Experimental status of the proton radius

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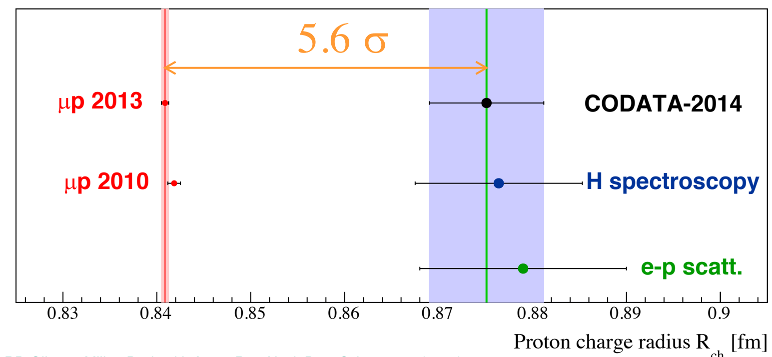
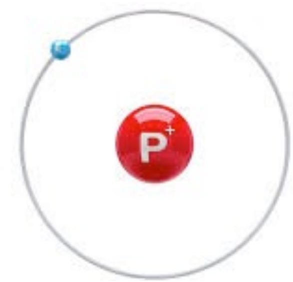
Proton Charge Radius and the puzzle

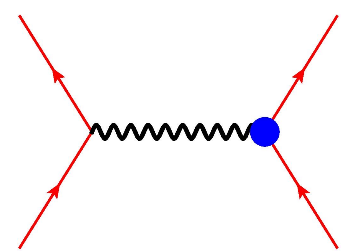
- Proton charge radius:
  1. An important quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

- 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,..)
     - ***μ**p* elastic scattering (MUSE, AMBER)





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

$$\Delta E = -4\pi\alpha G'^{p}_{E}(0)|\psi_{n0}(0)|^2\delta_{l0}$$
$$= 4\pi\alpha\frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.$$

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

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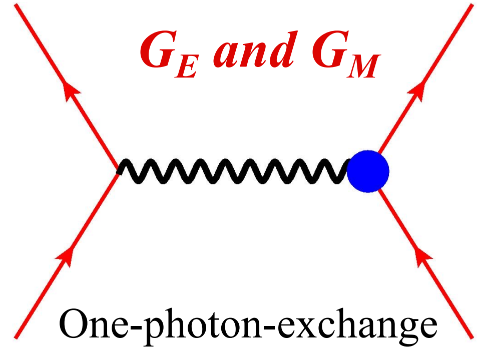
Electron-proton elastic scattering

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

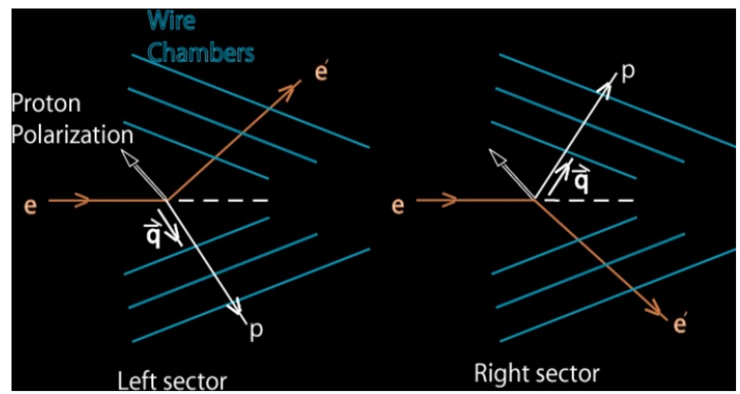
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E} \left(\frac{{G_E^p}^2 + \tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2\frac{\theta}{2} \right)$$

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



- **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)

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

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

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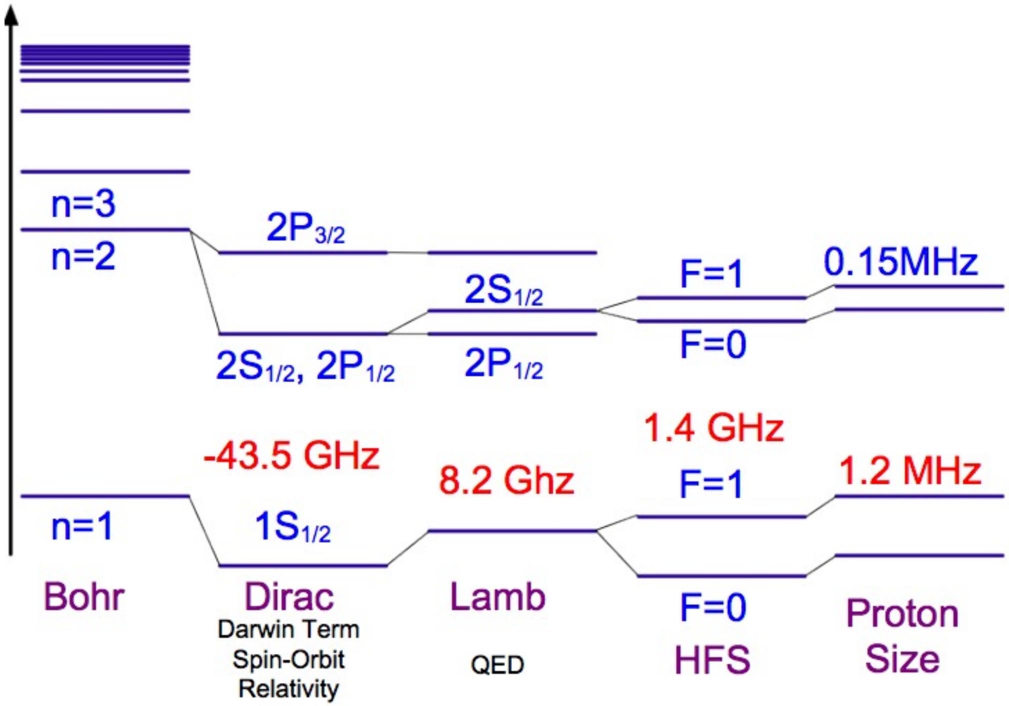
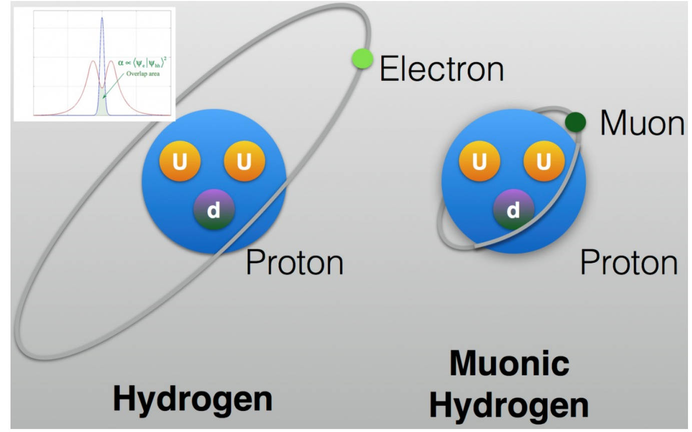
Hydrogen Spectroscopy





$$\Delta E = -4\pi\alpha G'^{p}_{E}(0)|\psi_{n0}(0)|^{2}\delta_{l0}$$
$$= 4\pi\alpha \frac{r_p^2}{6}|\psi_{n0}(0)|^{2}\delta_{l0}.$$

The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in 10^{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%

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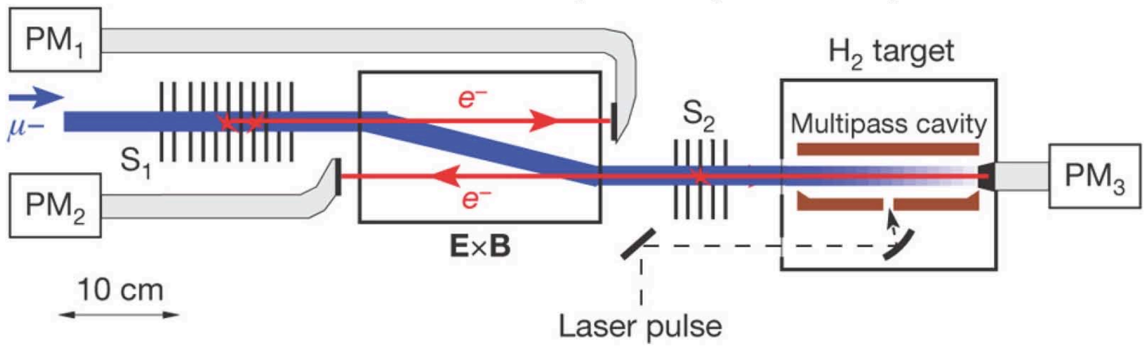
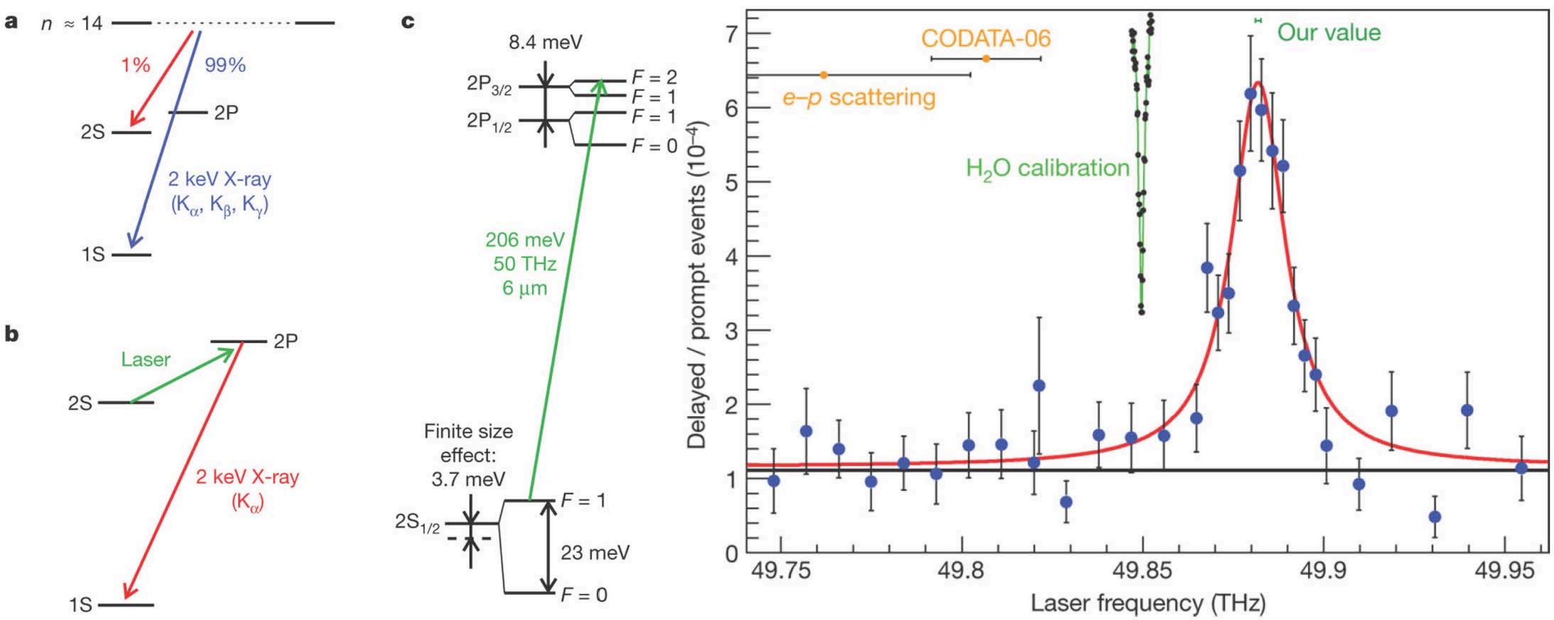
Muonic hydrogen Lamb shift at PSI (2010, 2013)

