



# *Experimental status of the proton radius*

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BNL & Duke University

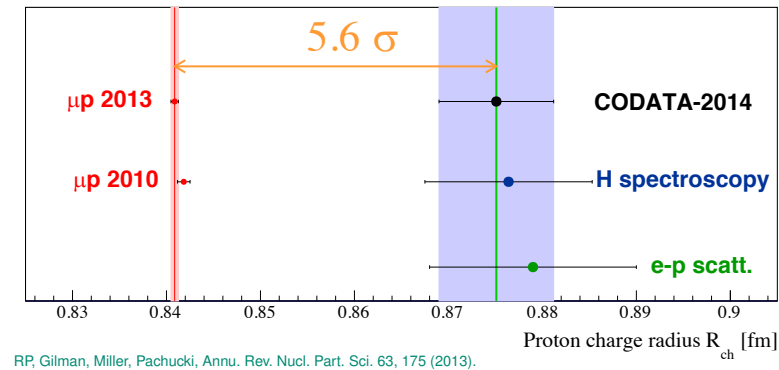
September 5-10, 2021  
PANIC 2021 Conference



# Proton Charge Radius and the puzzle

- Proton charge radius:

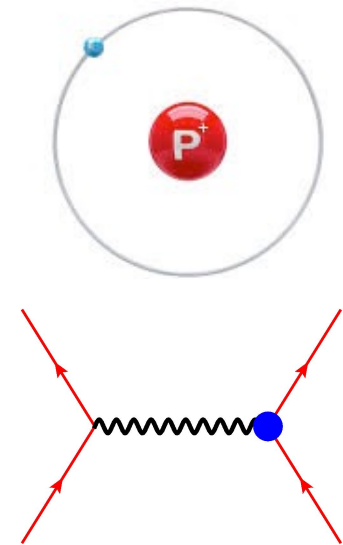
1. An important quantity for proton
2. Important for understanding how QCD works
3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ( $2S_{1/2} - 2P_{1/2}$ ) by as much as 2%, and critical in determining the Rydberg constant



- 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 (Mainz-A1, PRad,..)
  - *μp* elastic scattering (MUSE, AMBER)

➤ Important point: the proton radius measured in lepton scattering defined the same as in atomic spectroscopy (G.A. Miller, 2019)



$$\begin{aligned}\Delta E &= -4\pi\alpha G_E^{\prime p}(0)|\psi_{n0}(0)|^2\delta_{l0} \\ &= 4\pi\alpha \frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.\end{aligned}$$

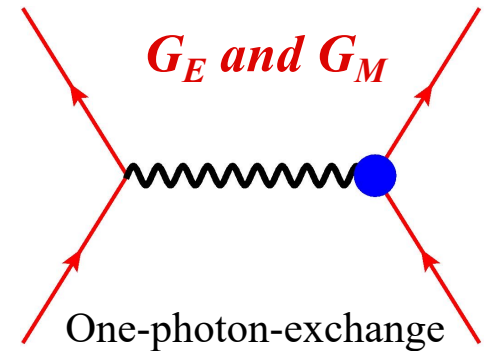
$$\sqrt{\langle r^2 \rangle} = \sqrt{-6 \frac{dG(q^2)}{dq^2} \Big|_{q^2=0}}$$

# Electron-proton elastic scattering

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

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

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

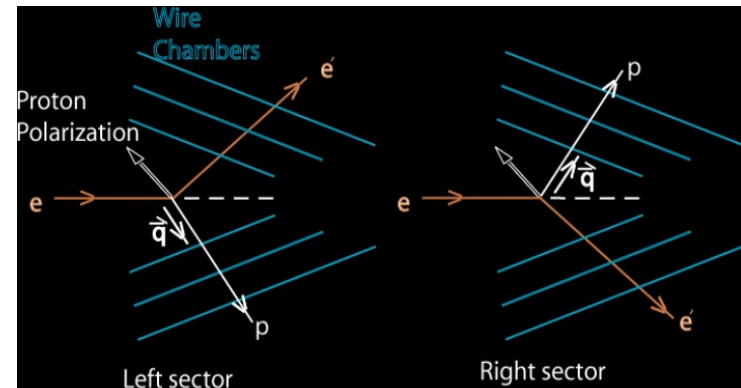


- Recoil proton polarization measurement (*pol beam only*)

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

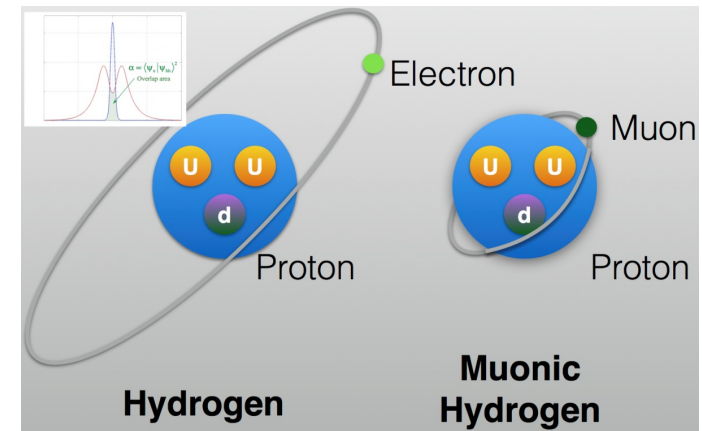
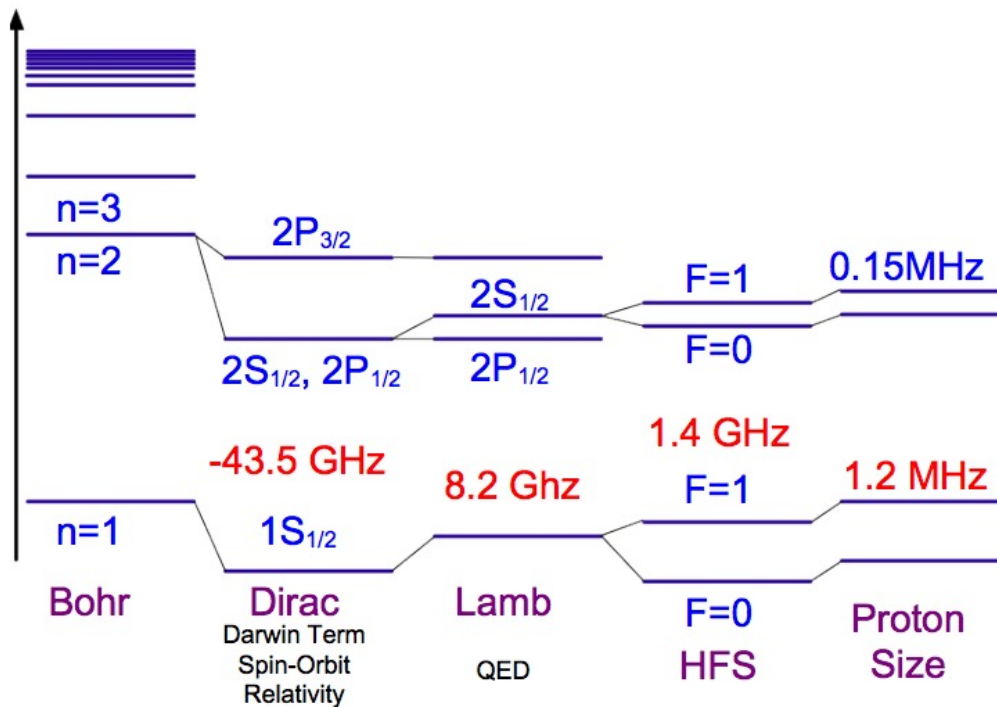
- Asymmetry (super-ratio) measurement (*pol beam and pol target*)

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



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

# Hydrogen Spectroscopy



$$\Delta E = -4\pi\alpha G_E^{\prime p}(0) |\psi_{n0}(0)|^2 \delta_{l0}$$

$$= 4\pi\alpha \frac{r_p^2}{6} |\psi_{n0}(0)|^2 \delta_{l0}.$$

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

Yields Rydberg constant  $R_\infty$  (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**

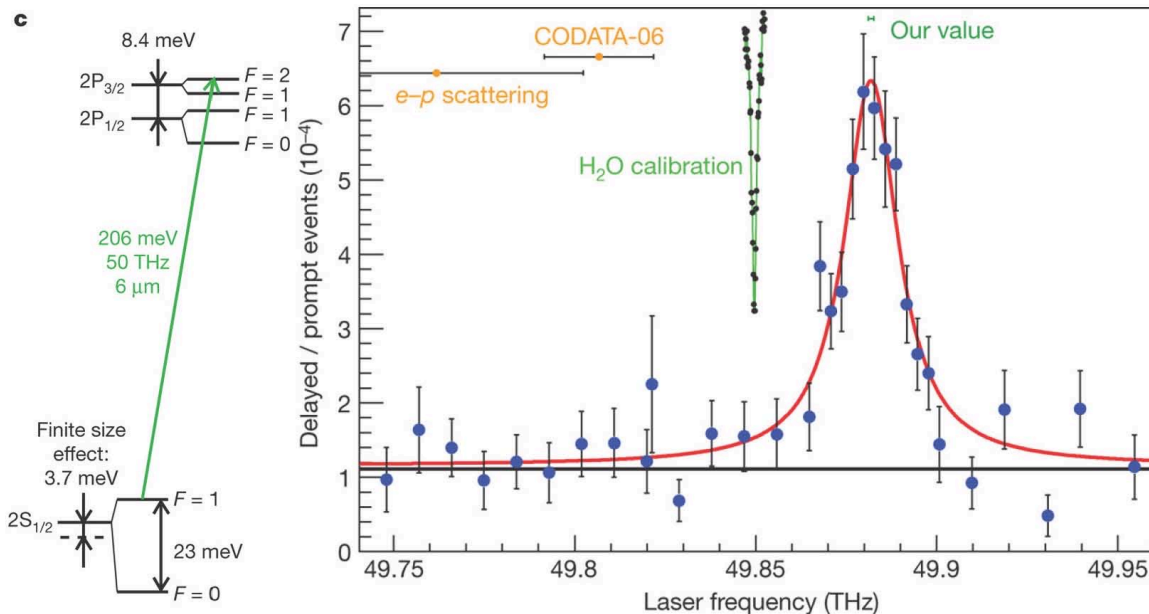
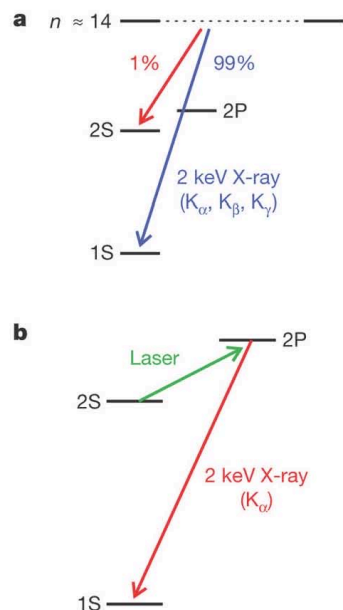
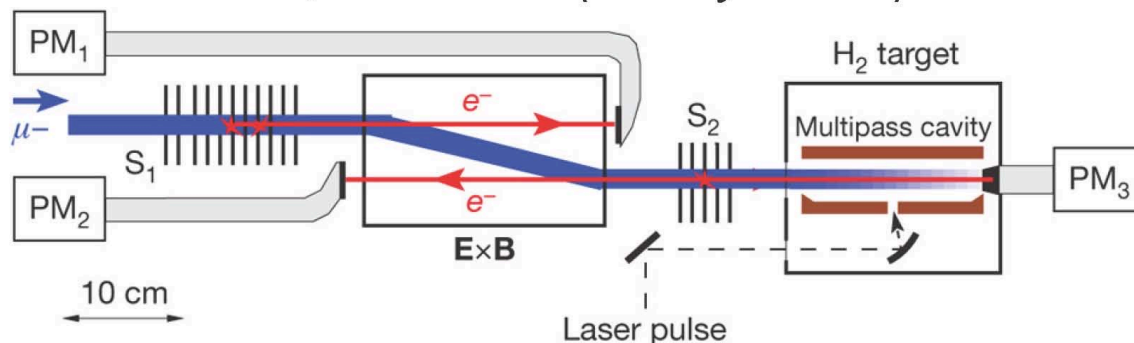
**Proton charge radius effect on the muonic hydrogen Lamb shift is 2%**



