Proton Charge Radius and the PRad Experiment

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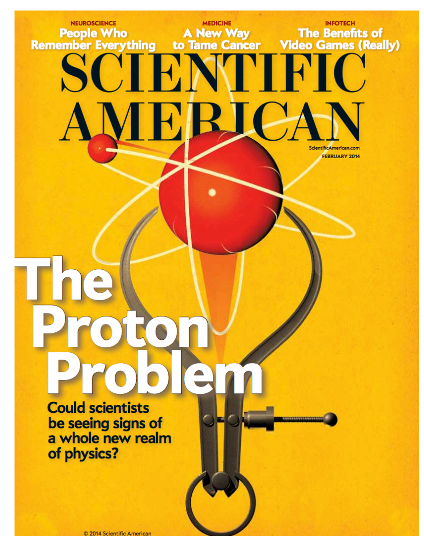
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Progress made on lattice
  - 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

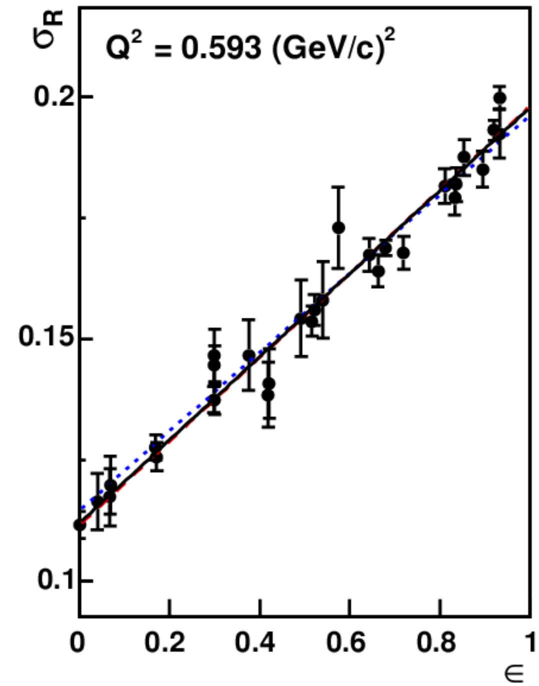


Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section

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



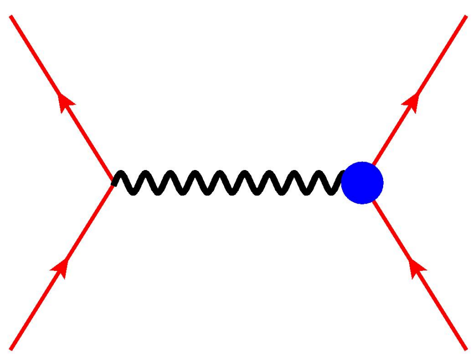
$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - Low Q^2 by G_E
    - High Q^2 by G_M

$$\tau = \frac{Q^2}{4M^2}$$

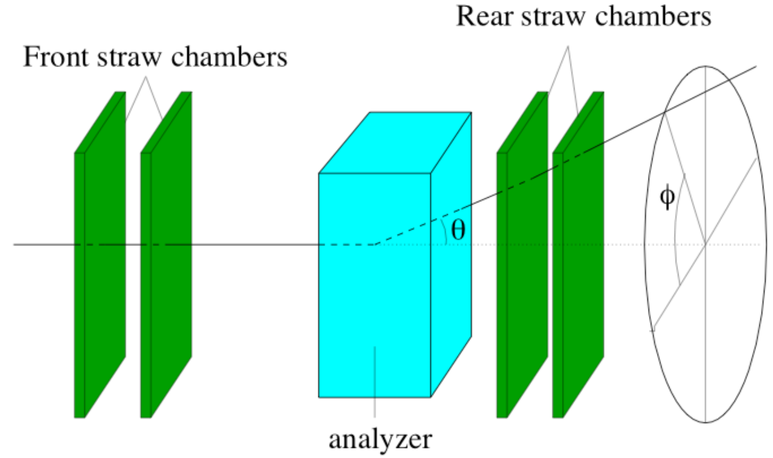
$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$

G_E or G_M



Electron-proton elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

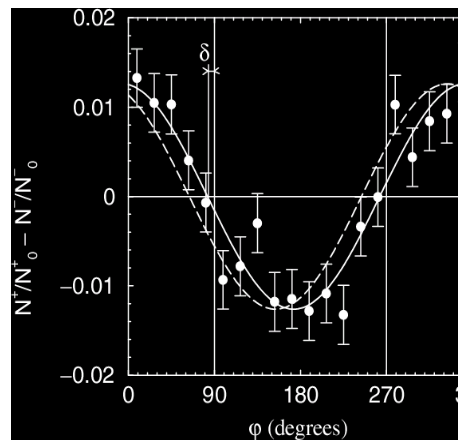
Polarization Transfer → $\frac{G_E^p}{G_M^p}$

