The PRad Experiment – Physics Overview

The PRad Experiment Readiness Review

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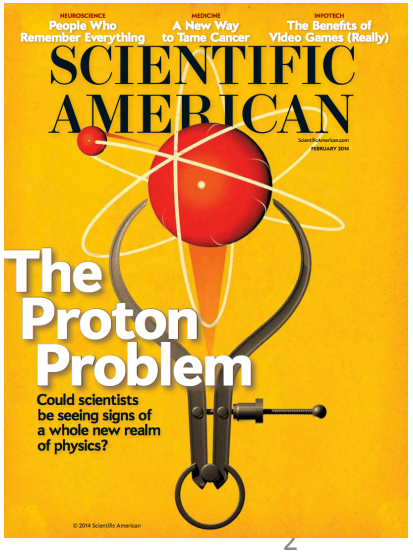
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  - An important physics input to the bound state QED calculations, affects muonic H Lamb shift $(2S_{1/2} - 2P_{1/2})$ by as much as 2%

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

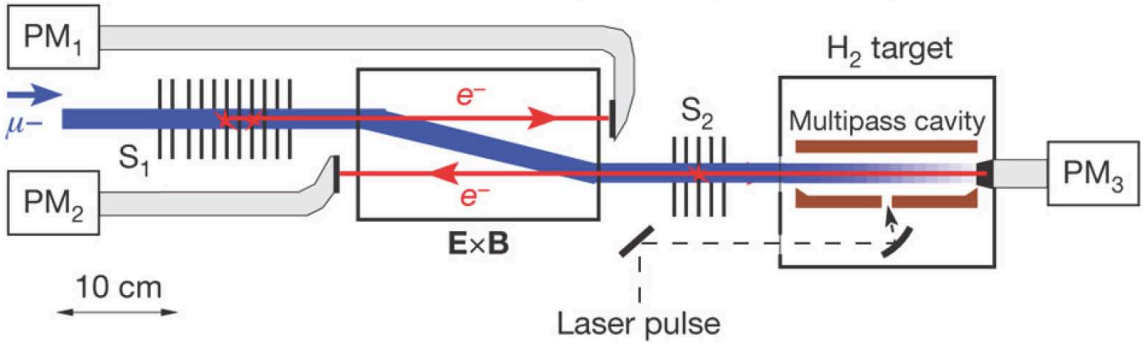
$$\sqrt{< r^2 >} = \sqrt{-6 \frac{dG(q^2)}{dq^2}|_{q^2=0}}$$

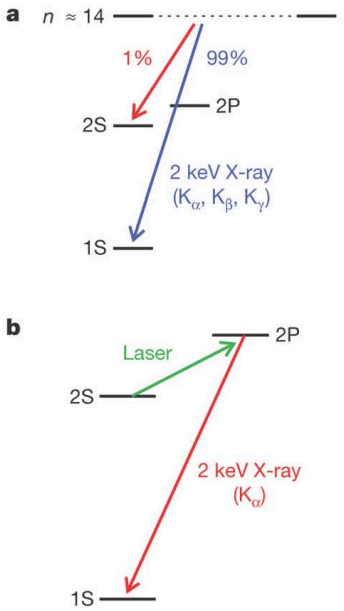
- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