# Muonic hydrogen Lamb shift at PSI (2010, 2013)

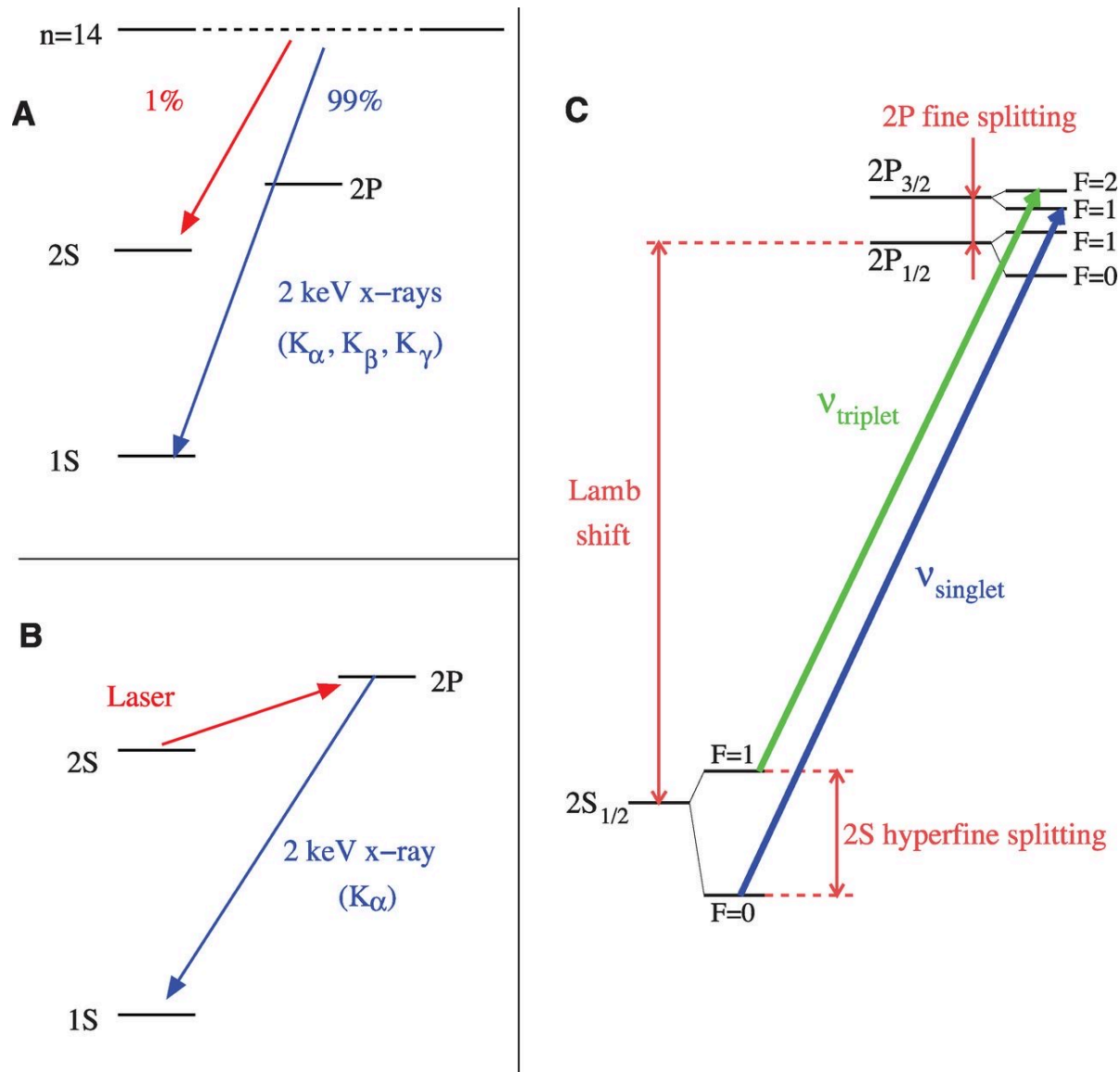


*Nature* **466**, 213-216 (8 July 2010)



2010 value is  $r_p = 0.84184(67)$  fm

# 2013 PSI results reported in Science



2013:  $r_p = 0.84087(39)$  fm,  
A. Antognini *et al.*, Science 339, 417 (2013)

# Electron-proton Scattering – Mainz A1 experiment

Three spectrometer facility of the A1 collaboration:

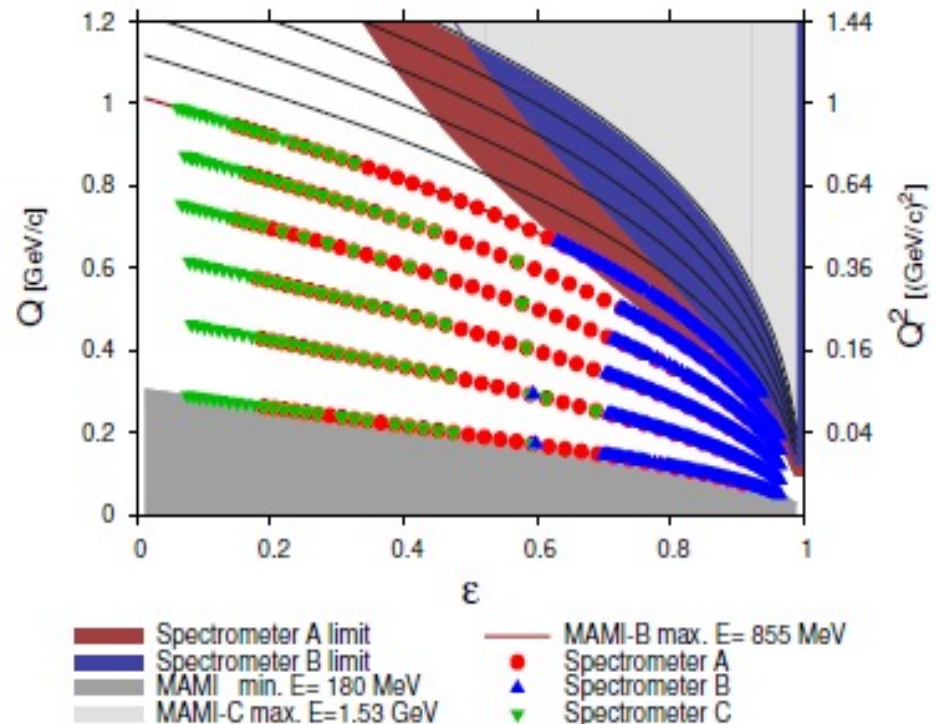


- Large amount of overlapping data sets
- Cross section measurement
- Statistical error  $\leq 0.2\%$
- Luminosity monitoring with spectrometer

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

J. Bernauer, PRL 105, 242001 (2010)

Measurements @ Mainz



5-7 $\sigma$  higher than muonic hydrogen result !

# JLab Recoil Proton Polarization Experiment

LHRS

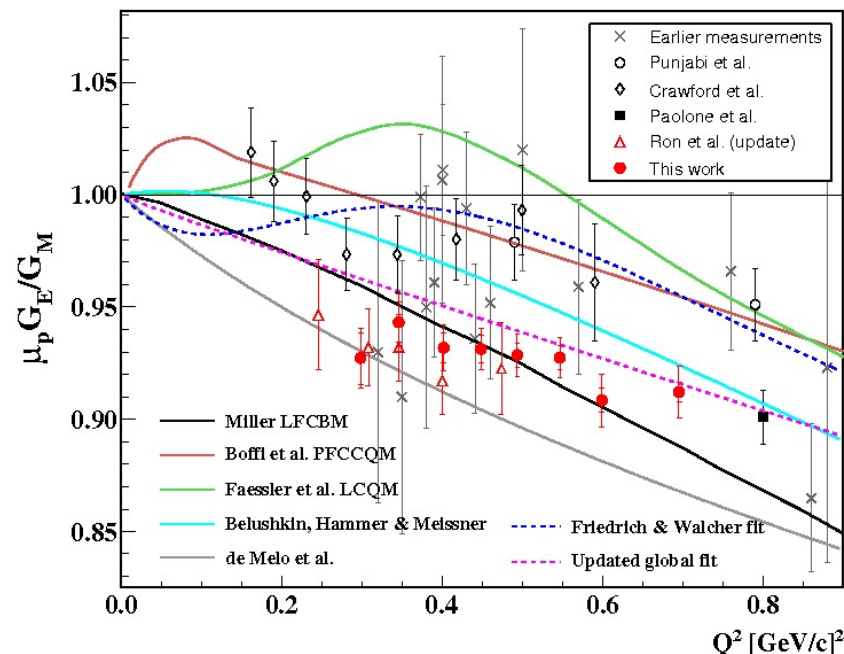
- $\Delta p/p_0: \pm 4.5\%$ ,
- out-of-plane:  $\pm 60$  mrad
- in-plane:  $\pm 30$  mrad
- $\Delta\Omega: 6.7$  msr
- QQDQ
- Dipole bending angle  $45^\circ$
- **VDC+FPF**
- $P_p: 0.55 \sim 0.93$  GeV/c

- $Q^2 = 0.3 - 0.7$  (GeV/c)<sup>2</sup>
  - $r_p = 0.875 \pm 0.010$  fm
- (global analysis not including Mainz A1)

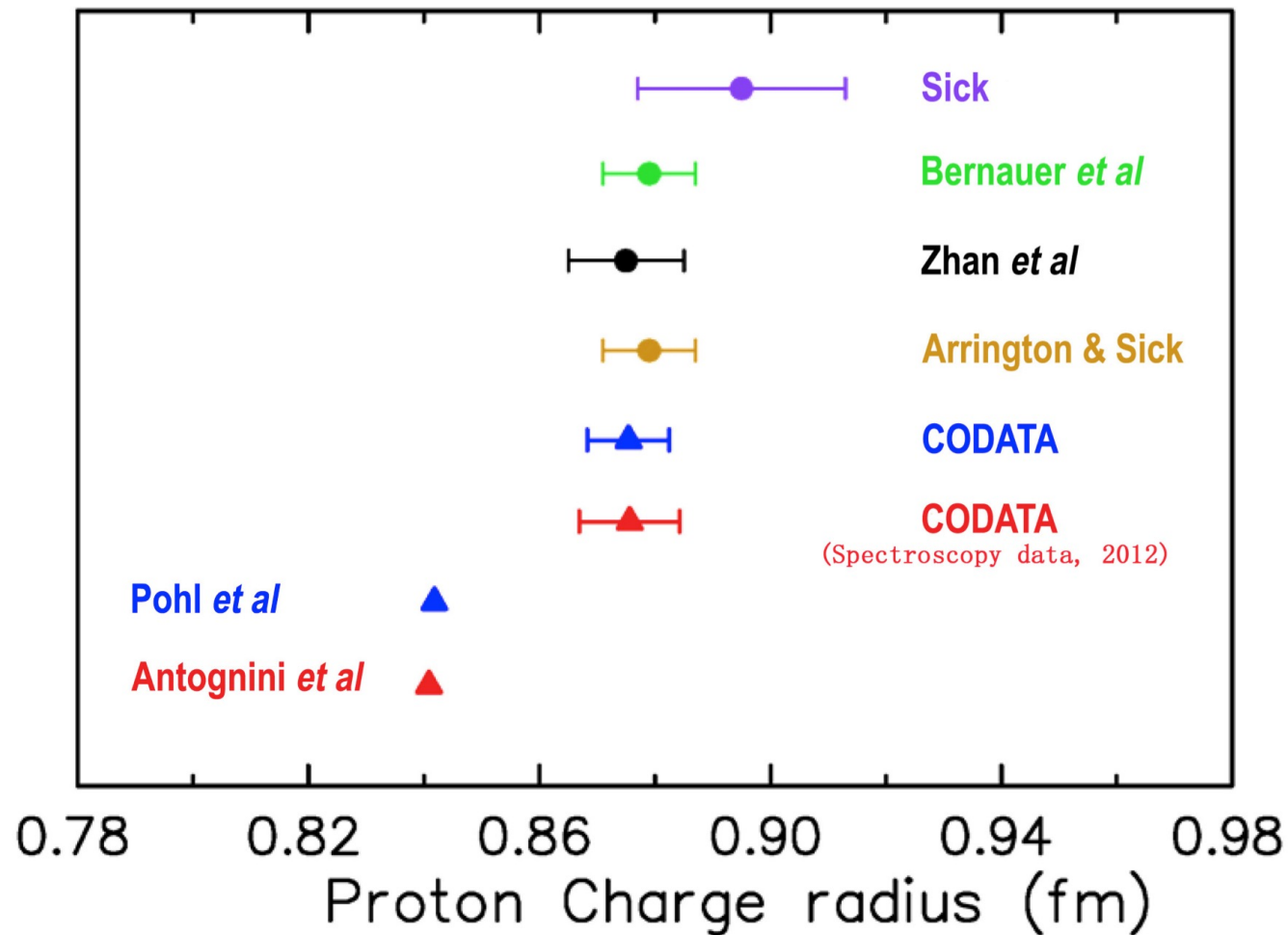
BigBite

$E_e: 1.192$  GeV  
 $P_b: \sim 83\%$

- Non-focusing Dipole
- Big acceptance.
  - $\Delta p: 200-900$  MeV
  - $\Delta\Omega: 96$  msr
- PS + Scint. + **SH**



## *The situation on the Proton Charge Radius in 2013*



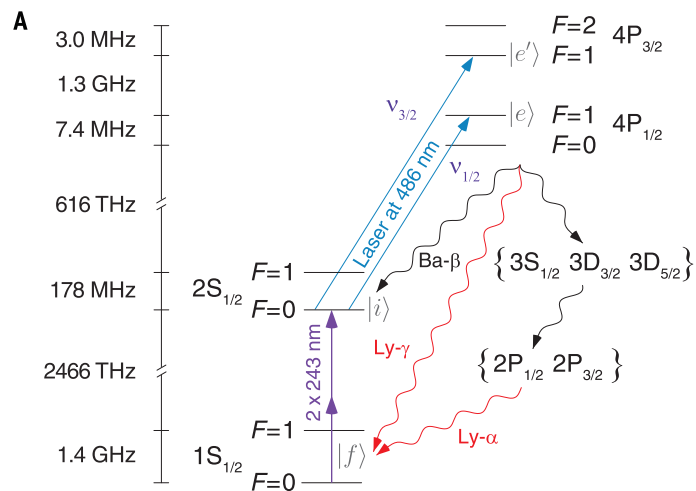
**This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so**



