text{fm}$$

Grinin et al., Science 370, 1061 (2020)



The Proton Radius Puzzle (in 2020, before PRad)



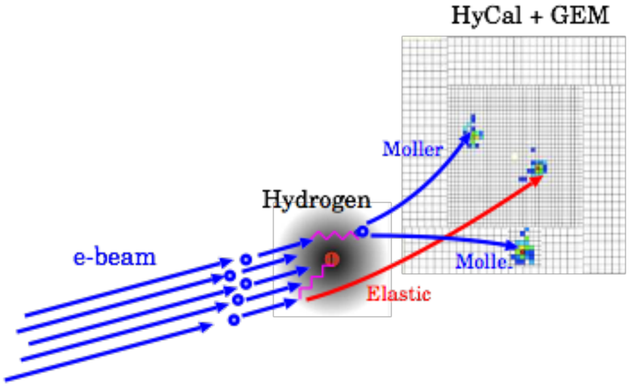
Experiment	Type	Transition(s)	$\sqrt{< r^2_{Ep} >}$ (fm)	r_∞ (m^{-1})
Pohl 2010	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$	0.84184(67)	
Antognini 2013	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$ $2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}$	0.84087(39)	
Beyer 2017	H	$2S - 4P$ with $(1S - 2S)$	0.8335(95)	10 973 731.568 076 (96)
Fleurbaey 2018	H	$1S - 3S$ with $(1S - 2S)$	0.877(13)	10 973 731.568 53(14)
Bezginov 2019	H	$2S_{1/2} - 2P_{1/2}$	0.833(10)	
Grinin 2020	H	$1S - 3S$ with $(1S - 2S)$	0.8482(38)	10 973 731.568 226(38)

Planning a New ep→ep Scattering Experiment

- Practically all ep-scattering experiments were 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_e, E'_e) to cover a reasonable Q^2 fitting interval
  - limitation on minimum Q^2: 10^{-3} GeV/C^2
  - limits on accuracy of cross sections ($d\sigma/d\Omega$): ~ 2 ÷ 3%
    - statistics is not a problem (<0.2%)
    - control of systematic uncertainties???

Three spectrometer facility of the A1 collaboration:

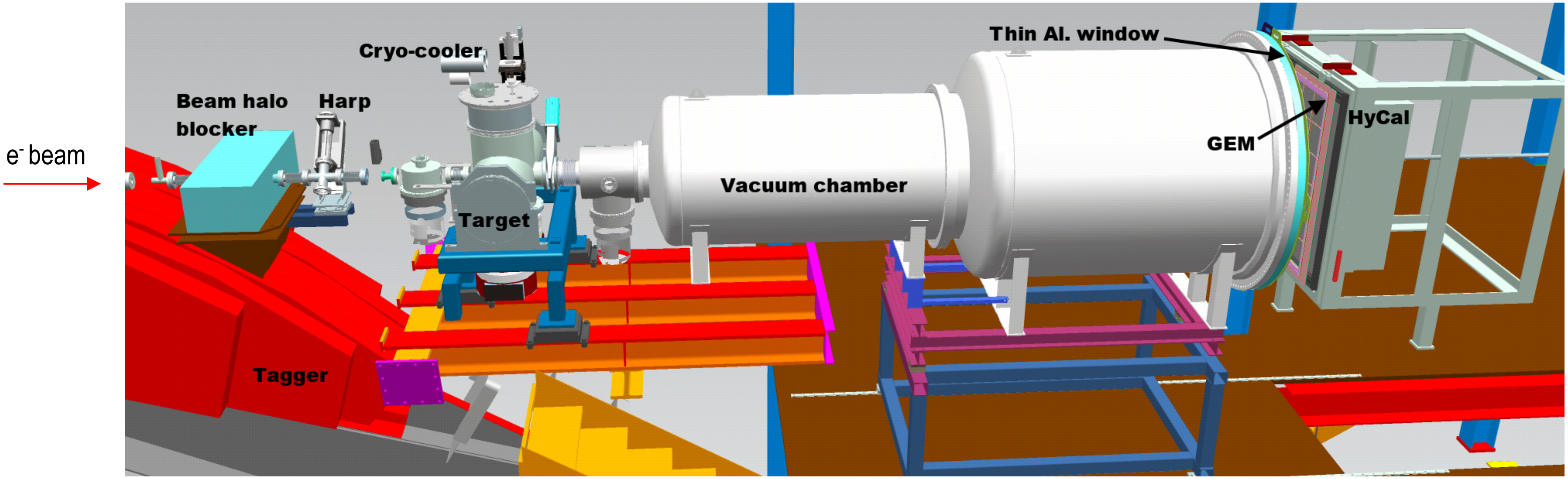
- PRad experimental approach:
  - ✓ use large acceptance, high resolution el.-magnetic calorimeter (HyCal)
  - ✓ all measurements with one experimental setting: $\vartheta_e = 0.6^0 - 7.0^0$
  - ✓ reach to smaller Q^2 range: ($Q^2 = 2\text{x}10^{-4} - 6\text{x}10^{-2}$) GeV/c^2
  - ✓ windowless H2 gas flow target (minimize experimental background)
  - ✓ simultaneous detection of ee → ee Moller scattering process (best known control of systematics).



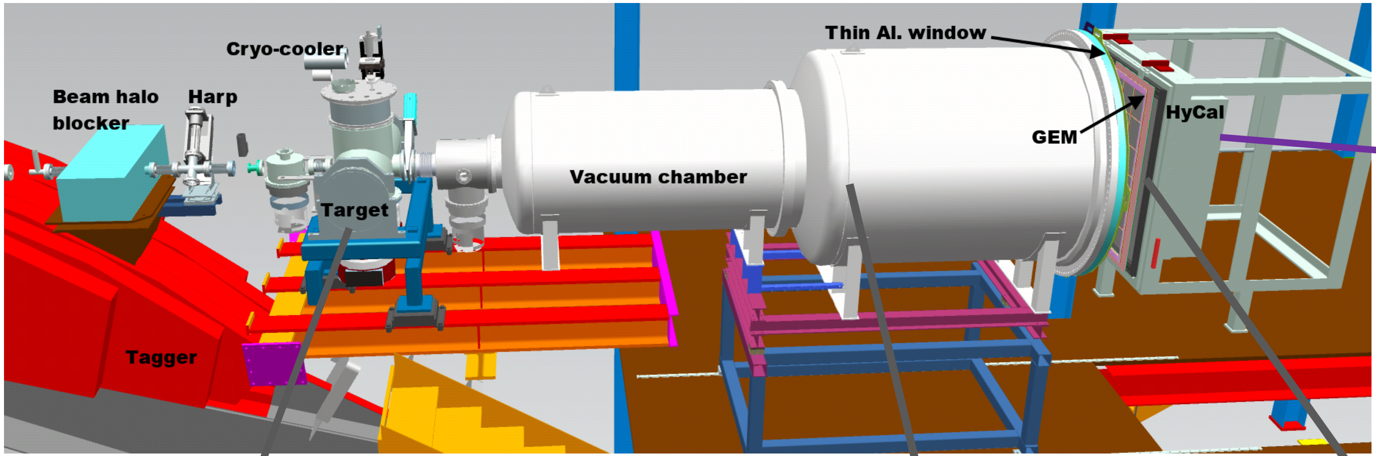
PRad Experimental Setup in Hall B at JLab (schematic view)