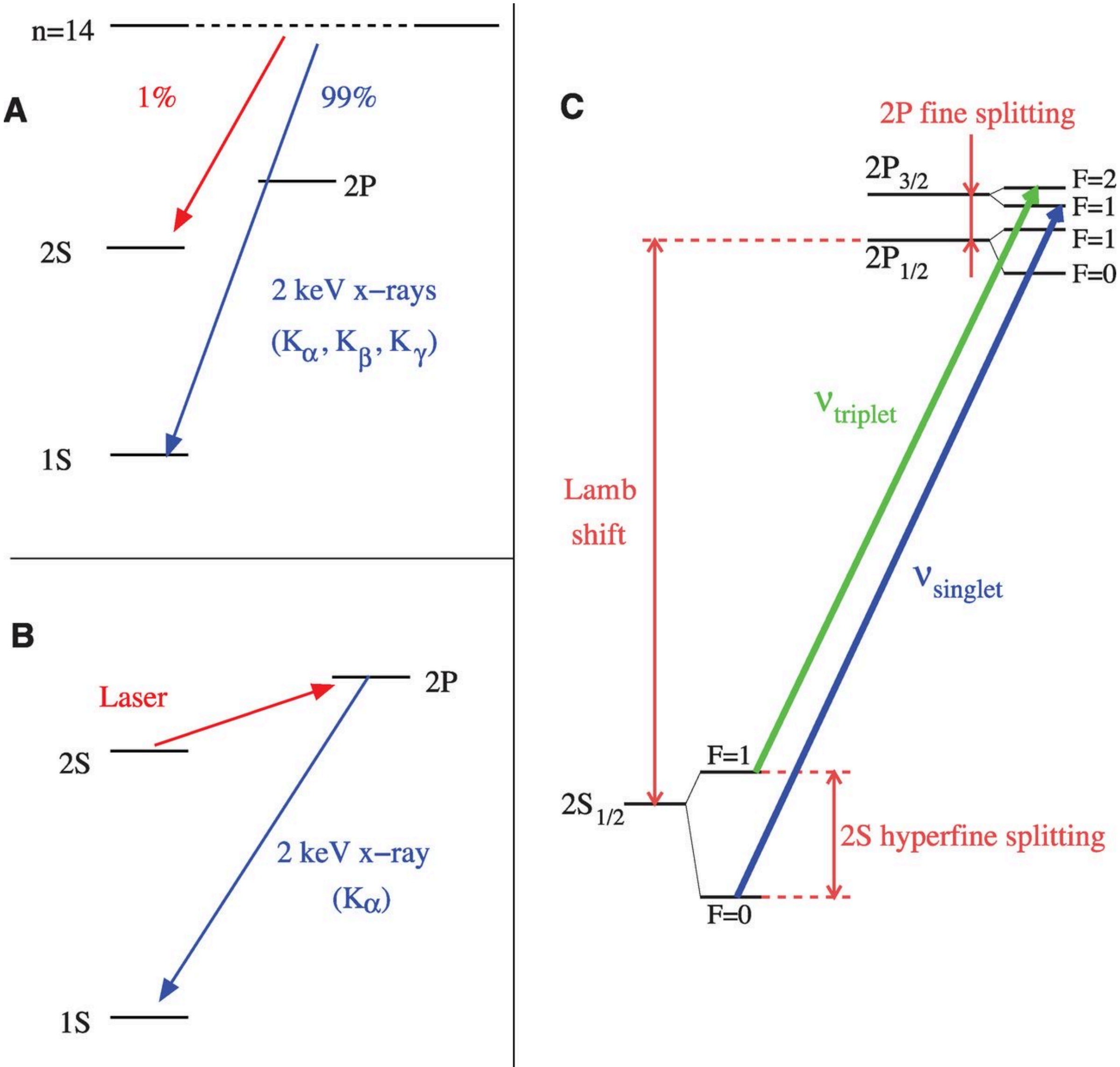
Nature **466**, 213-216 (8 July 2010)





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)

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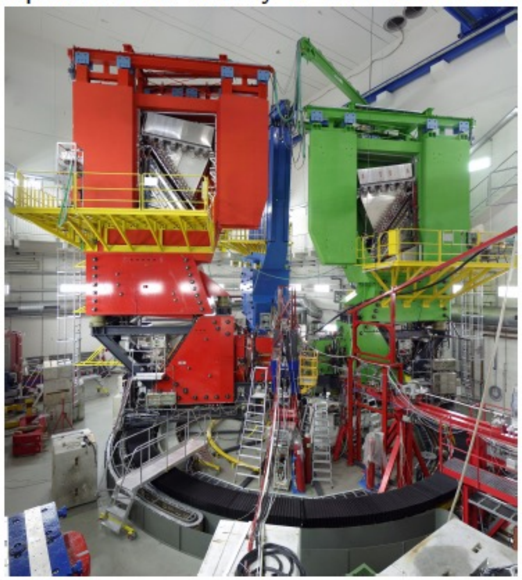
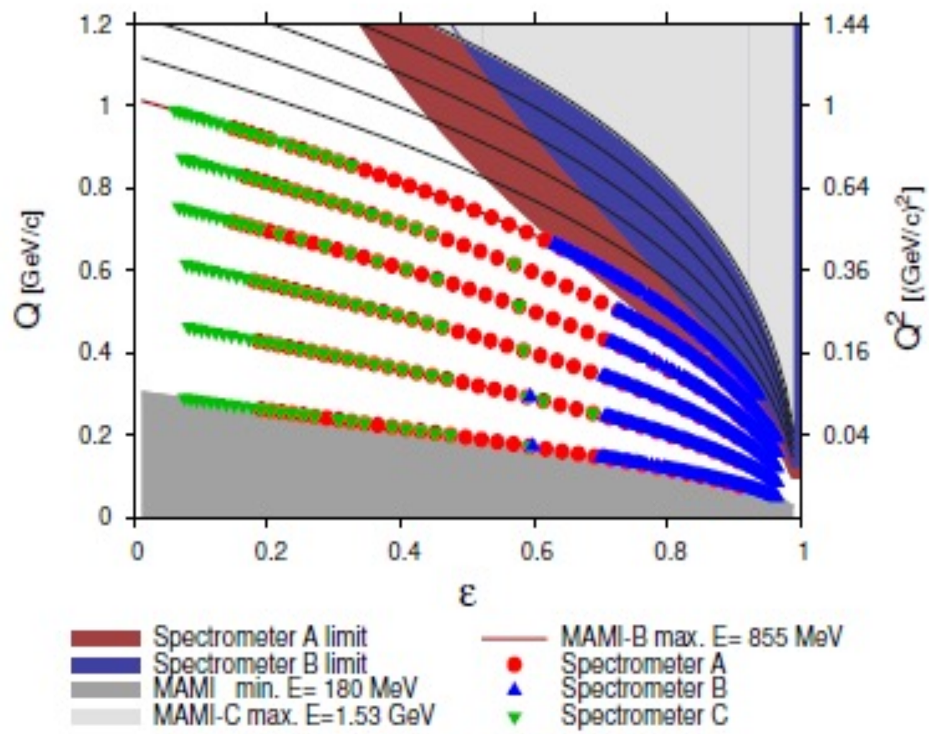
Electron-proton Scattering – Mainz A1 experiment

Three spectrometer facility of the A1 collaboration:



Measurements @ Mainz



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

- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105, 242001 (2010)

5-7σ higher than muonic hydrogen result !

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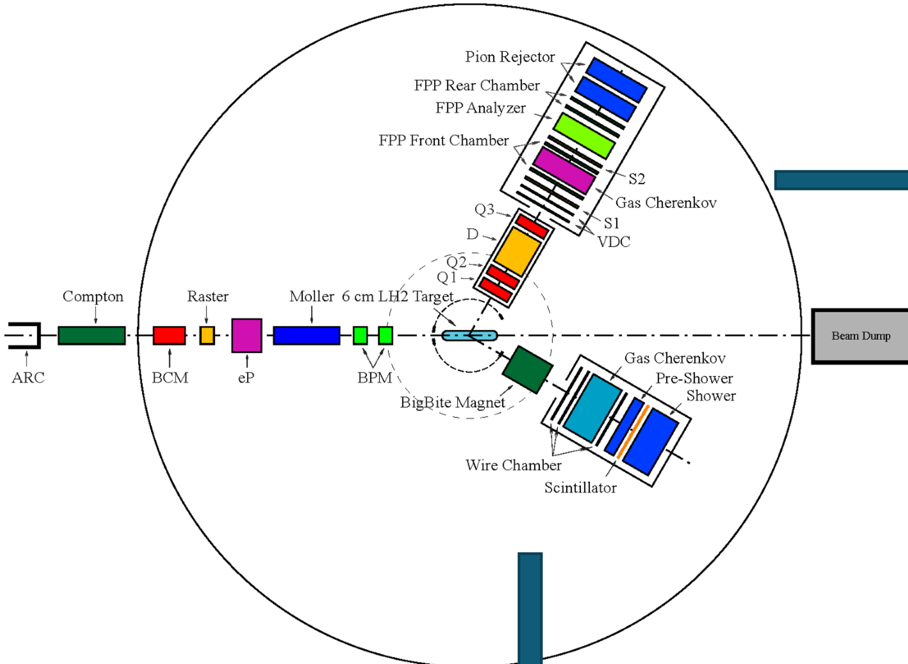
(J. Bernauer)

JLab Recoil Proton Polarization Experiment



LHRS

- $\Delta p/p0$: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

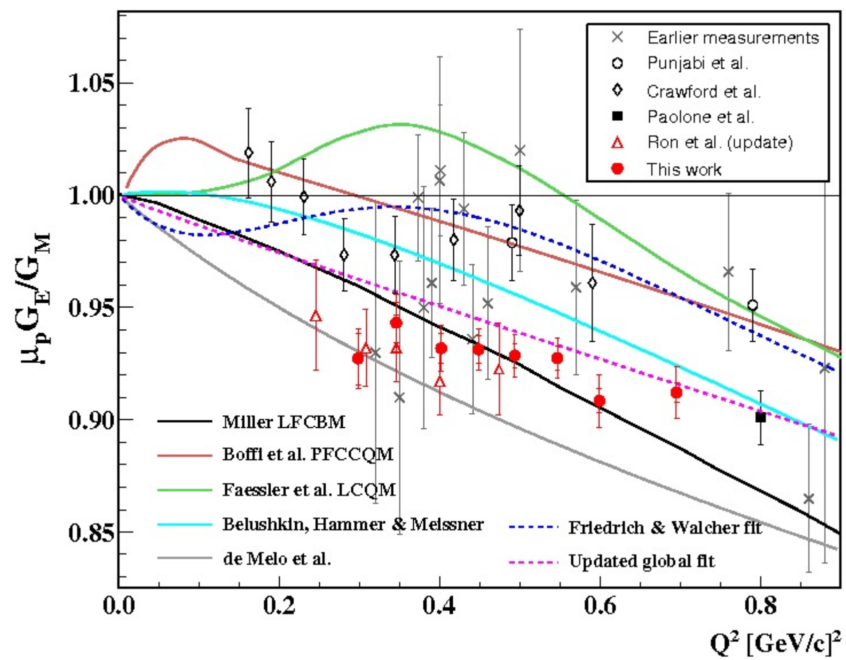
- **Q^2 = 0.3 – 0.7 $(GeV/c)^2$**
- **r_p =0.875±0. 010 fm**

(global analysis not including Mainz A1)