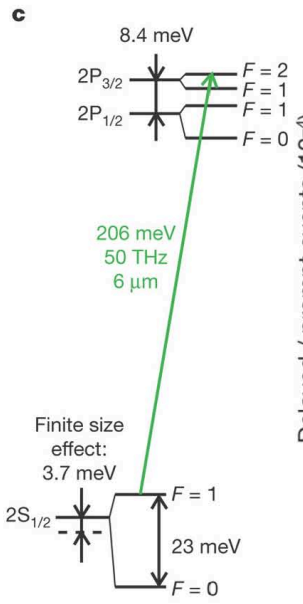


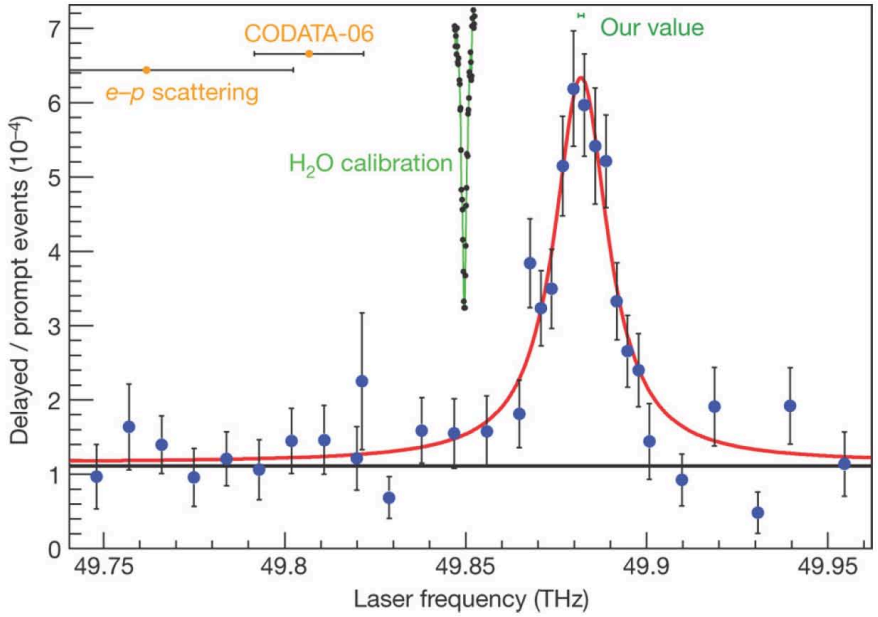
Muonic hydrogen Lamb shift at PSI (2010, 2013)