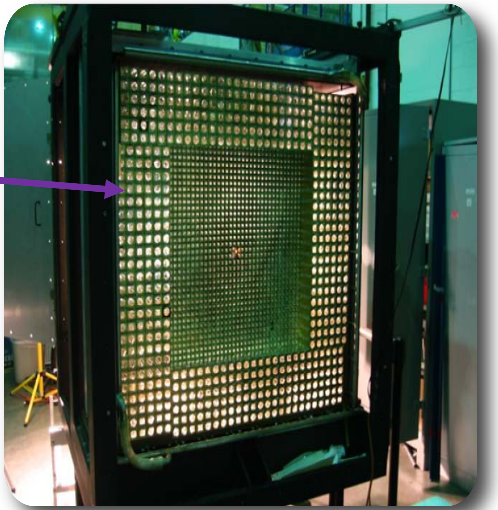
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

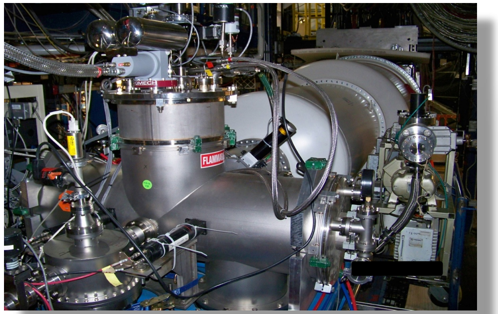
- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo "cleanup")
  - Harp 2H00 I

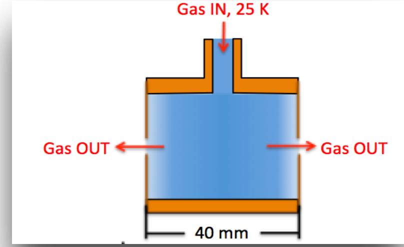


PRad Experimental Apparatus



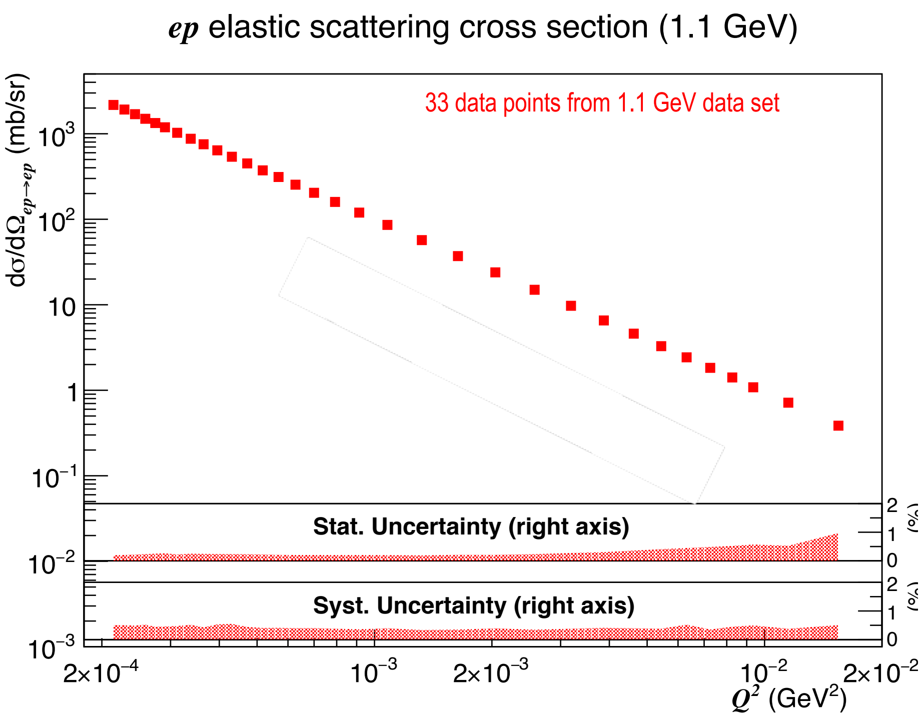


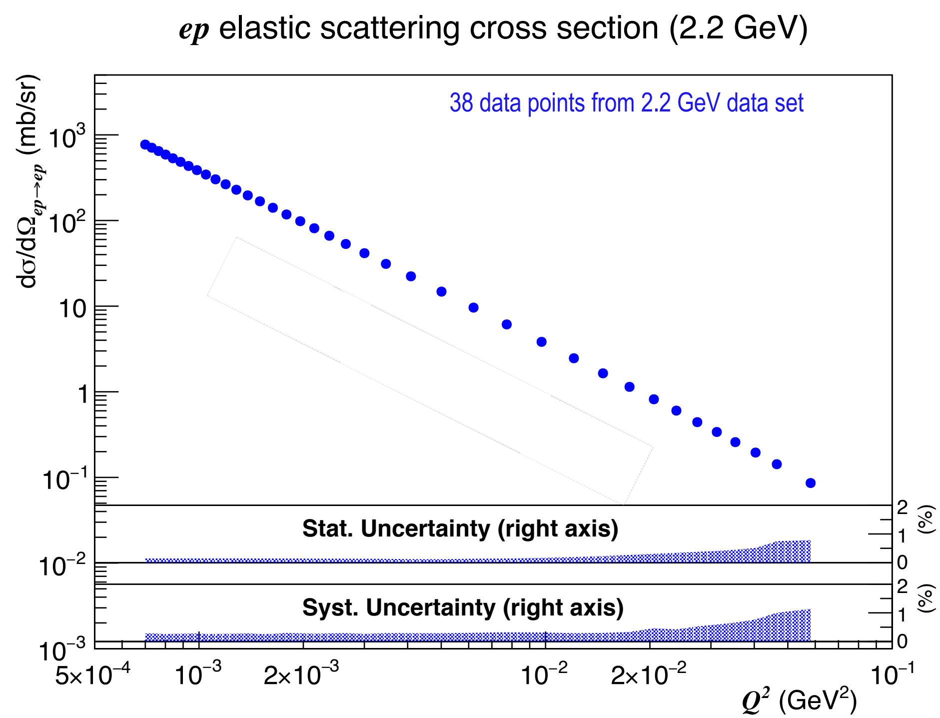




Extracted ep→ep Elastic Differential Cross Sections

- Extracted differential cross sections vs. Q^2, with 1.1 and 2 GeV data.
- Statistical uncertainty: ~0.2% for 1.1 GeV and ~0.15% for 2.2 GeV per point.
- Systematic uncertainties: 0.3% - 0.5% for 1.1 GeV and 0.3 – 1.1% for 2.2 GeV per point.





