

The Proton Charge Radius

Haiyan Gao

Duke University

International Conference on the Structure of Baryons

ICC JEJU, Korea, November 10-14, 2025



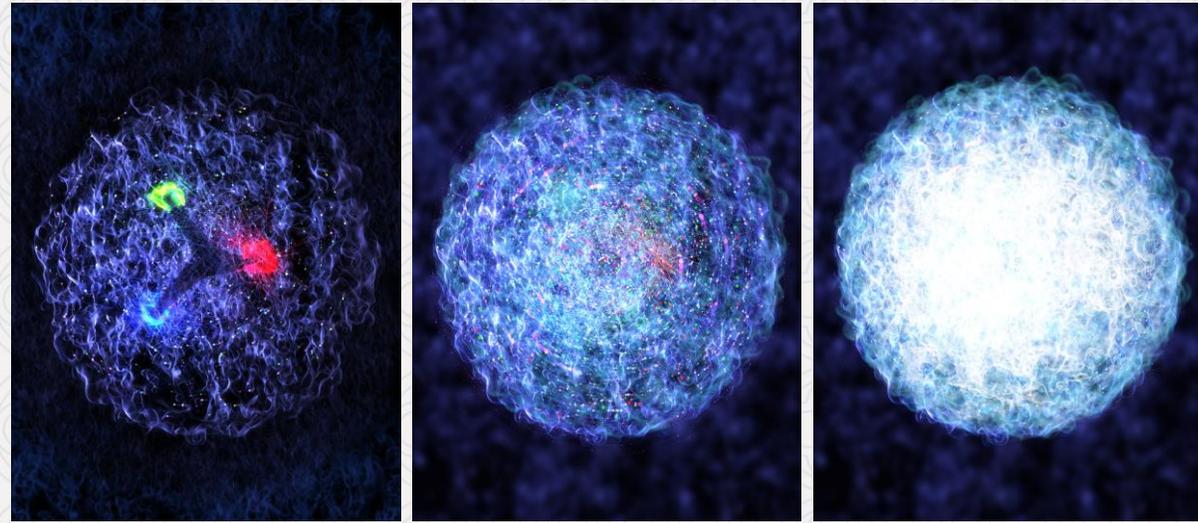
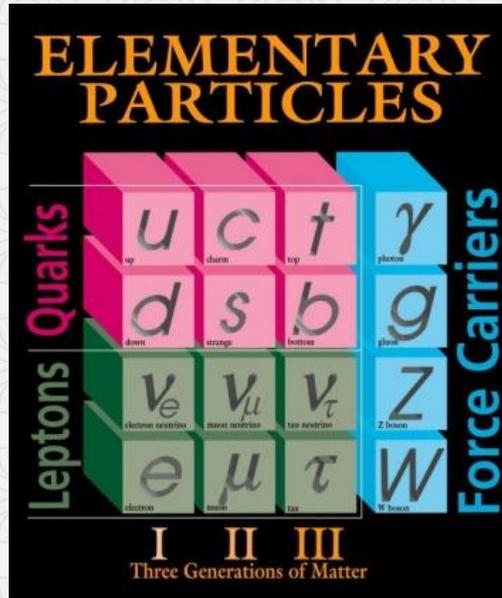
BARYONS 2025

INTERNATIONAL
CONFERENCE ON THE
STRUCTURE OF BARYONS

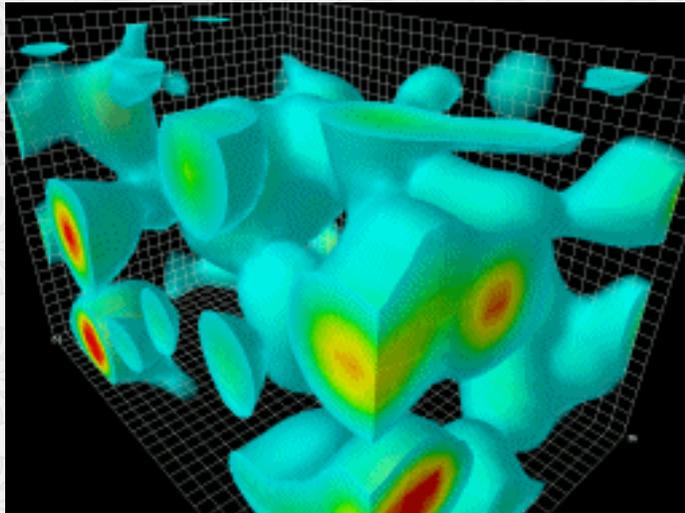
10-14 NOV 2025
ICC JEJU
KOREA



Structure of visible matter



Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.

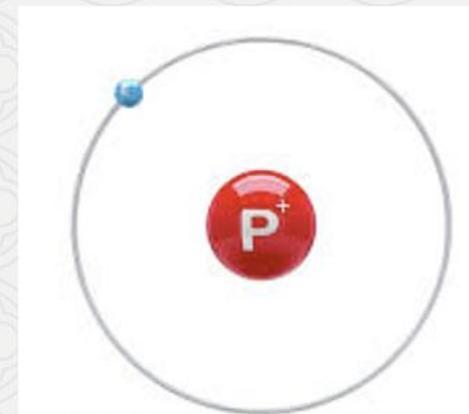
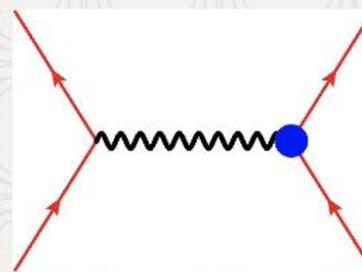
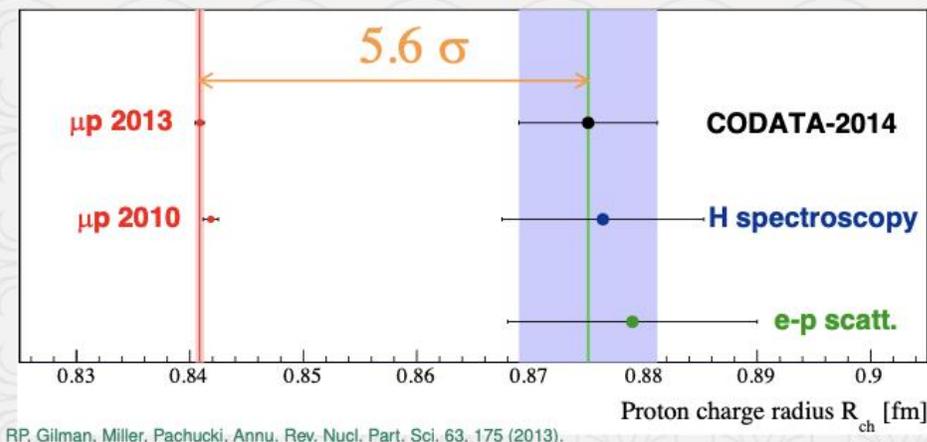


Credit: D. Leinweber

- **Charge and magnetism (current) distribution**
- **Spin and mass decomposition**
- **Quark momentum and flavor distribution**
- **Polarizabilities**
- **Strangeness, charm content**
- **Three-dimensional tomography**
- **more**

Proton Charge Radius and the Puzzle

- Proton charge radius:
 1. A fundamental quantity for proton
 2. Important for understanding how QCD works
 3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant
- Methods to measure the proton charge radius:
 1. Hydrogen spectroscopy (atomic physics)
 - Ordinary hydrogen
 - Muonic hydrogen
 2. Lepton-proton elastic scattering (nuclear physics)
 - ep elastic scattering (like PRad)
 - μp elastic scattering (like MUSE, COMPASS++/AMBER)
- Important point: the proton radius measured in lepton scattering is defined in the same way as in atomic spectroscopy (G.A. Miller, 2019)



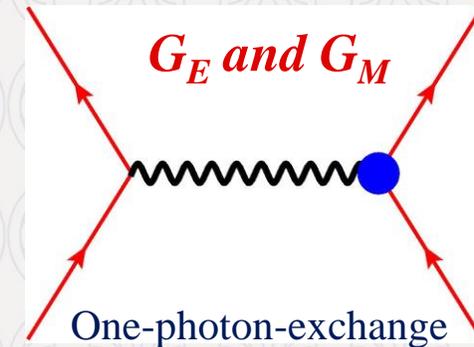
$$\sqrt{\langle r^2 \rangle} = \sqrt{-6 \frac{dG(q^2)}{dq^2} \Big|_{q^2=0}}$$

Electron-proton elastic scattering

- Unpolarized elastic e-p cross section (*Rosenbluth separation*)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^p{}^2 + \tau G_M^p{}^2}{1 + \tau} + 2\tau G_M^p{}^2 \tan^2 \frac{\theta}{2} \right)$$

$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2 \frac{\theta}{2} \right) \quad \tau = \frac{Q^2}{4M^2}$$



- Recoil proton polarization measurement (*pol beam only*)

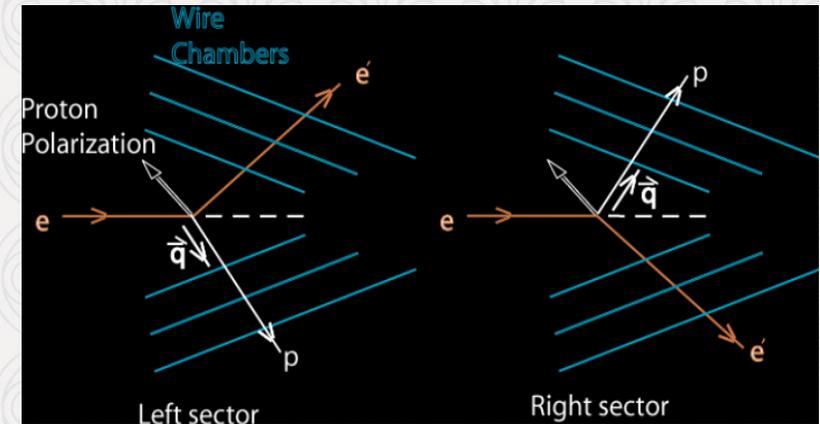
$$\frac{G_E^p}{G_M^p} = -\frac{P_t E + E'}{P_l 2M} \tan \frac{\theta}{2}$$

- Asymmetry (super-ratio) measurement

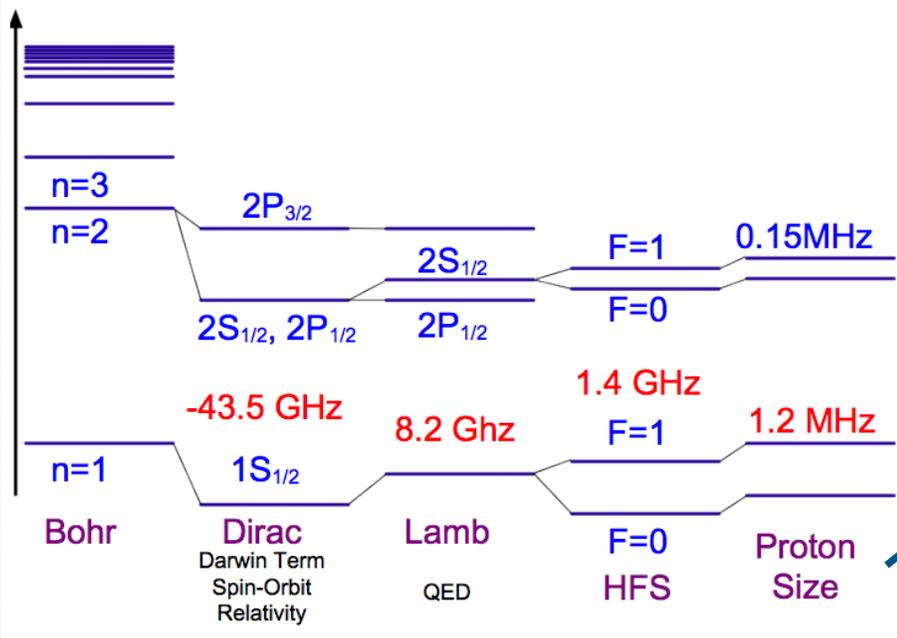
(*pol beam and pol target*)

$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}$$

$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos \theta^* G_M^p{}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin \theta^* \cos \phi^* G_M^p G_E^p}{(1+\tau) v_L G_E^p{}^2 + 2\tau v_T G_M^p{}^2}$$

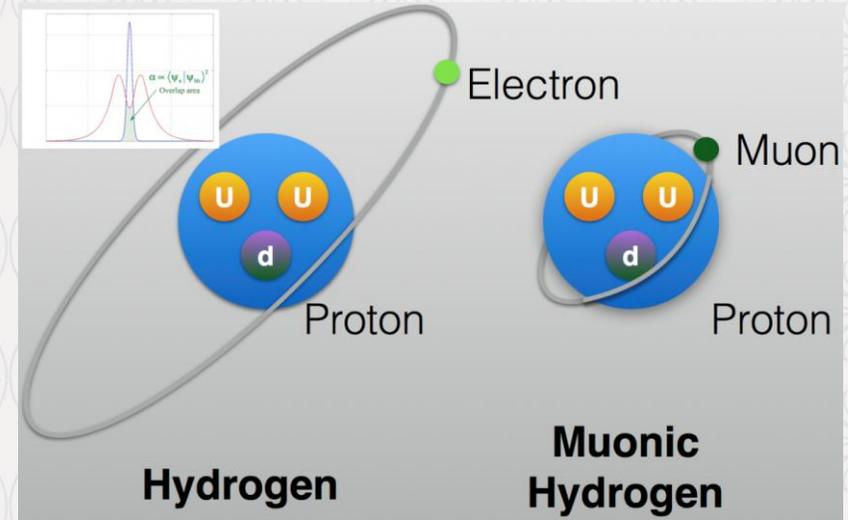


Hydrogen Spectroscopy



$$\Delta E_{\text{fin size}} = \frac{2\pi\alpha}{3} \langle r_{Ep}^2 \rangle |\psi_{nl}(0)|^2$$

$$= \frac{2\alpha^4}{3n^3} m_r^3 \langle r_{Ep}^2 \rangle \delta_{l0}$$



The absolute frequency of H energy levels has been measured with an accuracy of **1.4 part in 10^{14}** via comparison with an **atomic cesium fountain clock** as a primary frequency standard.