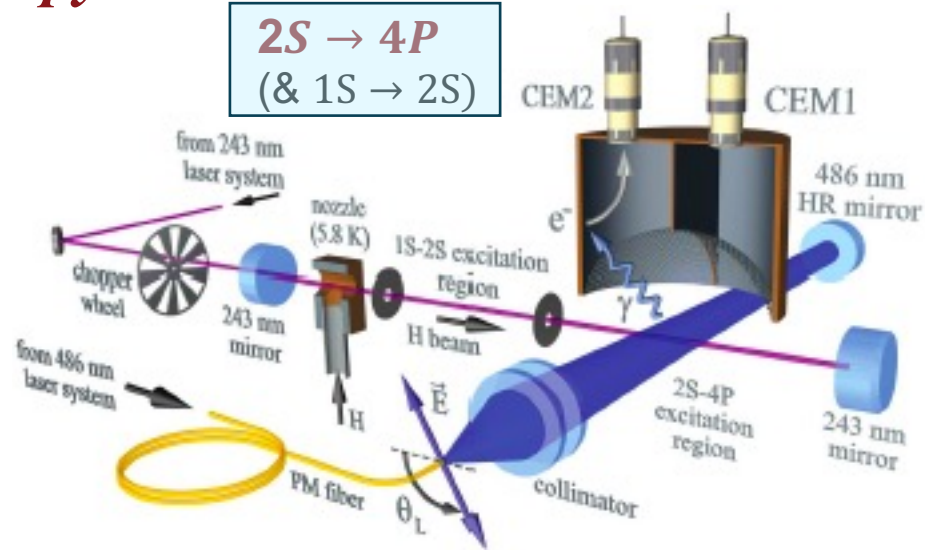
# *How to resolve the puzzle? - Incomplete list*

- **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 Rislw; Liu and Miller,....**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, Japan, Amber@CERN;**  
**H spectroscopy (Germany, France, Canada), ...**

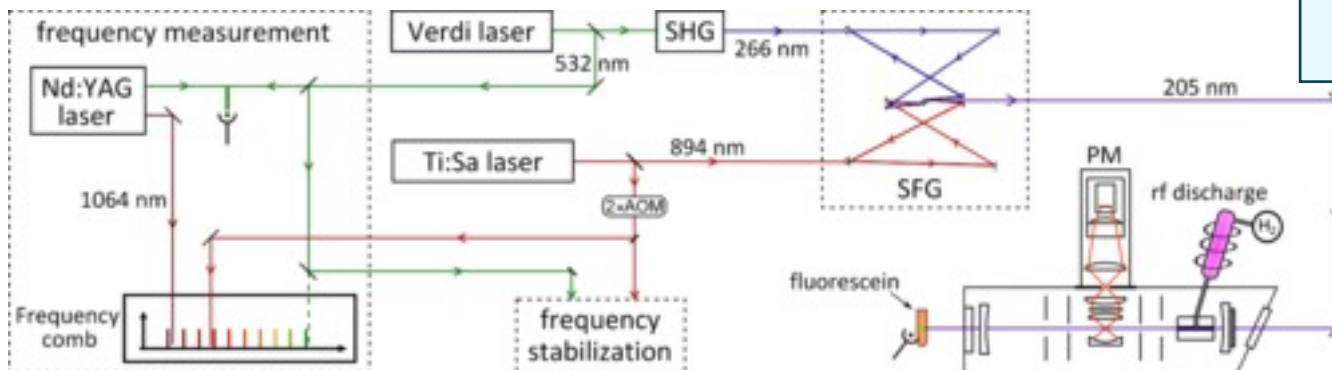
# Ordinary hydrogen spectroscopy



**$2S \rightarrow 4P$**   
(&  $1S \rightarrow 2S$ )



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

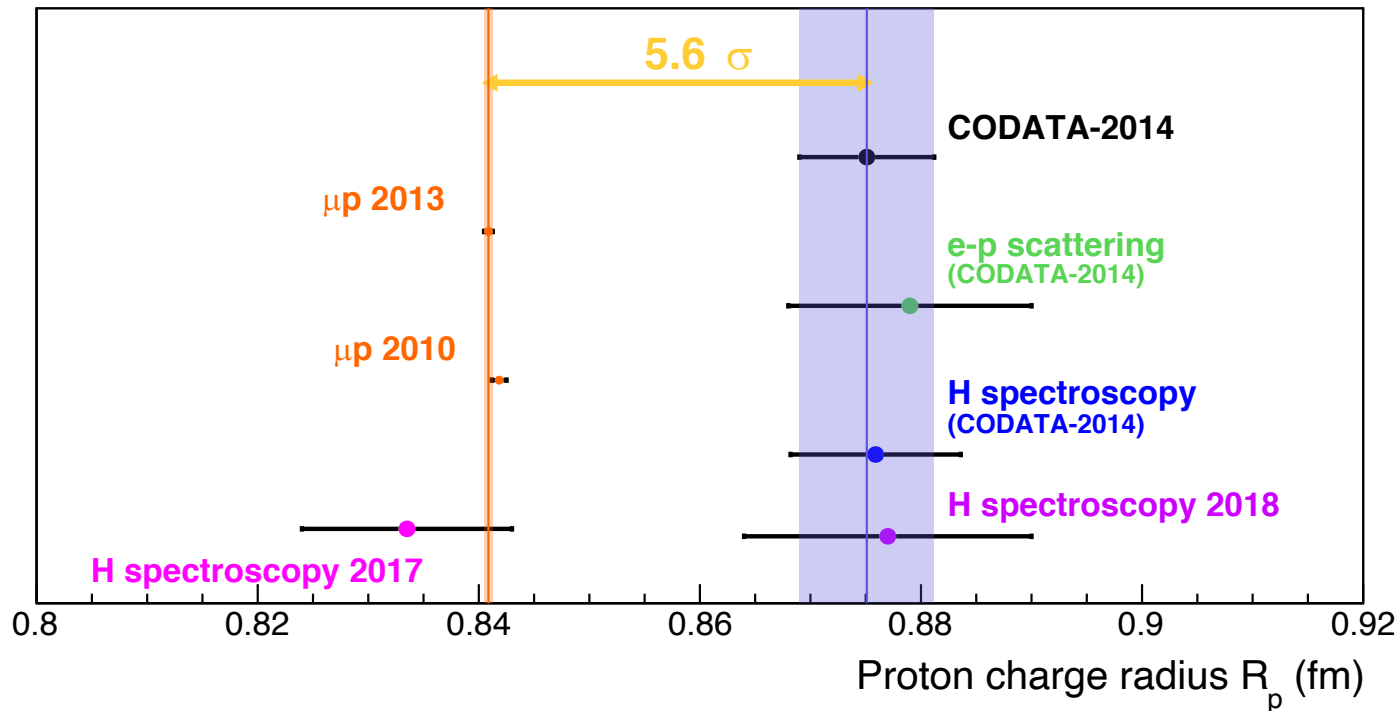


**$1S \rightarrow 3S$**   
(&  $1S \rightarrow 2S$ )

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



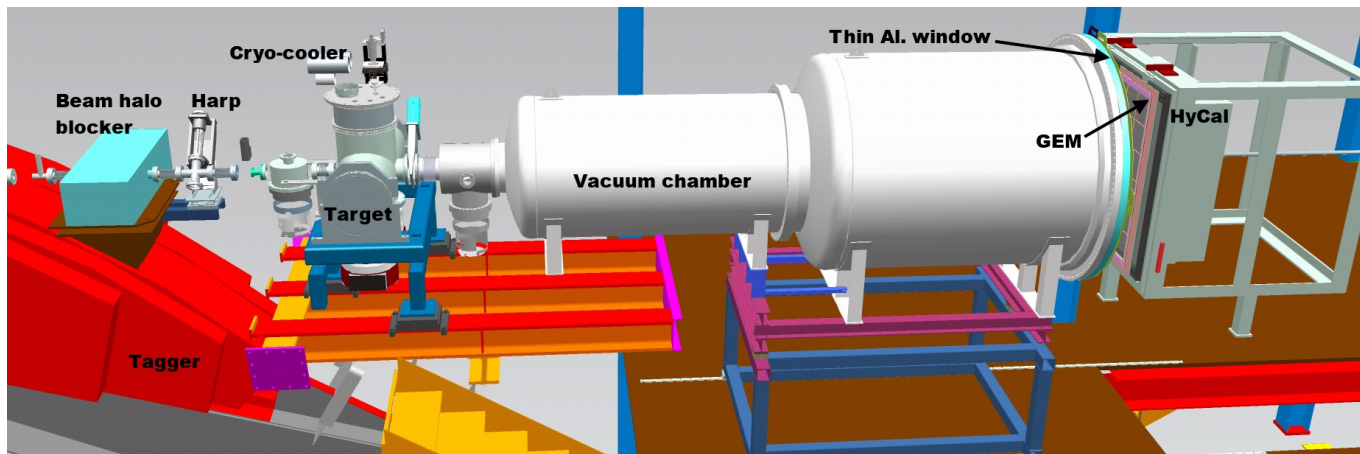
# The Proton Charge Radius Puzzle in 2018



Electron scattering:  $0.879 \pm 0.011$  fm (CODATA 2014)  
 Muon spectroscopy:  $0.8409 \pm 0.0004$  fm (CREMA 2010, 2013)  
 H spectroscopy (2017):  $0.8335 \pm 0.0095$  fm (A. Beyer et al. Science 358(2017) 6359)  
 H spectroscopy (2018):  $0.877 \pm 0.013$  fm (H. Fleurbaey et al. PRL.120(2018) 183001)

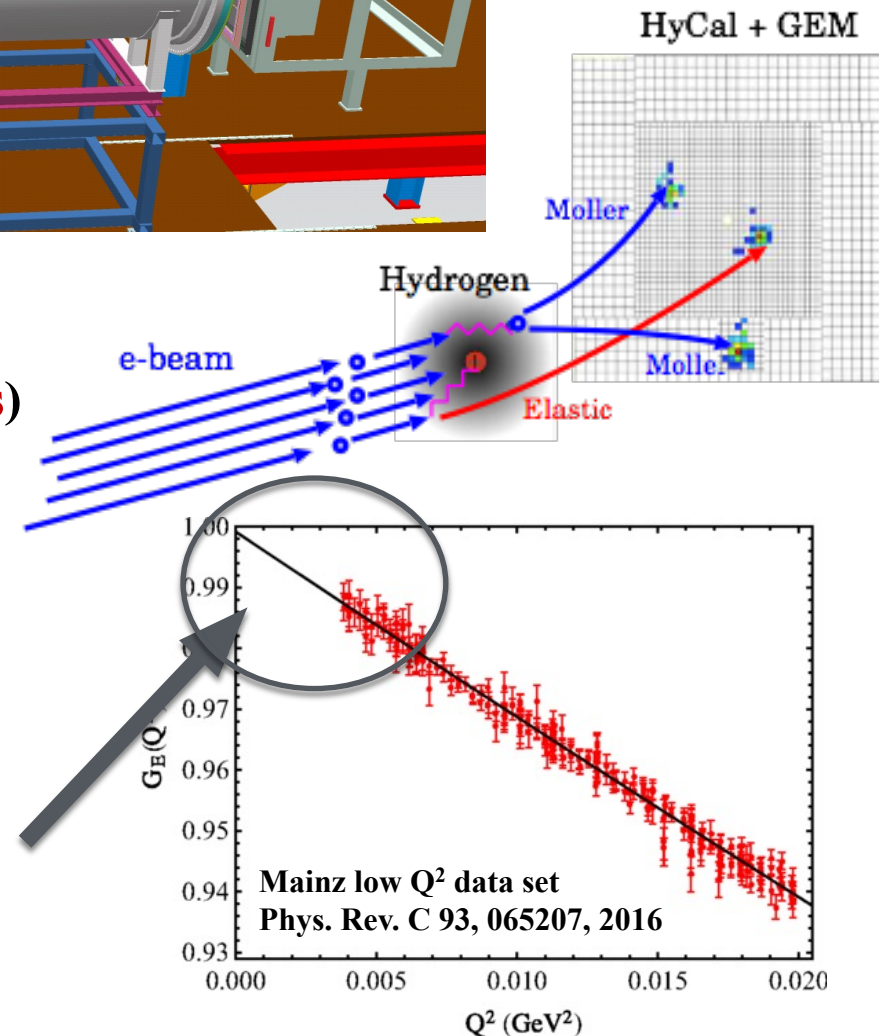
Not shown: ep scattering (ISR, 2017):  $0.810 \pm 0.035_{\text{stat.}} \pm 0.074_{\text{syst.}} \pm 0.003$  (delta\_a, delta\_b)  
 (Mihovilovic PLB 771 (2017);  $0.878 \pm 0.011_{\text{stat.}} \pm 0.031_{\text{syst.}} \pm 0.002_{\text{mod.}}$  (Mihovilovic 2021))