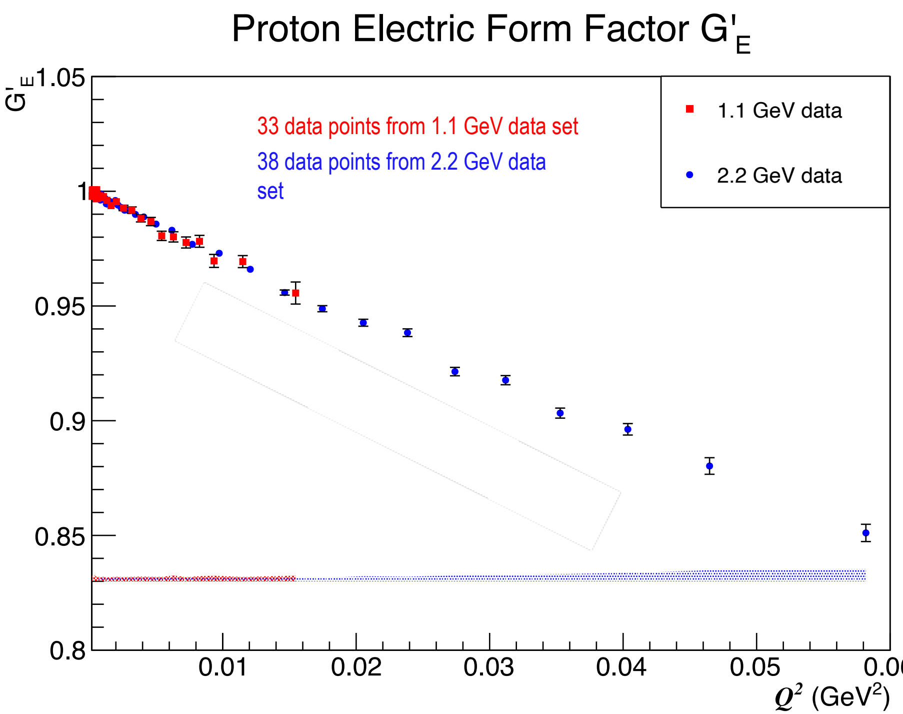
Extracted Proton Electric Form Factor, G_E vs. Q^2

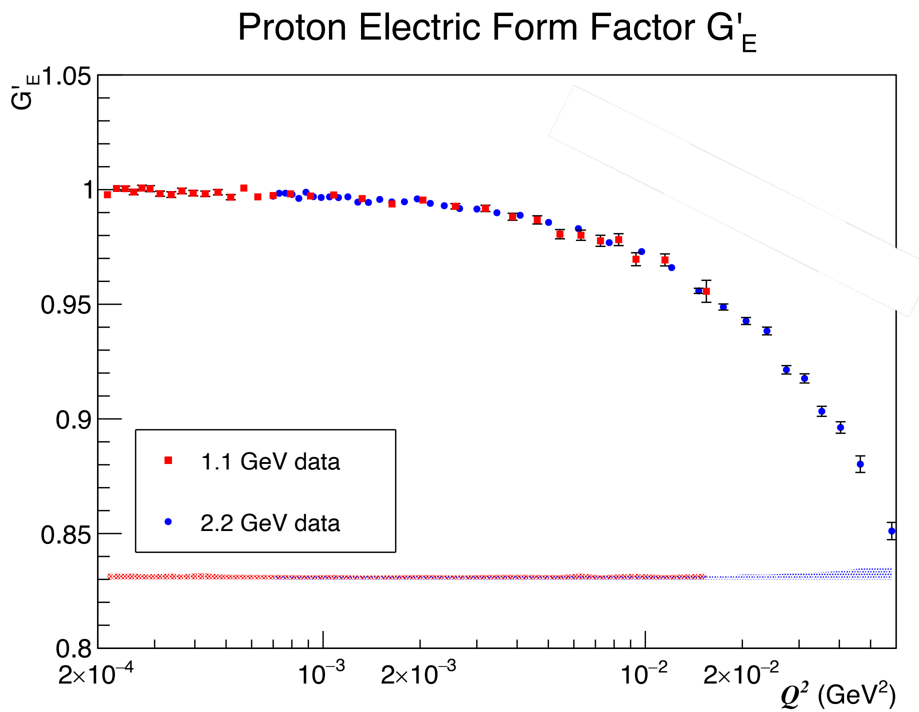
n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

Using rational (1,1)

$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$





n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.),

n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

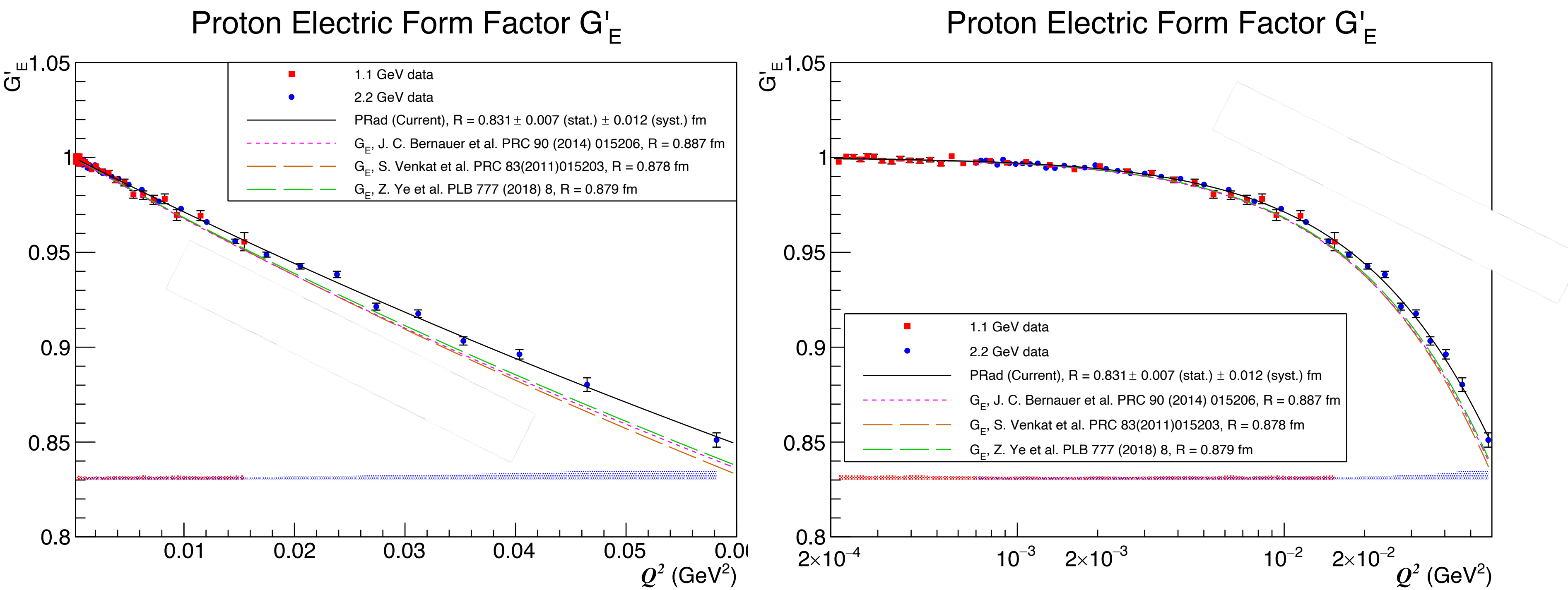
Proton Electric Form Factor (PRad Results)