Yields Rydberg constant R_∞ (one of the most precisely known constants)

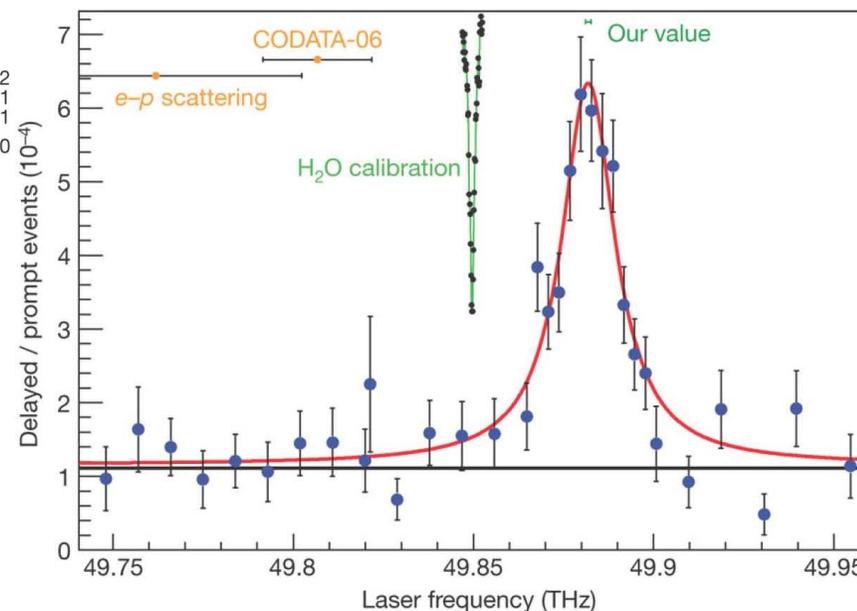
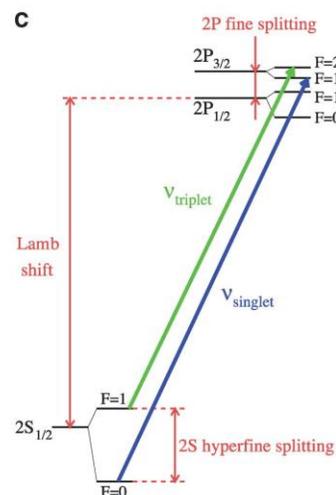
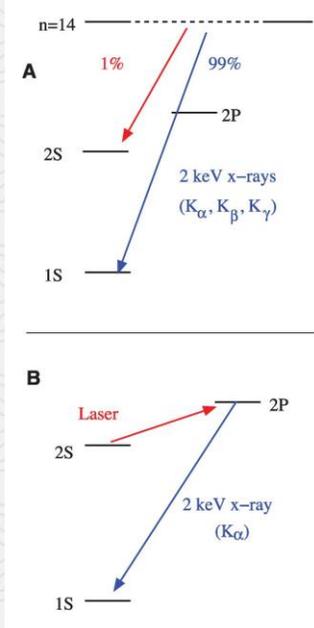
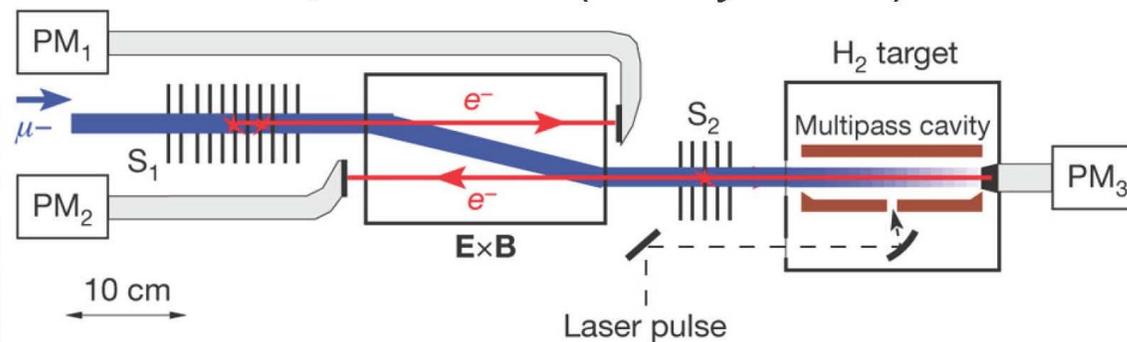
Comparing measurements to QED calculations that include corrections for the finite size of the proton can provide very precise value of the **rms proton charge radius**

Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

Muonic hydrogen Lamb shift at PSI (2010, 2013)



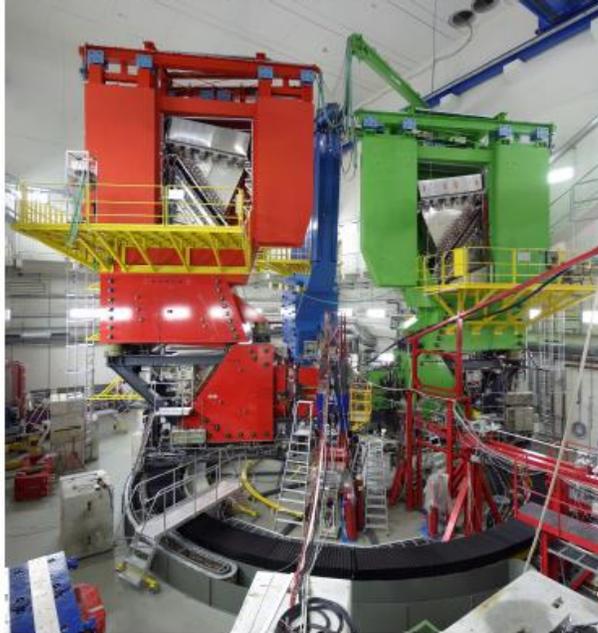
Nature 466, 213-216 (8 July 2010)



2010 value is $r_p = 0.84184(67)$ fm $r_p = 0.84087(39)$ fm, A. Antognini *et al.*, *Science* 339, 417 (2013)

Electron-proton Scattering – Mainz A1 experiment

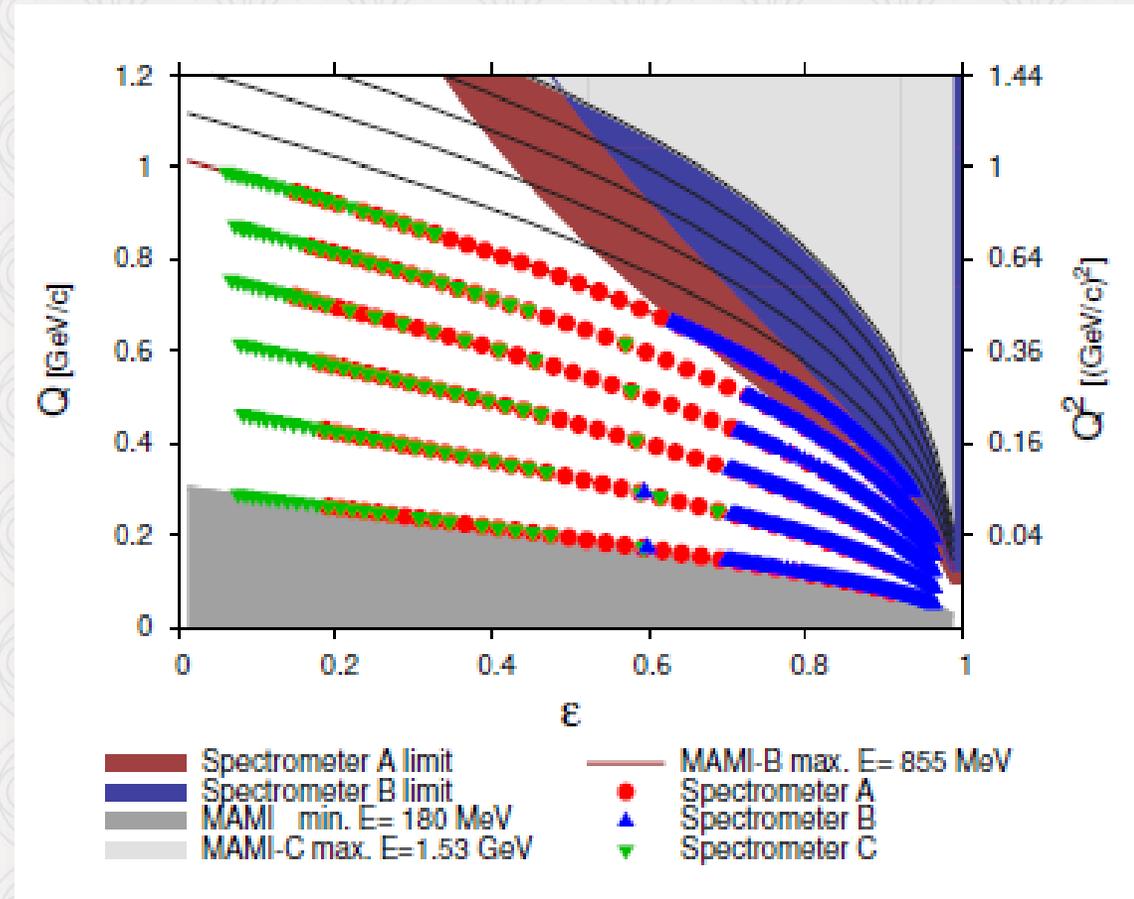
Three spectrometer facility of the A1 collaboration:



- Large amount of overlapping data sets
- Cross section measurement
- Statistical error $\leq 0.2\%$
- Luminosity monitoring with spectrometer

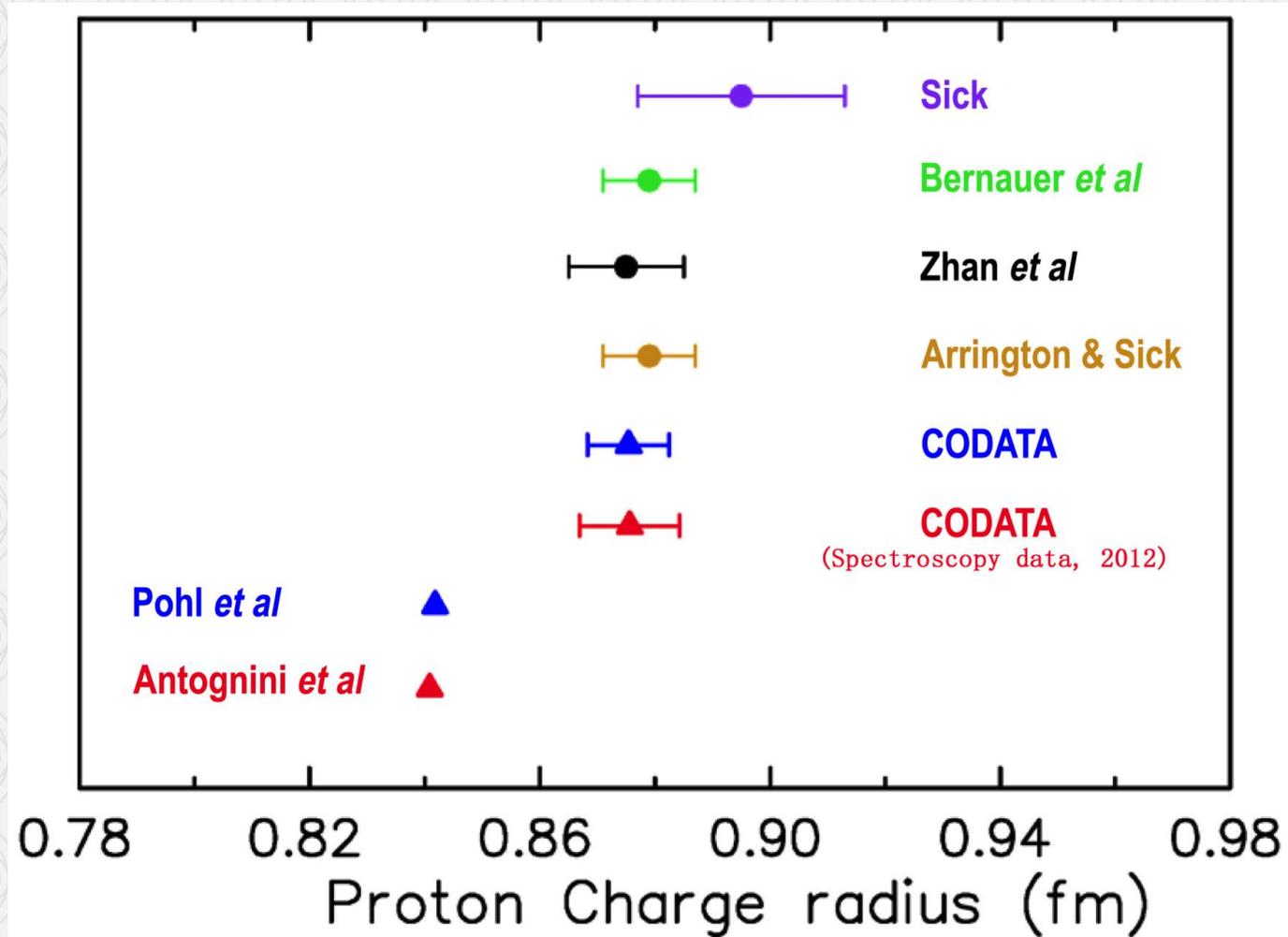
■ $Q^2 = 0.004 - 1.0 \text{ (GeV/c)}^2$
 result: $r_p = 0.879(5)_{\text{stat}}(4)_{\text{sys}}(2)_{\text{mod}}(4)_{\text{group}}$

J. Bernauer, PRL 105, 242001 (2010)



5-7 σ higher than muonic hydrogen result !