# The *PRad* Experiment in Hall B at JLab

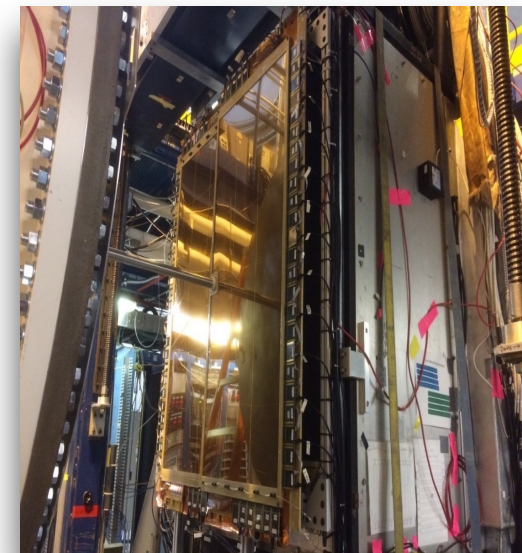
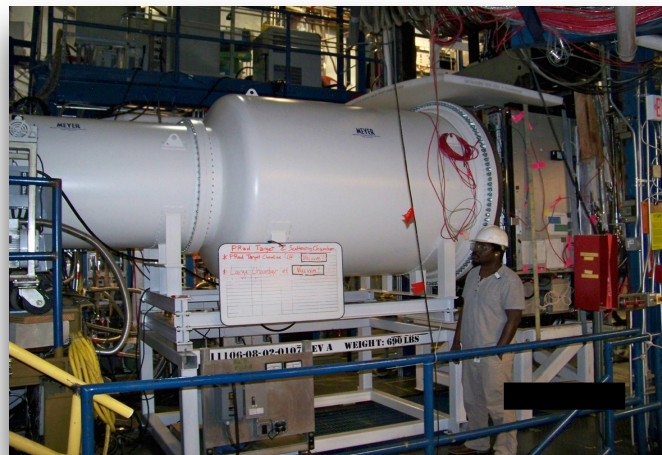
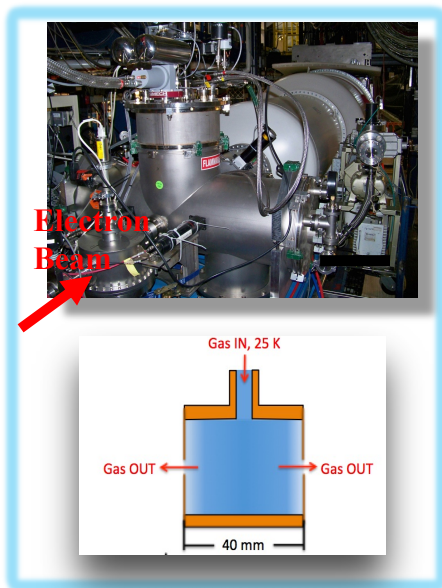
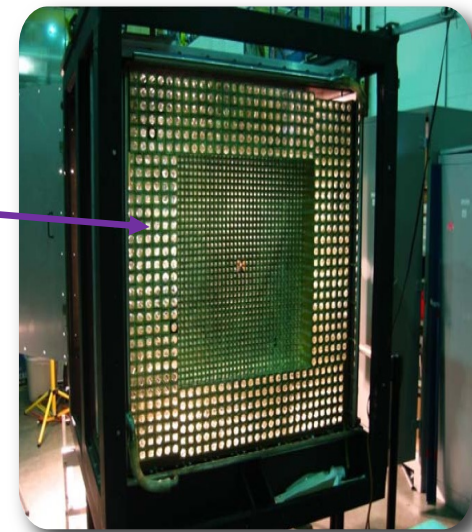
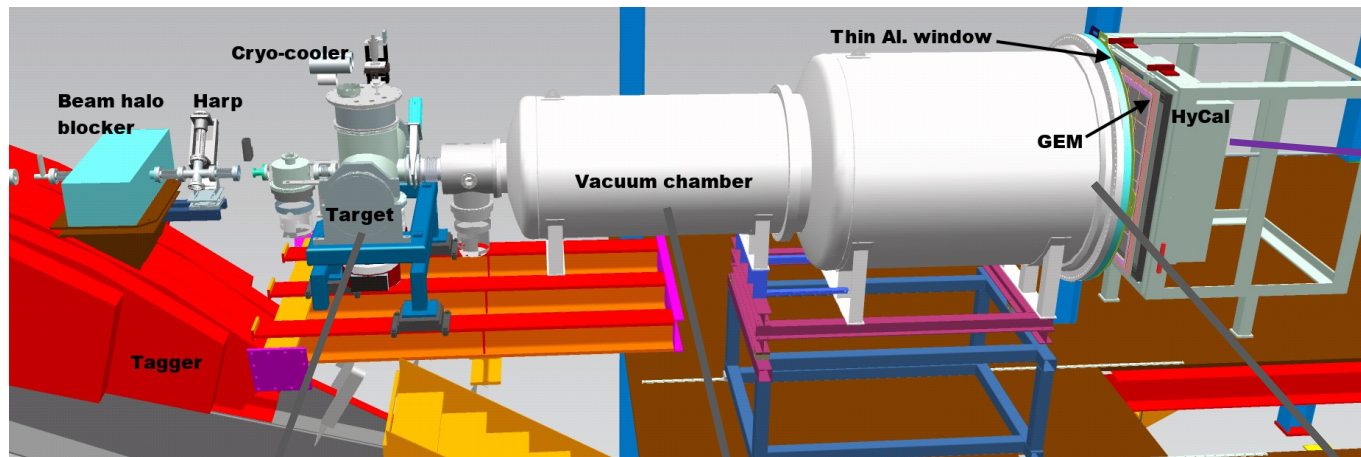


- High resolution, large acceptance, hybrid HyCal calorimeter (**PbWO<sub>4</sub>** and **Pb-Glass**)
- Windowless H<sub>2</sub> gas flow target
- Simultaneous detection of elastic and Moller electrons
- $Q^2$  range of  **$2 \times 10^{-4} - 0.06 \text{ GeV}^2$**
- XY – veto counters replaced by GEM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

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



# The *PRad* Experimental setup

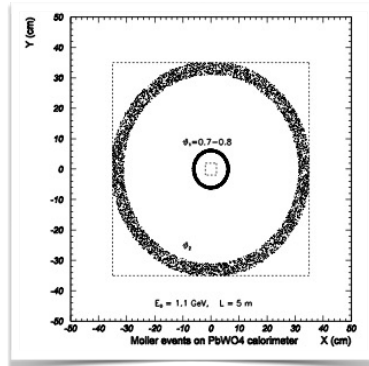




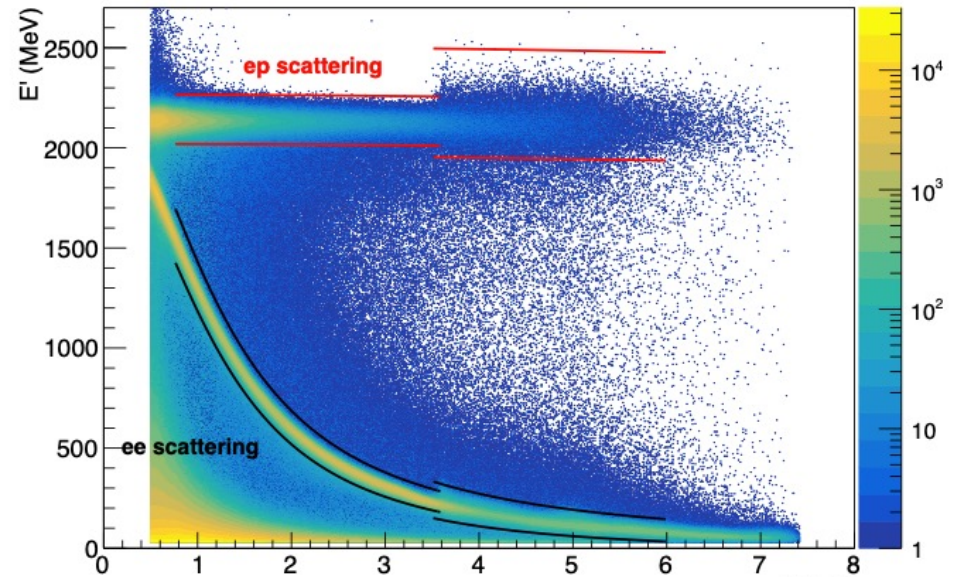
# Analysis – Event Selection

## Event selection method

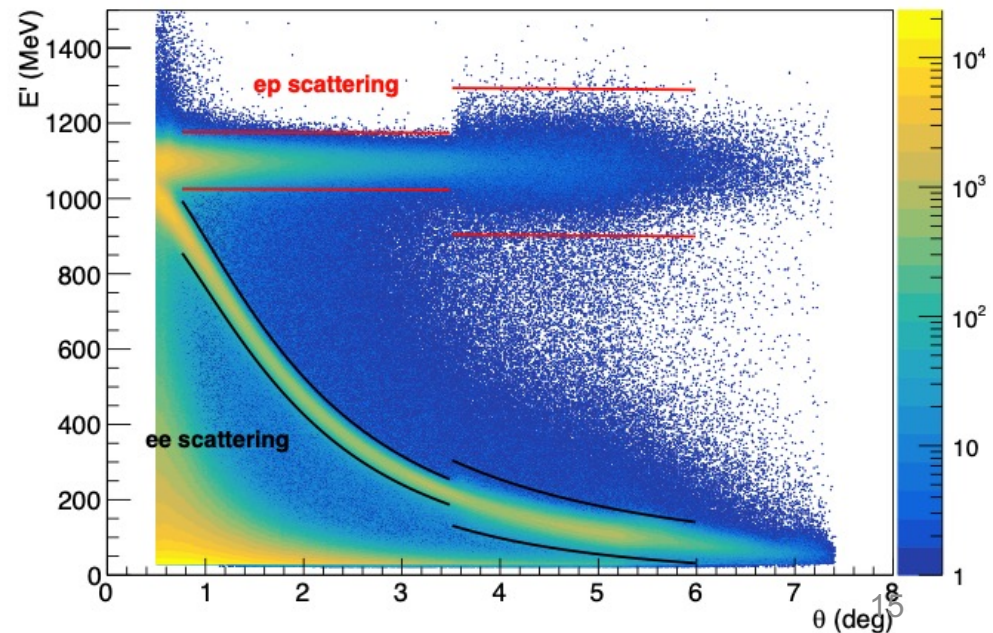
1. For all events, require hit matching between GEMs and HyCal
2. For  $ep$  and  $ee$  events, apply angle-dependent energy cut based on kinematics
  1. Cut size depend on local detector resolution
3. For  $ee$ , if requiring double-arm events, apply additional cuts
  1. Elasticity
  2. Co-planarity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



Cluster energy  $E'$  vs. scattering angle  $\theta$  (2.2GeV)



Cluster energy  $E'$  vs. scattering angle  $\theta$  (1.1GeV)



# Extraction of *ep* Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the *ep* cross section is normalized to the Møller cross section:

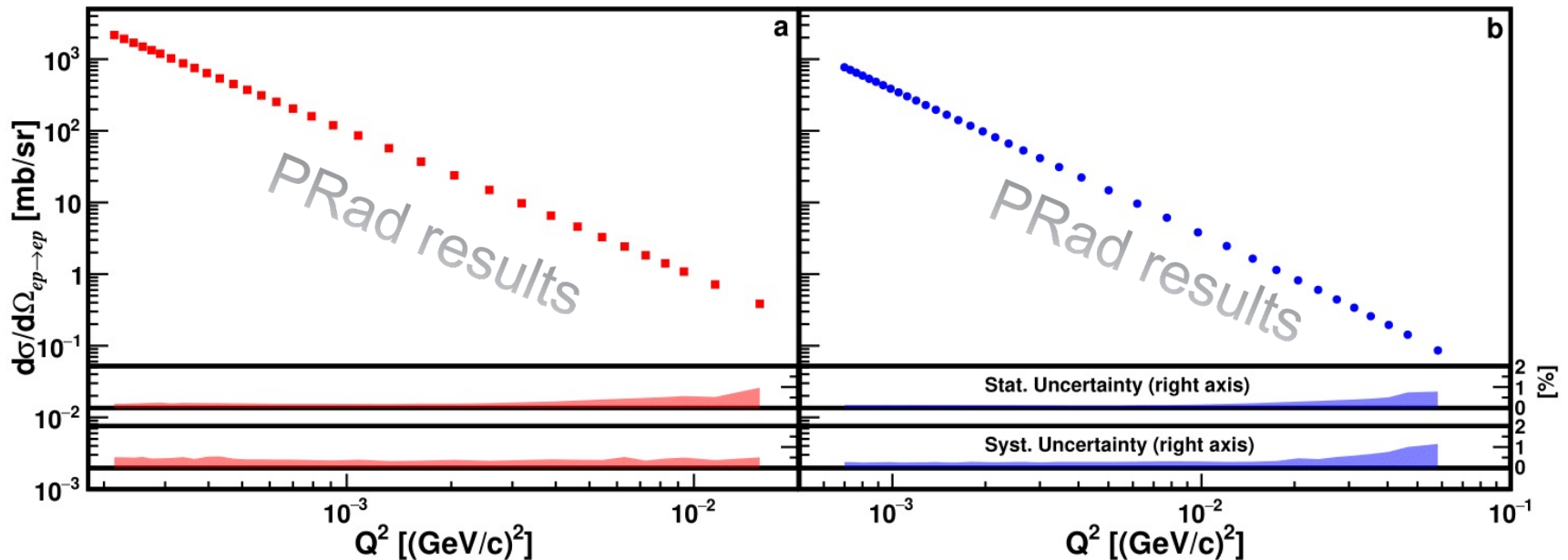
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \left[ \frac{N_{\text{exp}}(ep \rightarrow ep \text{ in } \theta_i \pm \Delta\theta_i)}{N_{\text{exp}}(ee \rightarrow ee)} \cdot \frac{\varepsilon_{\text{geom}}^{ee}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{ee}}{\varepsilon_{\text{det}}^{ep}} \right] \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