n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

Using rational (1,1)
$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

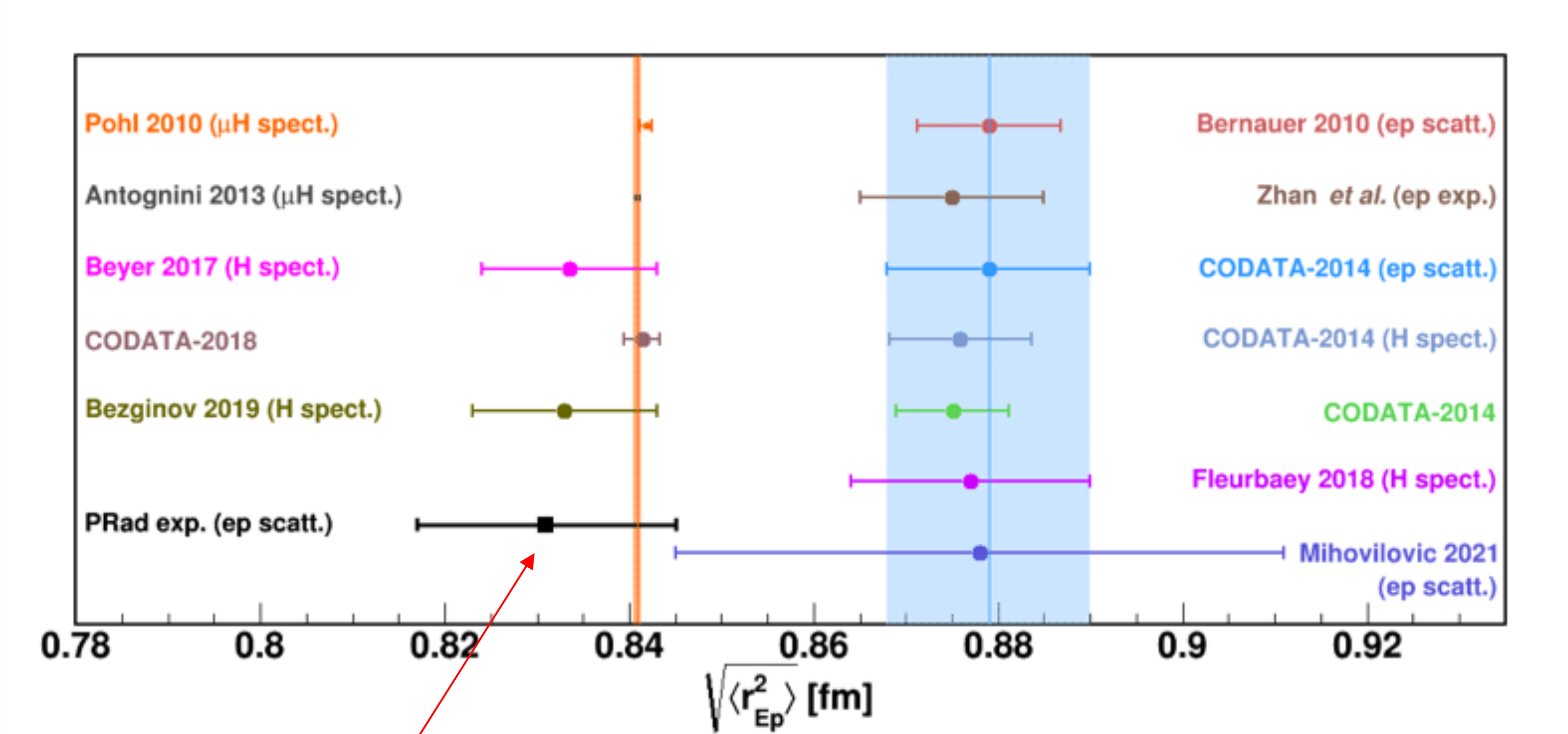
G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

PRad fit shown as $f(Q^2)$ r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



PRad final result: R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

Proton Radius at the Time of PRad Publication (2019)



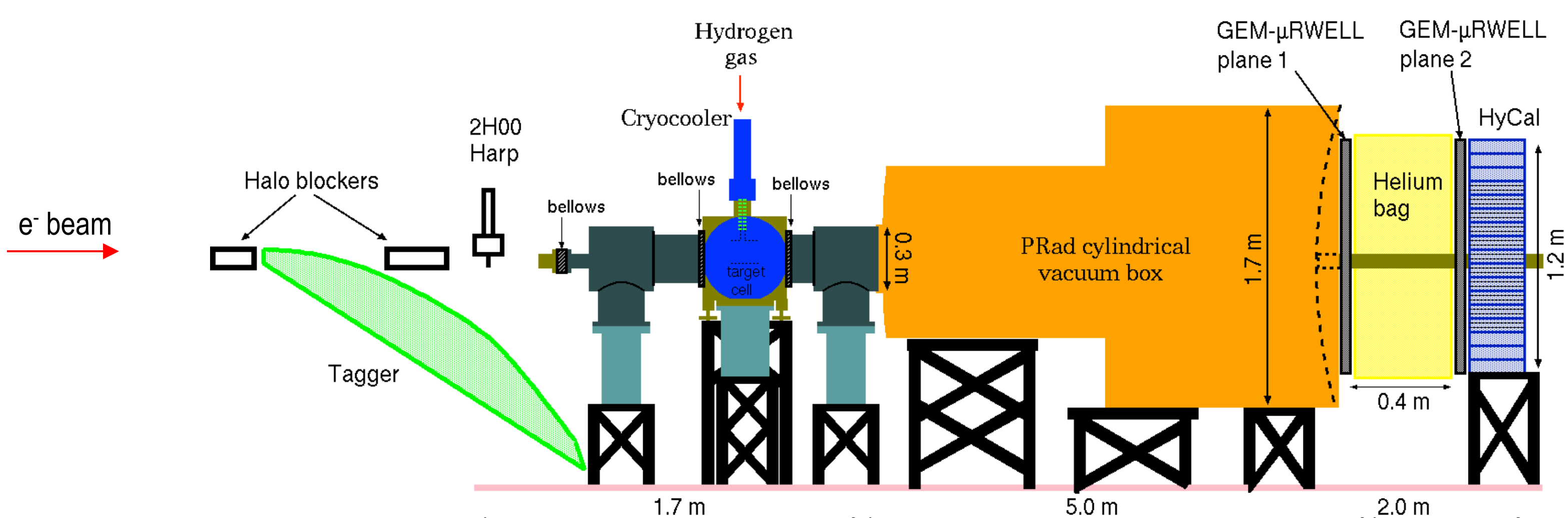
PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm

published in: Nature 575, 145–150 (2019)

New Experiments in Progress: PRad-II at JLab

- PRad-II is planning to improve the PRad accuracy by a factor of 3.8 (to $\pm 0.43\%$ on r_p) by:
  - Significantly improved statistics (4 times less uncertainties);
  - Hardware upgrades:
    - adding tracking capability (second plane of GEM/μRwell detectors).
    - small-size scintillator detectors just downstream the target to veto Moller electrons to reach the 10^{-5} GeV^2 Q^2 range.
    - adding new 'beam halo blacker" just before the Photon Tagger.
    - upgrade DAQ/electronics to fADC based electronics:
    - HyCal upgrade to all $PbWO_4$ crystals, essential for ep-inelastic background suppression at relatively higher Q^2 range (10^{-2} GeV^2) and uniformity over full acceptance.

