

# *The PRad Experiment – Physics Overview*

*The PRad Experiment Readiness Review*  
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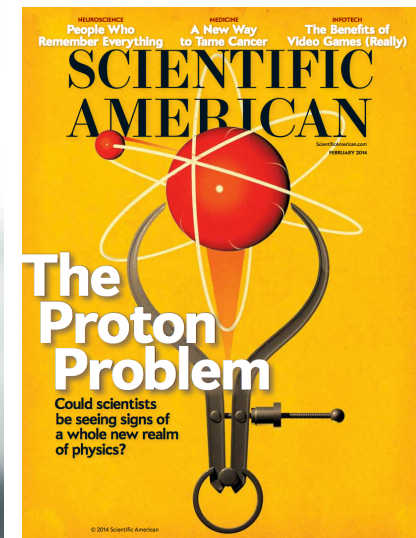


# *Proton Charge Radius*

- 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)

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

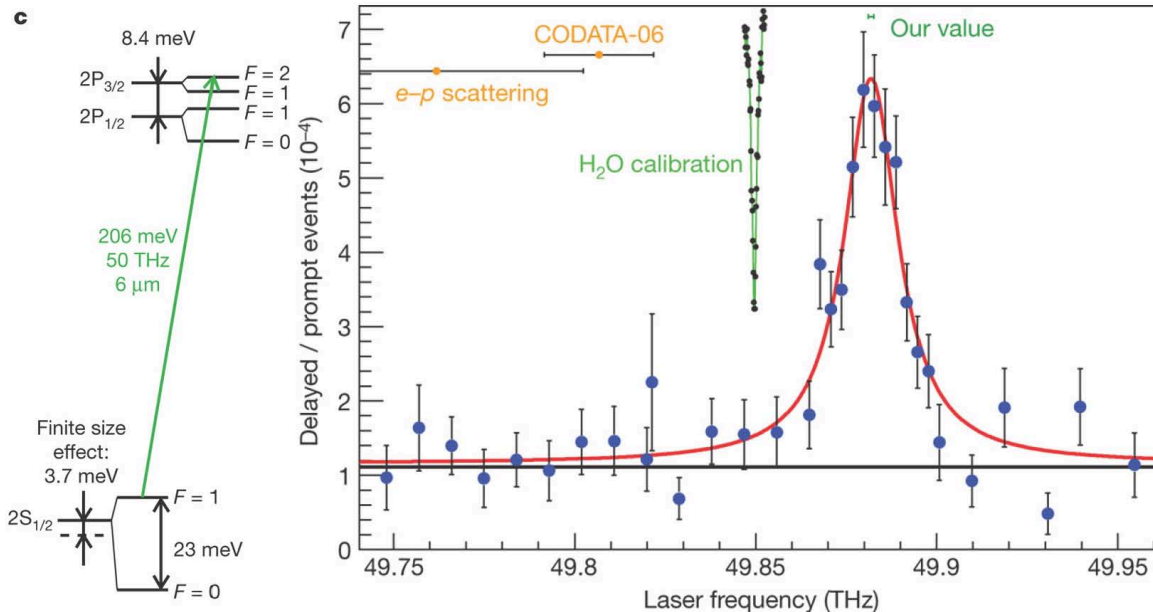
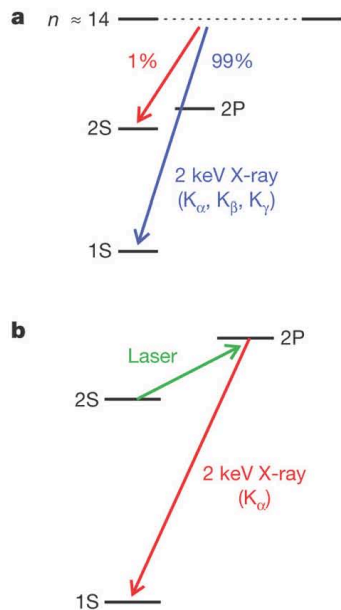
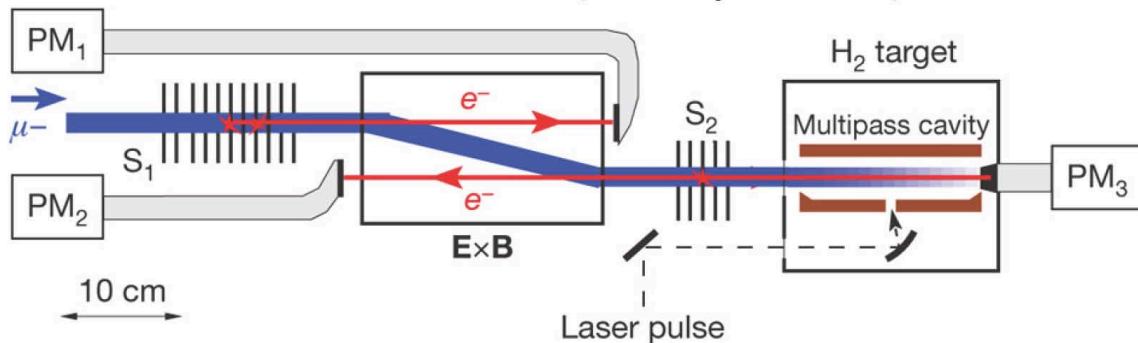
- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift



# 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:

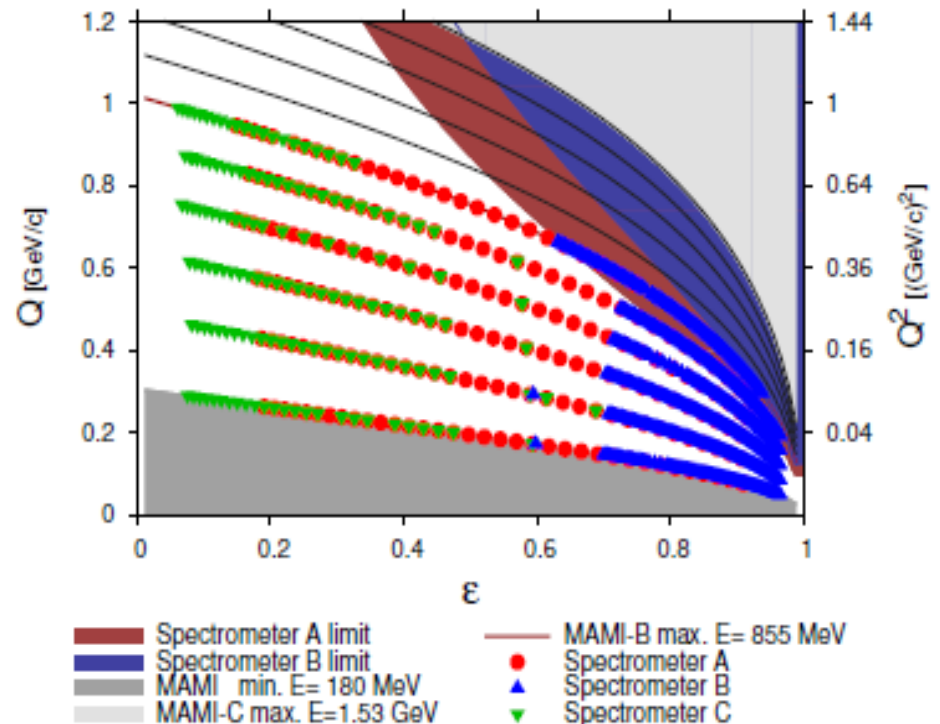


- Large amount of overlapping data sets
- Cross section measurement
- Statistical error  $\leq 0.2\%$
- Luminosity monitoring with spectrometer

■  $Q^2 = 0.004 - 1.0 \text{ (GeV/c)}^2$   
 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