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









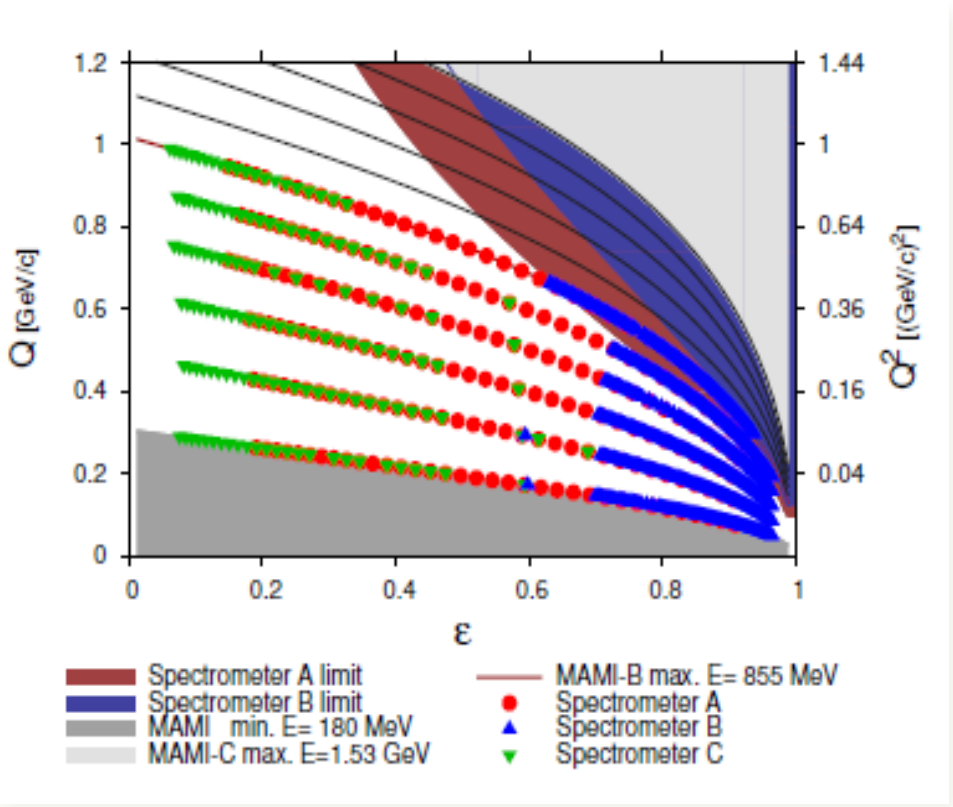
2010: new value is r_p = 0.84184(67) fm

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

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



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

- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

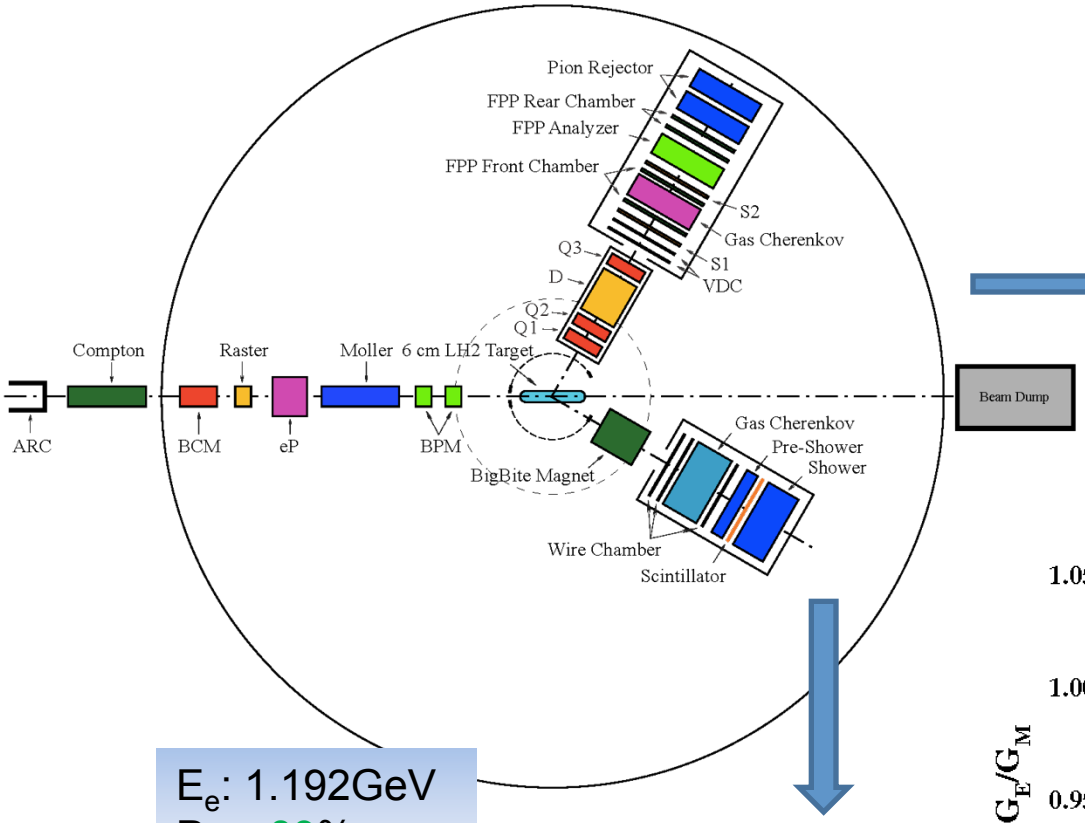
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