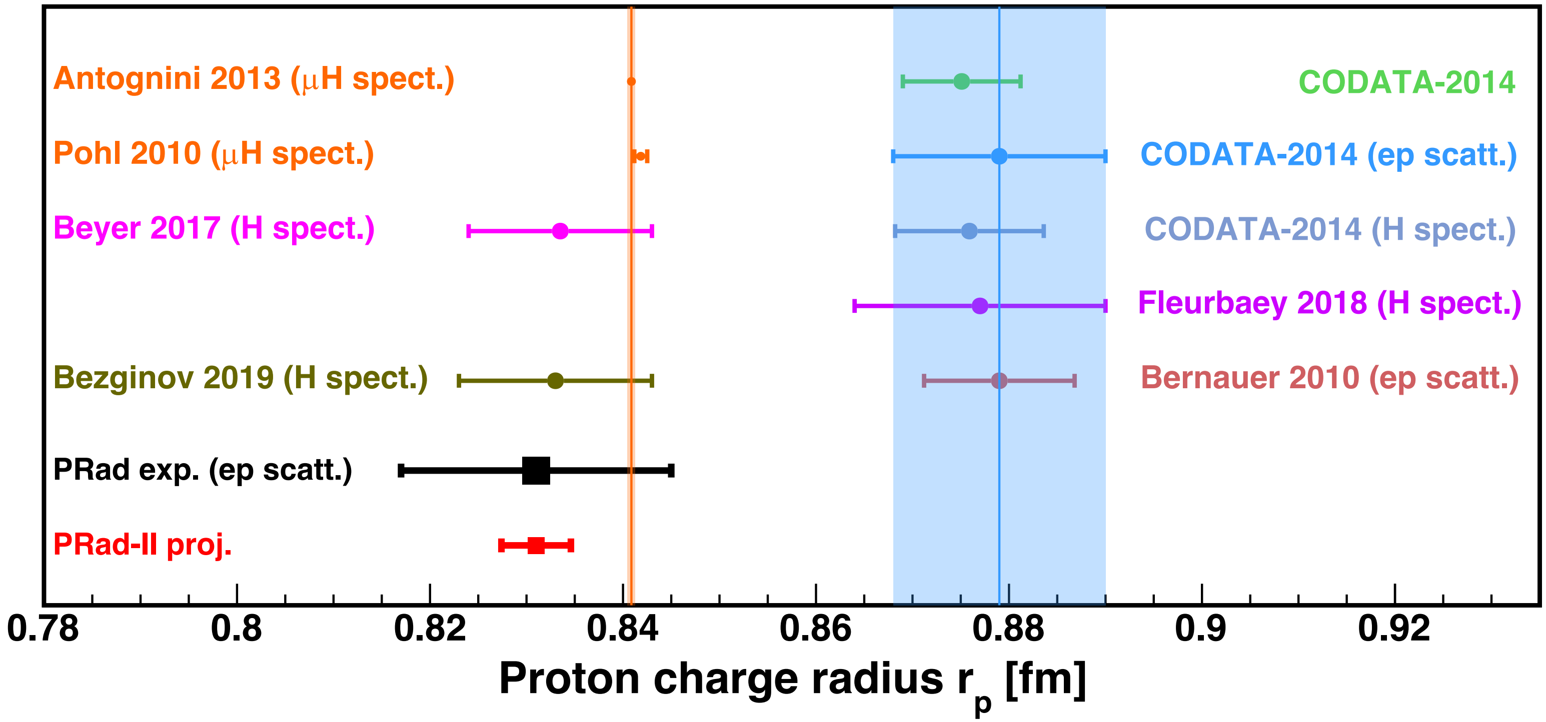
PRad-II Experimental Setup (Side View)



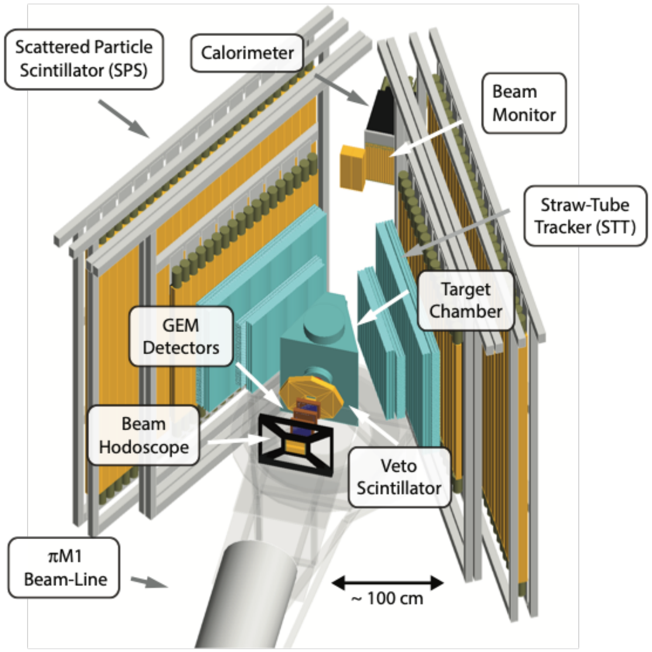
PRad-II Expected Accuracy

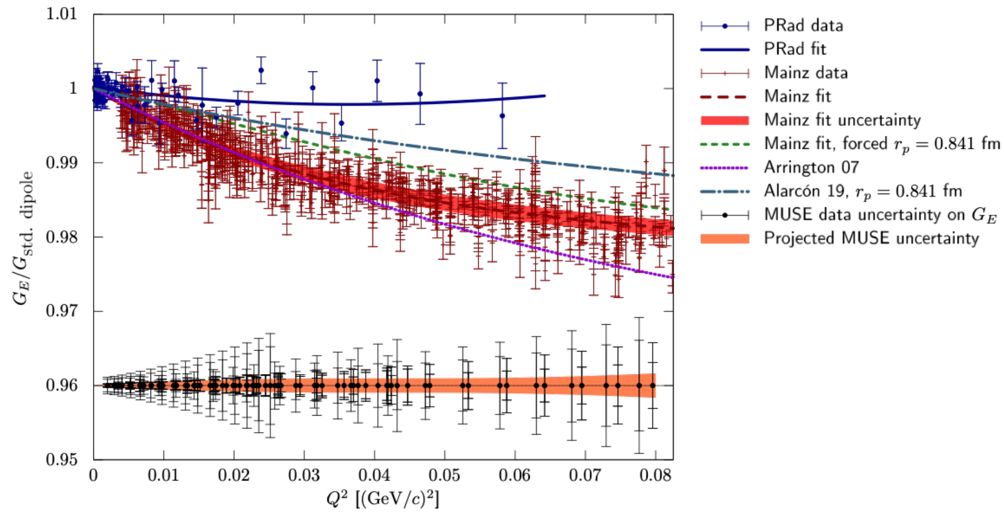
- Approved by Jlab's PAC-48 in August, 2020
- Expected total uncertainty: 0.43% (0.0036 fm)