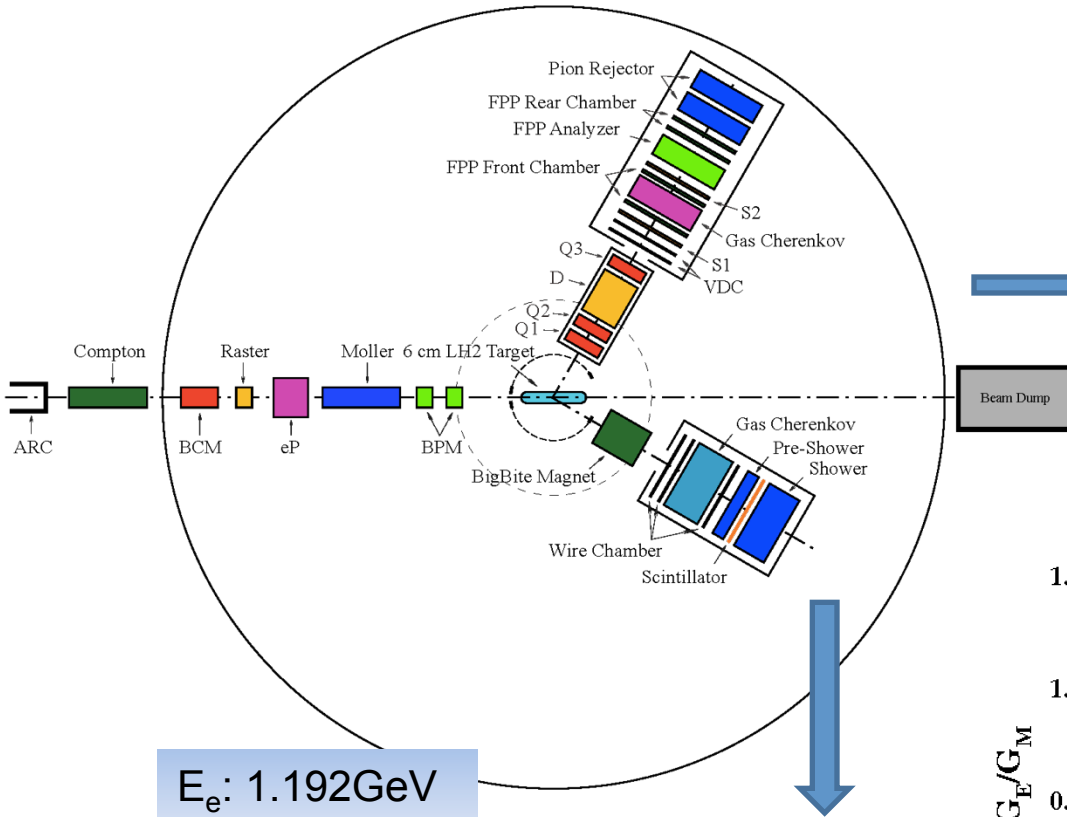


5-7 $\sigma$  higher than muonic hydrogen result !