The situation on the Proton Charge Radius in 2013



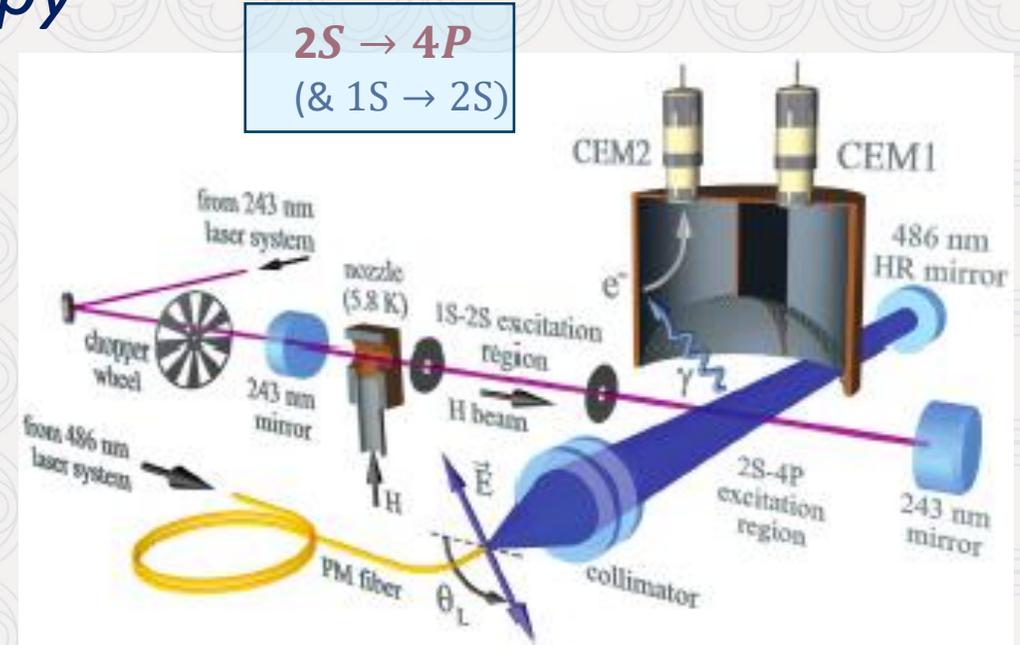
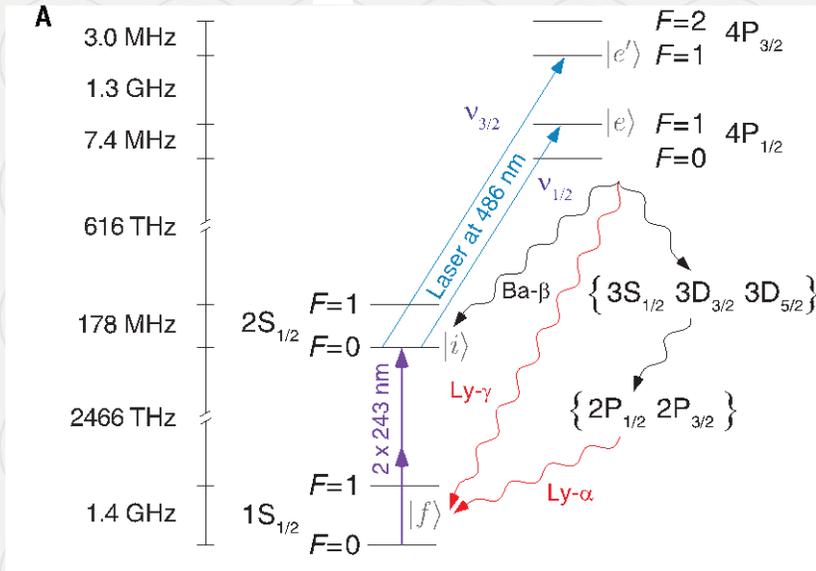
X. Zhan et al. Phys. Lett. B
705 (2011) 59-64
(Recoil proton polarization
Measurement together with
global analysis)

This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so

How to resolve the puzzle? - Incomplete list

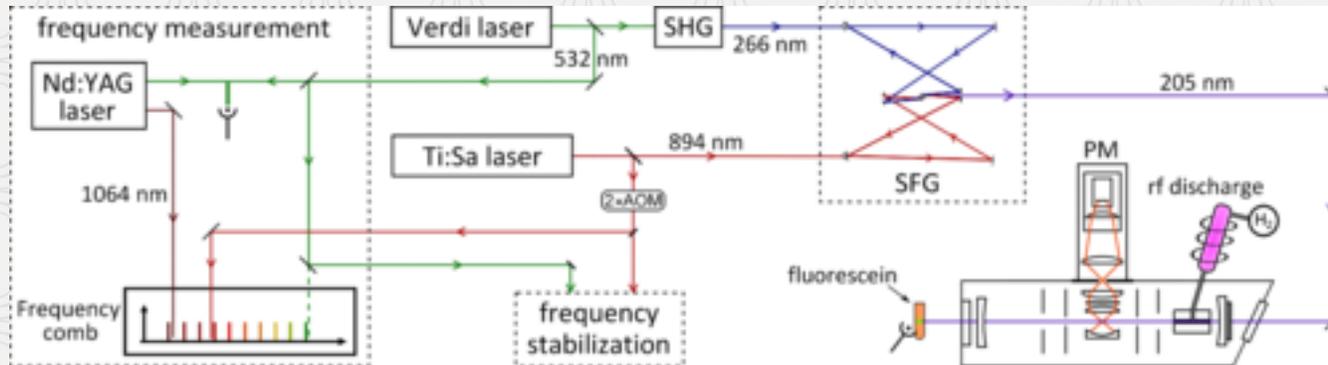
- **Revisit of the state-of-the-art QED calculations:** E. Borie (2005), Jentschura (2011), Hagelstein and Pascalutsa (2015),...
- **Contributions to the muonic H Lamb shift:** Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda....
- **Higher moments of the charge distribution and Zemach radii,** Distler, Bernauer and Walcher (2011), de Rujula (2010, 2011), Cloet and Miller (2011),...
- **Extrapolation in electron scattering:** Higinbotham et al. (2016), Griffioen, Carlson and Maddox (2016)
- **Reanalysis of ep elastic data:** Distler, Walcher, and Bernauer (2015), Arrington (2015), Horbatsch and Hessels (2015), T. Hayward, K. Griffioen (2018),.....
- **Discrepancy explained/somewhat explained by some authors, but not all agree:** Lorenz et al., Ronson, Donnelly et al.
- **Consistency re radius defined in ep and atomic experiments:** Miller
- **New physics: new particles,** Barger et al., Carlson and Rislow; Liu and Miller, Alvarado, Aranda and Bonilla....**New PV muonic force,** Batell et al.; Carlson and Freid; **Extra dimension:** Dahia and Lemos; **Quantum gravity at the Fermi scale** R. Onofrio,.....
- **Exps: Mainz, JLab (PRad), MUSE at PSI, ULQ2 in Japan, Amber@CERN; H spectroscopy (Germany, France, Canada, U.S.), ...**

Ordinary hydrogen spectroscopy



2S → 4P
(& 1S → 2S)

$$R_\infty = 10\,973\,731.568\,076(96) \text{ m}^{-1}, r_p = 0.8335(95) \text{ fm}, \text{Beyer et al., Science 358, 79 (2017)}$$

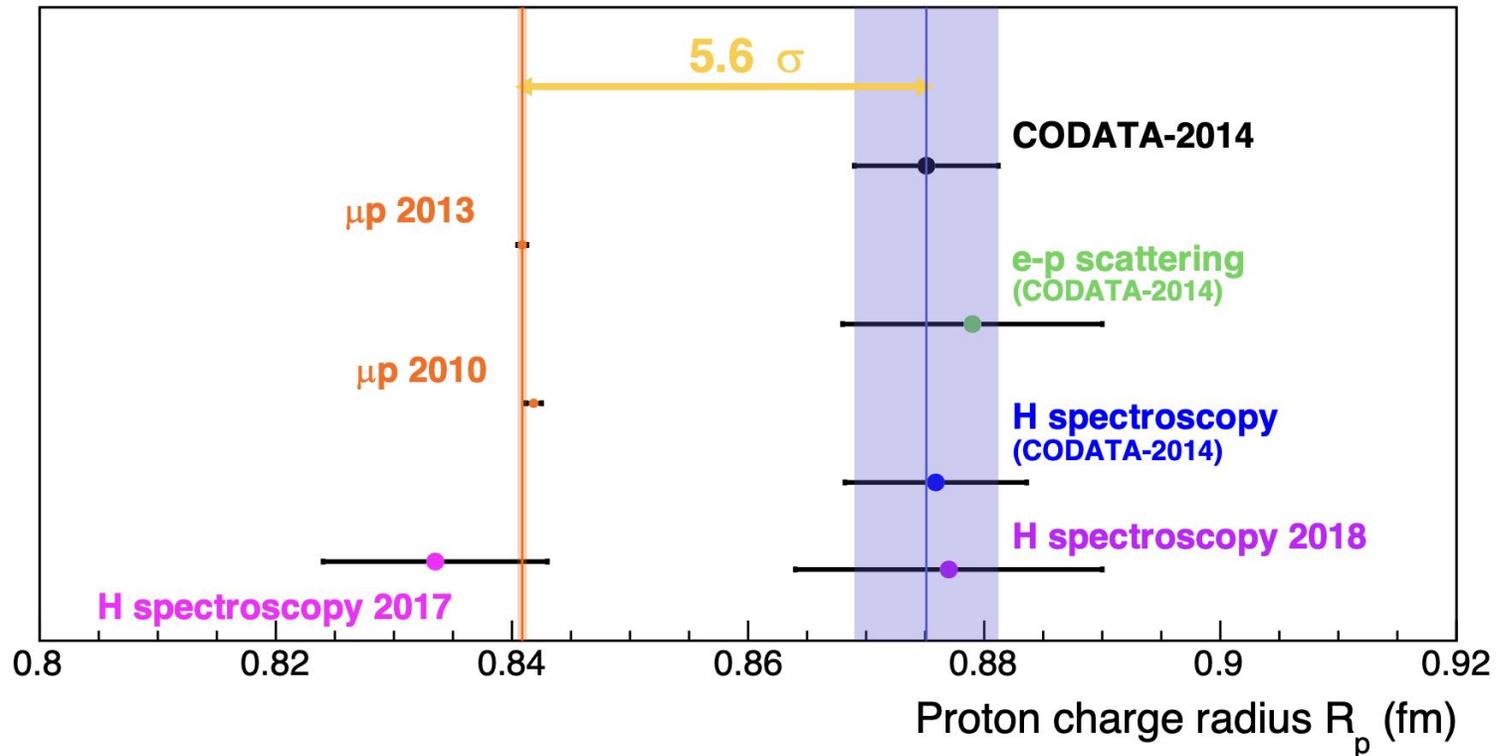


1S → 3S
(& 1S → 2S)

Parthey et al., PRL 107, 203001 (2011)
Matveev et al. PRL 110, 230801 (2013)

$$R_\infty = 10\,973\,731.568\,53(14) \text{ m}^{-1}, r_p = 0.877(13) \text{ fm}, \text{Fleurbay et al. PRL 120, 183001 (2018)}$$

The Proton Charge Radius Puzzle in 2018



Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)

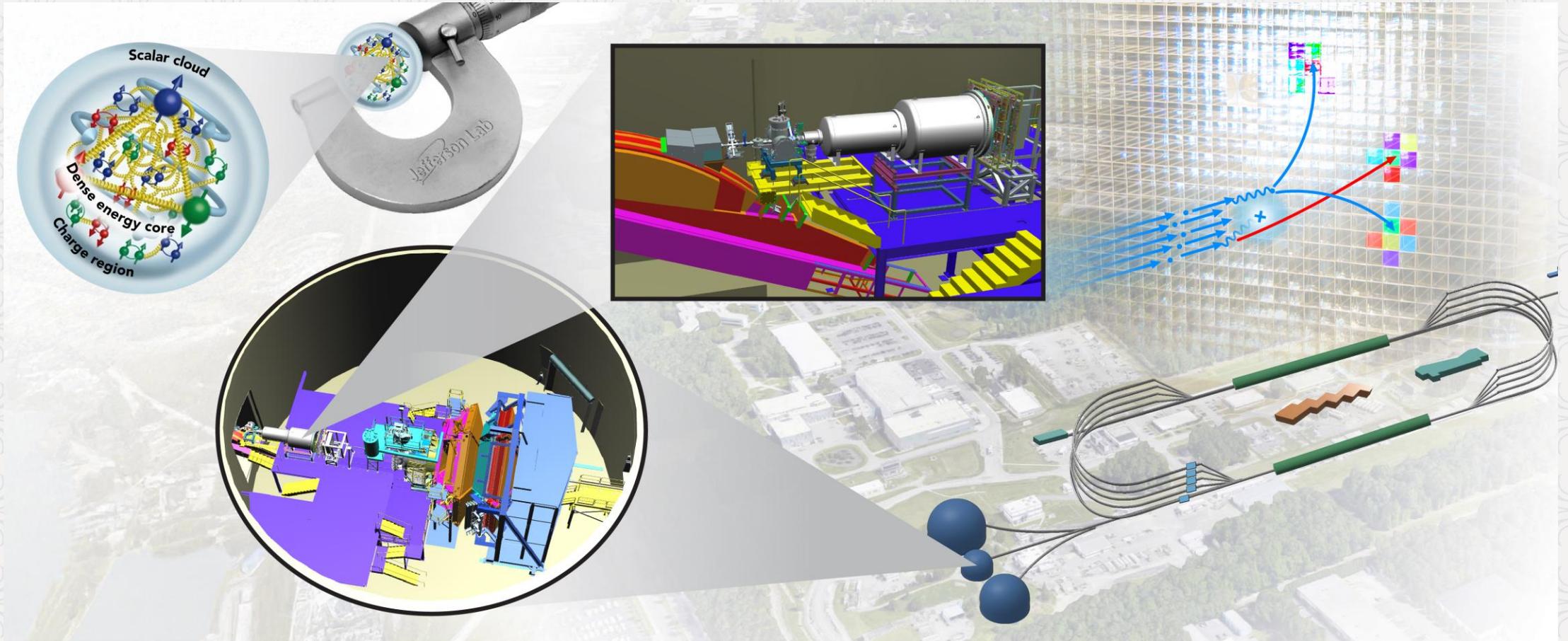
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)