BigBite

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

E_e: 1.192GeV
P_b: ~83%



X. Zhan et al. Phys. Lett. B 705 (2011) 59-64

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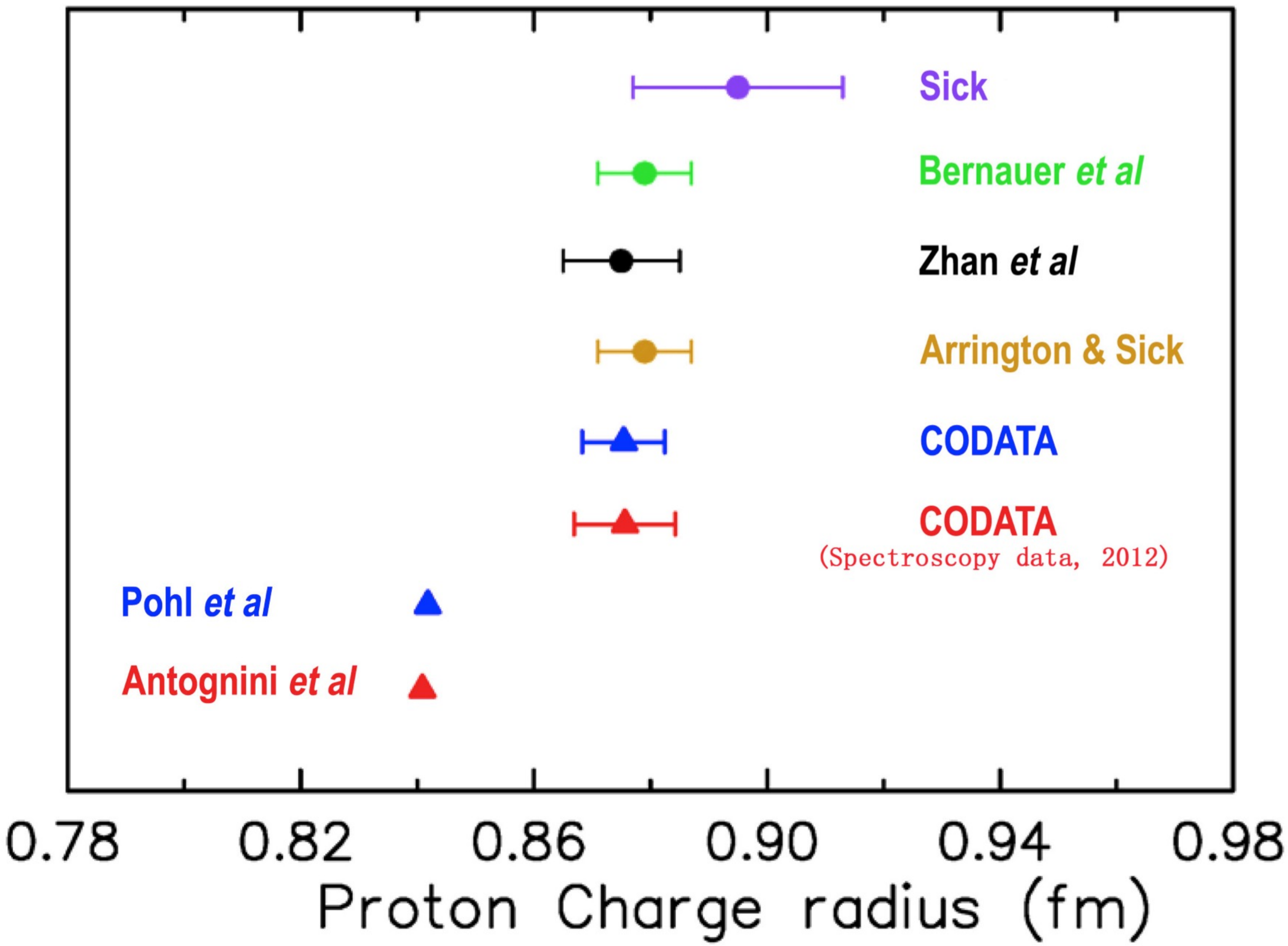
The situation on the Proton Charge Radius in 2013



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

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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,….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), …

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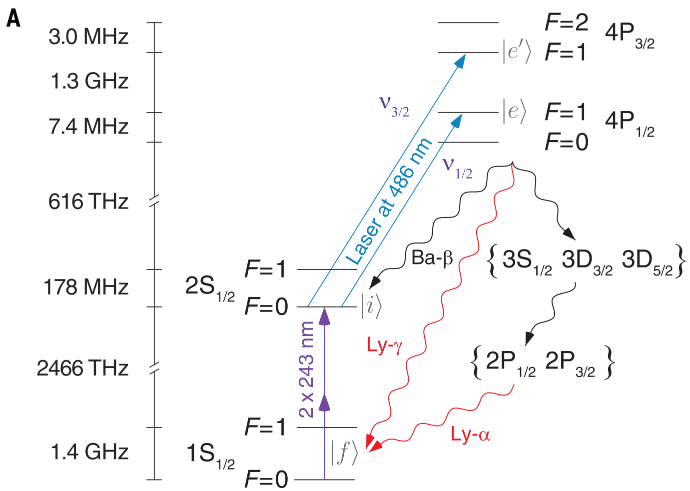
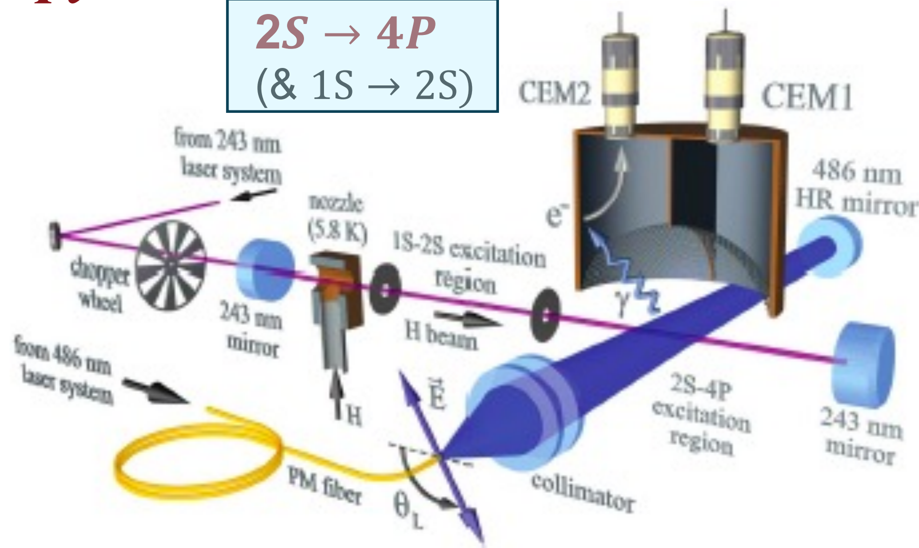
Ordinary hydrogen spectroscopy

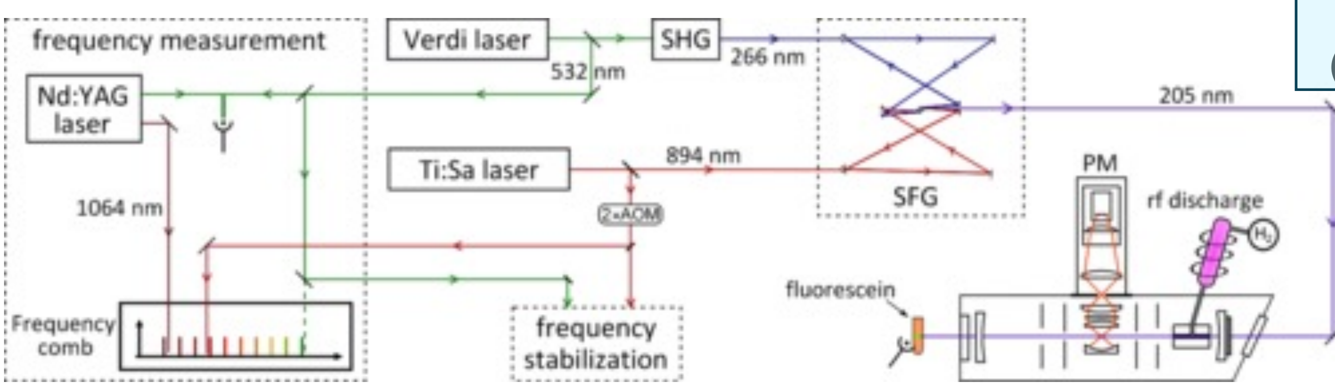
$2S \rightarrow 4P$
(& $1S \rightarrow 2S$)





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

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



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

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

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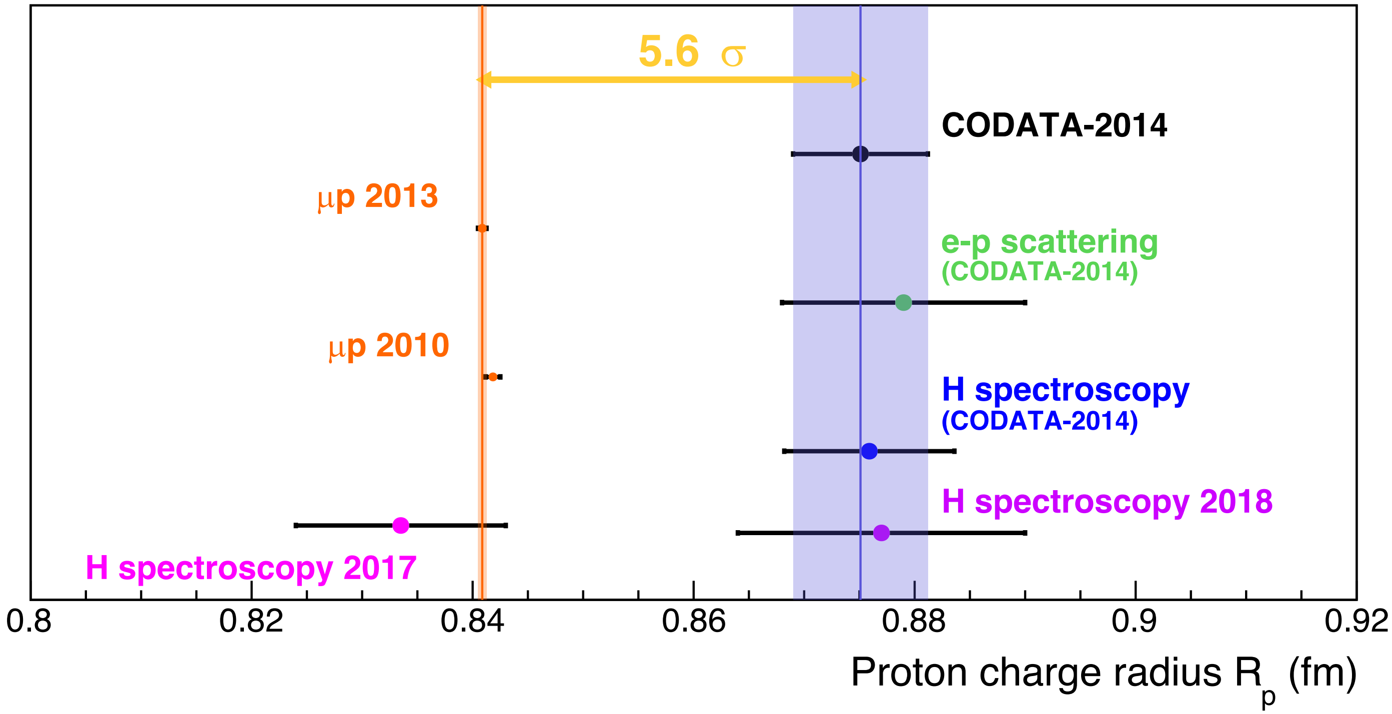
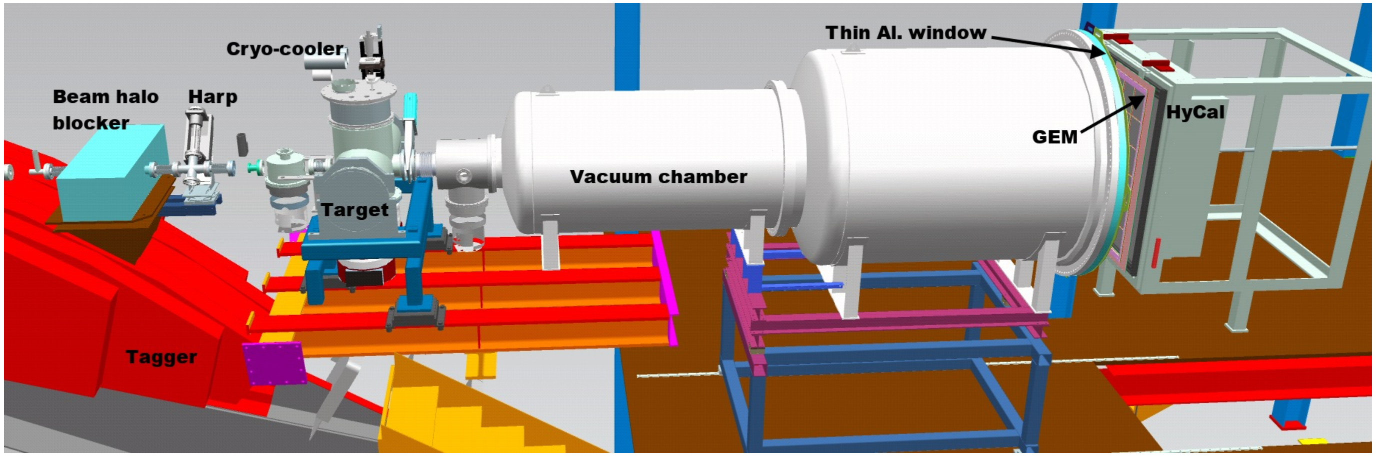
The Proton Charge Radius Puzzle in 2018