# 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+FPP
- $P_p: 0.55 \sim 0.93$  GeV/c

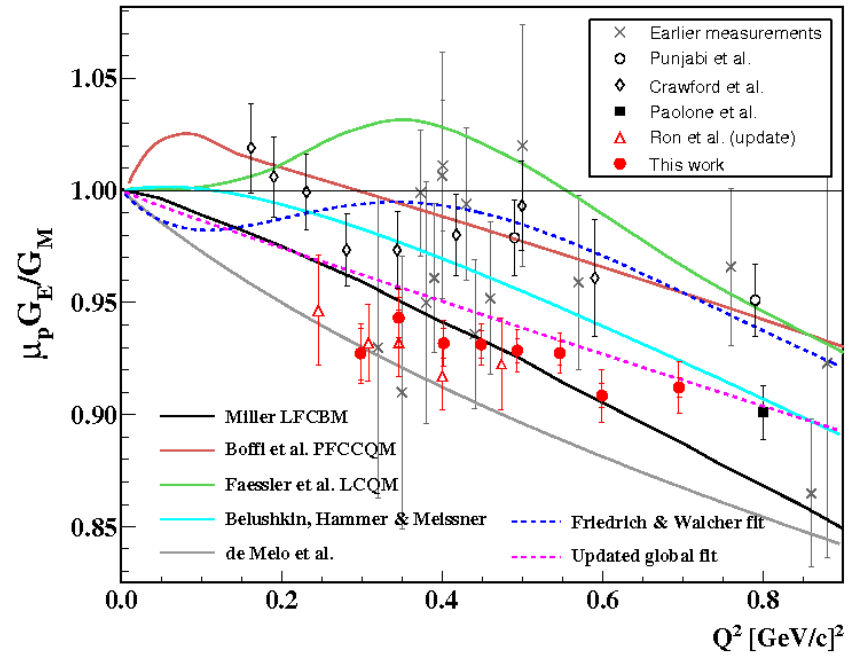


$E_e: 1.192$ GeV  
 $P_b: \sim 83\%$

## BigBite

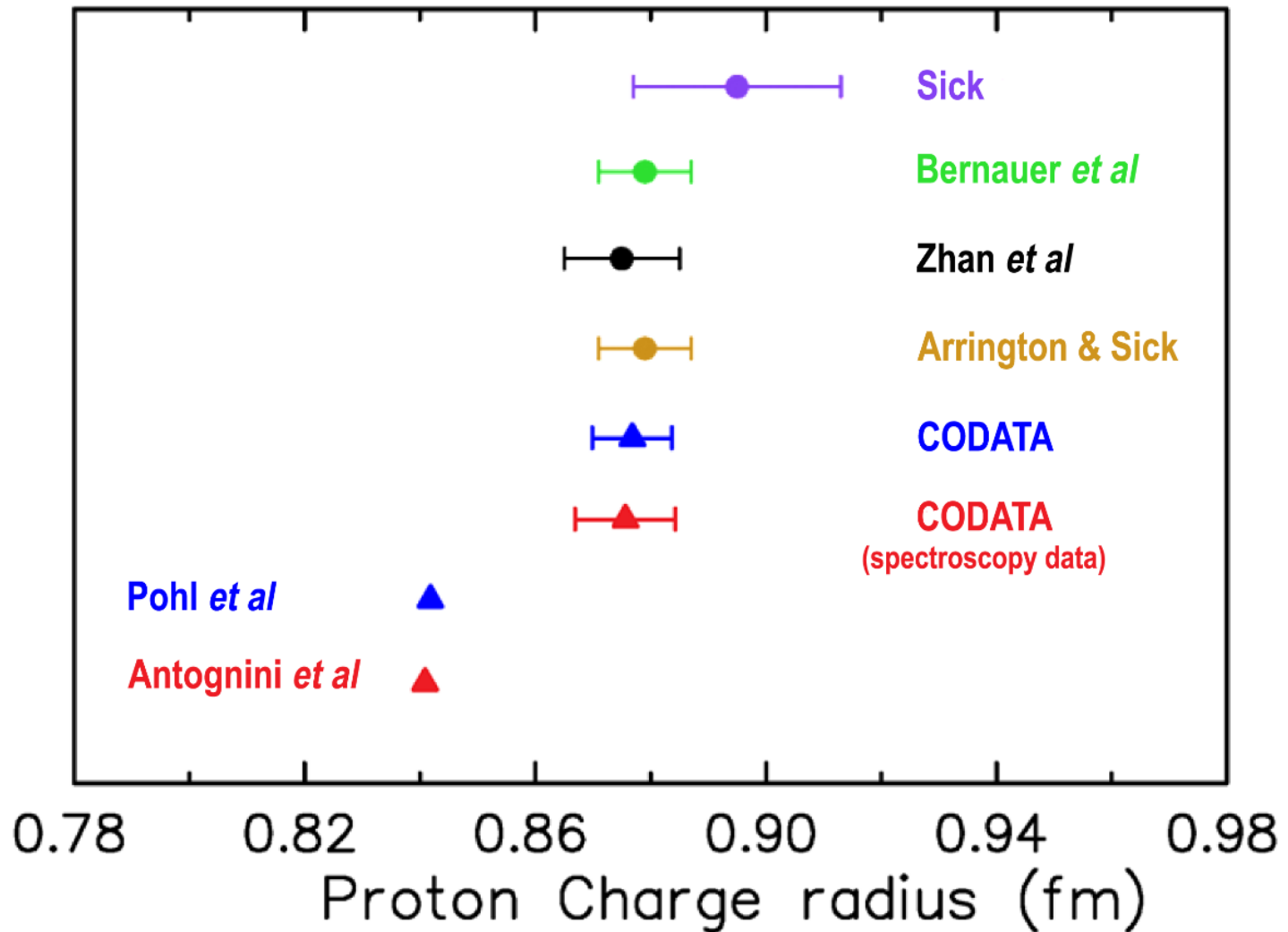
- Non-focusing Dipole
- Big acceptance.
  - $\Delta p: 200-900$ MeV
  - $\Delta\Omega: 96$ msr
- PS + Scint. + SH