H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)

H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

Not shown: ep scattering (ISR, 2017): $0.810 \pm 0.035_{\text{stat.}} \pm 0.074_{\text{syst.}} \pm 0.003$ (delta_a, delta_b)
 (Mihovilovic PLB 771 (2017); $0.878 \pm 0.011_{\text{stat.}} \pm 0.031_{\text{syst.}} \pm 0.002_{\text{mod.}}$ (Mihovilovic 2021))

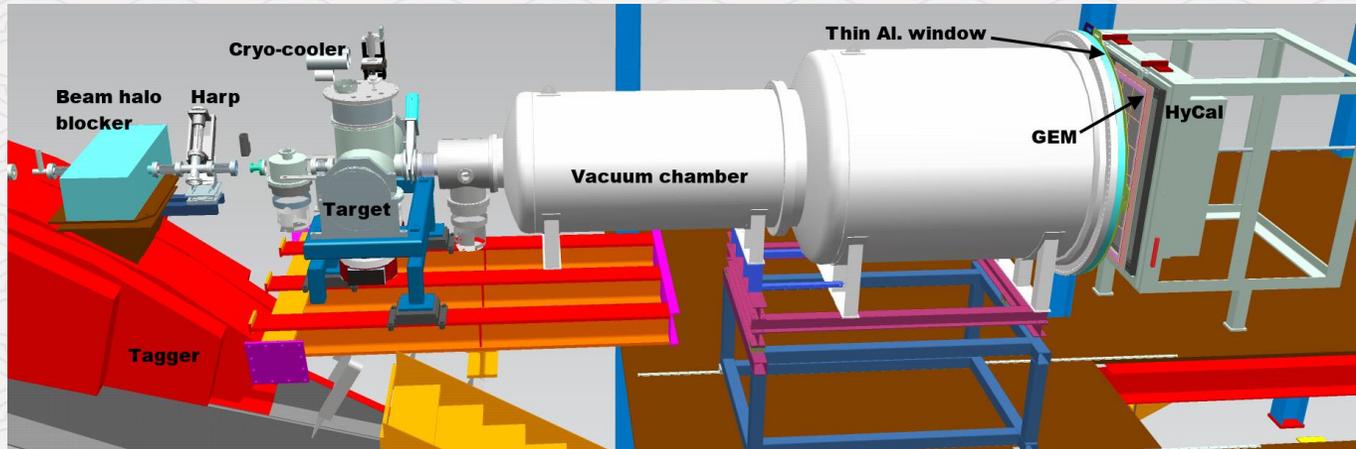
Proton Charge Radius at JLab (PRad & PRad-II)



<https://www.innovationnewsnetwork.com/how-large-is-the-proton-how-do-we-measure-it/61615/>

Duke

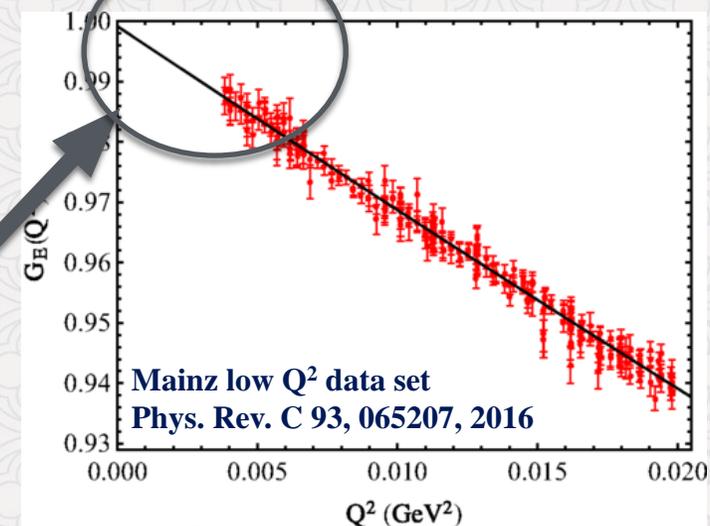
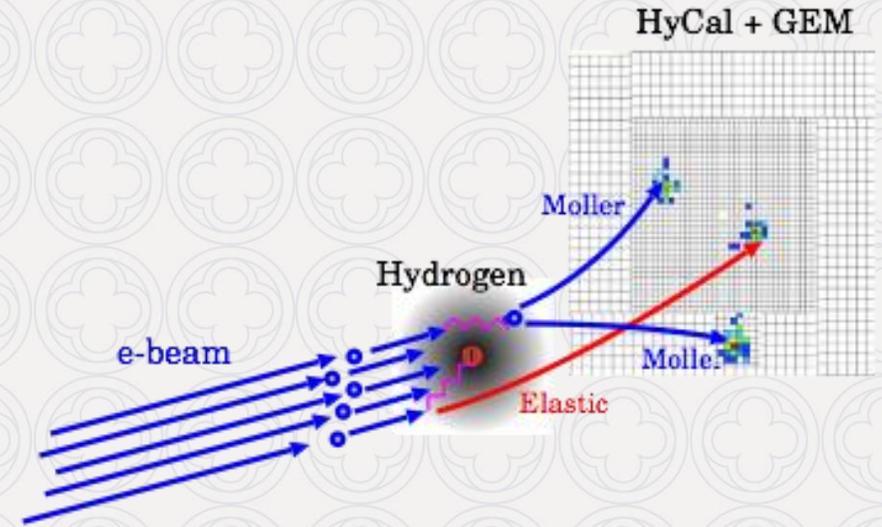
The PRad Experiment in Hall B at JLab



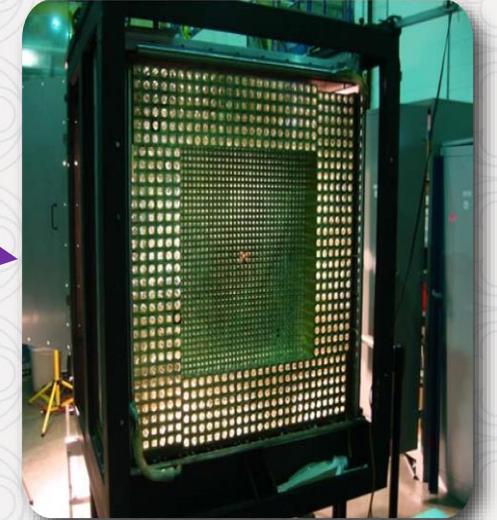
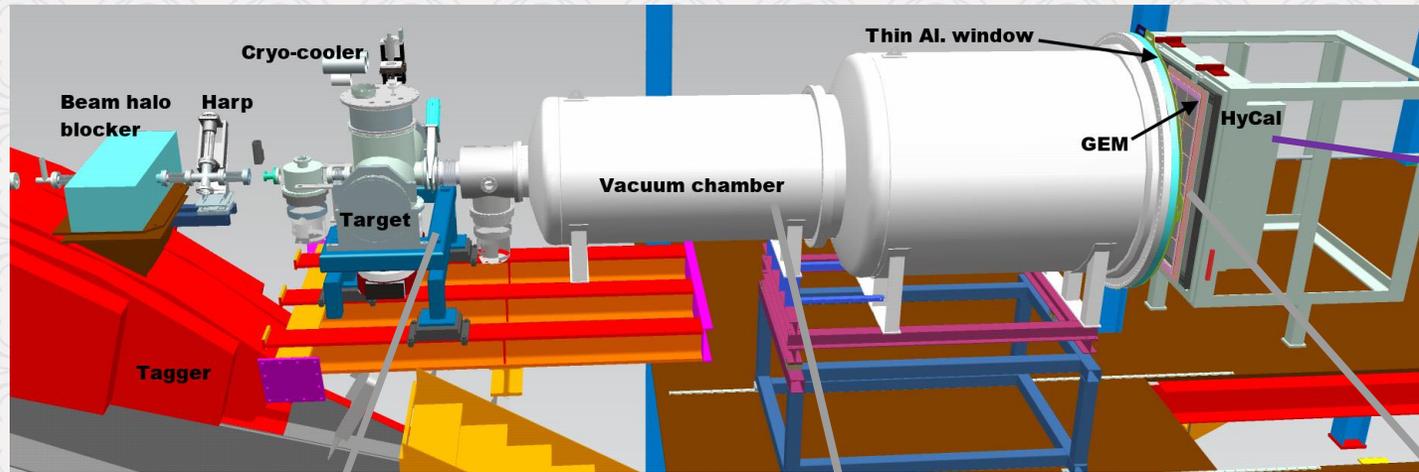
- High resolution, large acceptance, hybrid HyCal calorimeter (PbWO_4 and Pb-Glass)
- Windowless H_2 gas flow target
- Simultaneous detection of elastic e-p and Moller electrons
- Q^2 range of $2 \times 10^{-4} - 0.06 \text{ GeV}^2$
- XY – veto counters replaced by GEM detector
- Vacuum chamber

Spokespersons: A. Gasparian (contact),
H. Gao, D. Dutta, M. Khandaker

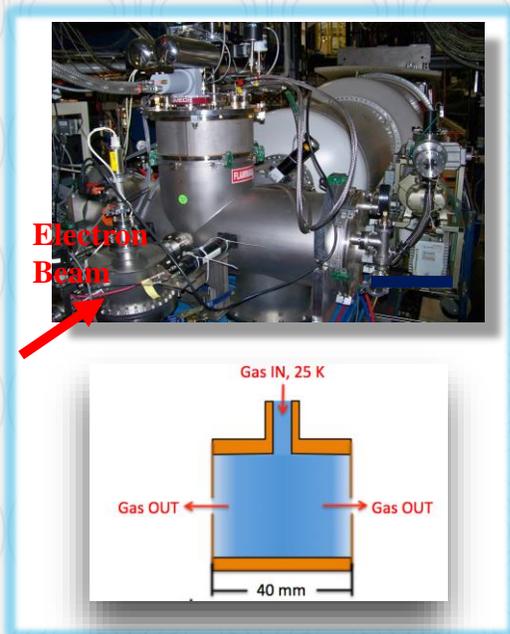
PRad result r_p : $0.831 \pm 0.0127 \text{ fm}$, Xiong *et al.*, *Nature* 575, 147–150 (2019)



The PRad Experimental setup



I Larin, Y Y. Zhang, *et al.*,
Science 6490, 506



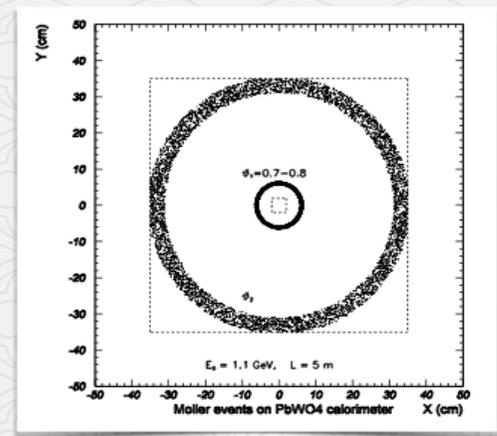
J. Pierce *et al.*, NIMA 1003, 165300 (2021)



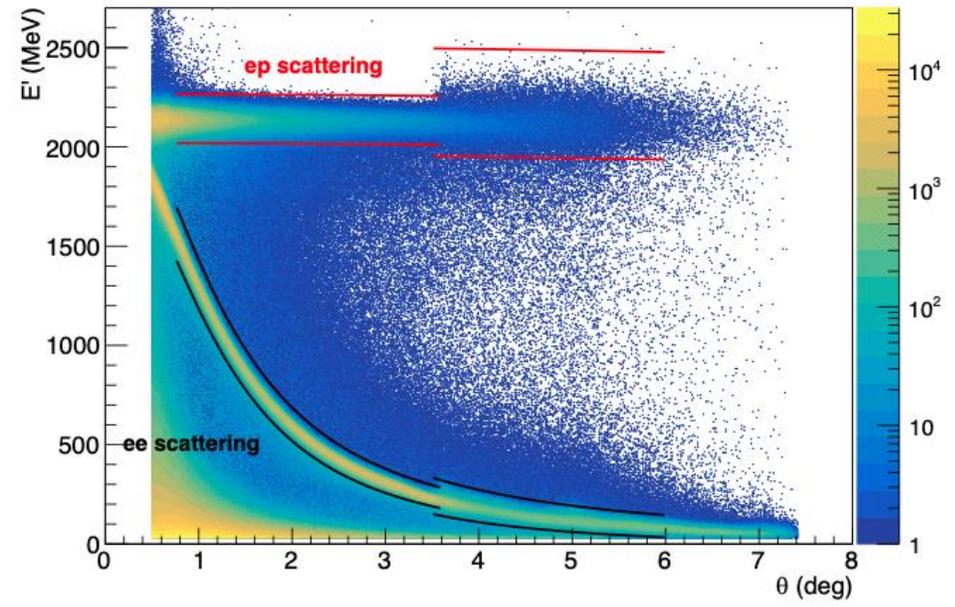
Analysis – Event Selection

Event selection method

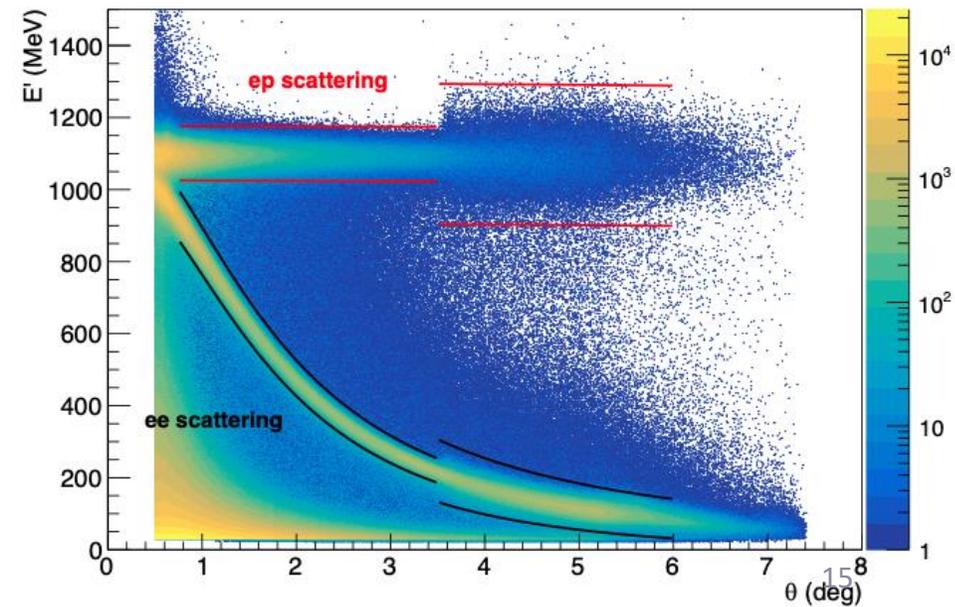
1. For all events, require hit matching between GEMs and HyCal
2. For *ep* and *ee* events, apply angle-dependent energy cut based on kinematics
 1. Cut size depend on local detector resolution
3. For *ee*, if requiring double-arm events, apply additional cuts
 1. Elasticity
 2. Co-planarity
 3. Vertex z