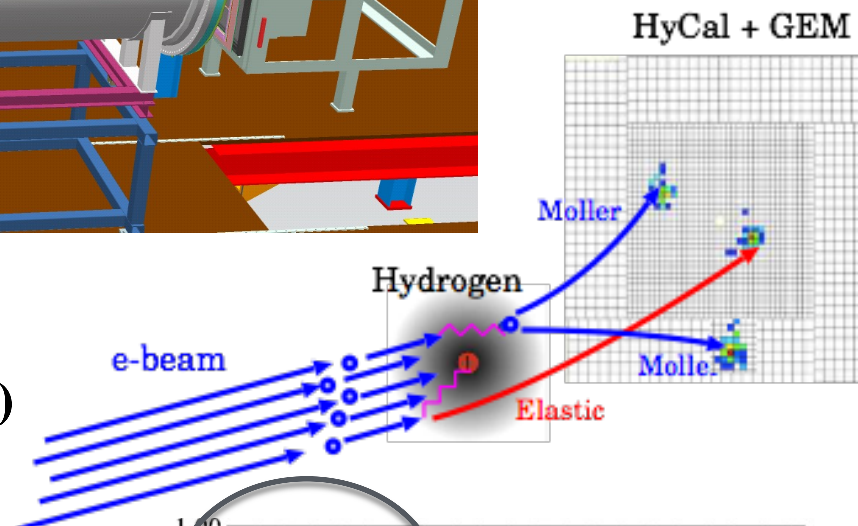


Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)
H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

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

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 and Moller electrons
- Q^2 range of 2×10^{-4} – 0.06 GeV^2
- XY – veto counters replaced by GEM detector
- Vacuum chamber

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

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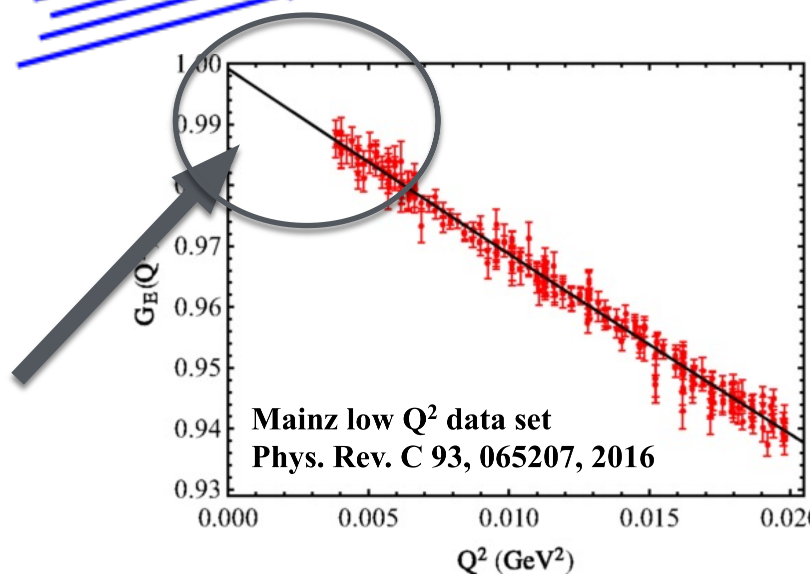
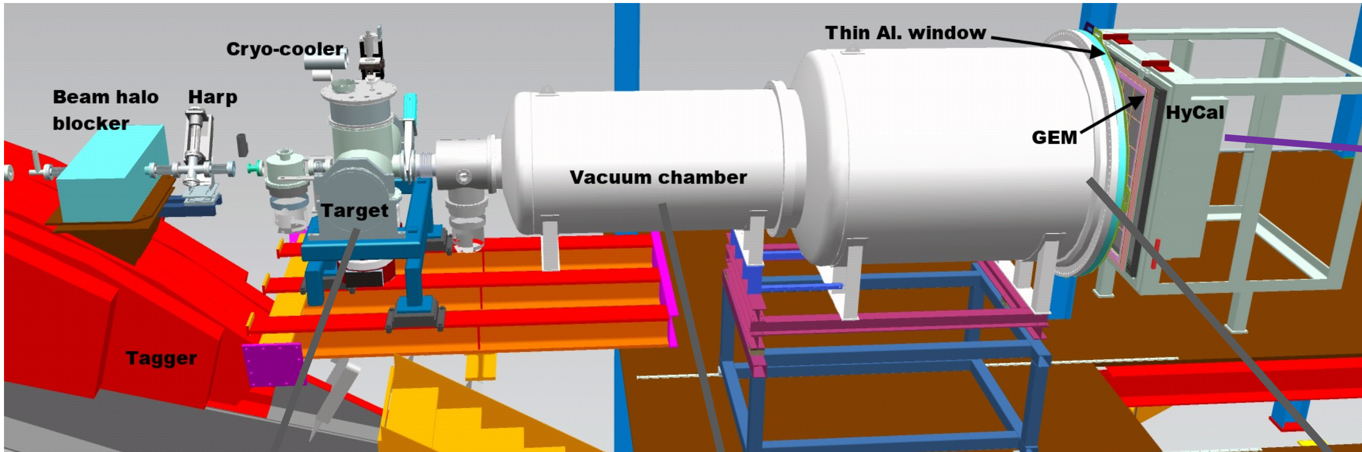
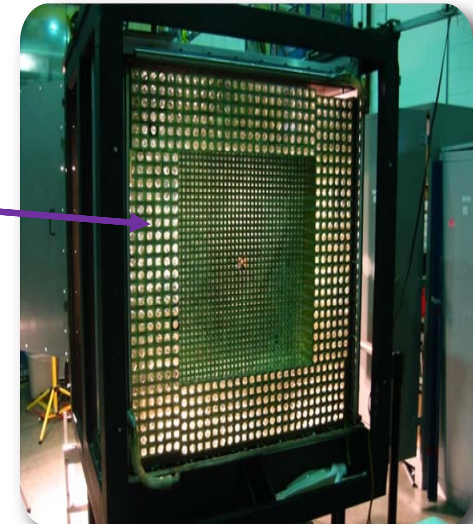
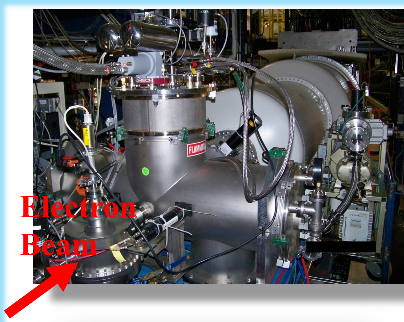
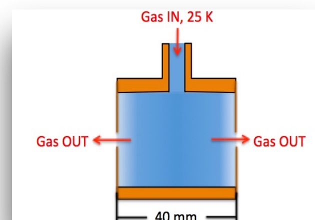


The *PRad Experimental setup*





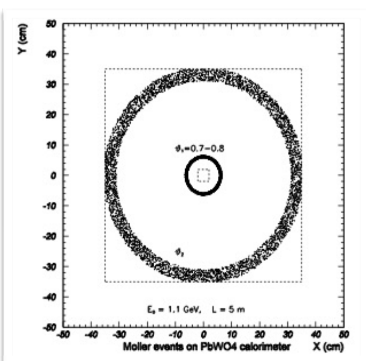


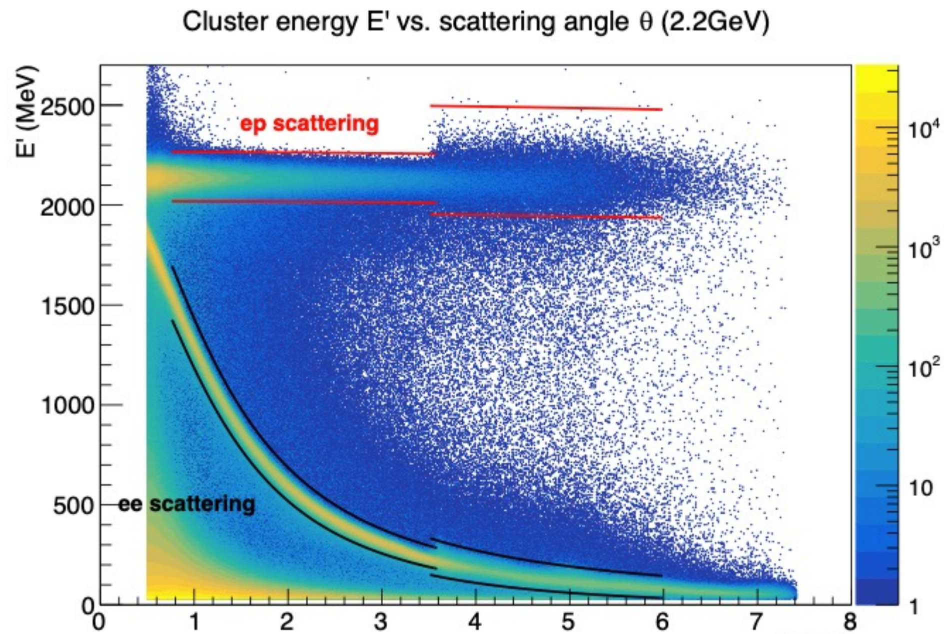


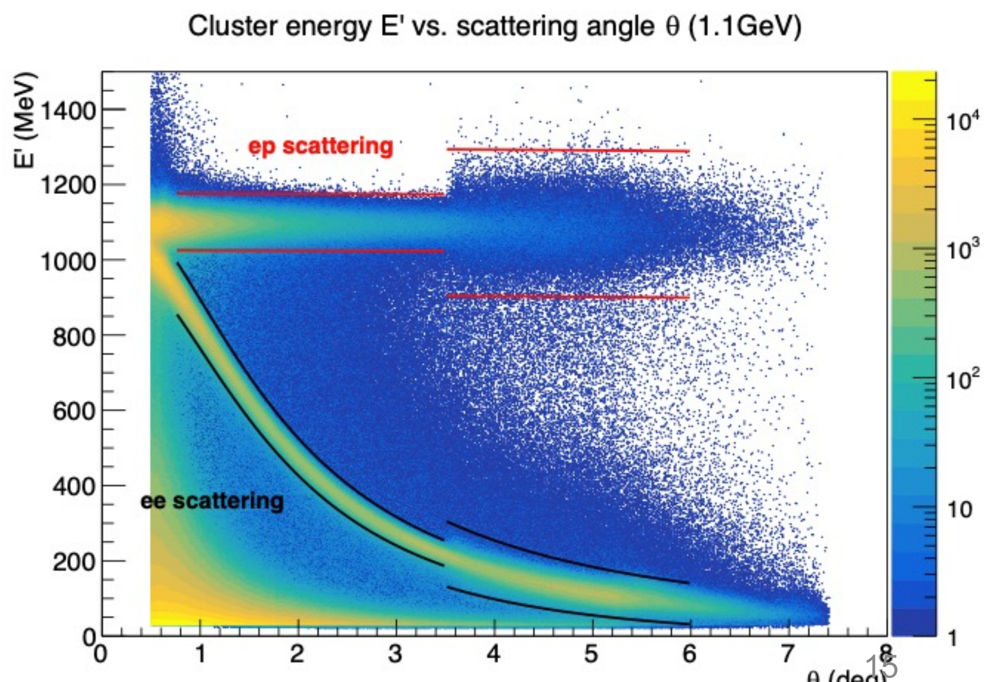
Analysis – Event Selection

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







Extraction of ep Elastic Scattering Cross Section

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

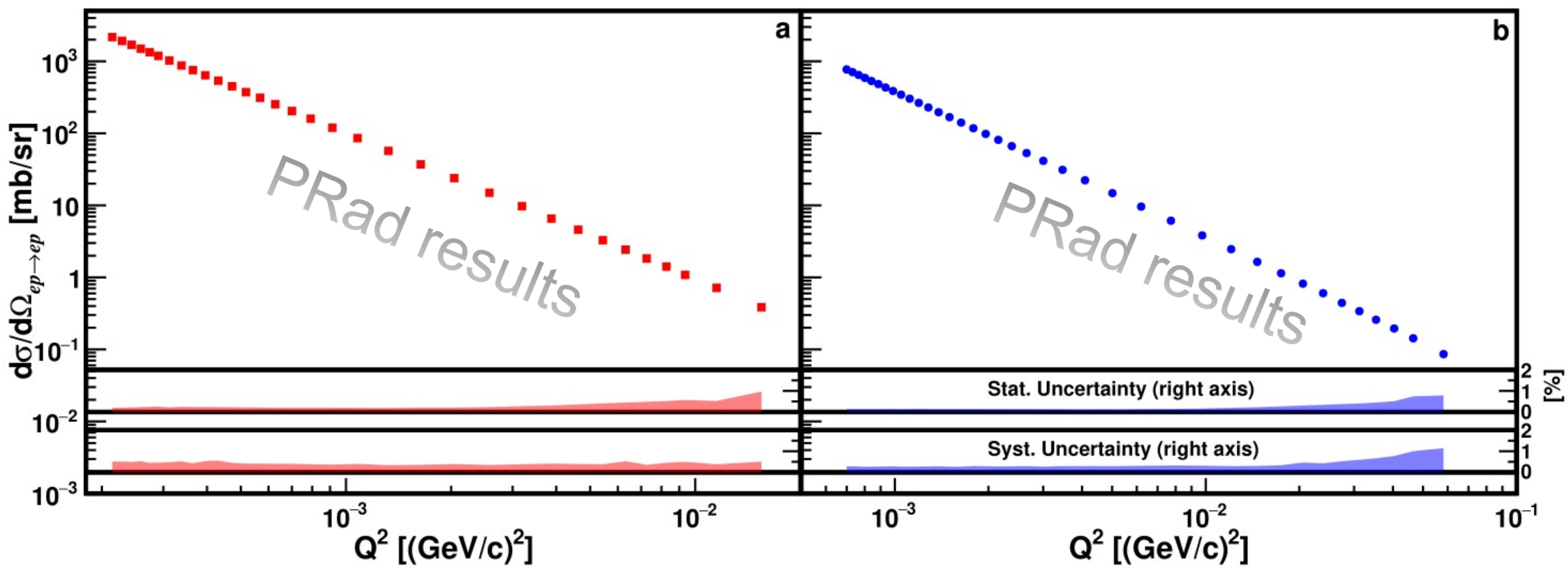
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \left[\frac{N_{\text{exp}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta_i)}{N_{\text{exp}}(ee \to ee)} \cdot \frac{\varepsilon_{\text{geom}}^{ee}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{ee}}{\varepsilon_{\text{det}}^{ep}}\right]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