- Method 1: bin-by-bin method** – taking *ep/ee* counts from the same angular bin
  - Cancellation of energy independent part of the efficiency and acceptance
  - Limited coverage due to double-arm Møller acceptance
- Method 2: integrated Møller method** – integrate Møller in a fixed angular range and use it as common normalization for all angular bins
  - Needs to know the GEM efficiency well
- Luminosity cancelled from both methods
- PRad: Bin-by-bin range: 0.7° to 1.6° for 2.2 GeV, 0.75° to 3.0° for 1.1 GeV. Larger angles use integrated Møller method (3.0° to 7.0° for 1.1 GeV; 1.6° to 7.0° for 2.2 GeV)
- PRad-II: two planes of GEM/ $\mu$ Rwell allow for **integrated Møller method** for the entire experiment
- Event generators for unpolarized elastic *ep* and Møller scatterings have been developed based on complete calculations of radiative corrections – **PRad-II with NNL for RC**
  1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  2. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (beyond ultra relativistic approximation)
- A Geant4 simulation package is used to study the radiative effects, and an iterative procedure applied

$$\sigma_{ep}^{\text{Born}(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{Born}(model)} \cdot \sigma_{ee}^{\text{Born}(model)}$$

# 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

# Proton Electric Form Factor $G'_E$ (Normalized)

- $n_1$  and  $n_2$  obtained by fitting PRad  $G_E$  to  $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$
- $G'_E$  as normalized electric Form factor:  $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$
- PRad fit shown as  $f(Q^2)$

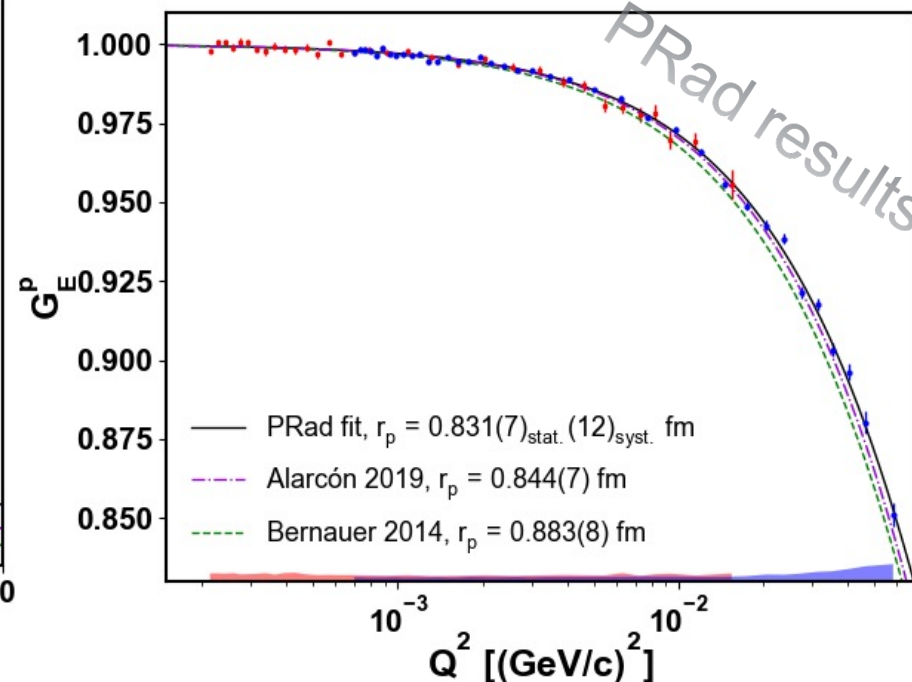
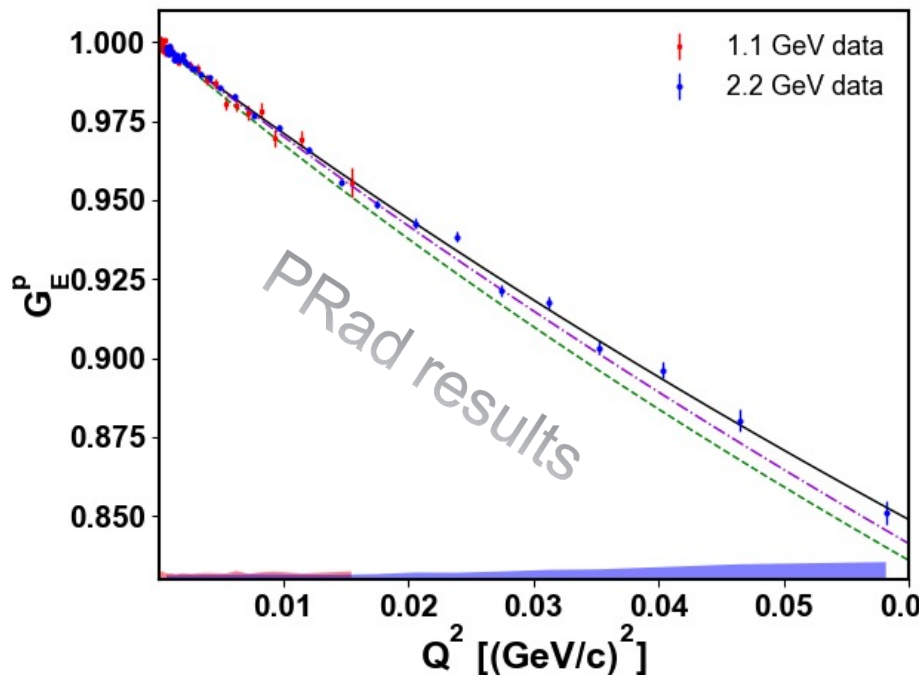
Using rational (1,1)  

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

*Yan et al., PRC 98, 025204 (2018)*

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

*Xiong et al., Nature 575, 147–150 (2019)*



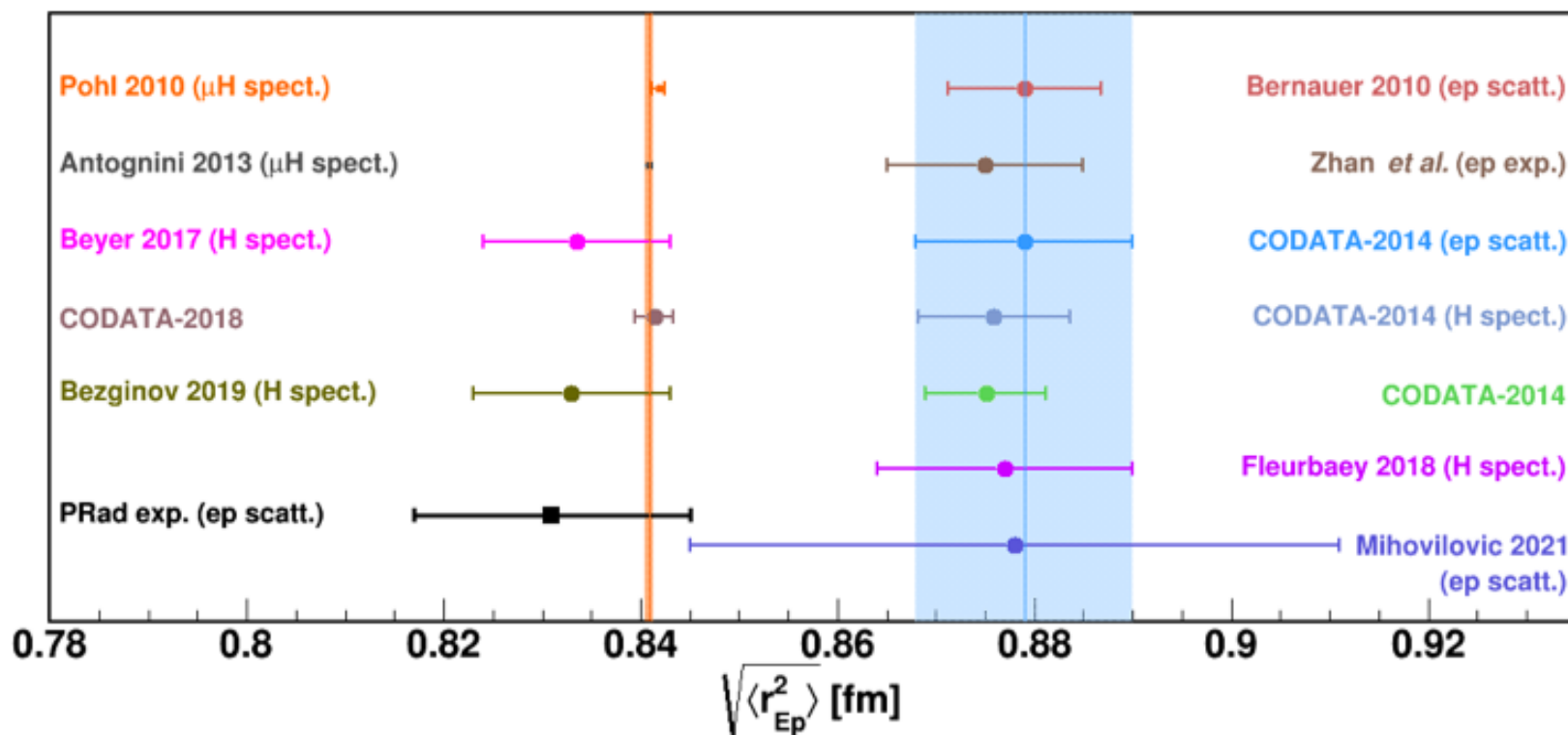
$$n_1 = 1.0002 \pm 0.0002 \text{ (stat.)} \pm 0.0020 \text{ (syst.)},$$

$$n_2 = 0.9983 \pm 0.0002 \text{ (stat.)} \pm 0.0013 \text{ (syst.)}$$



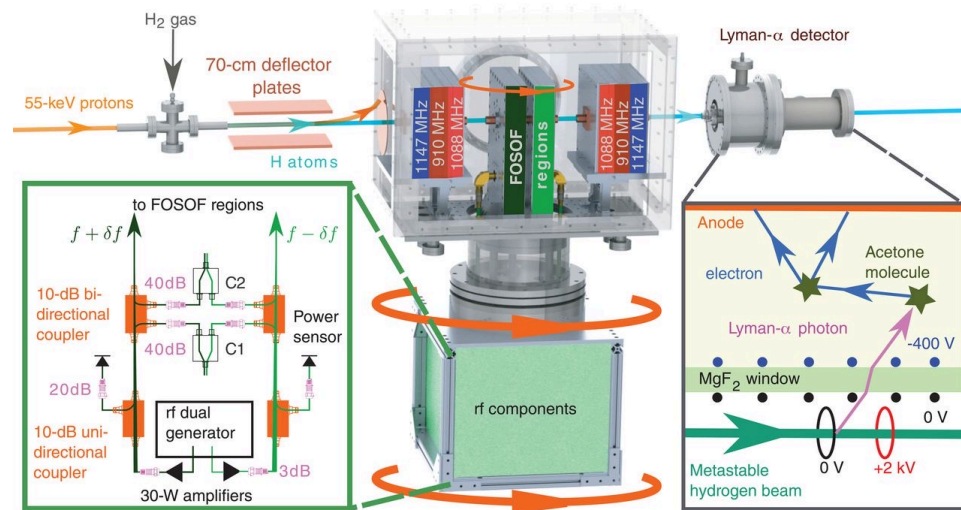
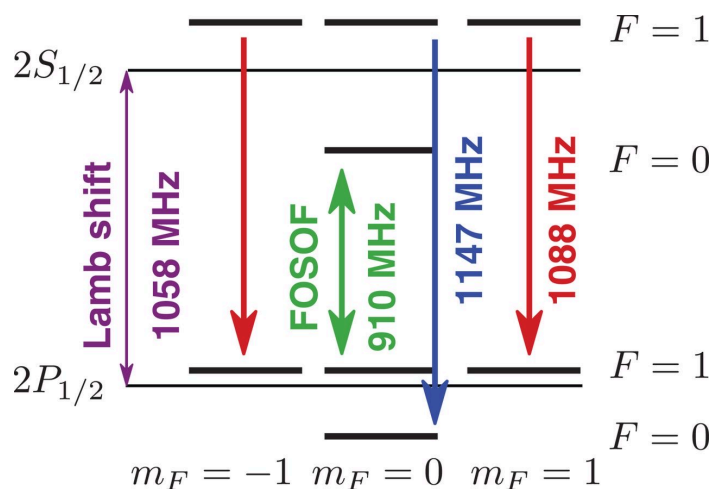
# *Proton radius at the time of PRad publication*