Cluster energy E' vs. scattering angle θ (2.2GeV)

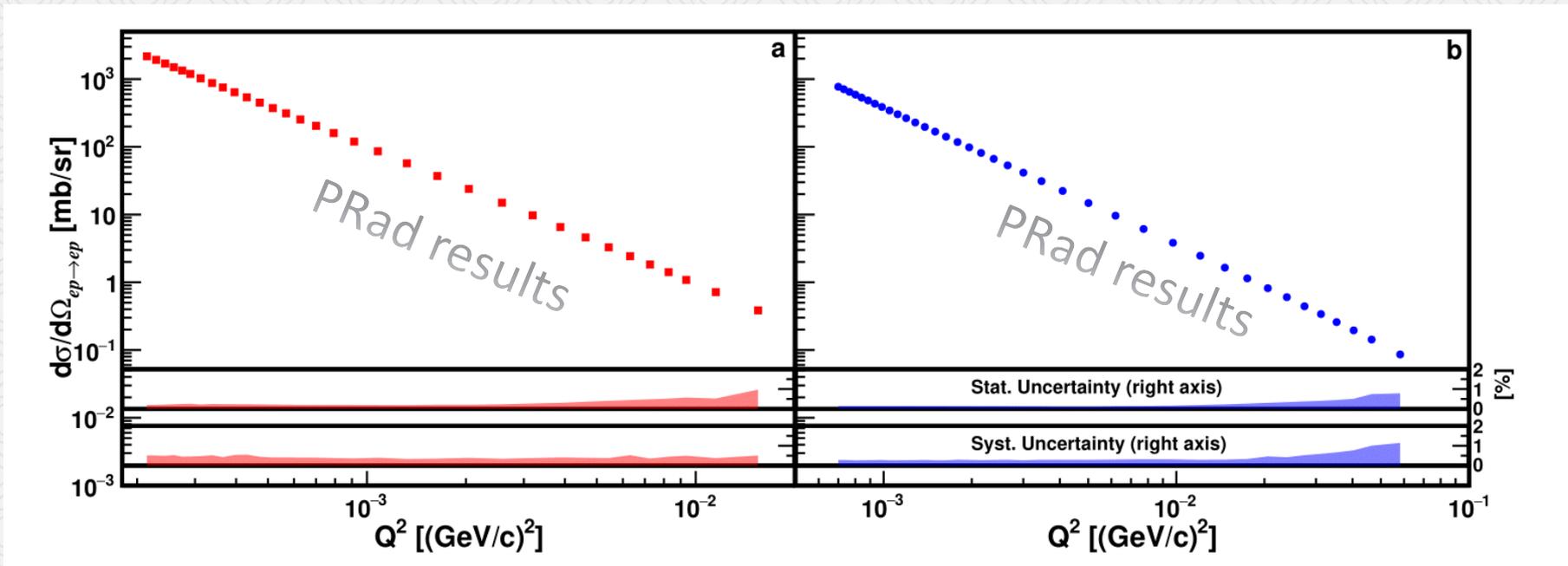


Cluster energy E' vs. scattering angle θ (1.1GeV)



Elastic ep Cross Sections

- Differential cross section v.s. Q^2 , with 2.2 and 1.1 GeV data
- Statistical uncertainties: $\sim 0.15\%$ for 2.2 GeV, $\sim 0.2\%$ for 1.1 GeV per point
- Systematic uncertainties: $0.3\% \sim 1.1\%$ for 2.2 GeV, $0.3\% \sim 0.5\%$ for 1.1 GeV (shown as shadow area)



Systematic uncertainties shown as bands *Xiong et al., Nature 575, 147–150 (2019)*

Proton Electric Form Factor G'_E (Normalized)

- n_1 and n_2 obtained by fitting PRad G_E to

$$\begin{cases} n_1 f(Q^2), & \text{for 1 GeV data} \\ n_2 f(Q^2), & \text{for 2 GeV data} \end{cases}$$

Using rational (1,1)

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

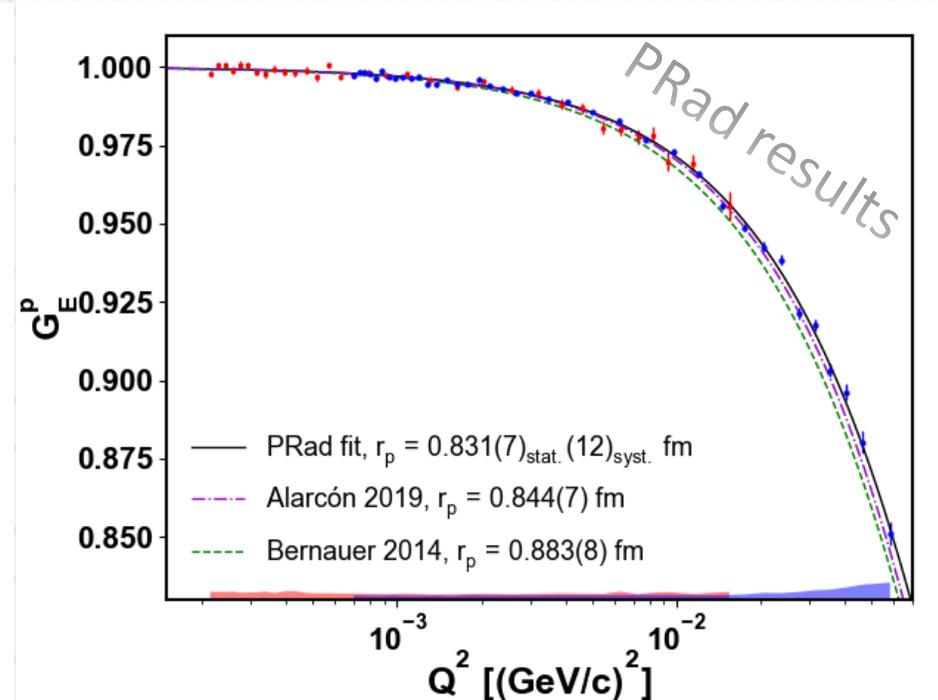
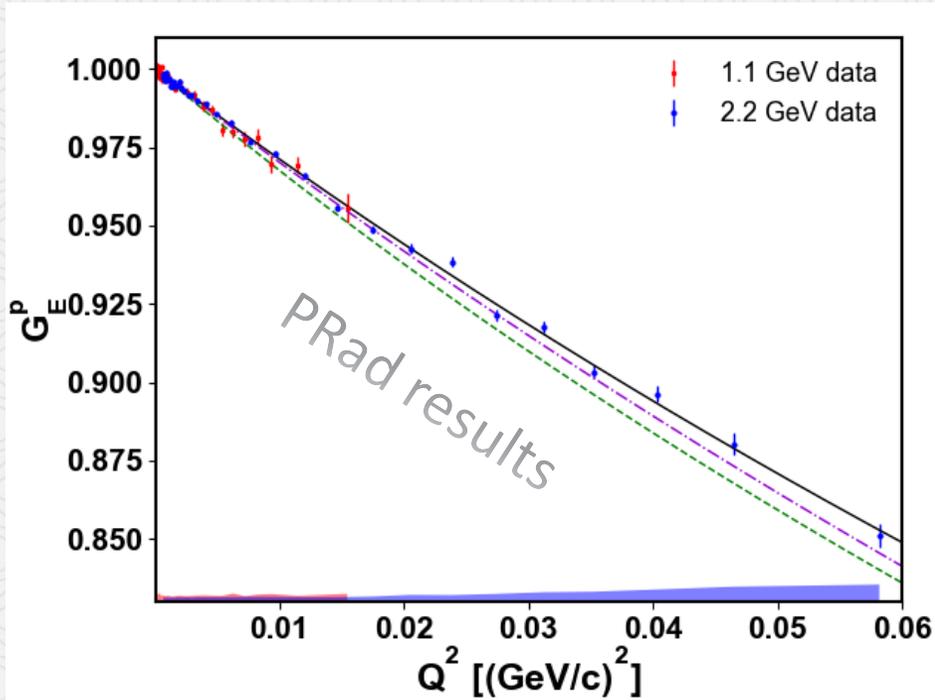
- G'_E as normalized electric Form factor:

$$\begin{cases} G_E/n_1, & \text{for 1 GeV data} \\ G_E/n_2, & \text{for 2 GeV data} \end{cases}$$

Yan et al. PRC98,025204 (2018)

- PRad fit shown as $f(Q^2)$

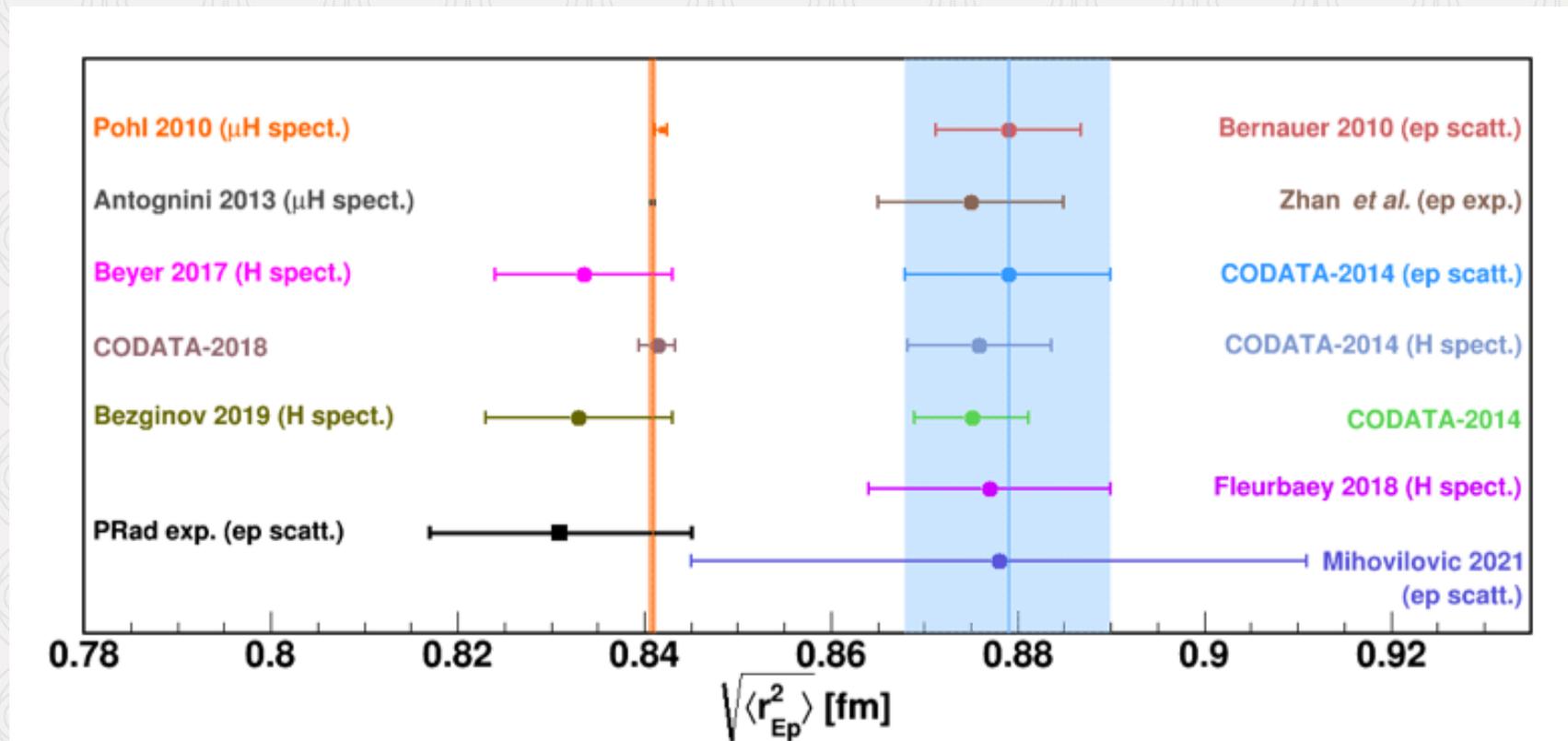
$$r_p = 0.831 \pm 0.007 \text{ (stat.)} \pm 0.012 \text{ (syst.) fm}$$



$$n_1 = 1.0002 \pm 0.0002 \text{ (stat.)} \pm 0.0020 \text{ (syst.)}, \quad n_2 = 0.9983 \pm 0.0002 \text{ (stat.)} \pm 0.0013 \text{ (syst.)}$$