- 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^{o} to 1.6^{o} for 2.2 GeV, 0.75^{o} to 3.0^{o} for 1.1 GeV. Larger angles use integrated Møller method (3.0^{o} to 7.0^{o} for 1.1 GeV; 1.6^{o} to 7.0^{o} for 2.2 GeV)
- PRad-II: two planes of GEM/μRwell 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

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

Elastic ep Cross Sections

- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data
- Statistical uncertainties: ~0.15% for 2.2 GeV, ~0.2% for 1.1 GeV per point
- Systematic uncertainties: 0.3%~1.1% for 2.2 GeV, 0.3%~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 $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

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

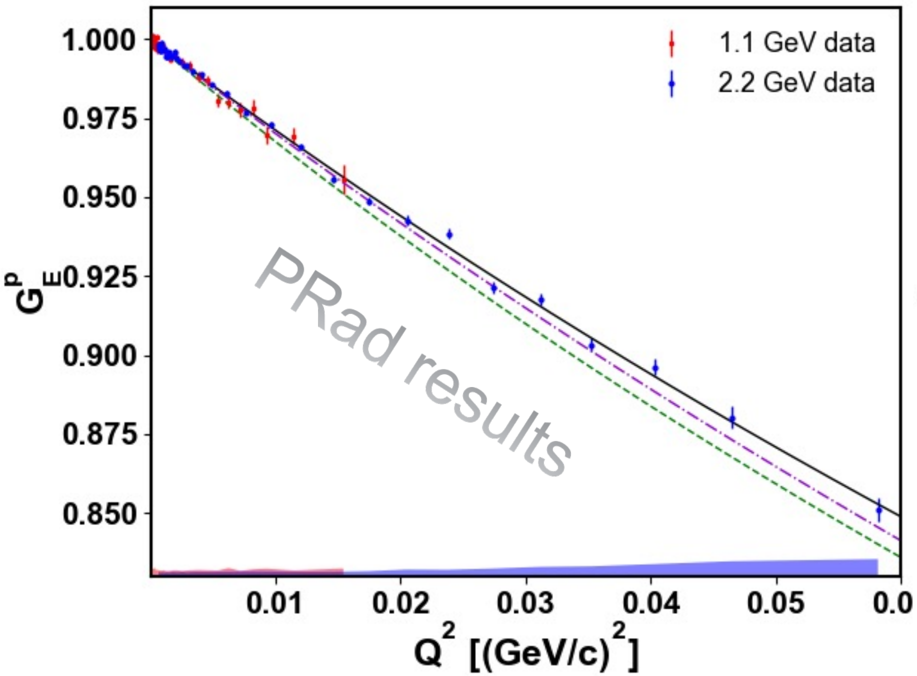
- G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

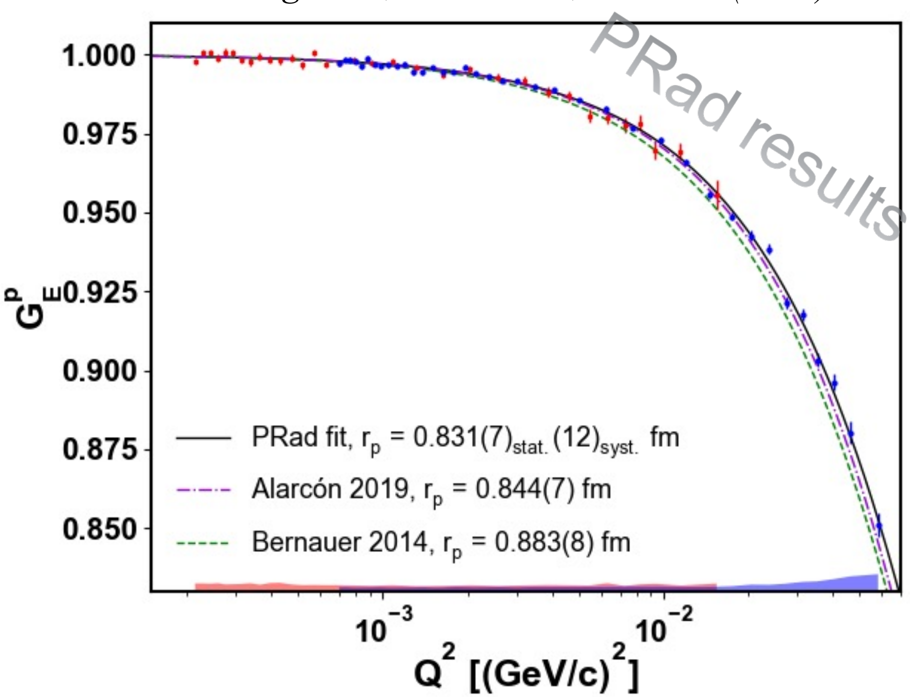
Yan et al., PRC 98, 025204 (2018)

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

r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

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





n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.),
n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

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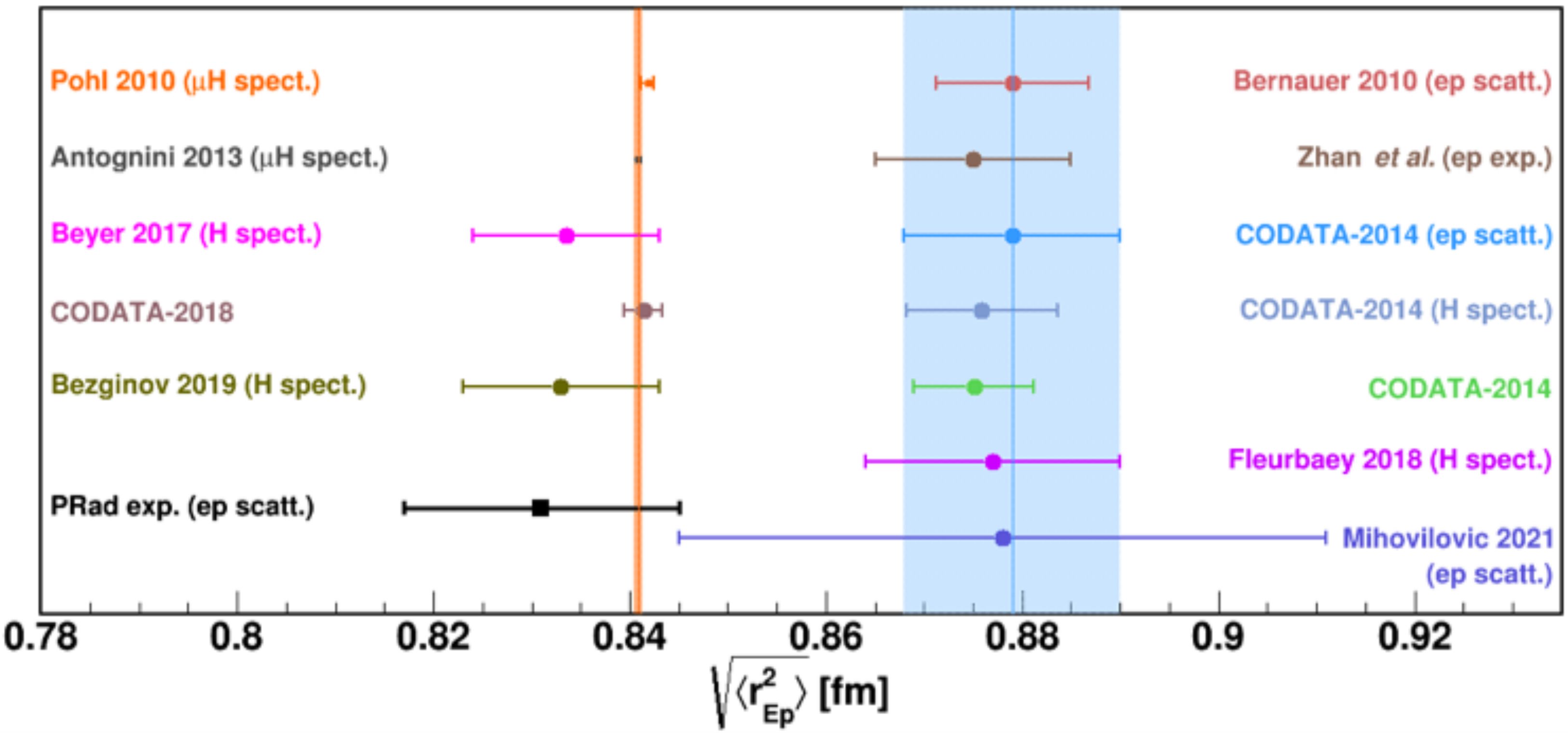
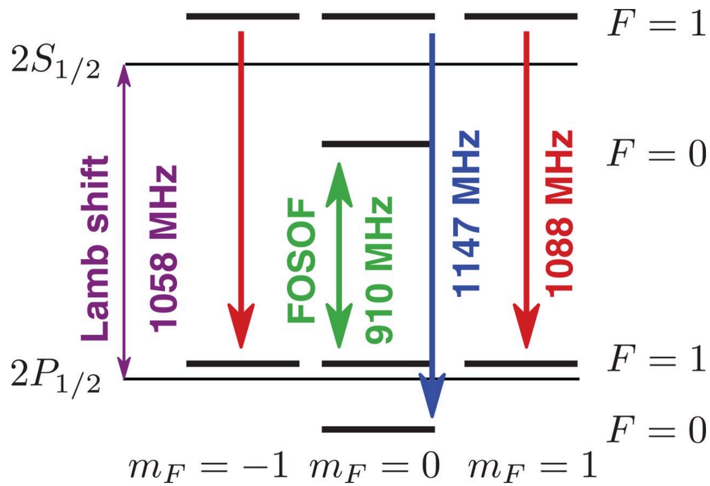
Proton radius at the time of PRad publication

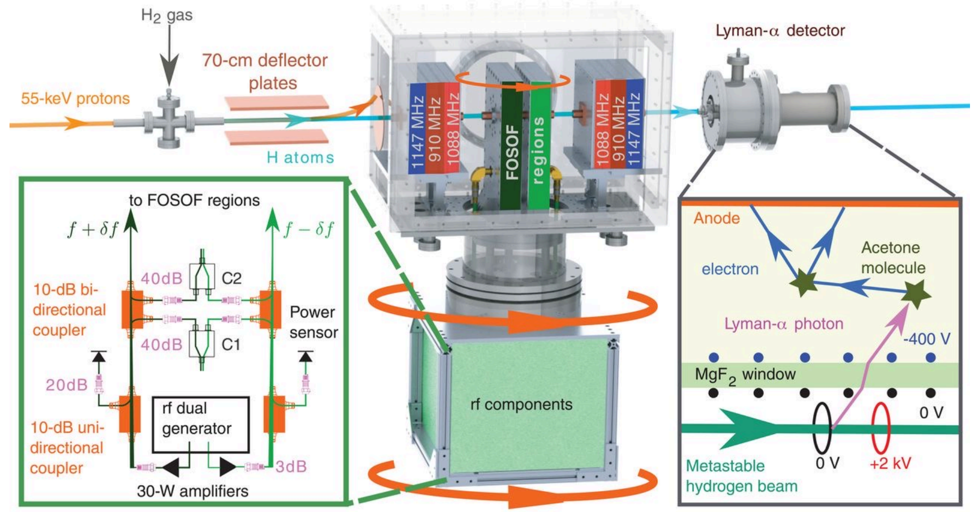
- PRad result r_p : 0.831 +/- 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*
- H Lamb Shift: 0.833 +/- 0.010 fm Bezginov *et al., Science* **365**, 1007-1012 (2019)
- CODATA 2018 value of r_p: 0.8414 +/- 0.0019 fm, *E. Tiesinga et al., RMP 93, 025010(2021)*



CODATA has also shifted the value of the Rydberg constant.