Jlab Recoil Proton Polarization Experiment



LHRS

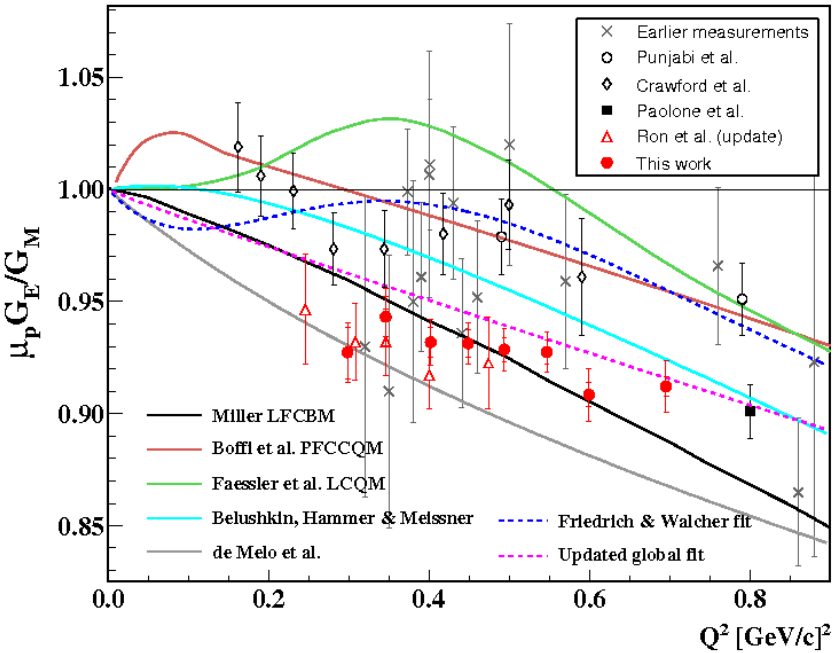
- Δp/p0: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

BigBite

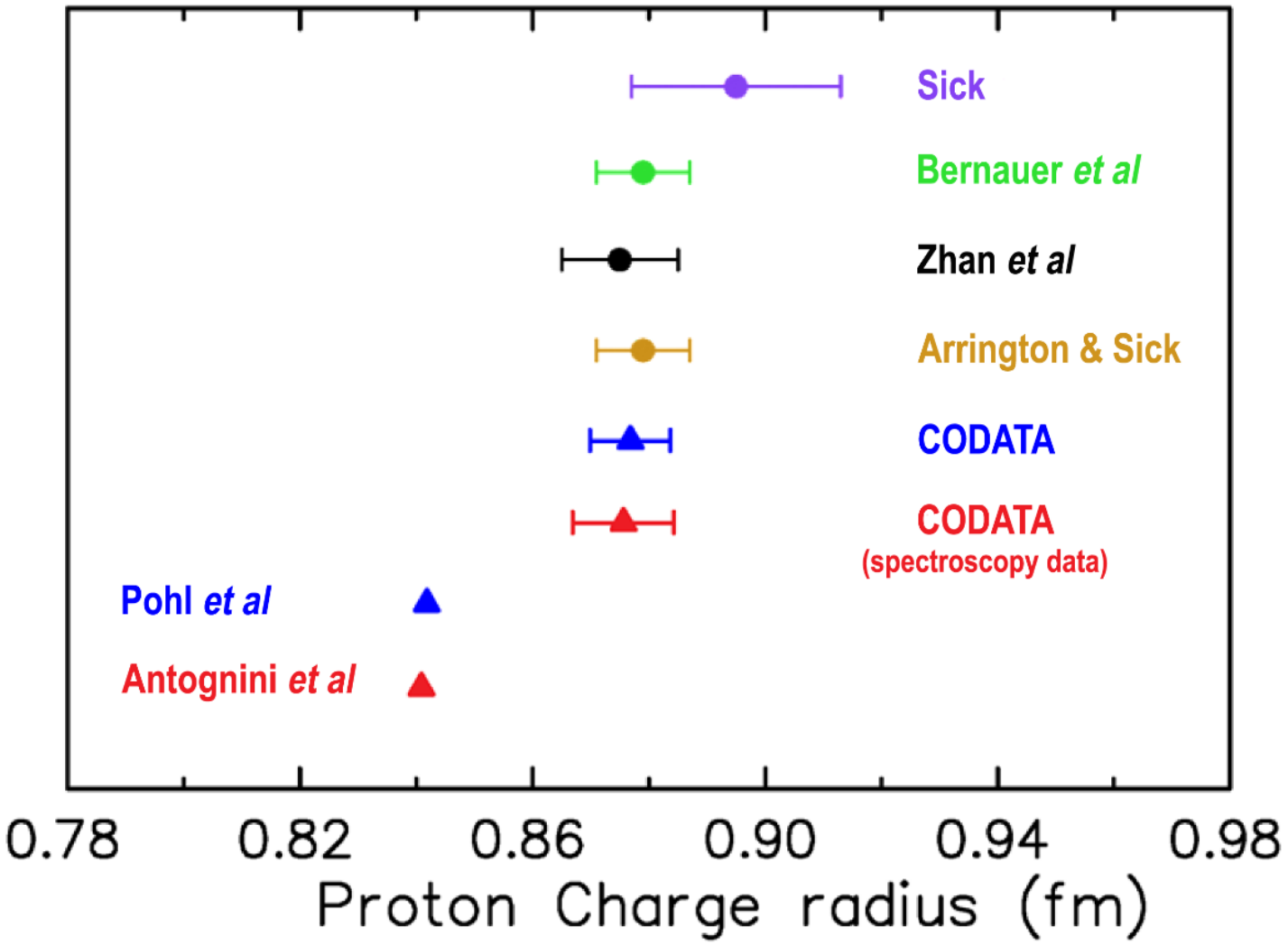
- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - ΔΩ: 96msr
- PS + Scint. + SH