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



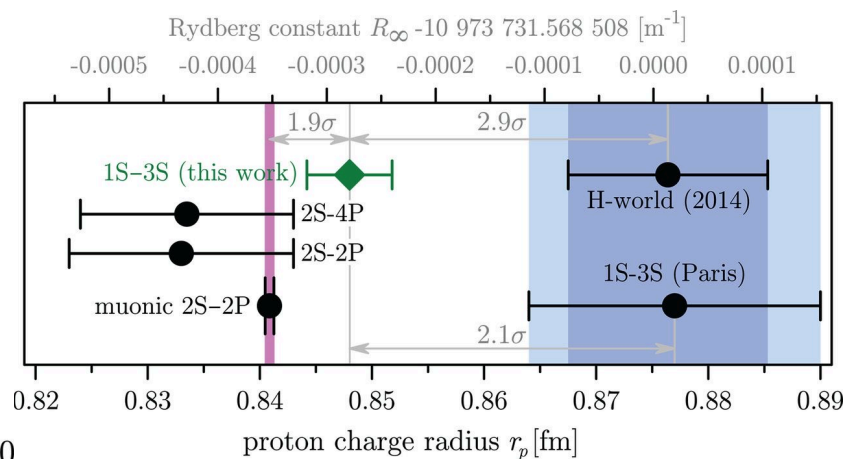
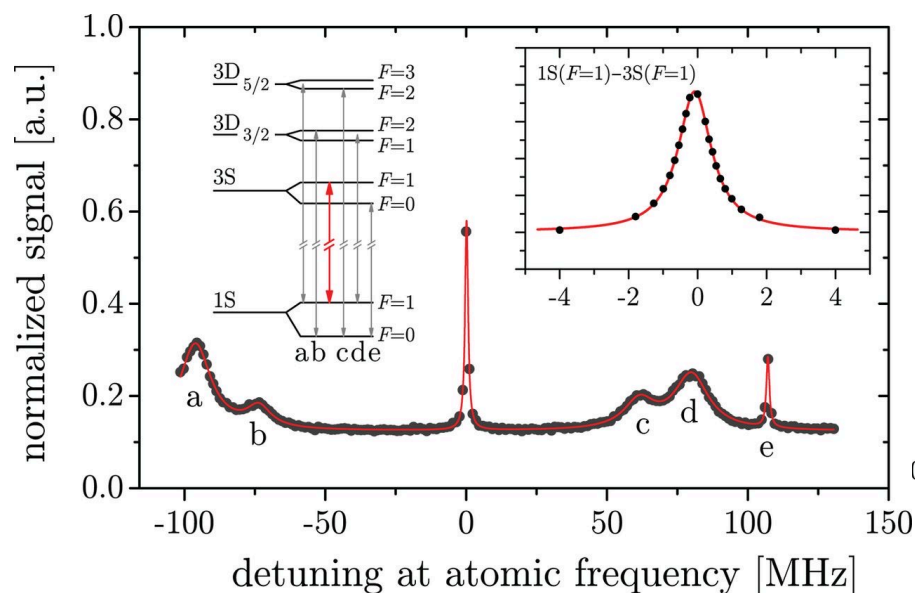
**CODATA has also shifted the value of the Rydberg constant.**

# More from ordinary hydrogen spectroscopy



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

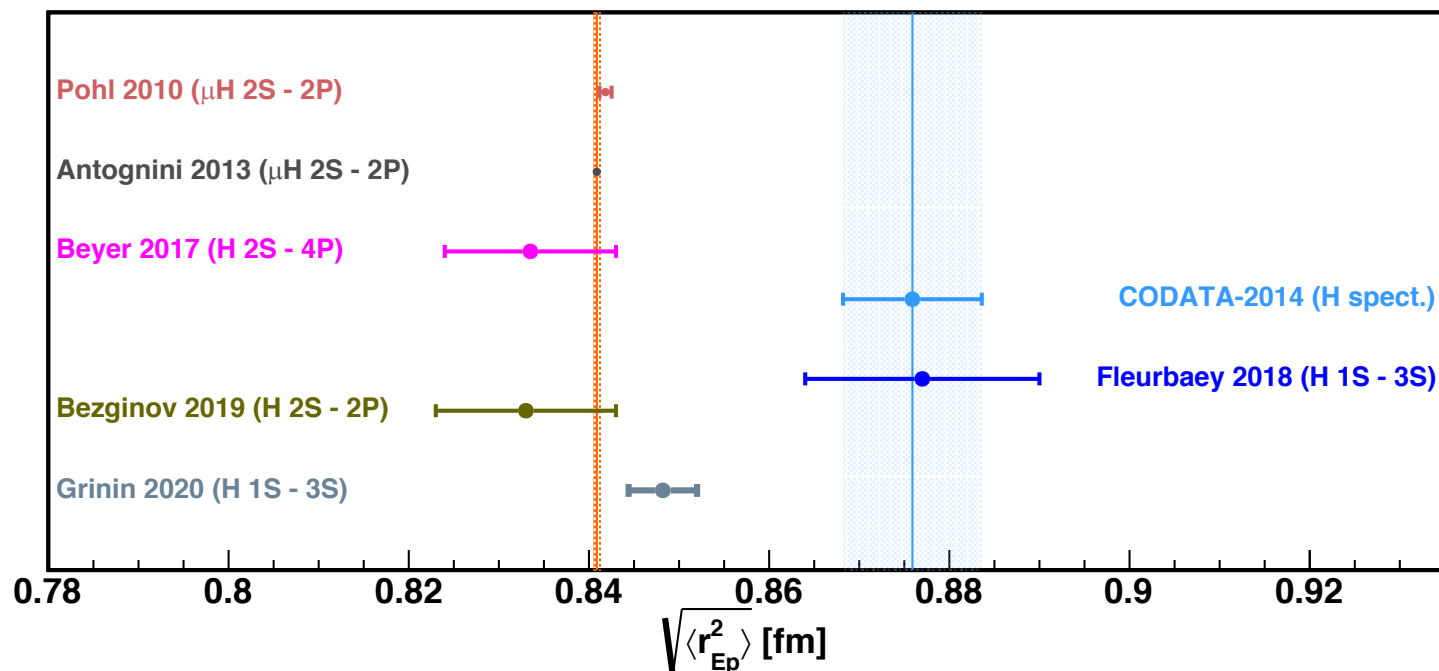
$$r_p = 0.833(10) \text{ fm}$$



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

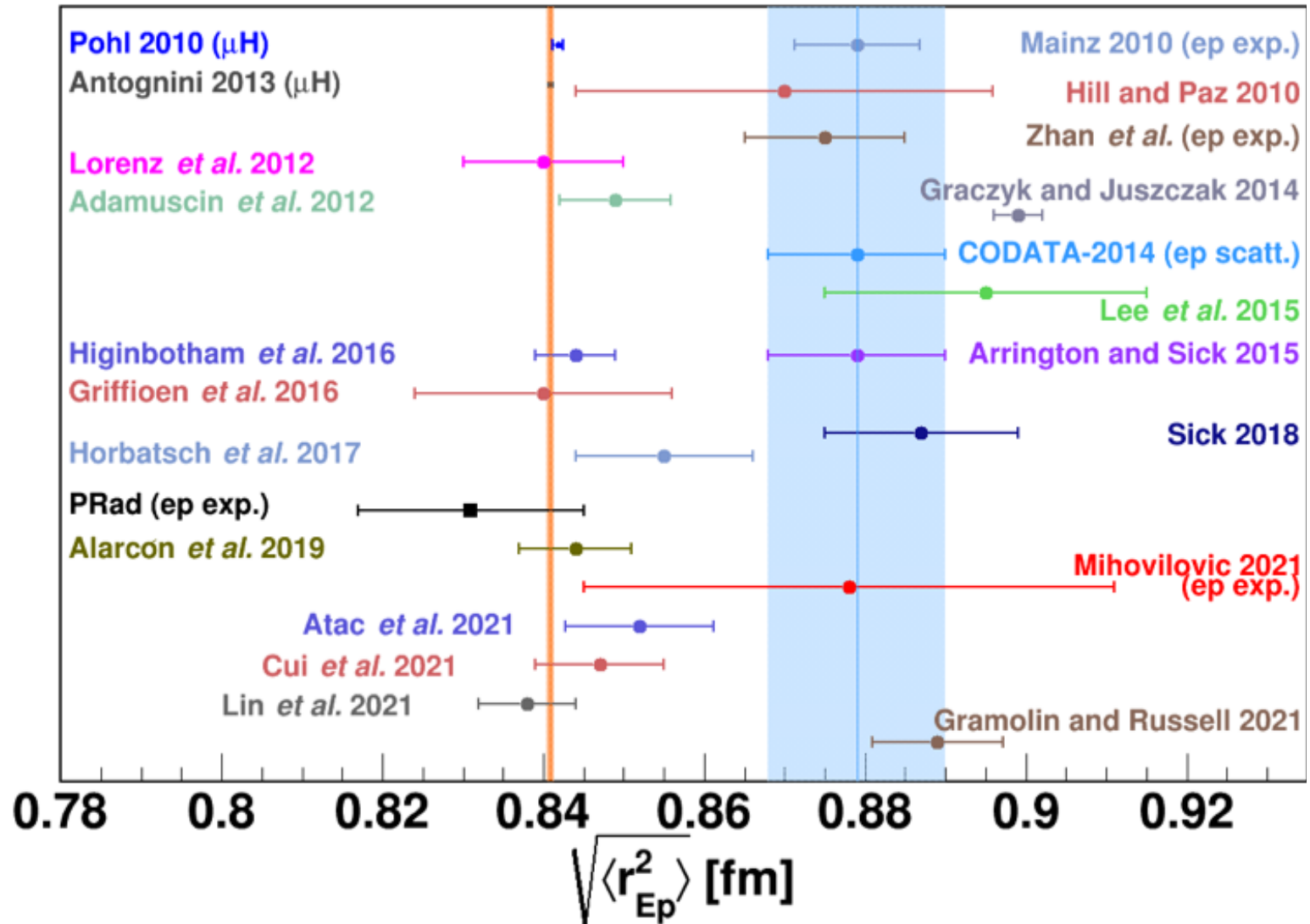
$$r_p = 0.8482(38) \text{ fm}$$

# Proton radius from ordinary and muonic H spectroscopy

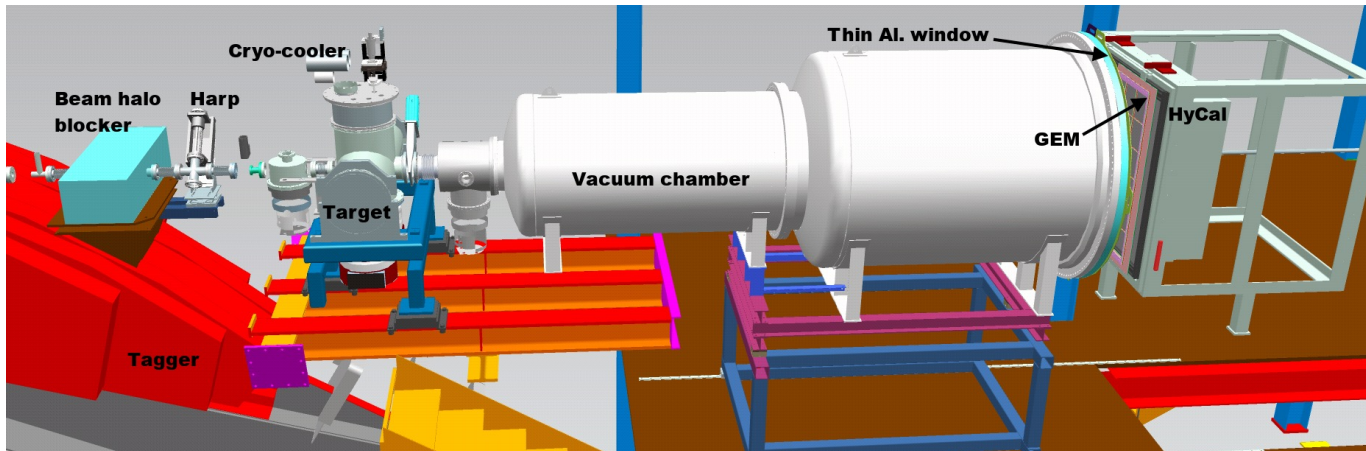
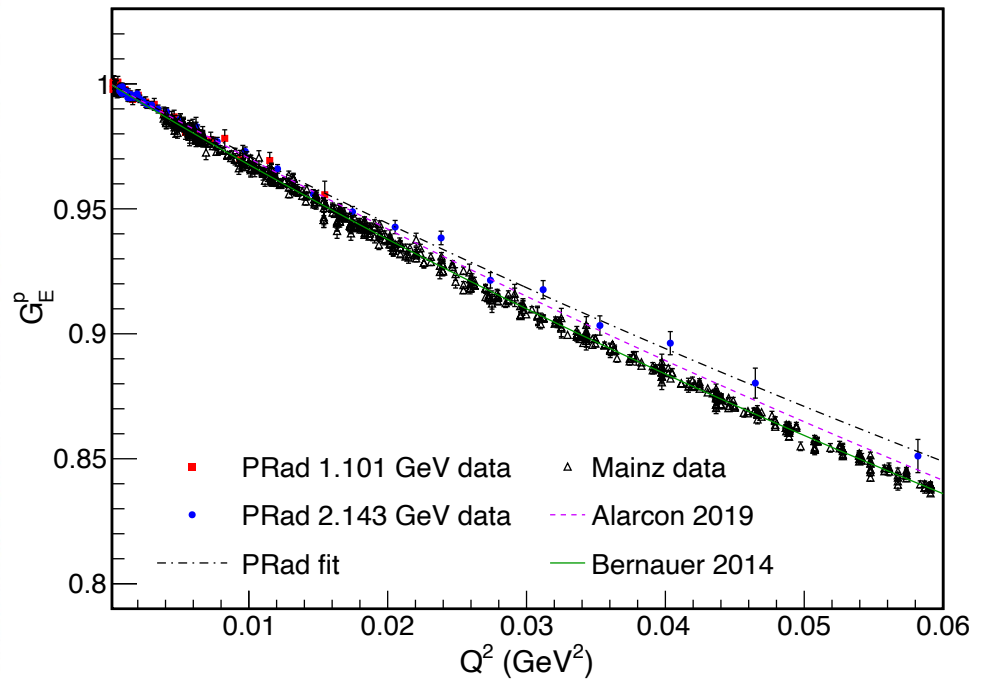