A. Gasparian et al. arXiv:2009.10510



New Experiments in Progress: MUSE Experiment at PSI



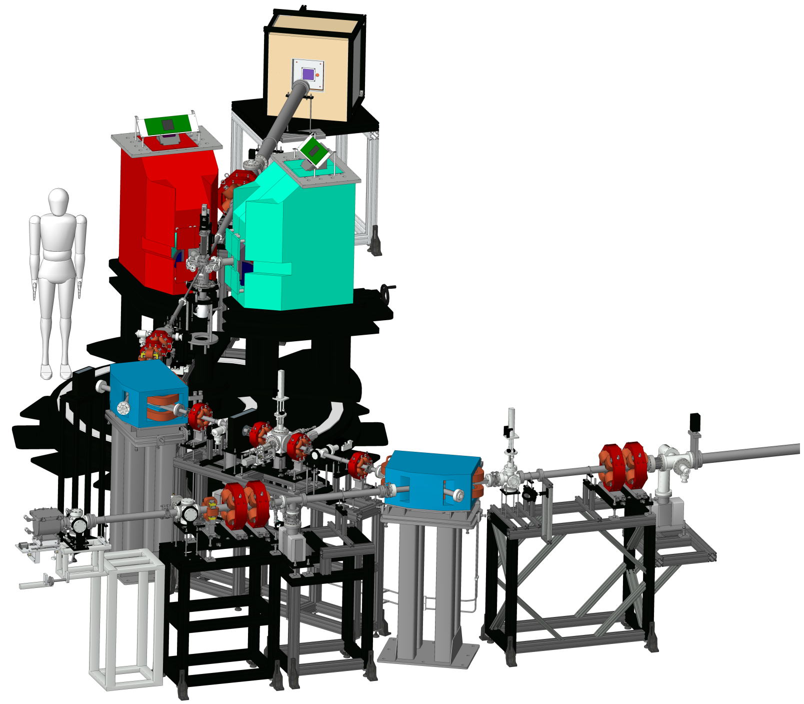


- Simultaneous $\mu^{\mp}p$ and $e^{\mp}p$ elastic scattering cross sections:
  - P_{beam} = 115, 153, 210 MeV/c
  - scattering angle: 20^0 - 100^0
    - determine r_{Ep}
    - test lepton universality
    - measure two photon exchange (TPE)

    - delayed ~ 1.5 years due to COVID
    - Currently at PSI re-establishing all systems in preparation for production data taking, starting this fall, through 2023.

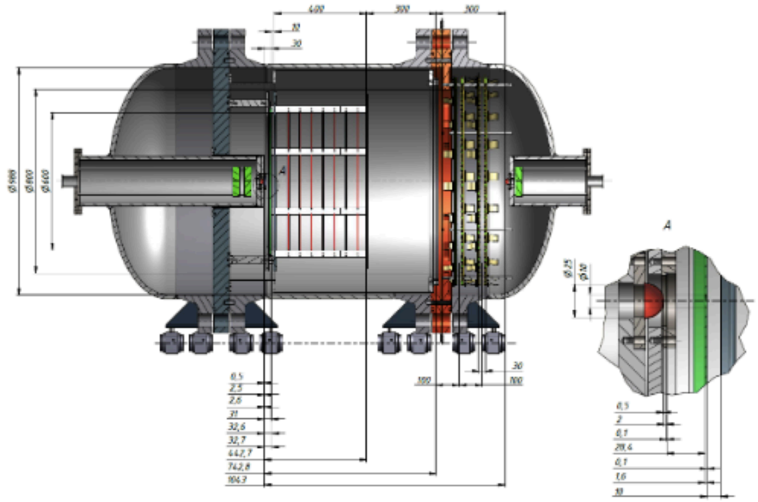
New Experiments in Progress: ULQ^2 Experiment at Tohoku University

- ep-elastic scattering experiment with a magnetic spectrometer:
  - P_{beam} = 20 - 60 MeV/c
  - scattering angle: $30^0 – 150^0$
  - target: CH_2
  - Q^2 range: $3x10^{-4} – 8x10^{-3}$ GeV/c^2
  - Current status:
    - ✓ 1st spectrometer fully commissioned
    - ✓ 2nd spectrometer installed, commissioning in progress
    - ✓ Scattering chamber under construction, installation in December
    - ✓ Physics run from next April.

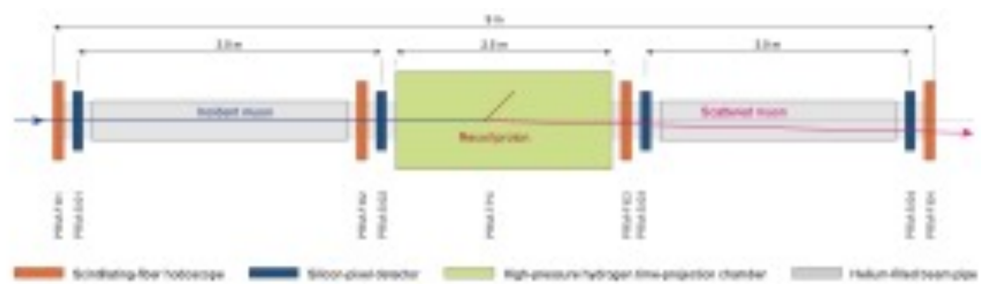


New Experiments in Preparation

- PRES at MAMI Mainz:
  High pressure hydrogen gas TPC detector
  - ep→ep scattering at moderate energies;
  - detection of recoil proton only;
  - promising to reach Q^2 10^{-5} GeV/c^2 range;
  - extraction of the proton radius (< 0.6%);
  - first collaboration meeting in March, 2020.

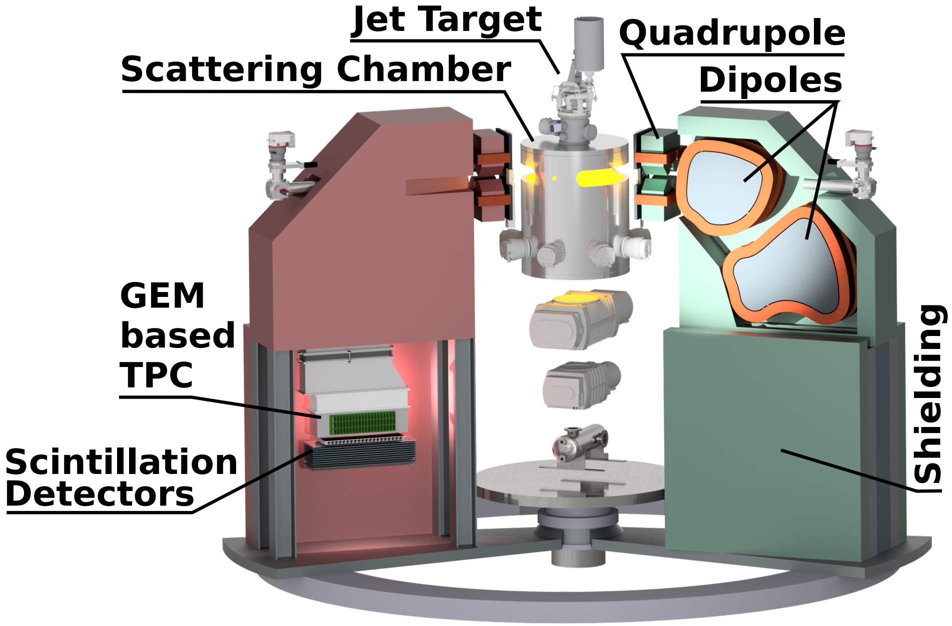


- AMBER at CERN:
  The same high pressure hydrogen TPC detector
  - $\mu p \rightarrow \mu p$ scattering at high energies;
  - Q^2 range: 10^{-4} – 1 GeV^2
  - detection of the recoil proton;
  - extract the proton radius;
  - in planning stage.