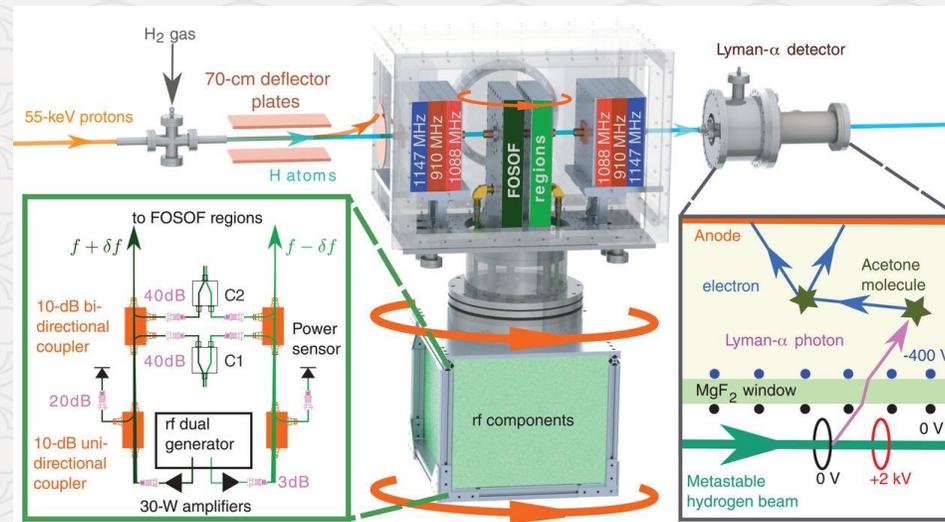
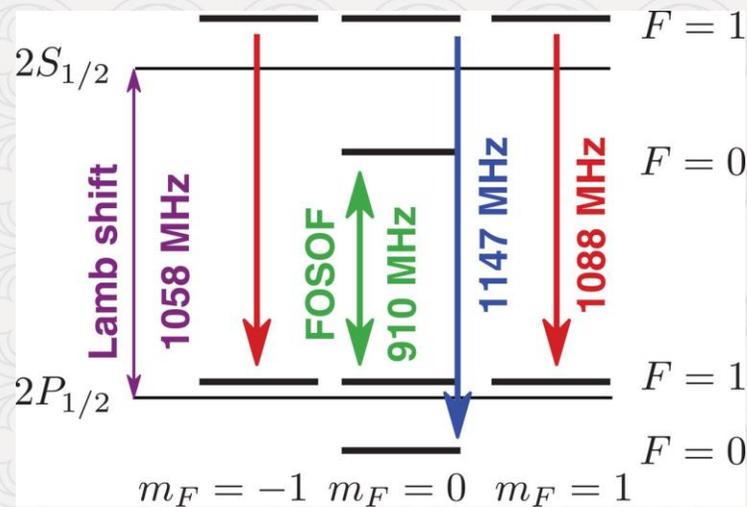
Proton radius at the time of PRad publication

- PRad result r_p : 0.831 ± 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*
- H Lamb Shift: 0.833 ± 0.010 fm *Bezginov et al., Science 365, 1007-1012 (2019)*
- CODATA 2018 value of r_p : 0.8414 ± 0.0019 fm, *E. Tiesinga et al., RMP 93, 025010(2021)*

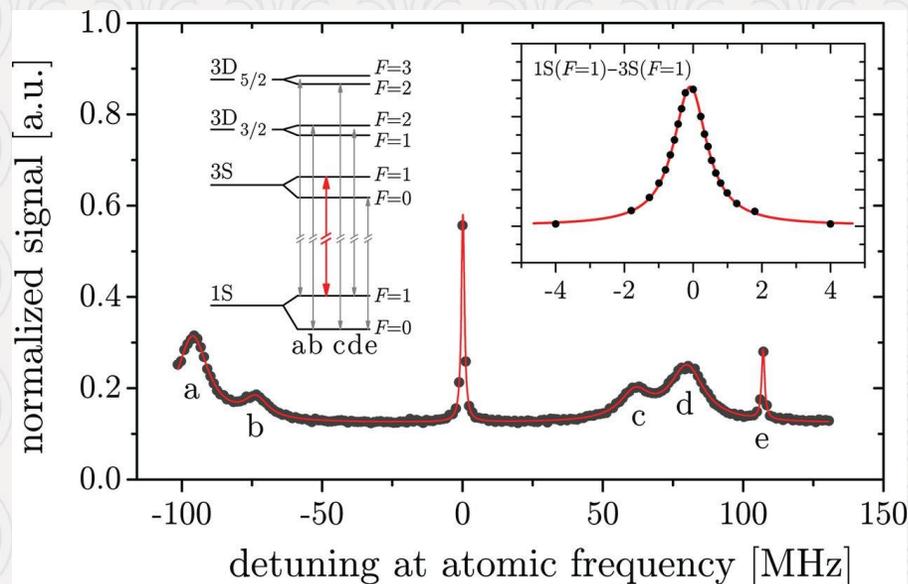


CODATA has also shifted the value of the Rydberg constant.

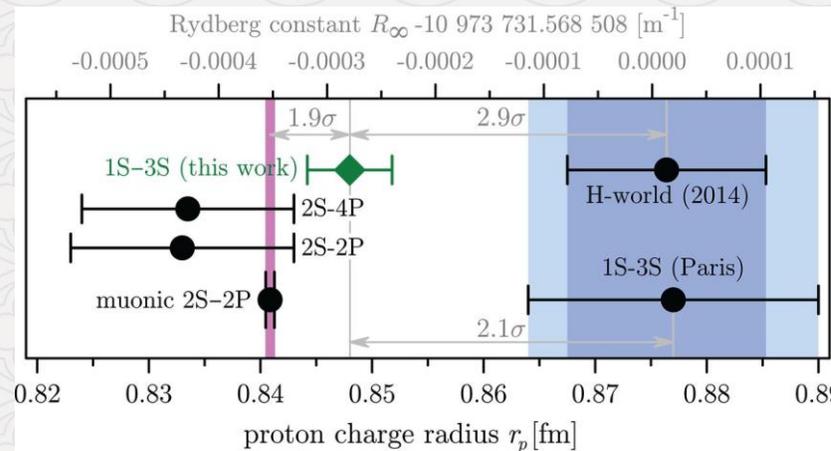
More from ordinary hydrogen spectroscopy



Bezginov *et al.*, Science 365, 1007 (2019) $r_p = 0.833(10)$ fm

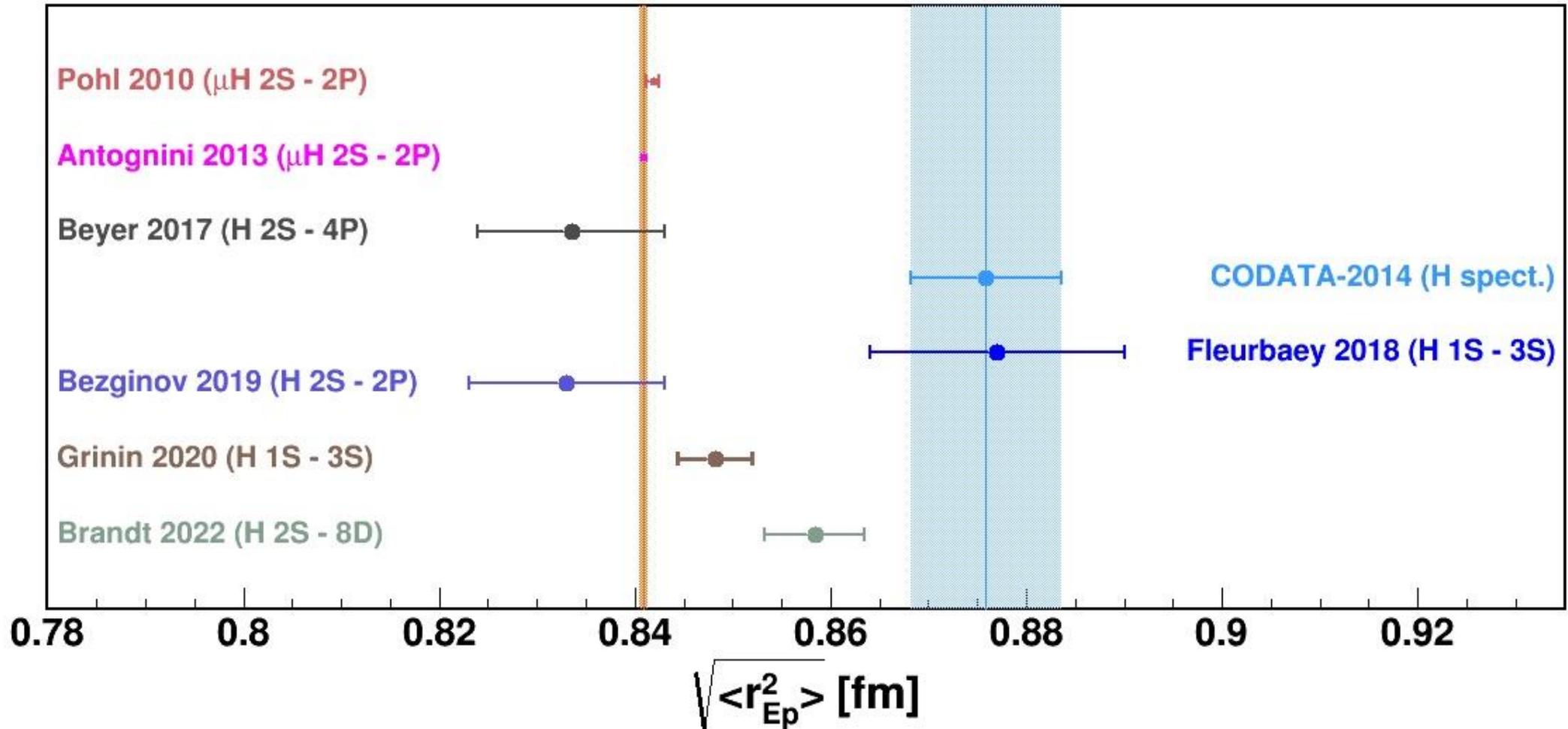


Gao and Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)

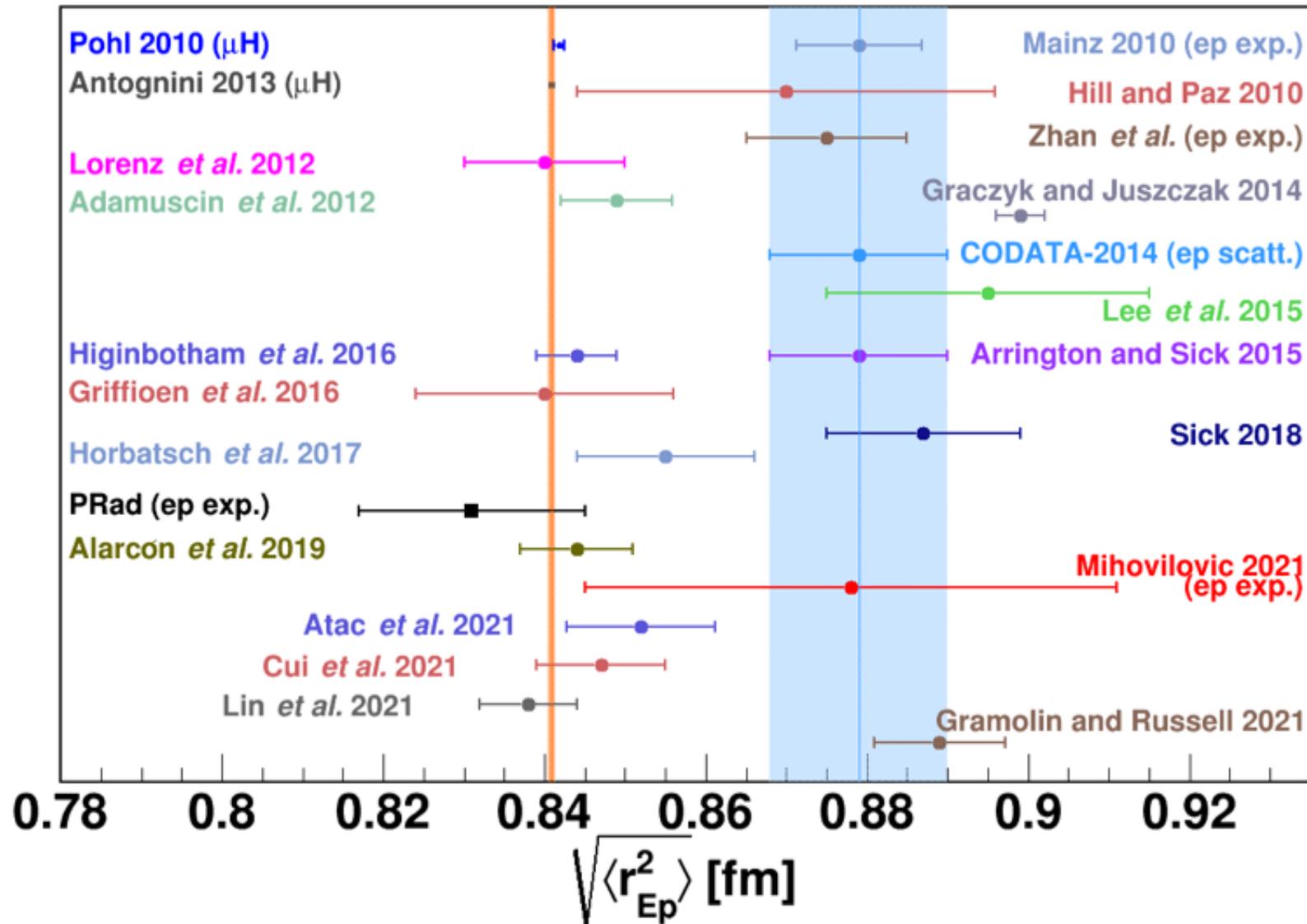


Grinin *et al.*, Science 370, 1061 (2020) $r_p = 0.8482(38)$ fm

Proton radius from ordinary and muonic H spectroscopy



(Re)analyses of $e-p$ scattering data



Gao and Vanderhaeghen,
Rev. Mod. Phys. 94, 015002 (2022)

Some more recent work:

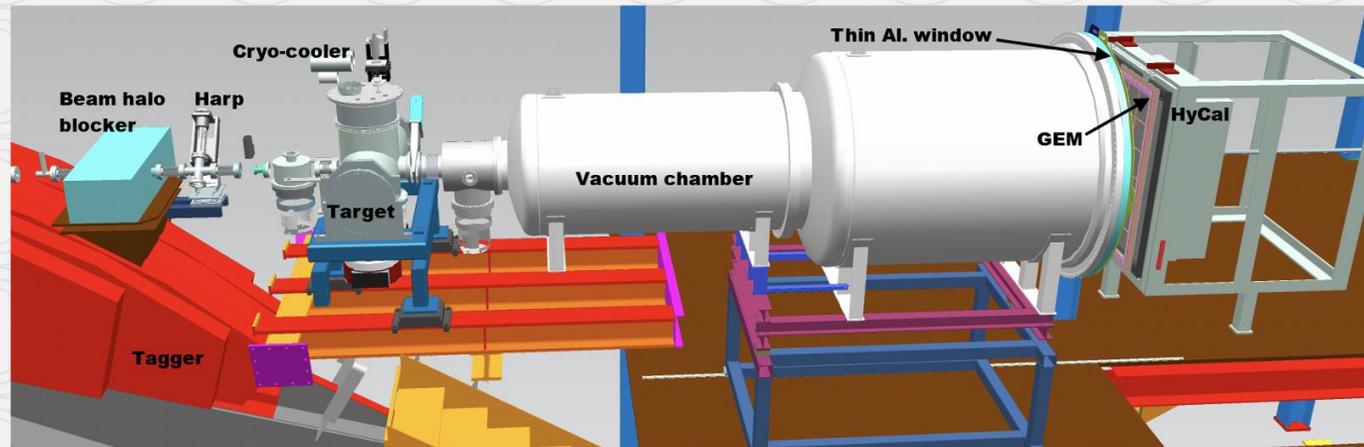
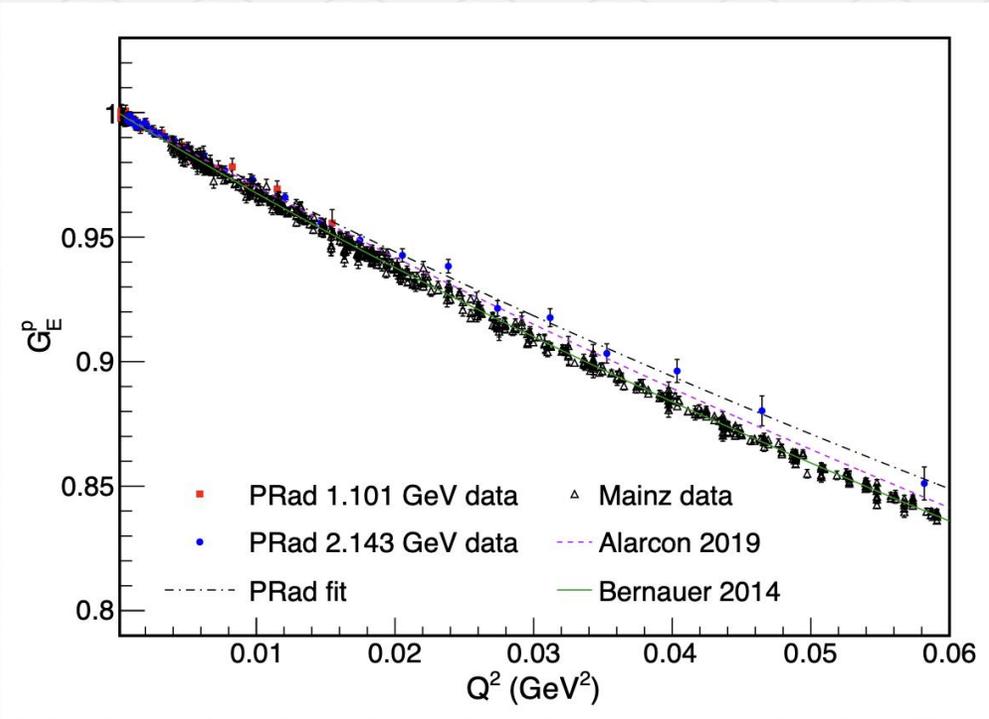
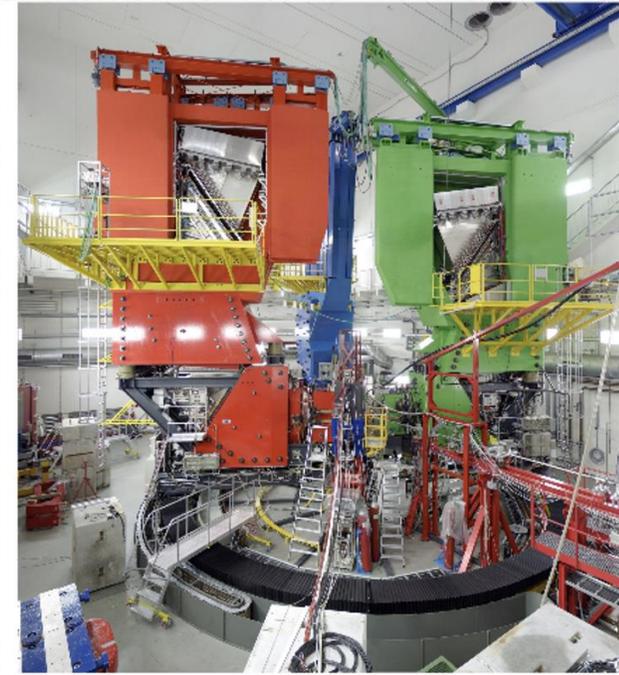
Cui *et al.* 2022

Chinese Phys. C **46** 122001

Qattan (PRC 2025)

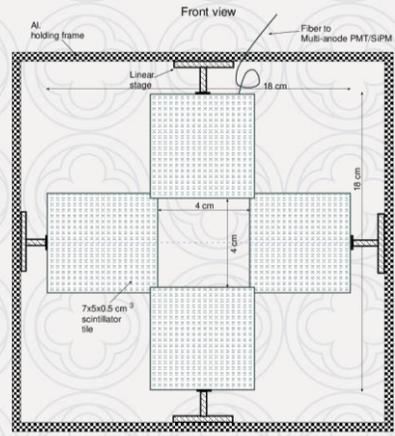
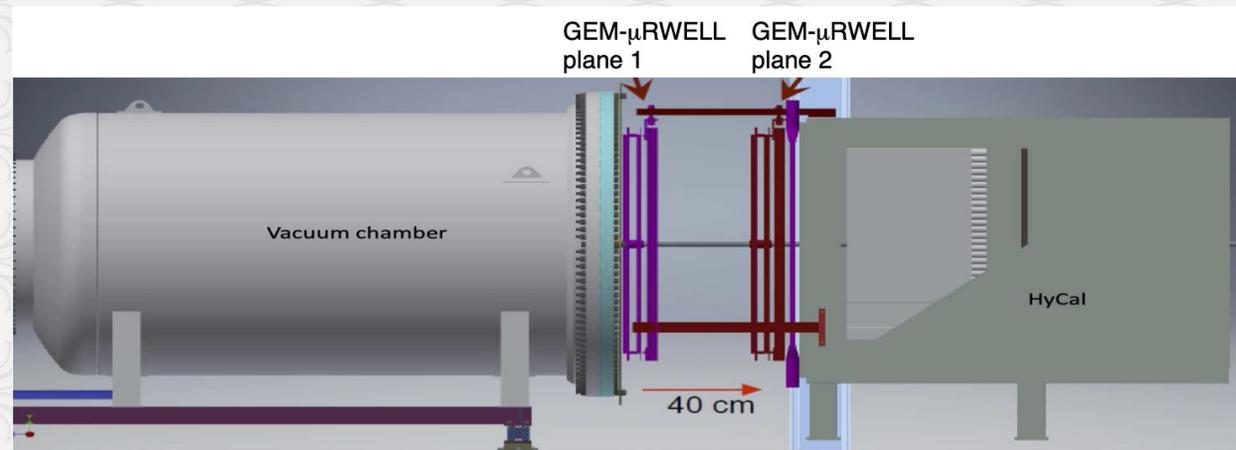
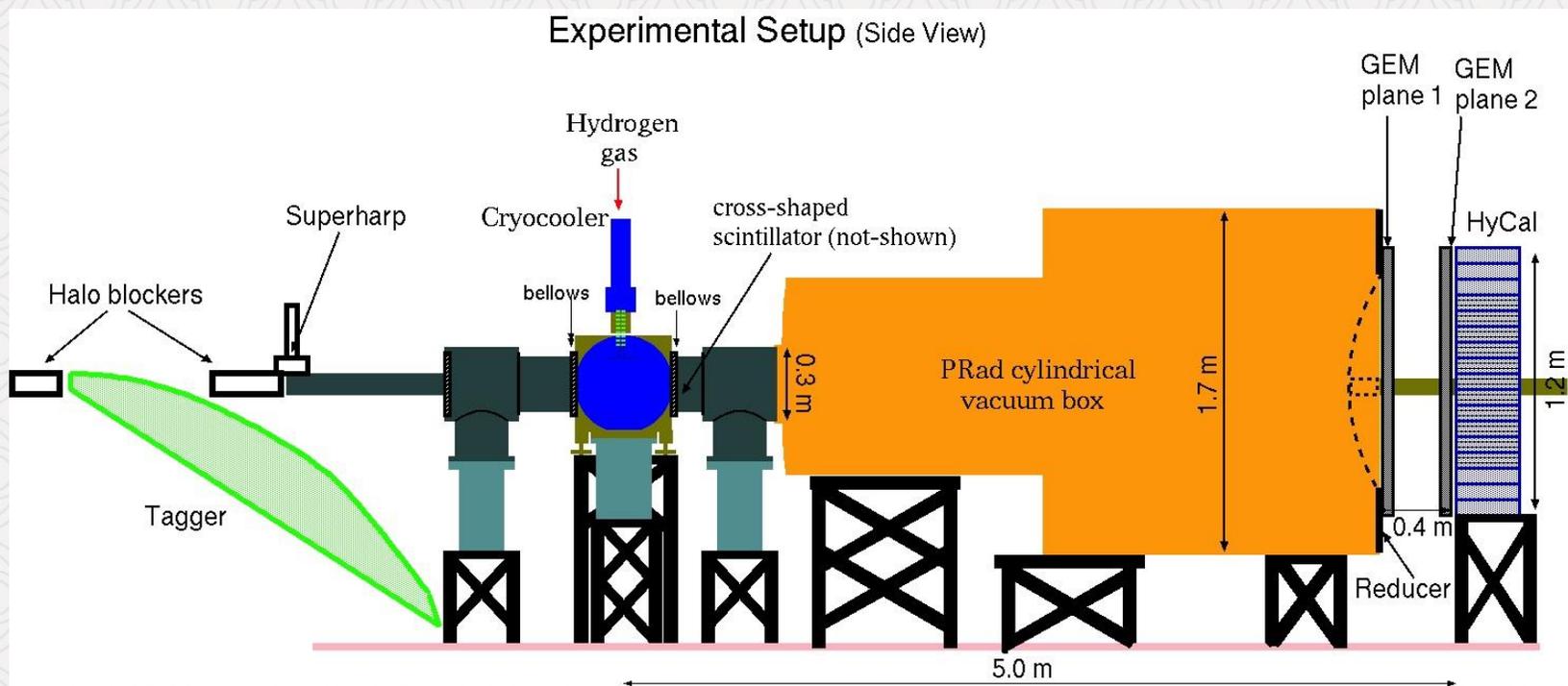
Goharipour *et al.* (PLB 2025)