Experiment	Type	Transition(s)	$\sqrt{\langle r_{Ep}^2 \rangle}$ (fm)	$r_{\infty}$ ( $\text{m}^{-1}$ )
Pohl 2010	$\mu\text{H}$	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$	0.84184(67)	
Antognini 2013	$\mu\text{H}$	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$	0.84087(39)	
		$2S_{1/2}^{F=0} - 2P_{3/2}^{F=1}$		
Beyer 2017	H	$2S - 4P$ 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)	10 973 731.568 226(38)
Grinin 2020	H	$1S - 3S$ with $(1S - 2S)$	0.8482(38)	

# *(Re)analyses of e-p scattering data*



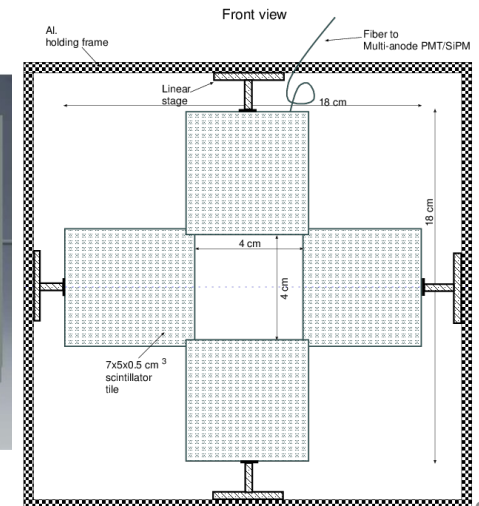
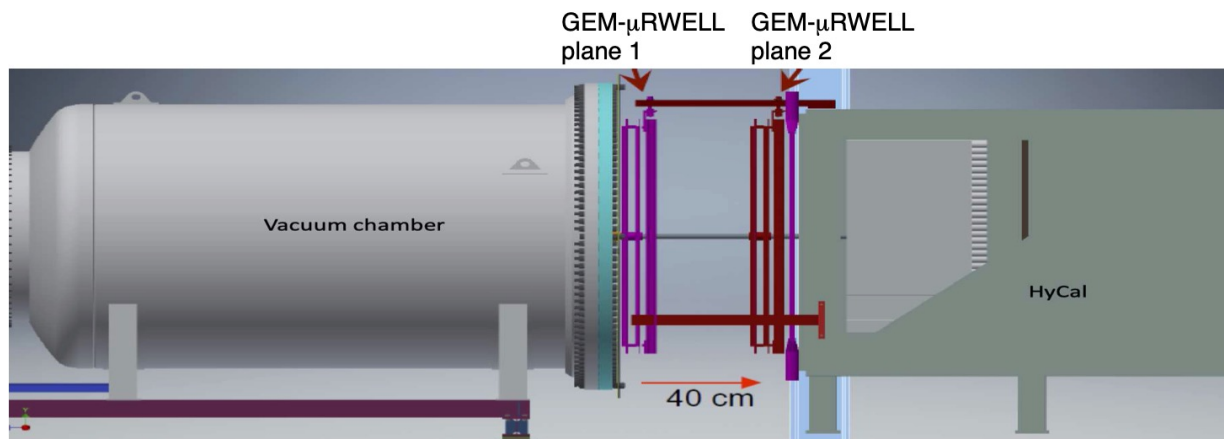
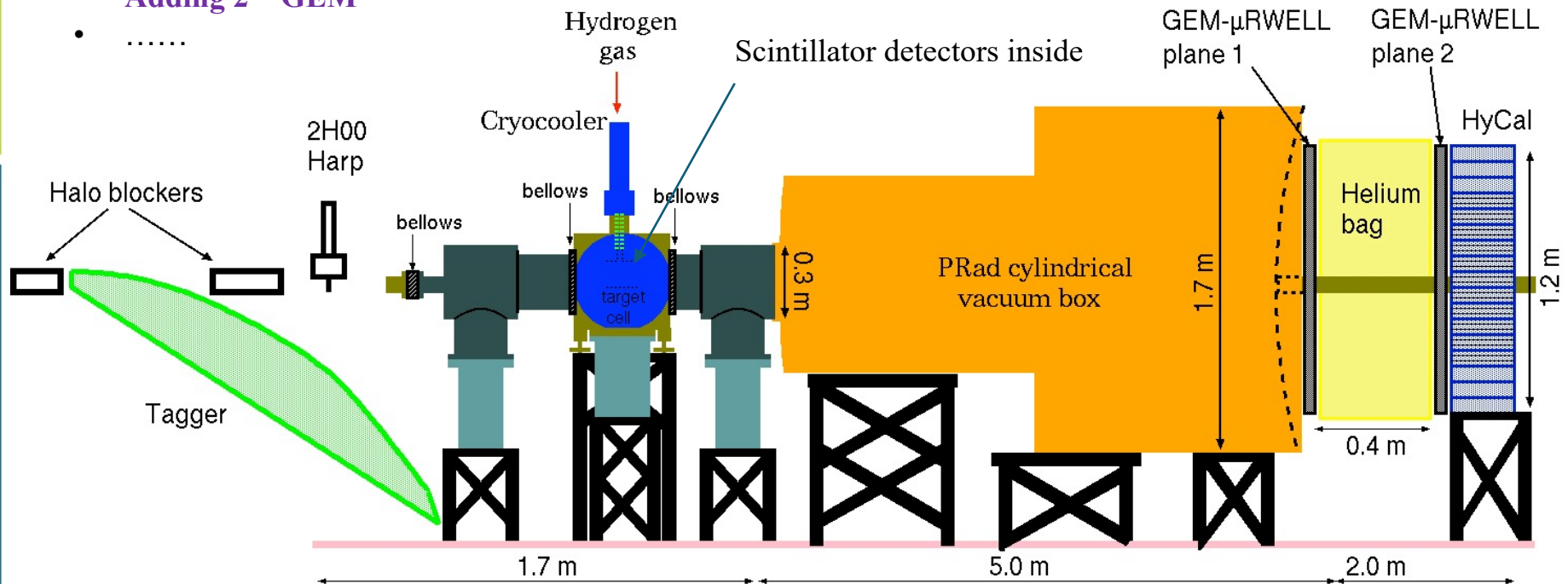
# *e-p scattering: magnetic spectrometer and calorimetric method*





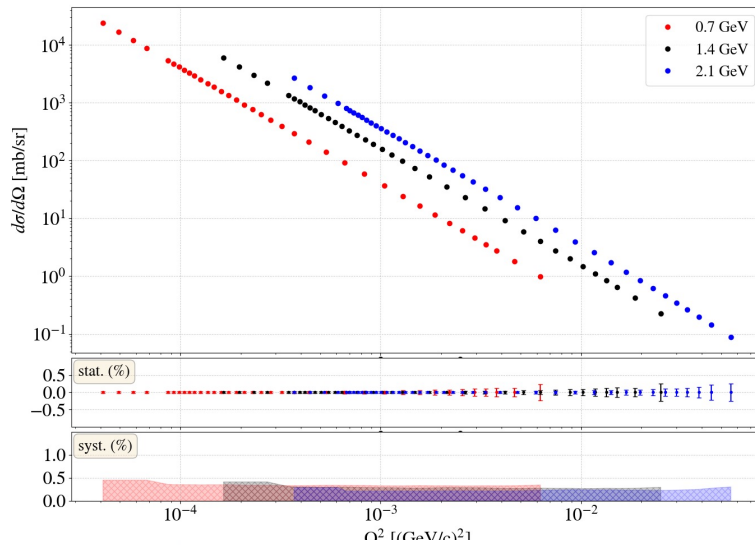
# PRad-II Experimental Setup (Side View)

- Upgrade HyCal
- Adding 2<sup>nd</sup> GEM
- .....

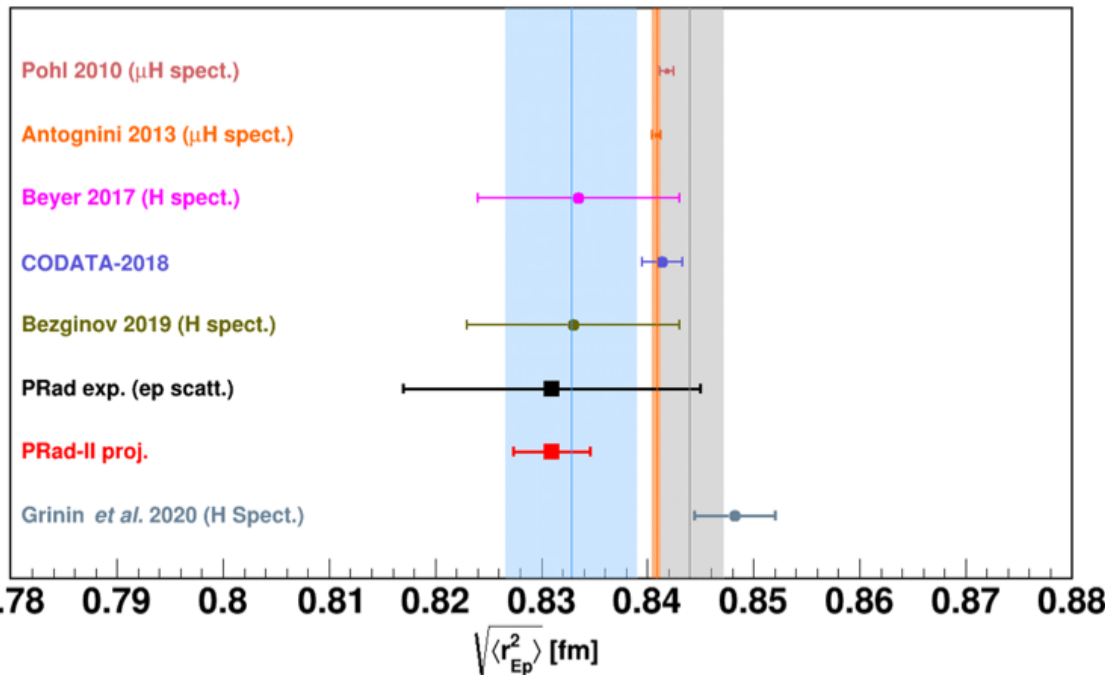
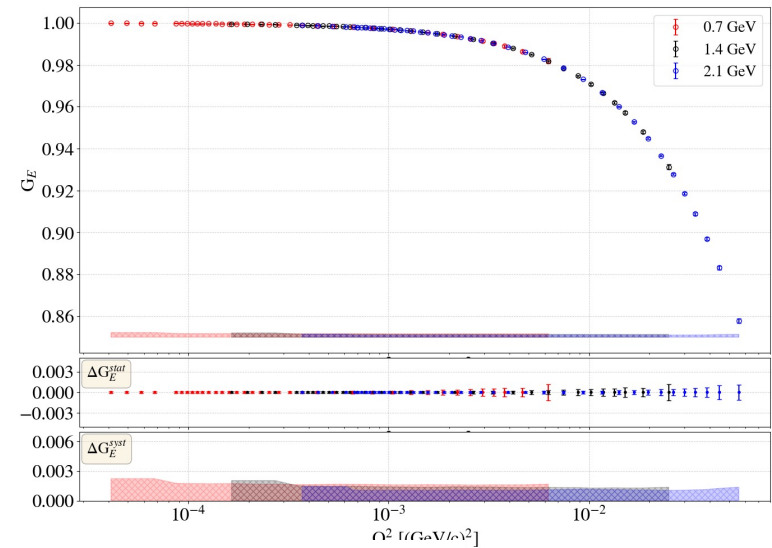