Planning Experiments: MAGIX@MESA Experiment at Mainz

- ep-elastic scattering experiment with a magnetic spectrometer:
  - P_{beam} = 20 - 105 MeV/c
  - scattering angle: $30^0 – 150^0$
  - target: H_2 jet
  - Q^2 range: $\sim 10^{-4} – 8\times10^{-2}$ GeV/c^2
  - Current status:
    - ✓ In the planning stage



Experiment	Beam	Laboratory	Q^2 $(GeV/c)^2$	δr_p (fm)	Status
MUSE	$e^{\pm}, \mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future
ULQ^2	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim$ 1% (rel.)	Future

Summary and Outlook

- In last decade major progress made in resolving the proton charge radius *puzzle*.
- Most of the recent ordinary hydrogen spectroscopy measurements are consistent with muonic results (smaller radius).
- The result from the recent PRad ep-scattering experiment also consistent with muonic results (smaller radius).
  - ✓ first ep-scattering experiment using a non-magnetic spectrometer;
  - ✓ data in a large Q^2 range have been recorded with the same experimental setting, $[2x10^{-4} \div 6x10^{-2}]$ GeV/C^2.
  - ✓ lowest Q^2 range ($\sim 10^{-4}$ GeV/C^2) has been reached for the first time in ep-scattering experiments.
- PRad results disagree with all modern ep-scattering experiments.
- Is the "*Proton Radius Puzzle*" solved???
  - ➢ new and further improved measurements from lepton-scattering experiments are needed:
    - PRad-II at JLab, MUSE at PSI, ULQ^2 at Tohoku University, AMBER at CERN, PRES at MAMI, MAGIX@MESA …

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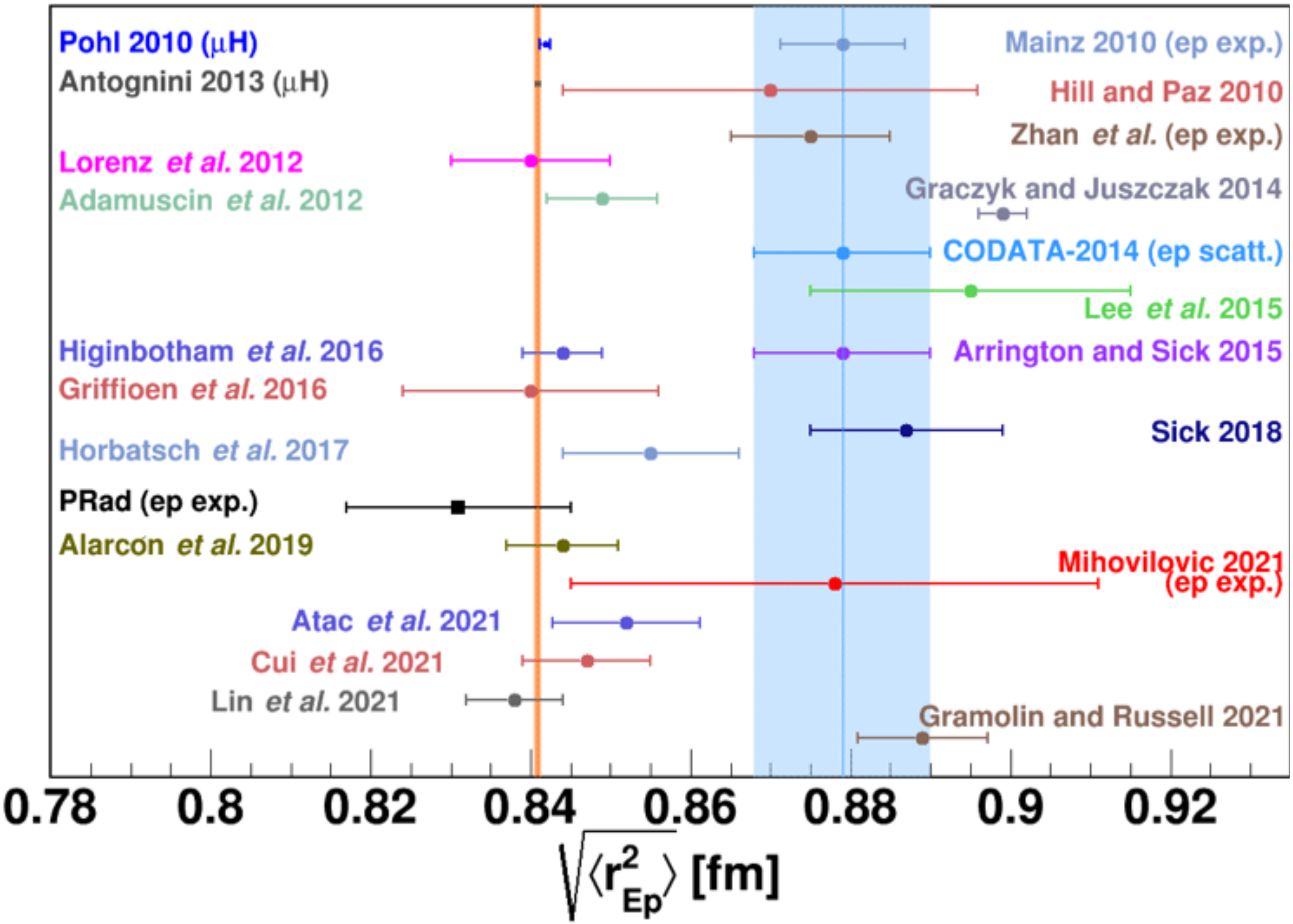
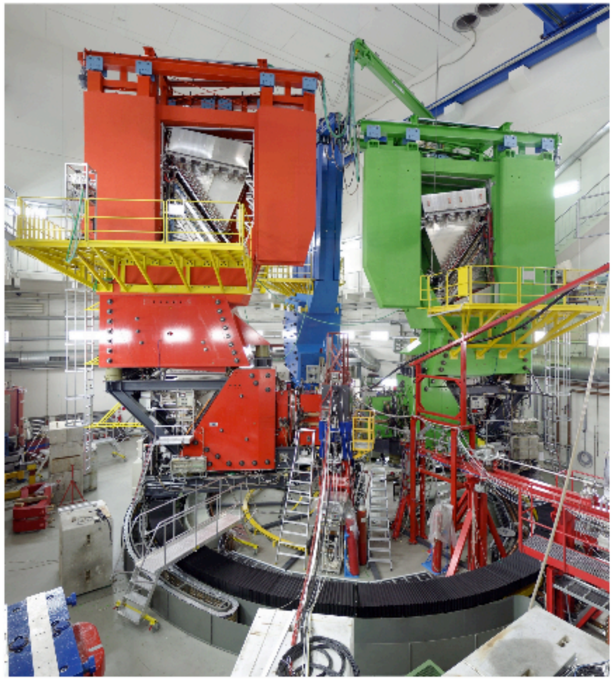
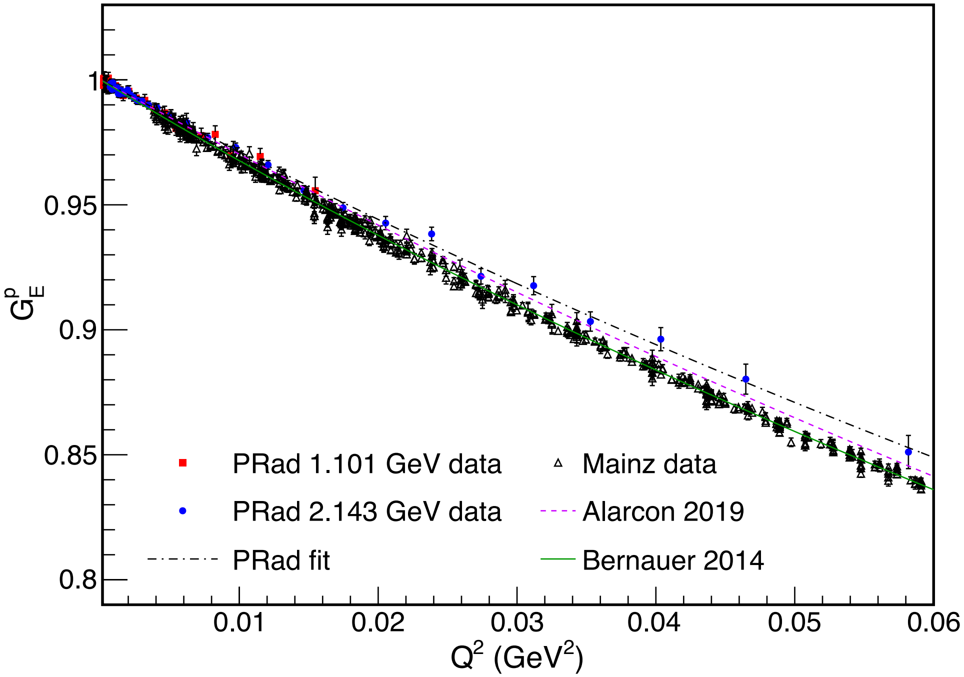
Thank you!