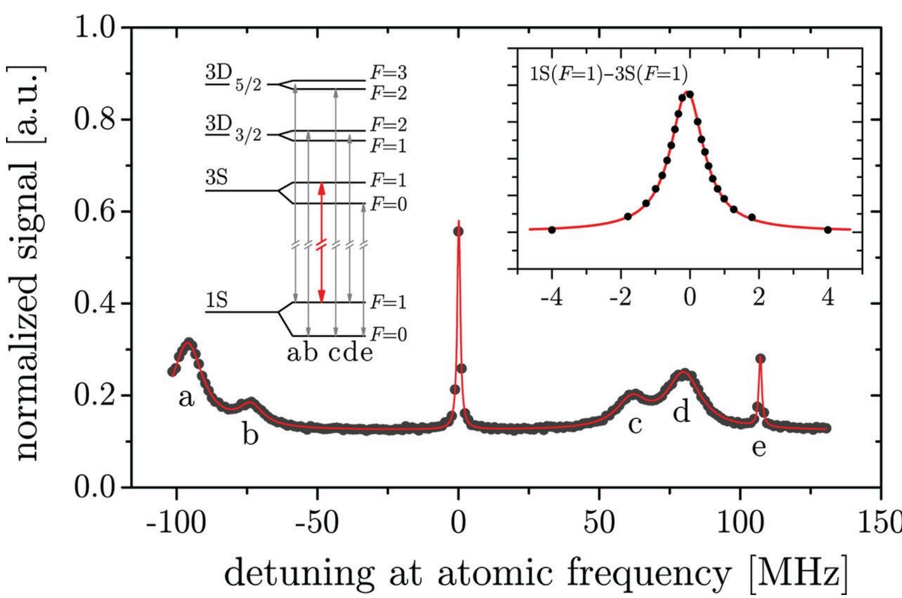
More from ordinary hydrogen spectroscopy

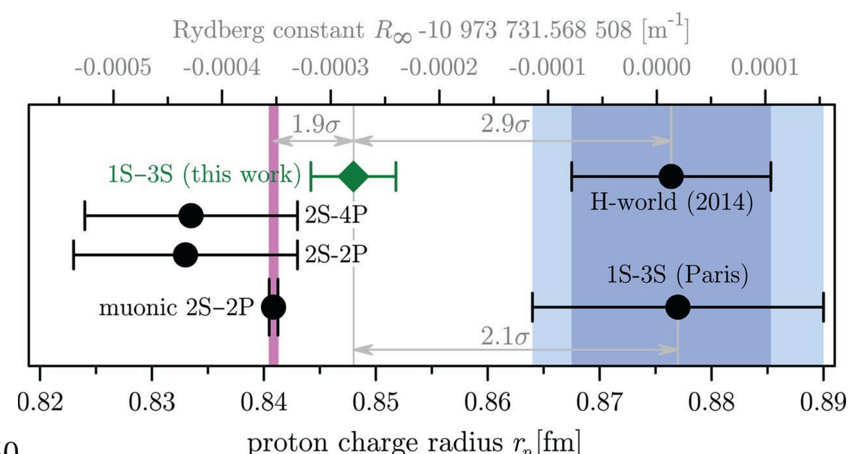




Bezginov *et al.*, Science 365, 1007 (2019)

$r_p = 0.833(10)$ fm

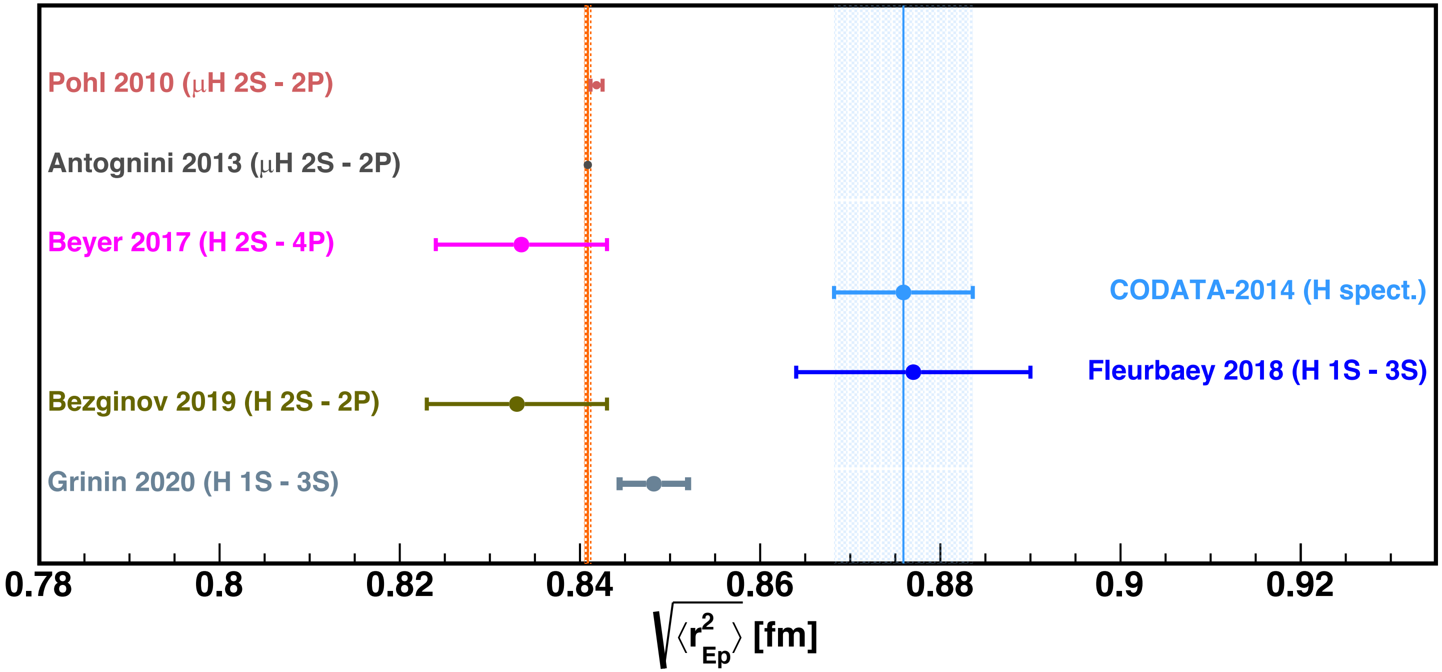




Grinin *et al.*, Science 370, 1061 (2020)

$r_p = 0.8482(38)$ fm

Proton radius from ordinary and muonic H spectroscopy



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)

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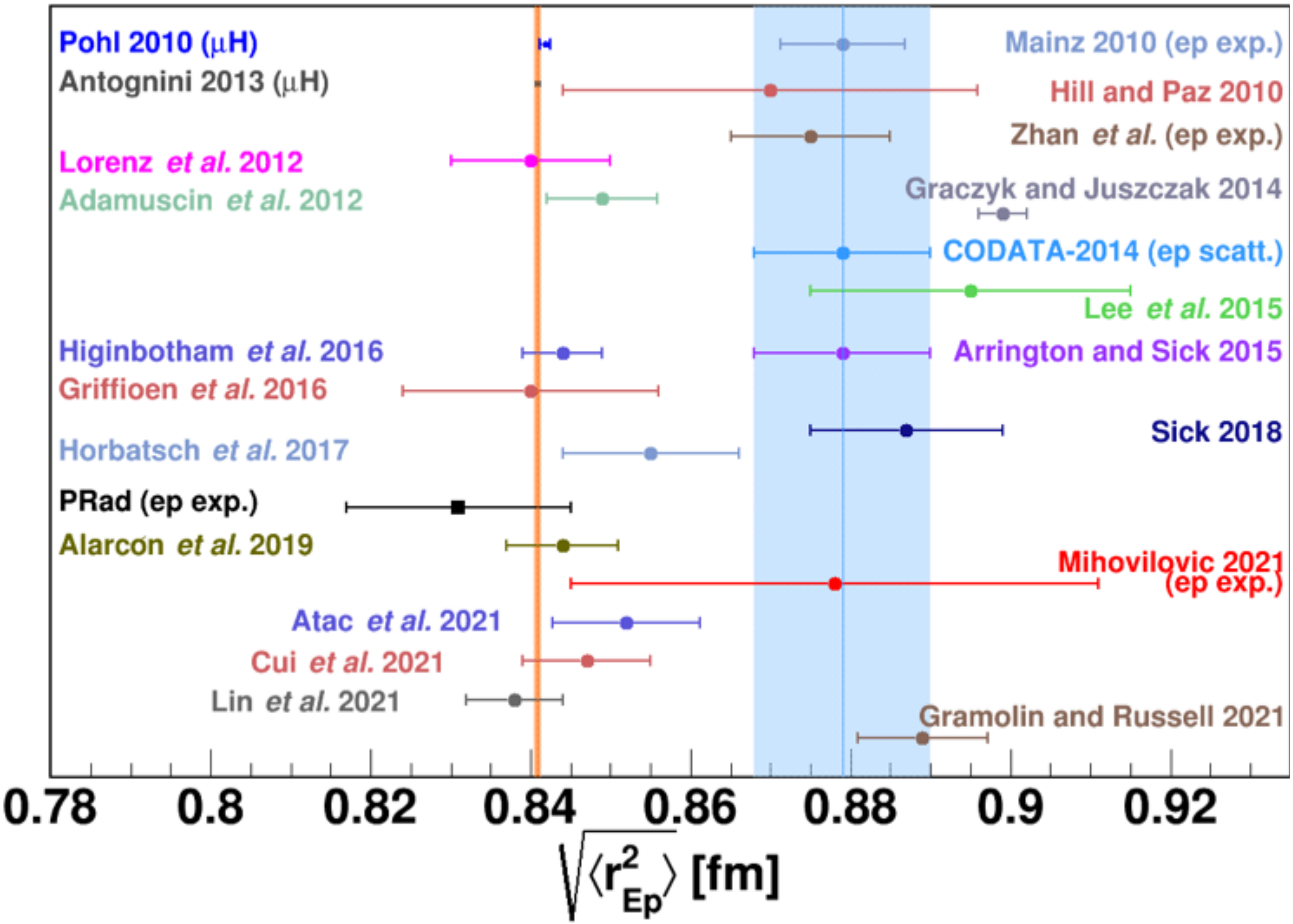
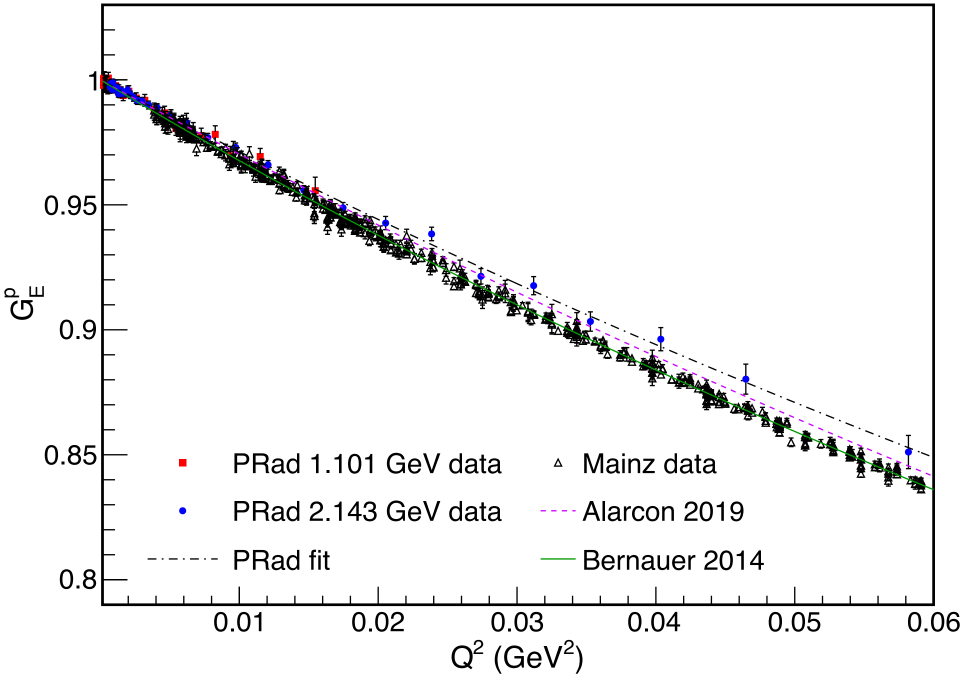
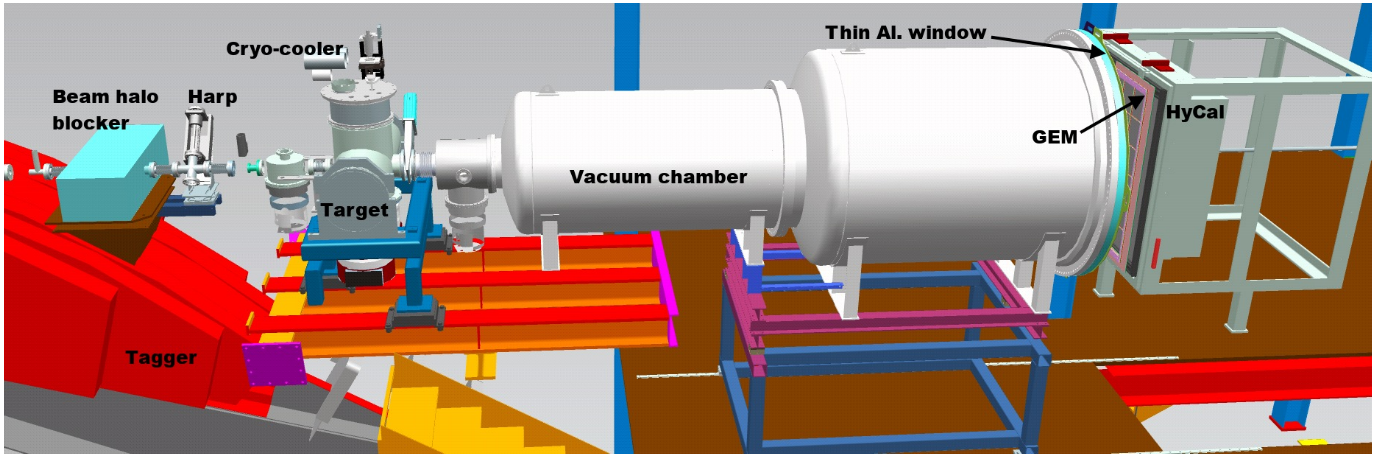
(Re)analyses of e-p scattering data