**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 <sup>nd</sup> 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]	$-5.1975(1) r_p^2$	(620)
Finite size of order $(Z\alpha)^5$	$0.0347(30) r_p^3$	(20)
Finite size of order $(Z\alpha)^6$	-0.0005	
Correction to VP	$-0.0109 r_p^2$	
Additional size for VP [19]	$-0.0164 r_p^3$	
Proton polarizability [18, 33]	0.015	40
Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$	8.352	10
$2P_{3/2}^{F=2}$ hyperfine splitting	1.2724	
$2S_{1/2}^{F=1}$ 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

# *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  $Q^2$  data, and spline extension to high  $Q^2$  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.
  - **Distler, Walcher, and Bernauer, arXiv1511.00479**

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



# *New Physics or what? - Incomplete list*

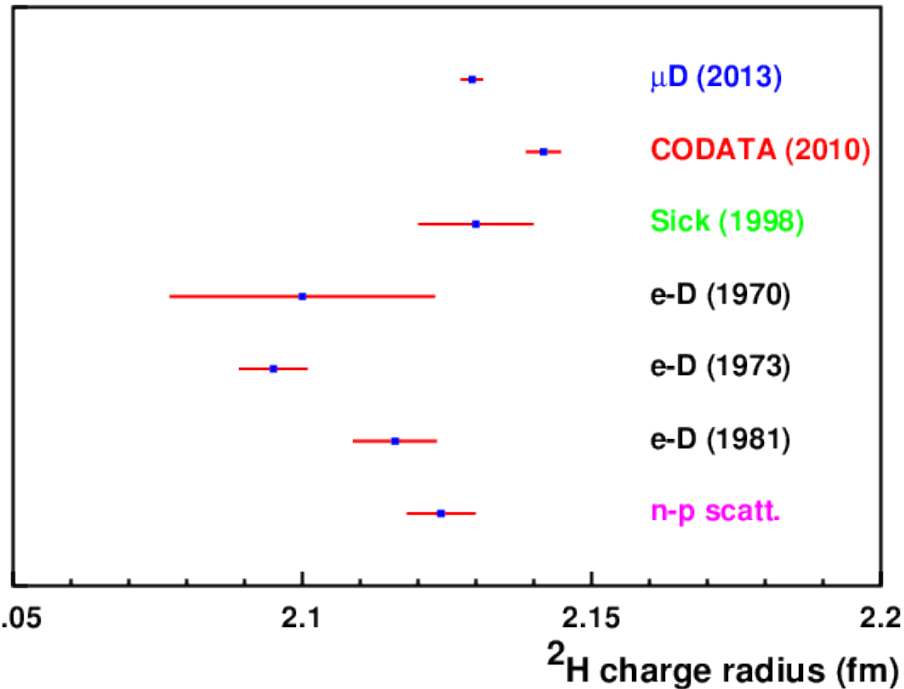
- **New physics: new particles**, Barger et al., Carlson and Rislw; Liu and Miller,....New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;.....
- **Contributions to the muonic H Lamb shift**: Carlson and Vanderhaeghen,; 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**

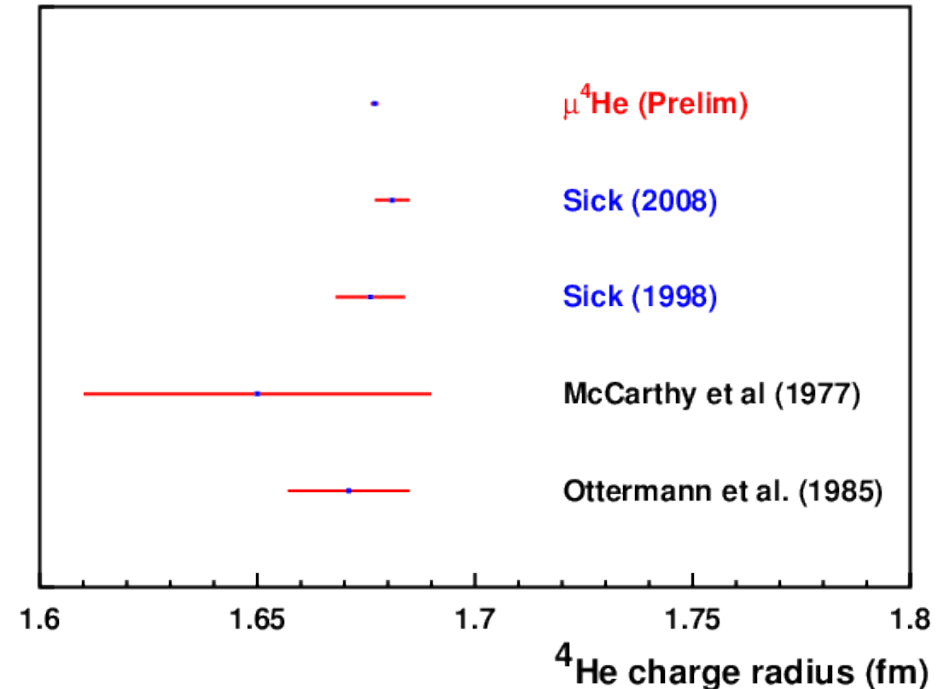
- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift**