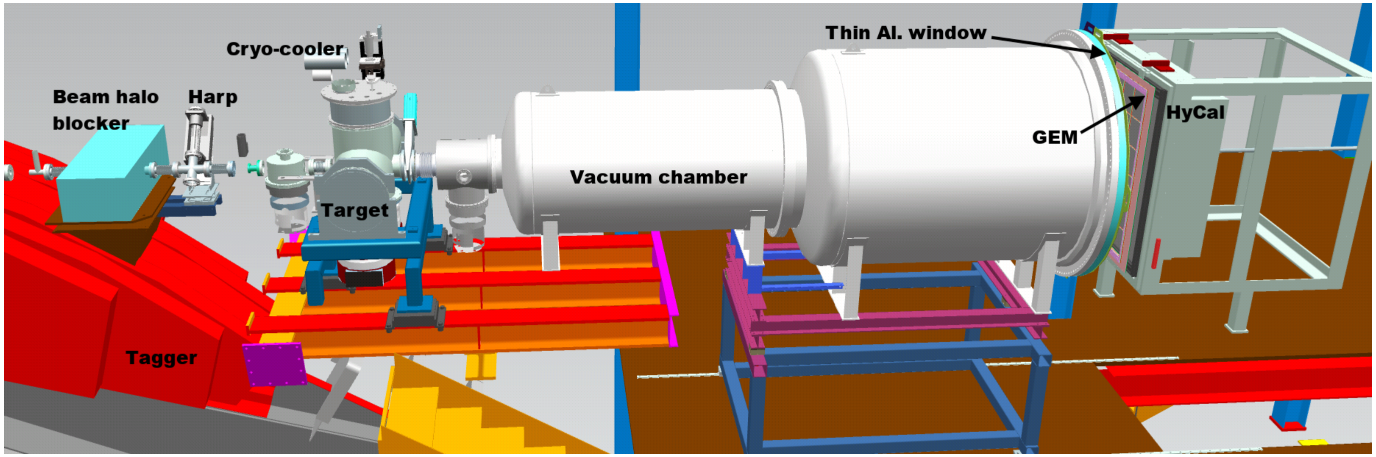
(Re)analysis of e-p Scattering Data



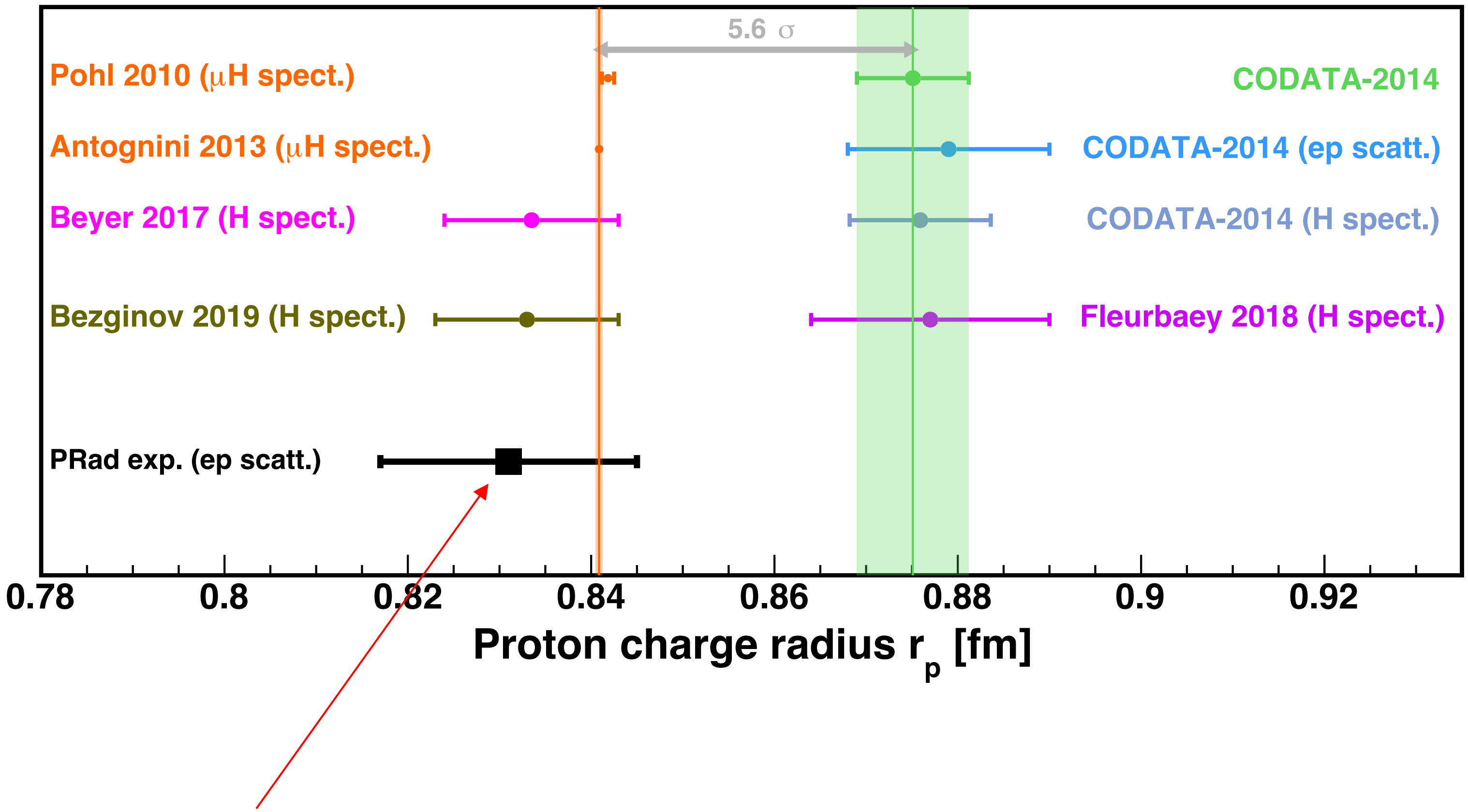
e-p Scattering: Magnetic Spectrometer vs. Calorimetric Method







The PRad Final Result on the Radius



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

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