New pol. Target data soon from Hall A



X. Zhan et al. Phys. Lett. B 705 (2011) 59-64
C. Crawford et al. PRL98, 052301 (2007)

The proton radius puzzle



Arrington and Sick (2015) from reanalysis of ep data

Revisits of QED Calculations….

An additional 0.31 meV to match CODATA value

Contribution	Value [meV]	Uncertainty [10^{-4} meV]
Uehling	205.0282	
Källen–Sabry	1.5081	
VP iteration	0.151	
Mixed $\mu - e$ VP	0.00007	
Hadronic VP [21, 23]	0.011	20
Sixth order VP [24]	0.00761	
Whichmann–Kroll	−0.00103	
Virtual Delbrück	0.00135	
Light–by–light	–	10
Muon self–energy and muonic VP (2^{nd} order)	−0.66788	
Fourth order electron loops	−0.00169	
VP insertion in self energy [17]	−0.0055	10
Proton self–energy [18]	−0.0099	
Recoil [17, 43]	0.0575	
Recoil correction to VP (one–photon)	−0.0041	
Recoil (two–photon) [19]	−0.04497	
Recoil higher order [19]	−0.0096	
Recoil finite size [32]	0.013	10
Finite size of order $(Z\alpha)^4$ [32] $-5.1975(1)\, r_{\text{p}}^2$	−3.979	(620)
Finite size of order $(Z\alpha)^5$ $0.0347(30)\, r_{\text{p}}^3$	0.0232	(20)
Finite size of order $(Z\alpha)^6$	−0.0005	
Correction to VP $-0.0109\, r_{\text{p}}^2$	−0.0083	
Additional size for VP [19] $-0.0164\, r_{\text{p}}^2$	−0.0128	
Proton polarizability [18, 33]	0.015	40
Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$	8.352	10
$2P_{3/2}^{\text{F}=2}$ hyperfine splitting	1.2724	
$2S_{1/2}^{\text{F}=1}$ hyperfine splitting [42], $(-22.8148/4)$	−5.7037	20

Evaluation by Jentschura, Annals Phys. 326, 500 (2011)
Recent summary by A. Antognini et al., arXiv:1208.2637

Birse and McGovern, arXiv:1206.3030
0.015(4) meV (proton polarizability)

J.M. Alarcon, et al. 1312.1219
0.008 meV

G.A. Miller, arXiv:1209.4667

New experiments at HIGS and Mainz on proton polarizabilities

Talk by S. Karshenboim

Visits and revisits of e-p scattering data

- Re-analysis of existing proton form factor data
  - D. W. Higinbotham, arXiv:1510.01293: two parameter dipole form fit describes the data at both low Q^2 and high Q^2 well, and the result is consistent with PSI value
  - K. Griffioen, C. Carson, S. Maddox, arXiv:1509.06676: re-analysis of Mainz data, focusing on the low Q^2 part with a polynomial form fit.
  - M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, simple fits (one-parameter model, dipole model, linear model) for low Q2 data, and spline extension to high Q2 data, these fits can all describe data well, but the extracted radius varies from 0.84 ~ 0.89 fm. So current data is not able to resolve the puzzle.
  - J. Arrington, arXiv:1506.00873: re-analysis of world data, found the previous scattering results might underestimate the uncertainty.