Gao and Vanderhaeghen, arXiv:2105.00571

e-p scattering: magnetic spectrometer and calorimetric method





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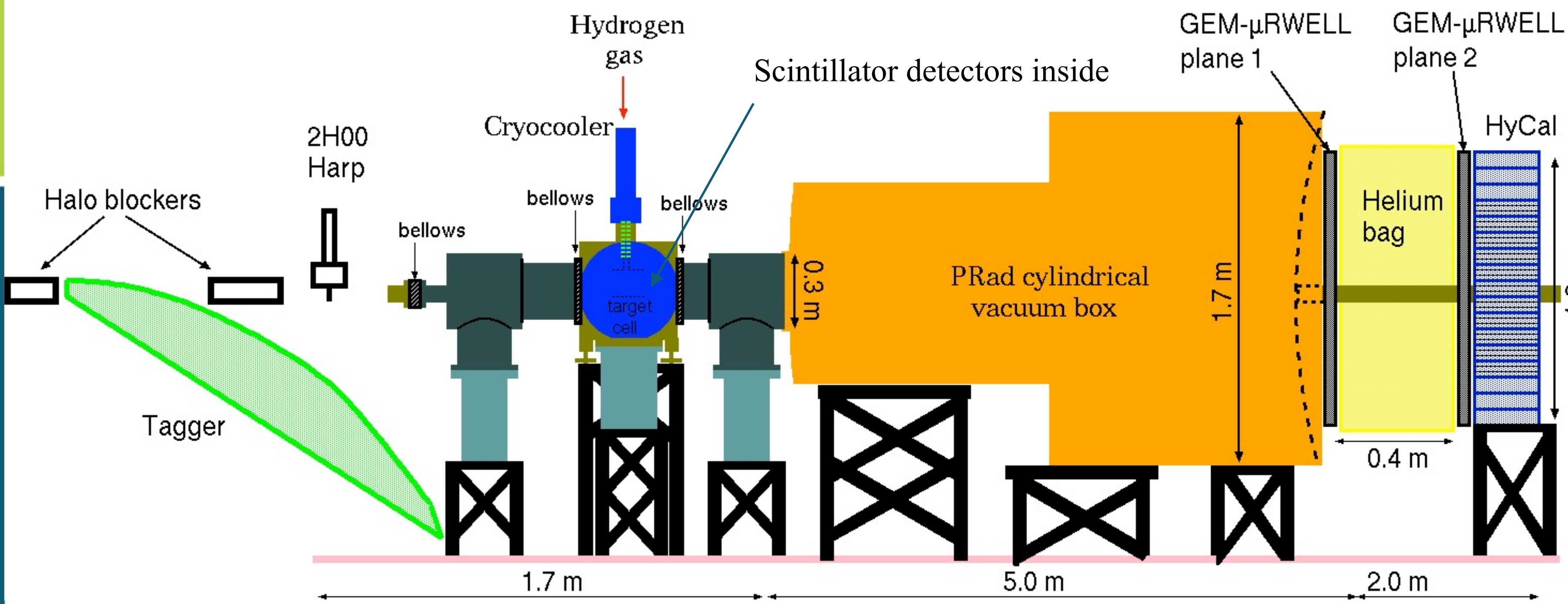
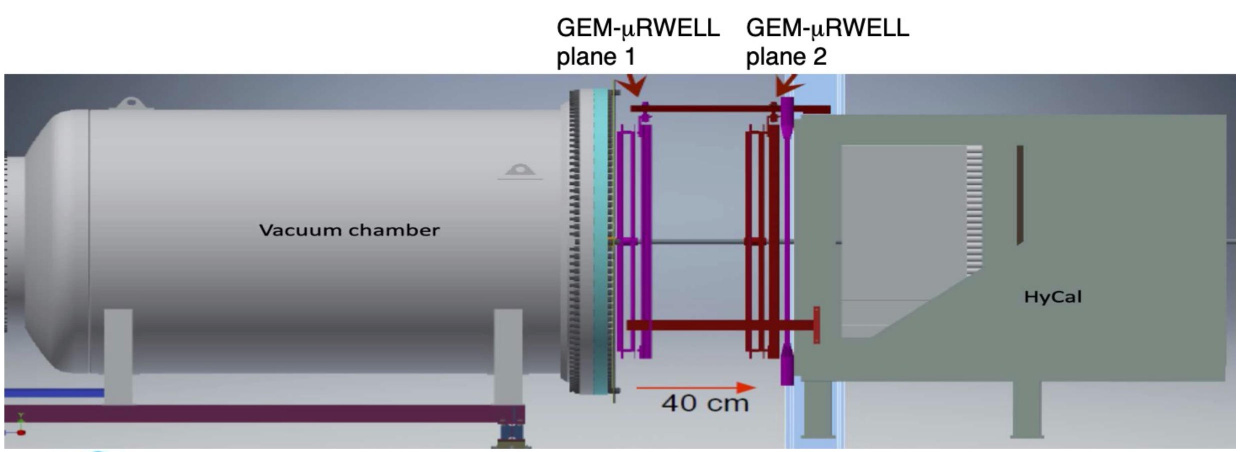
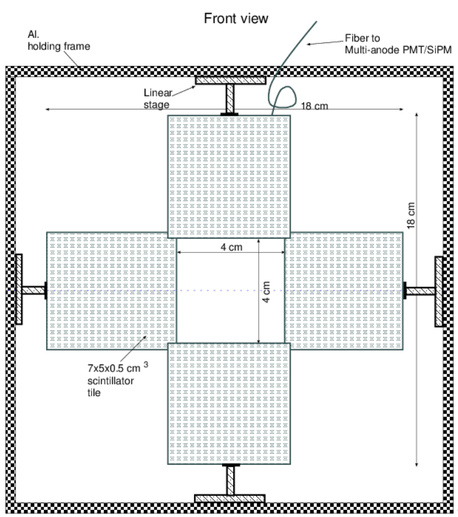
PRad-II Experimental Setup (Side View)







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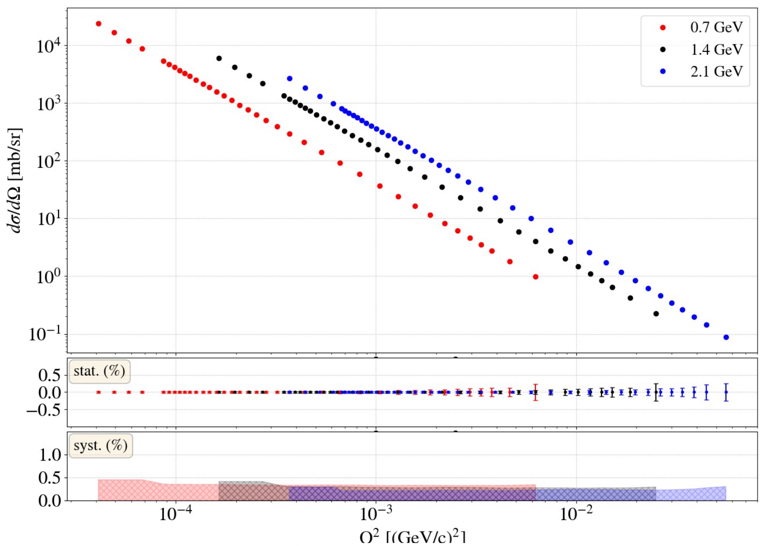
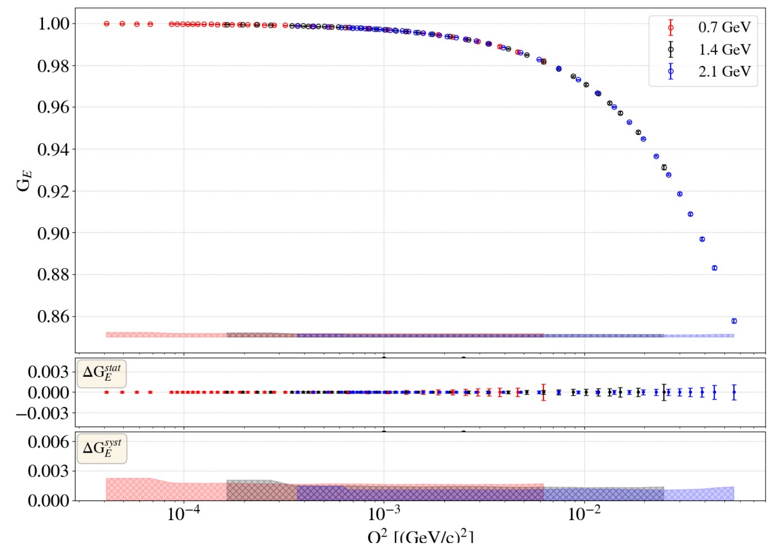
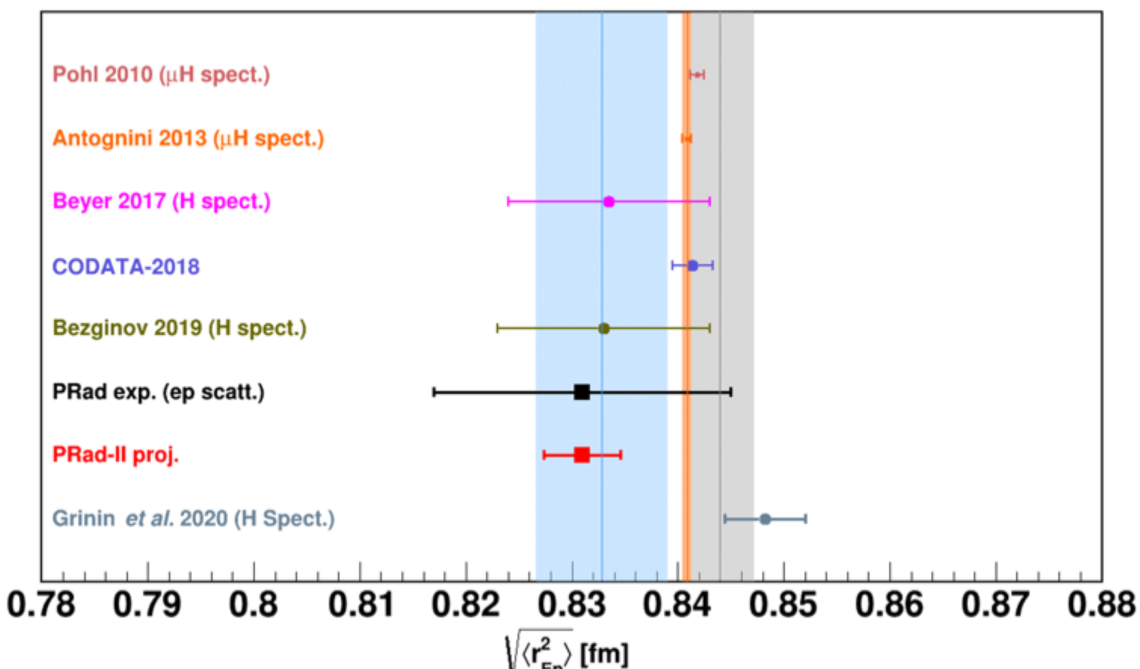
Projections for PRad-II