# Projections for PRad-II

Differential Cross section



Electric form factor

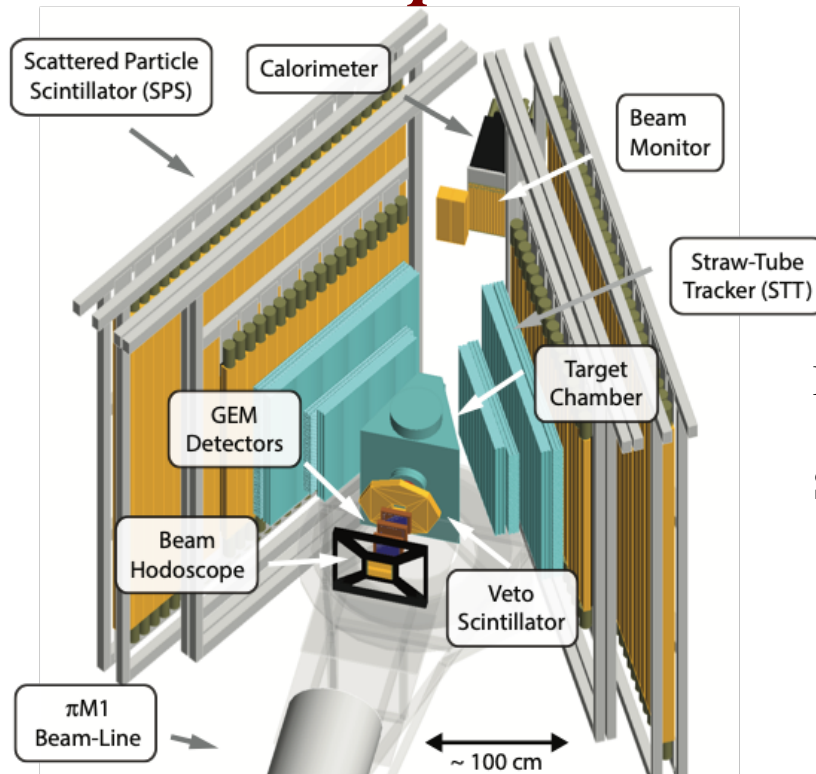


**PRad-II goal:**  
**0.0036 fm**

Gasparian *et al.*  
arXiv:2009.10510



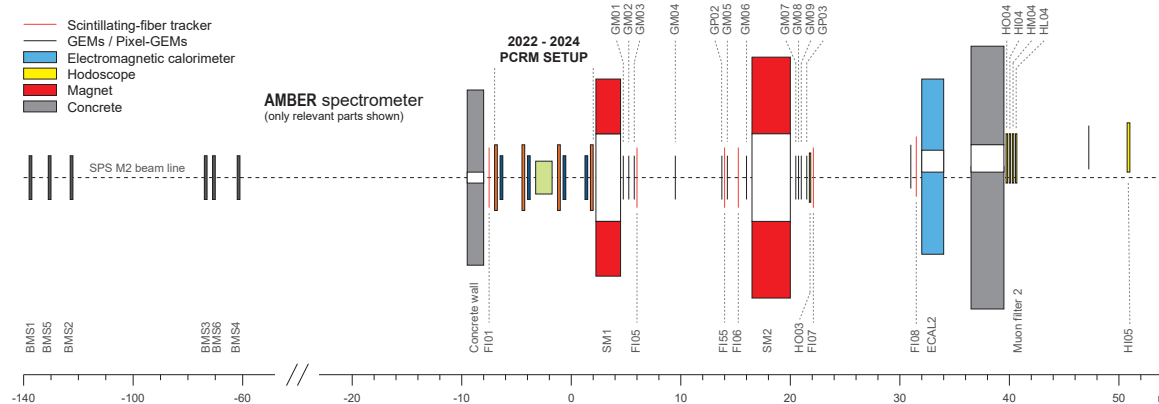
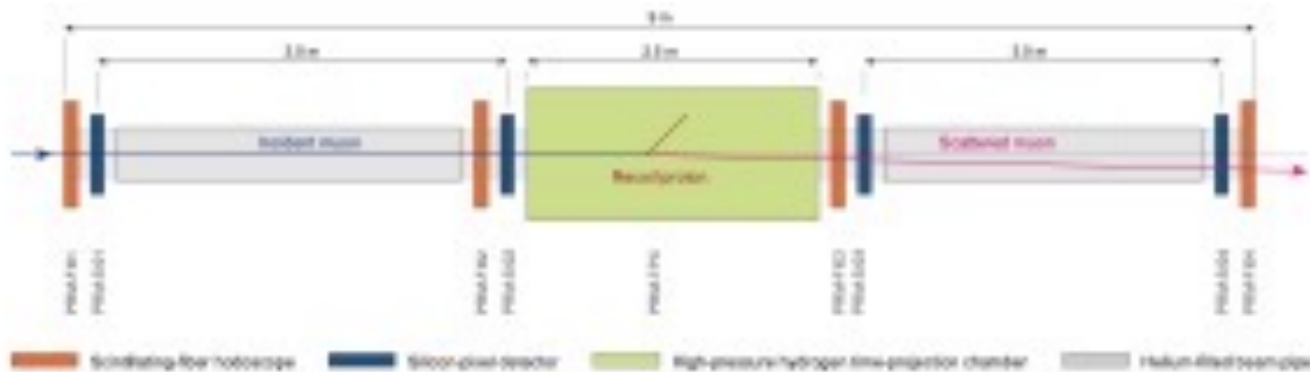
# The MUSE Experiment at PSI



Beam momentum values:  
115, 153, 210 MeV/c  
Scattering angle:  $20^\circ$  -  $100^\circ$

Experiment	Beam	Laboratory	$Q^2$ (GeV/c) <sup>2</sup>	$\delta r_p$ (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	$4 \times 10^{-5} - 6 \times 10^{-2}$	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 <sup>2</sup>	$e^-$	Tohoku University	$3 \times 10^{-4} - 8 \times 10^{-3}$	$\sim 1\%$ (rel.)	Future

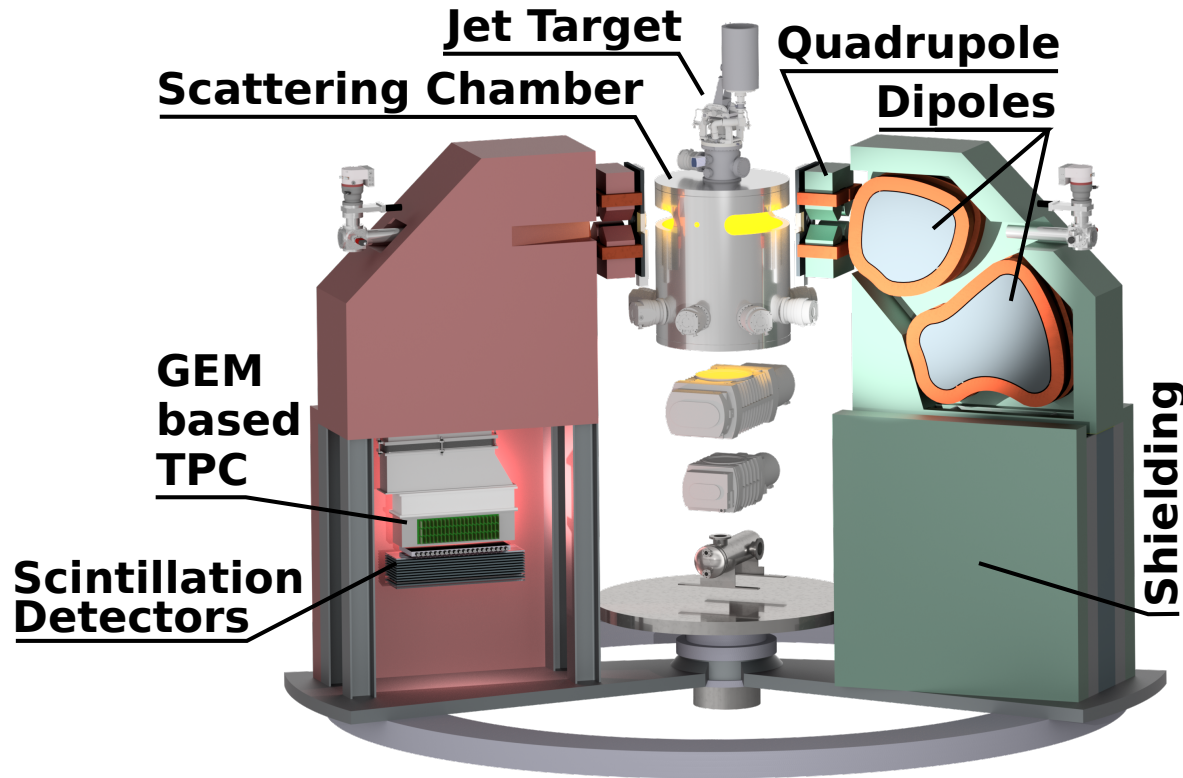
# The Amber Experiment at CERN



M2 Beam-line:  
100 GeV muons

Experiment	Beam	Laboratory	$Q^2$ (GeV/c) <sup>2</sup>	$\delta r_p$ (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	$4 \times 10^{-5} - 6 \times 10^{-2}$	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 <sup>2</sup>	$e^-$	Tohoku University	$3 \times 10^{-4} - 8 \times 10^{-3}$	$\sim 1\%$ (rel.)	Future

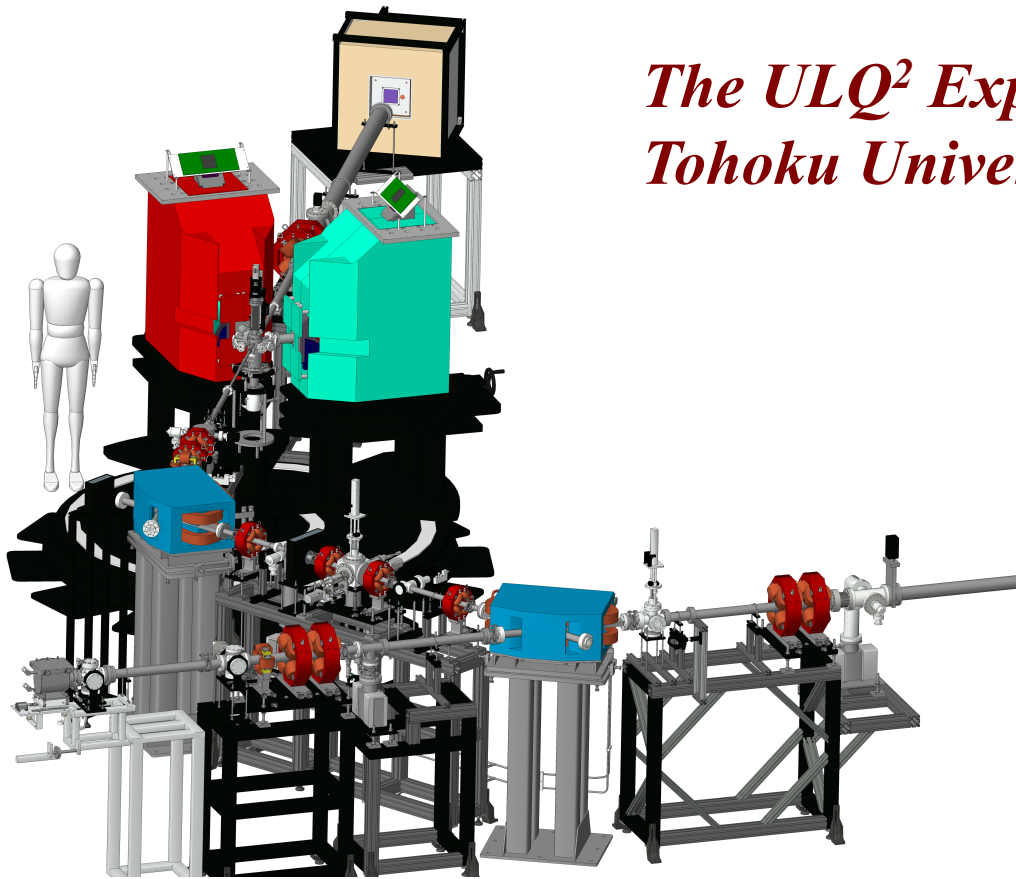
# The MAGIX@MESA Experiment at Mainz



Electron beam momentum:  
20-105 MeV/c

Experiment	Beam	Laboratory	$Q^2$ (GeV/c) <sup>2</sup>	$\delta r_p$ (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	$4 \times 10^{-5} - 6 \times 10^{-2}$	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 <sup>2</sup>	$e^-$	Tohoku University	$3 \times 10^{-4} - 8 \times 10^{-3}$	$\sim 1\%$ (rel.)	Future

# *The ULQ<sup>2</sup> Experiment at Tohoku University*



Beam momentum values:  
 20-60 MeV/c  
 Scattering angle: 30<sup>0</sup> -150<sup>0</sup>  
 Target CH<sub>2</sub>  
 Focal plane detector:  
 Single-sided Silicon  
 Detectors

Experiment	Beam	Laboratory	$Q^2$ (GeV/c) <sup>2</sup>	$\delta r_p$ (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	$4 \times 10^{-5} - 6 \times 10^{-2}$	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 <sup>2</sup>	$e^-$	Tohoku University	$3 \times 10^{-4} - 8 \times 10^{-3}$	$\sim 1\%$ (rel.)	Future

# Summary

- The proton remains puzzling after years of studies, but major progress made in resolving the charge radius puzzle
- The PRad – a first electron-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 will be expected from lepton scattering including PRad-II aiming at 0.0036 fm
- **Stay Tuned!**

**Acknowledgement: The PRad collaboration, J. Bernauer, R. Gilman, S. Paul, T. Suda, W. Xiong, J. Zhou, S. Strauch, H. Merkel, M. Vanderhaeghen, and others**

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