All these studies emphasize even more the importance of low Q^2 e-p scattering data

New Physics or what? - Incomplete list

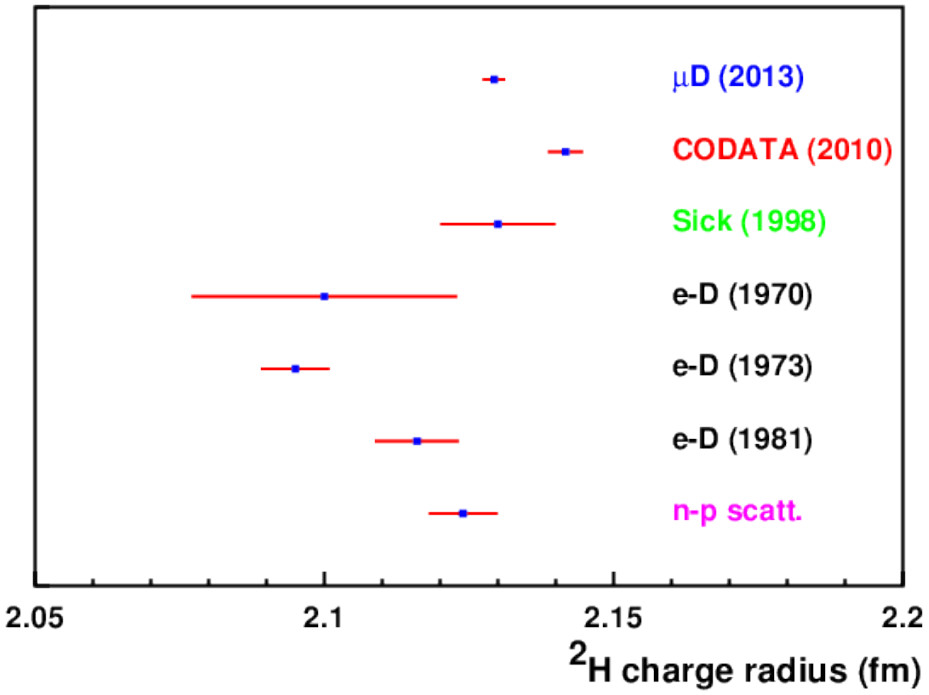
- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, 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,…..
- J.A. Arrington, G. Lee, J. R. Arrington, R. J. Hill discuss systematics in extraction from ep data, no resolution on discrepancy
- Donnelly, Milner and Hasell discuss interpretation of ep data,……

Discrepancy explained by some but others disagree

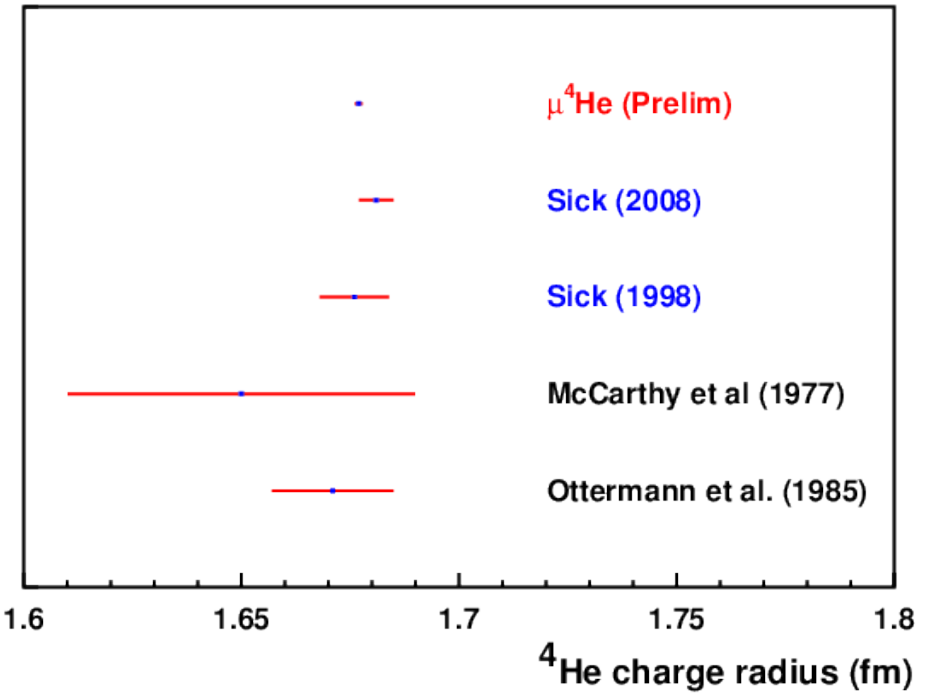
- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift**