# Charge Radius of Other Light Nuclei

## Deuterium

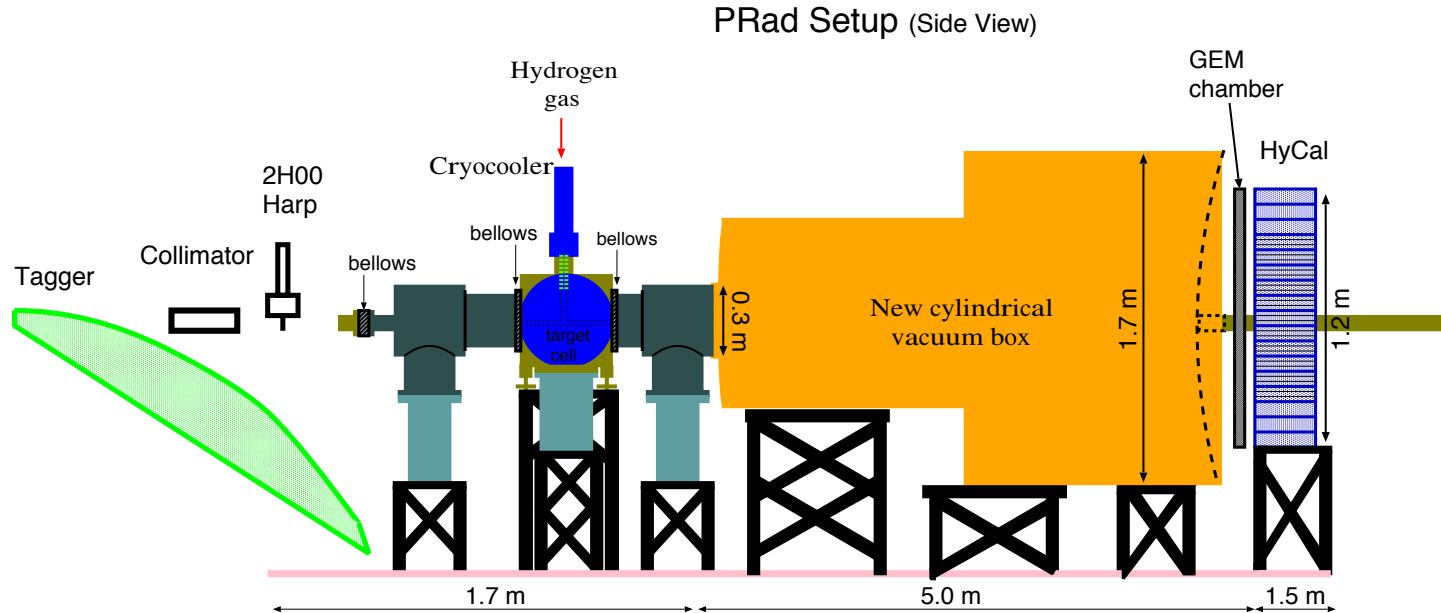


## Helium



Electron scattering consistent with  $\mu$ -spectroscopy

# PRad Experimental Setup 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<sup>2</sup> range of **2x10<sup>-4</sup> – 0.14 GeV<sup>2</sup>**
- XY – veto counters replaced by GEM detector
- Vacuum box