e-p scattering: magnetic spectrometer and calorimetric method

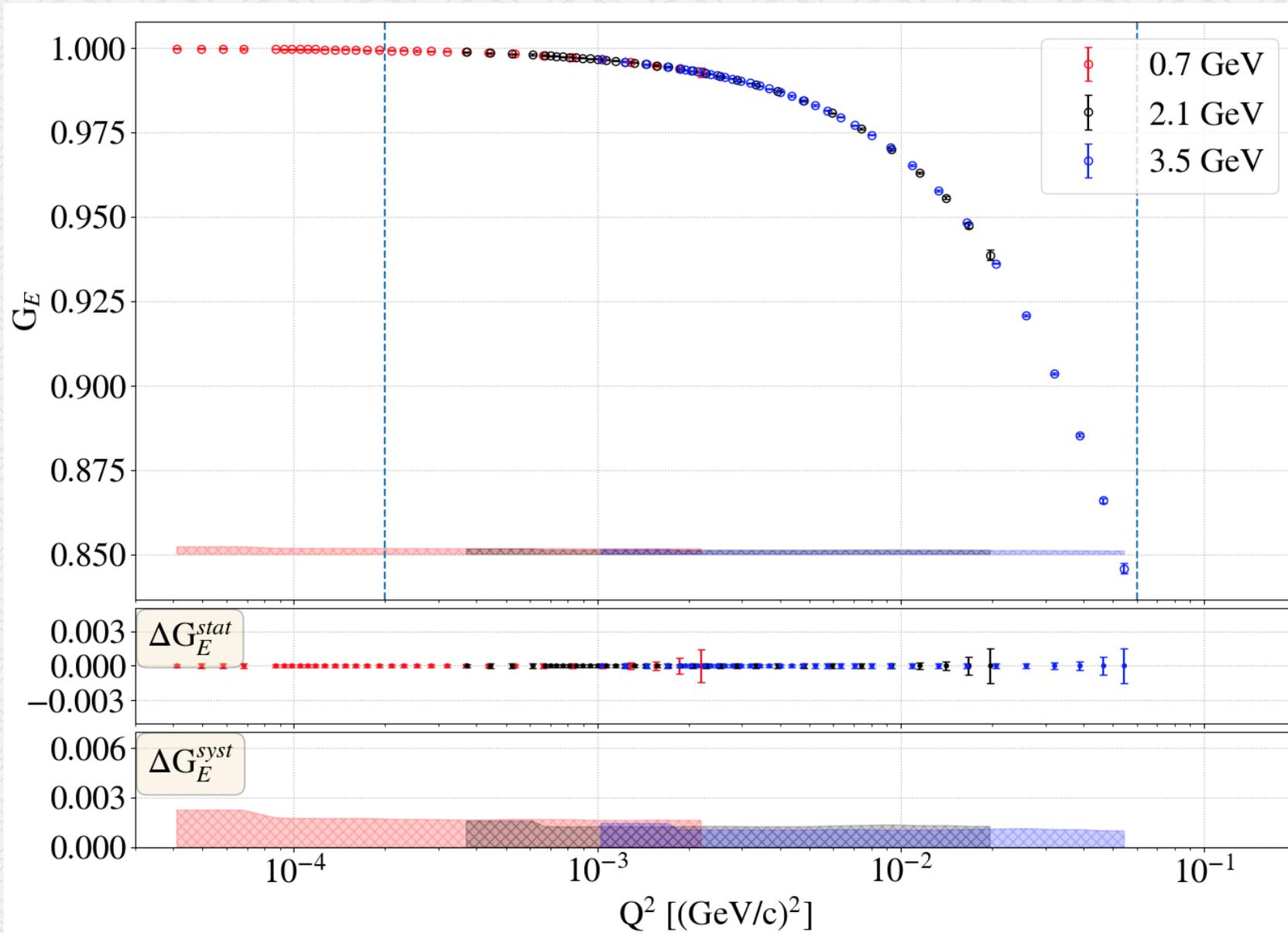


PRad-II: goals and approaches

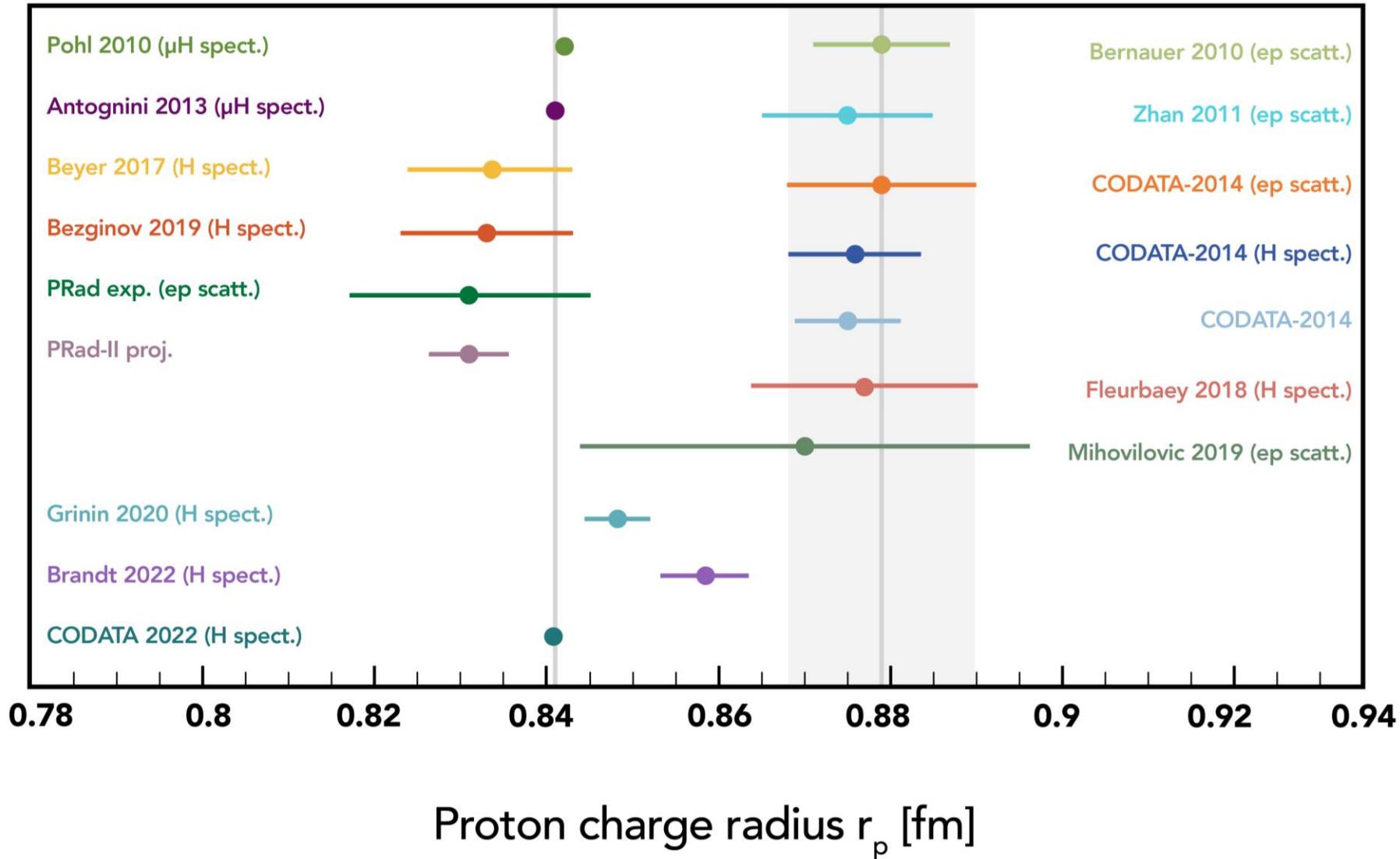
- Reduce the uncertainty of the r_p measurement by a factor of **3!**
- Precise measurement of G_E to investigate the difference between the Mainz data and PRad
- Reach an unprecedented low values of $Q^2 : 4 \times 10^{-5} \text{ (GeV/c)}^2$
- How?
 - Improving tracking capability by adding a second plane of tracking detector
 - Adding new rectangular cross shaped scintillator detectors to separate Moller from ep electrons in scattering angular range of 0.5° - 0.8°
 - Upgrading HyCal electronics for readout
 - Converting to FADC based readout
 - Suppressing beamline background
 - Improving vacuum
 - Adding second beam halo blocker upstream of the tagger
 - Reducing statistical uncertainties by a factor of 4 compared with PRad
 - Three beam energies: 0.7, 2.1, 3.5 GeV – ***0.7 GeV is critical to reach the lowest Q^2 ($4 \times 10^{-5} \text{ (GeV/c)}^2$)***
 - Improve radiative correction calculations by going to NNL order
 - Potential target improvement (***not used in projection***)



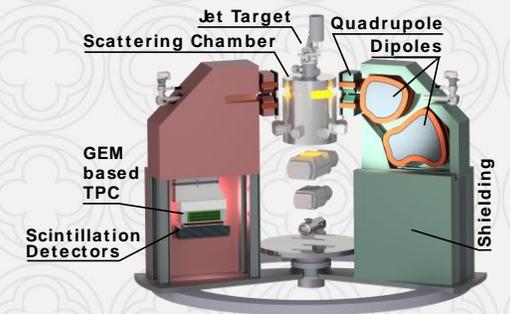
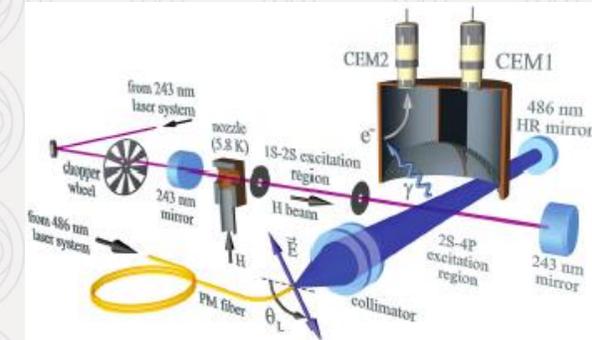
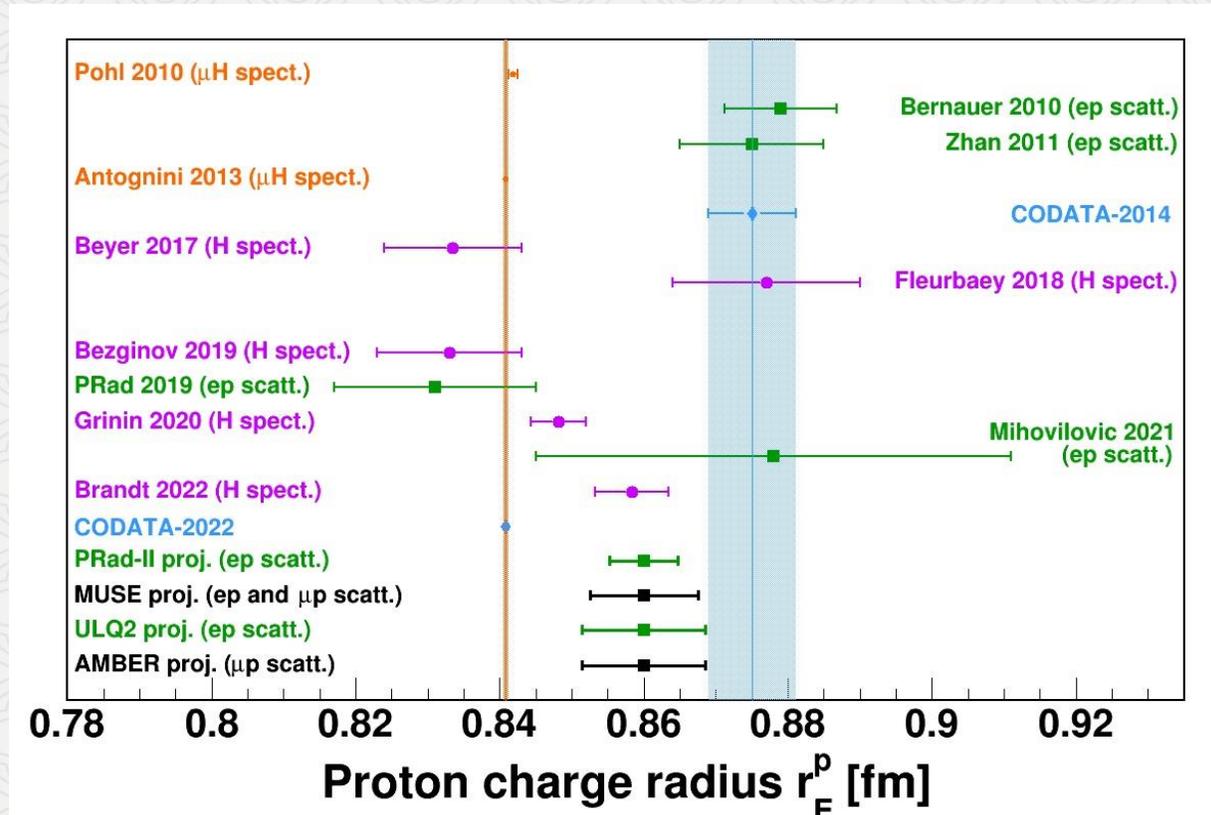
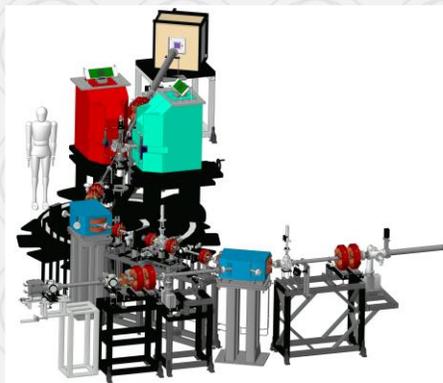
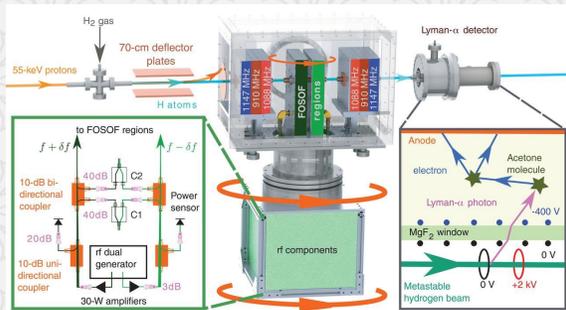
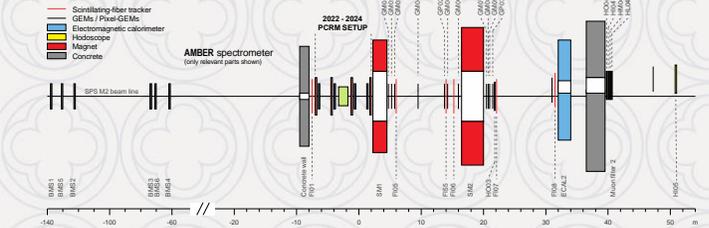
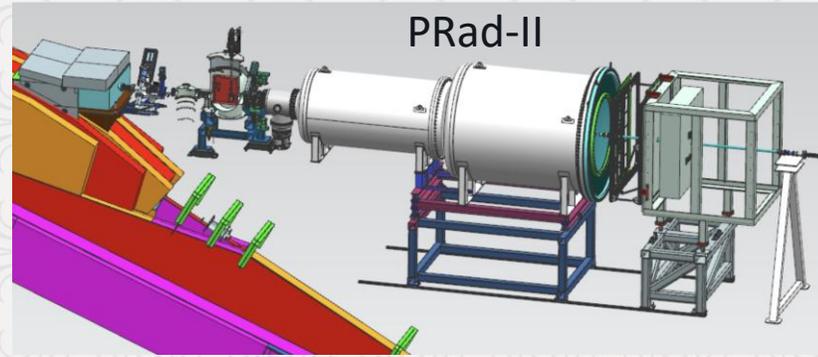
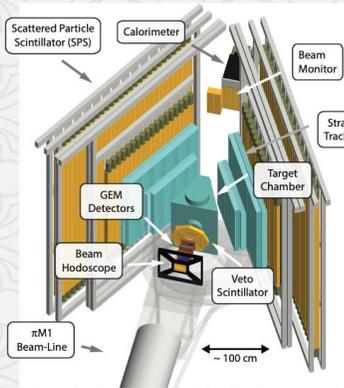
Simulated PRad-II Uncertainties on G_E



Projected PRad-II on r_p



World-wide effort in Nuclear and Atomic Physics on Proton Charge Radius



Summary

- The proton charge radius puzzle not resolved yet, but major progress made
- The PRad – a first ep scattering experiment using a non-magnetic spectrometer – obtained a result consistent with muonic hydrogen measurements
- Most of the recent ordinary hydrogen spectroscopy measurements are consistent with muonic results
- New results expected from lepton scattering including PRad-II

Acknowledgment: The PRad Collaboration (some collaborators are not shown in the picture)

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