Charge Radius of Other Light Nuclei

Deuterium

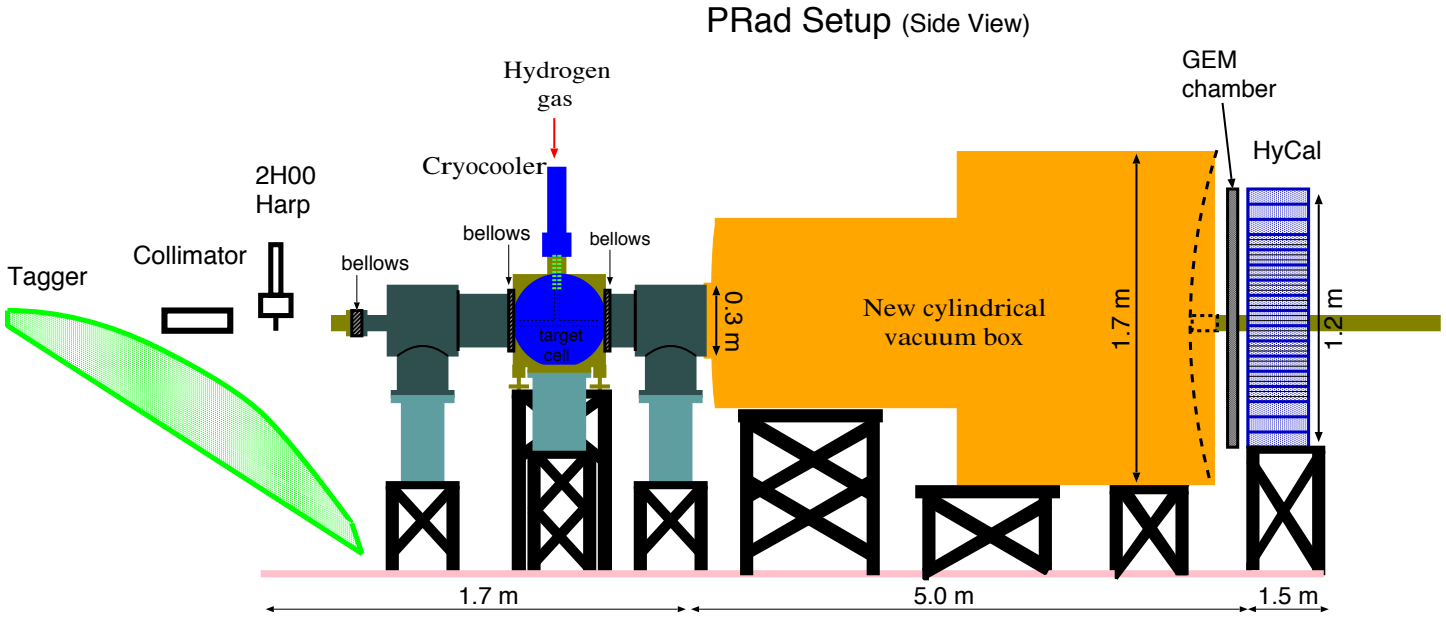


Helium



Electron scattering consistent with μ-spectroscopy

PRad Experimental Setup in Hall B at JLab



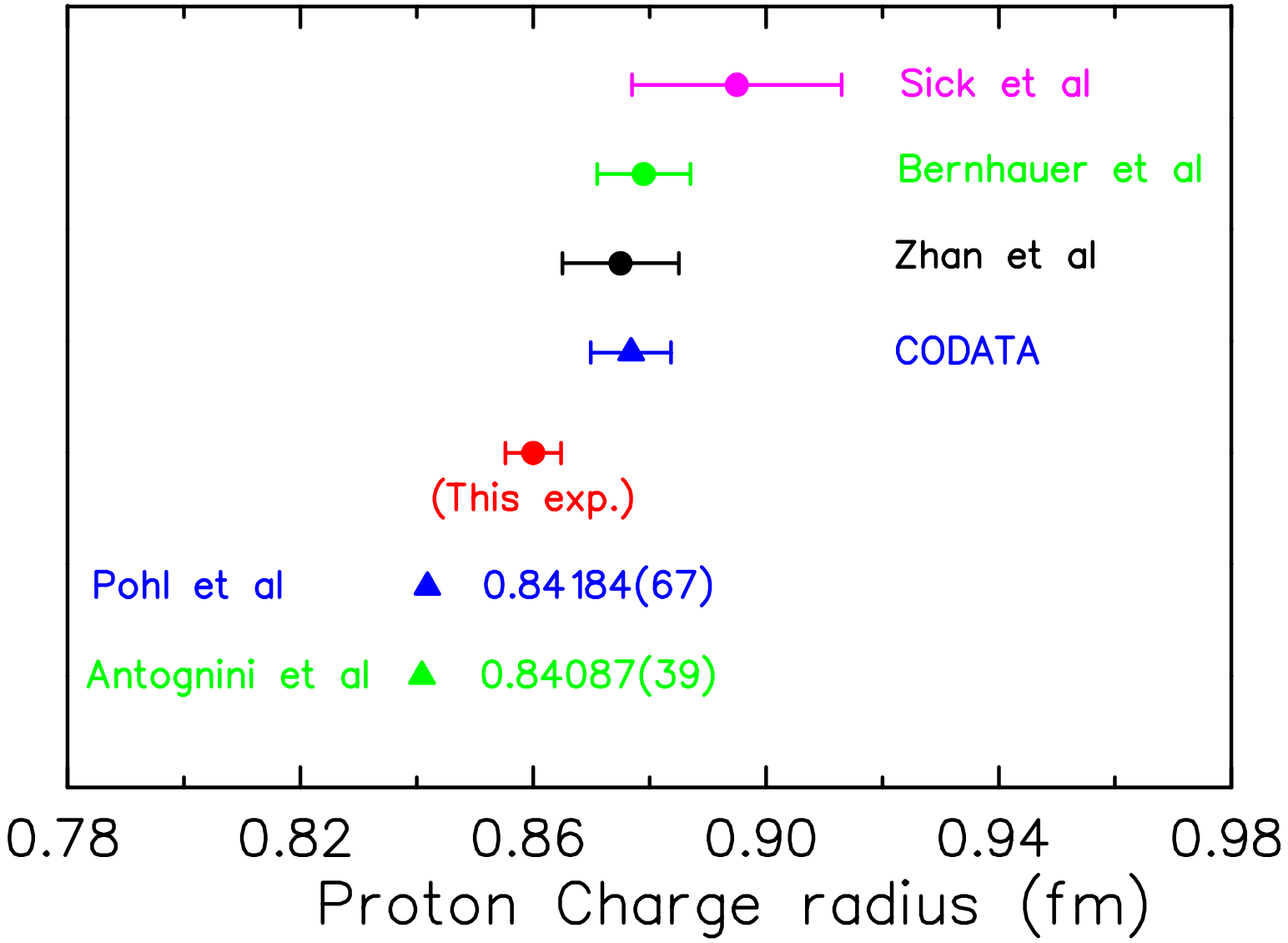
- **High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2×10^{-4} – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

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

Future sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

PRad Projected Result



Summary

- Proton charge radius puzzle prompts intensive theoretical and experimental efforts
- After new data from muonic systems, many papers, and many analyses, proton charge radius puzzle remains
- All point to the importance of low Q^2 data
- PRad is timely in elucidating the proton charge radius puzzle
- And we are ready!!!!

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