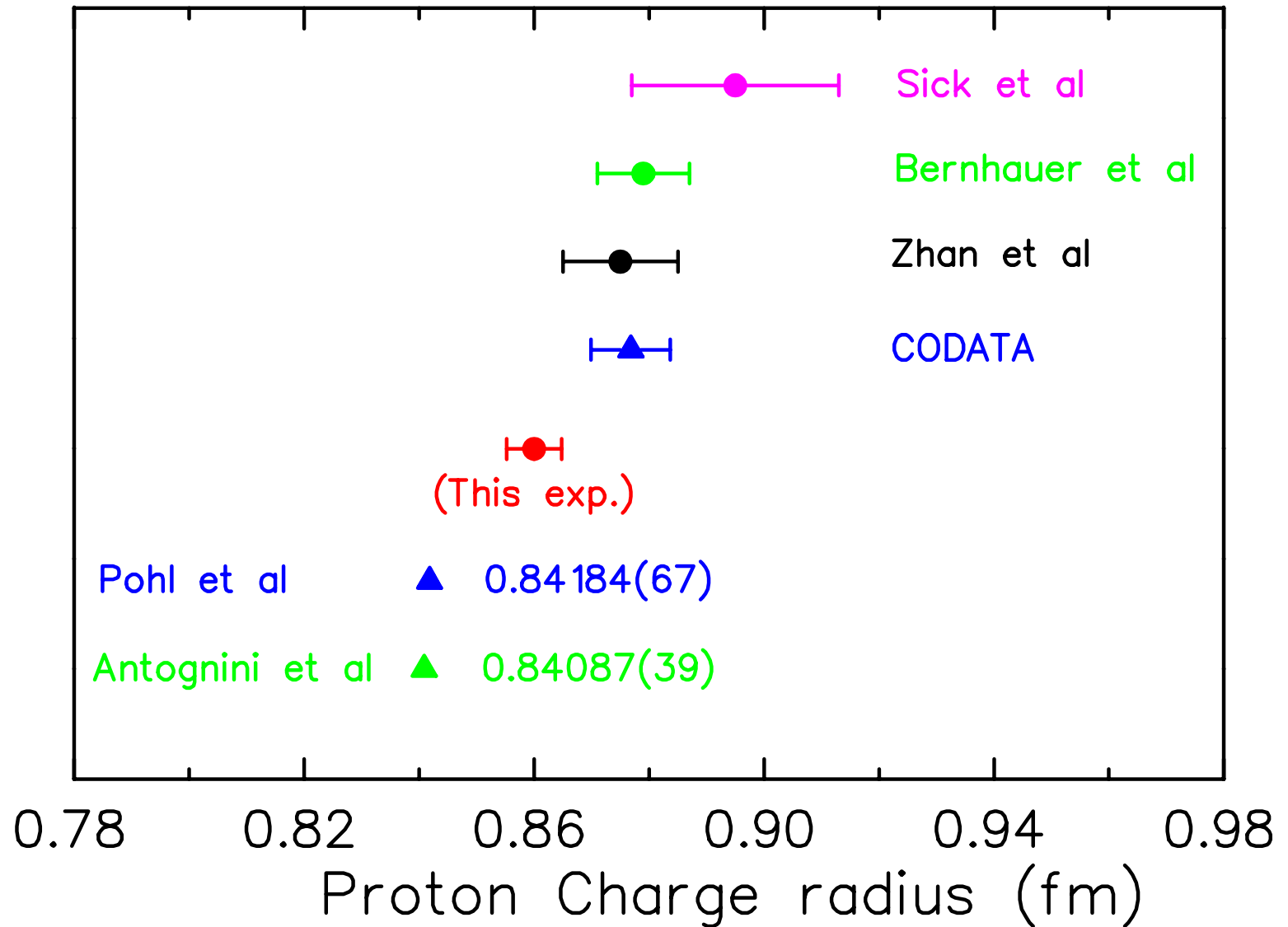
Spokespersons: A. Gasparian,  
D. Dutta, H. Gao, M. Khandaker

Future sub 1% measurements:

- (1) ep elastic scattering at Jlab (PRad)
- (2)  $\mu$ p elastic scattering at PSI - 16 U.S. institutions! (MUSE)
- (3) ISR experiments at Mainz

Ongoing H spectroscopy experiments<sup>11</sup>

# *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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