Differential Cross section



Electric form factor





PRad-II goal: 0.0036 fm

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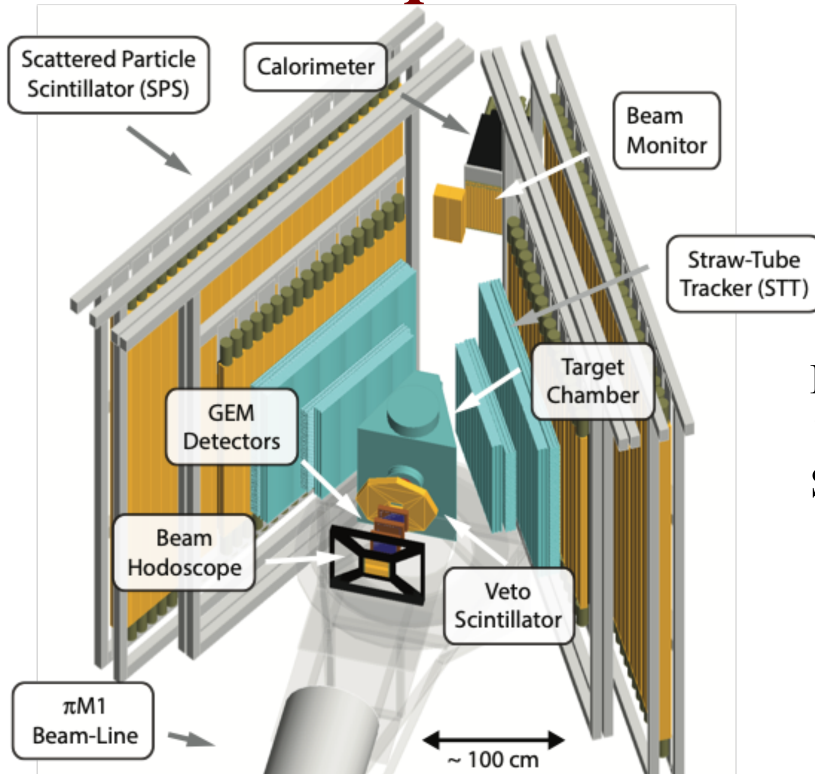
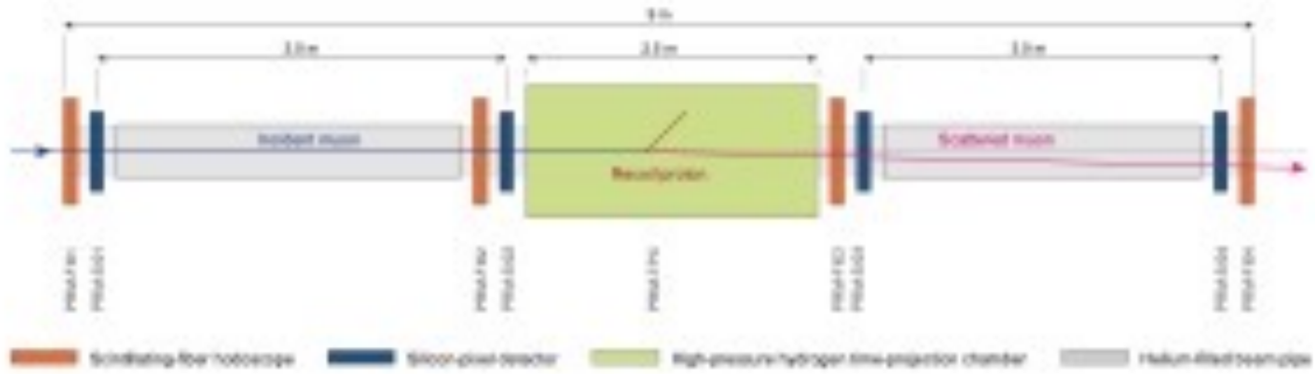
The MUSE Experiment at PSI

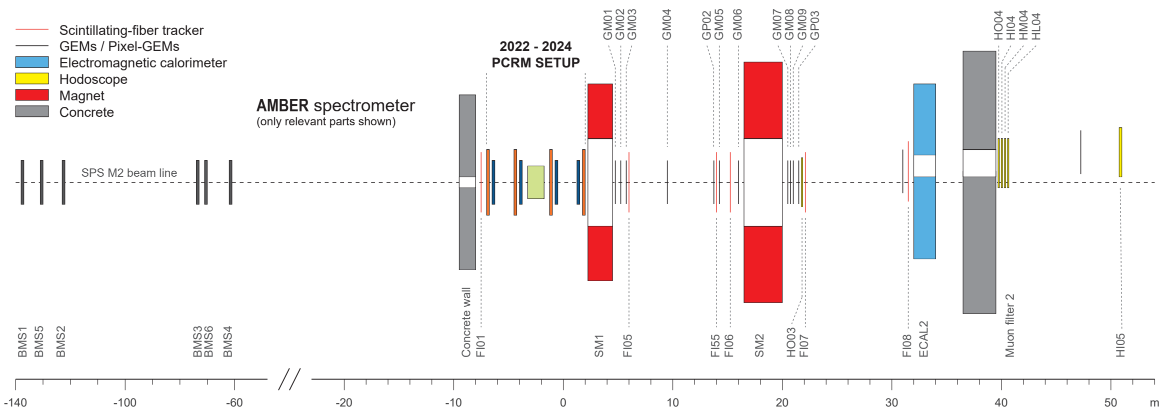


Beam momentum values:
115, 153, 210 MeV/c
Scattering angle: 20^0 -100^0

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	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

The Amber Experiment at CERN

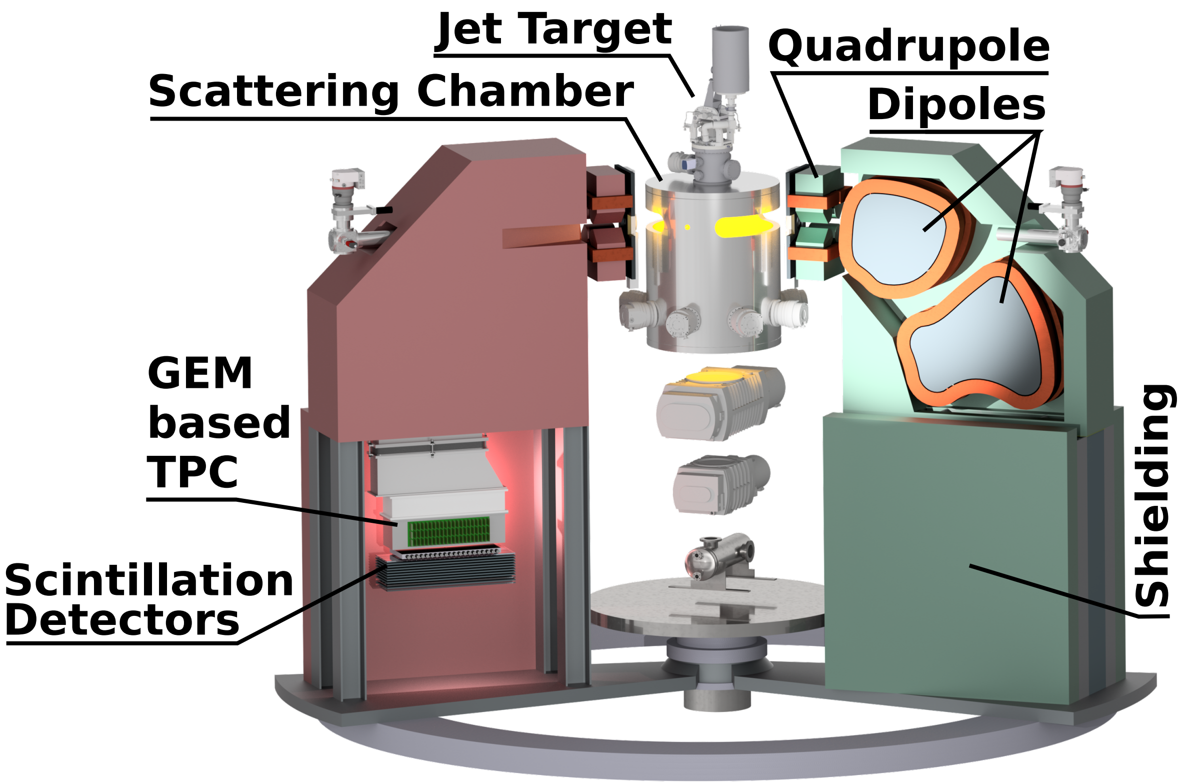




M2 Beam-line:
100 GeV muons

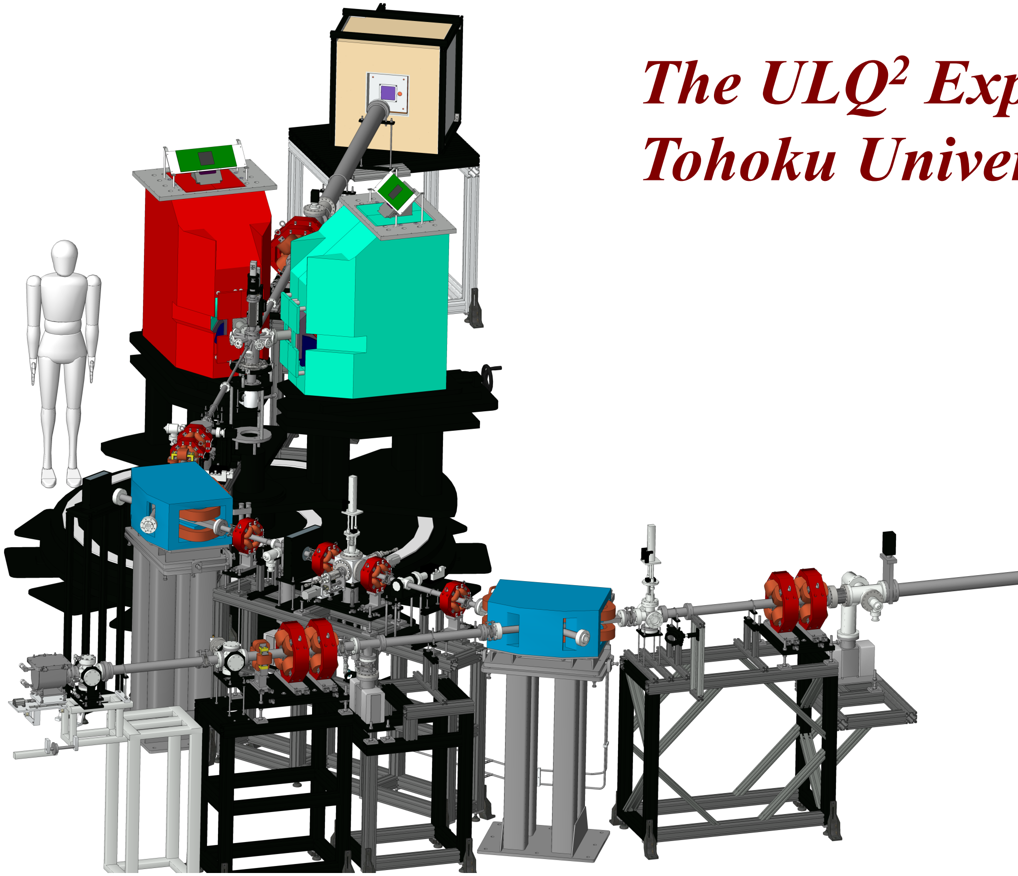
Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status
MUSE	$e^\pm$, $\mu^\pm$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^\pm$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-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

The MAGIX@MESA Experiment at Mainz



Electron beam momentum:
20-105 MeV/c

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	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



The ULQ^2 Experiment at Tohoku University

Beam momentum values:
20-60 MeV/c
Scattering angle: 30^0 -150^0
Target CH_2
Focal plane detector:
Single-sided Silicon
Detectors

Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	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

- 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!**

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