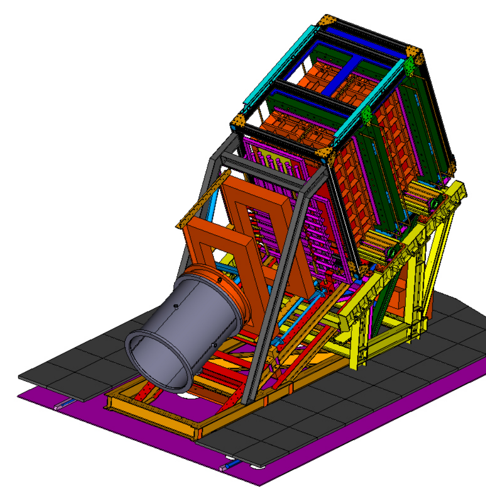


- Recoil proton polarization

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

- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio





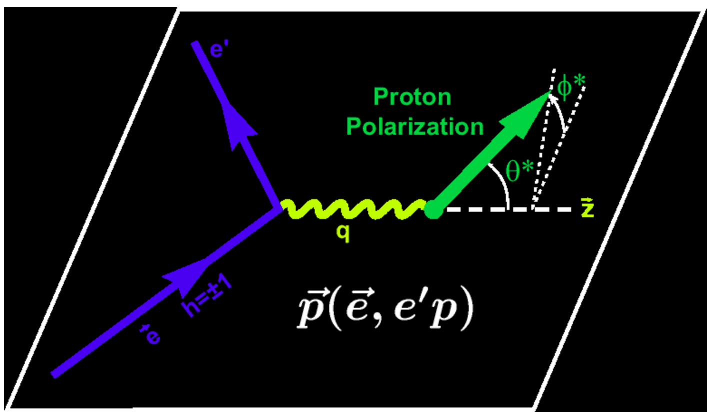
Focal-plane polarimeter

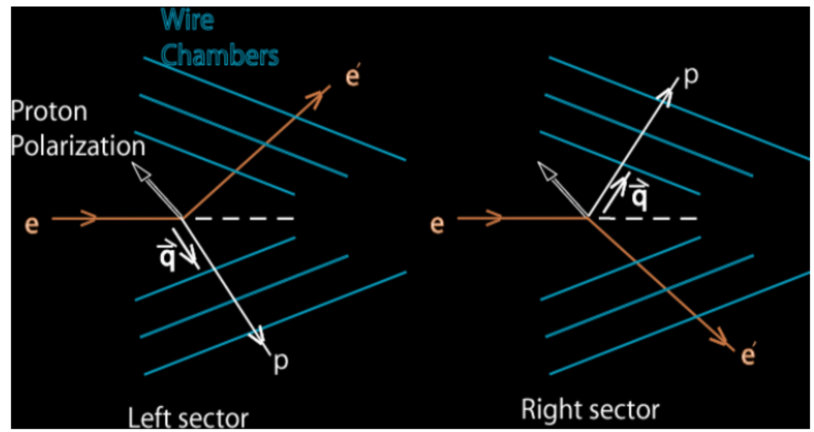
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

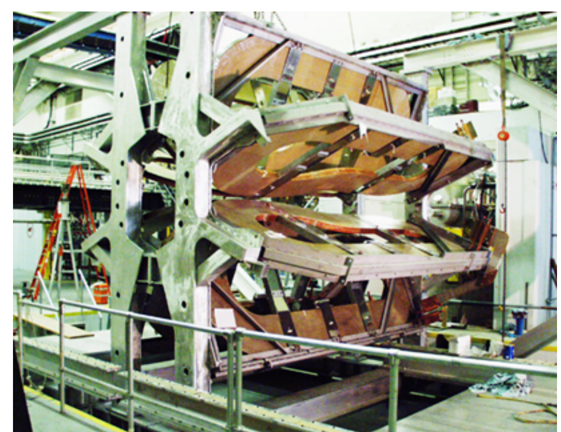
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)}\, v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





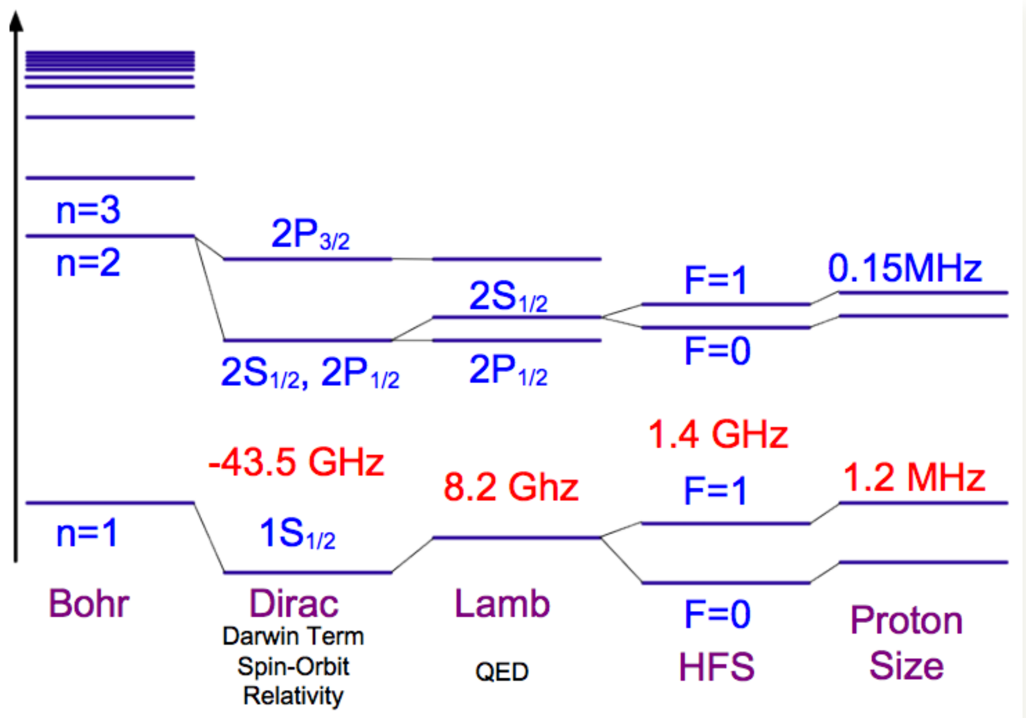
- Super-ratio

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



BLAST pioneered the technique, later also used in Jlab Hall A experiment

Hydrogen Spectroscopy



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.

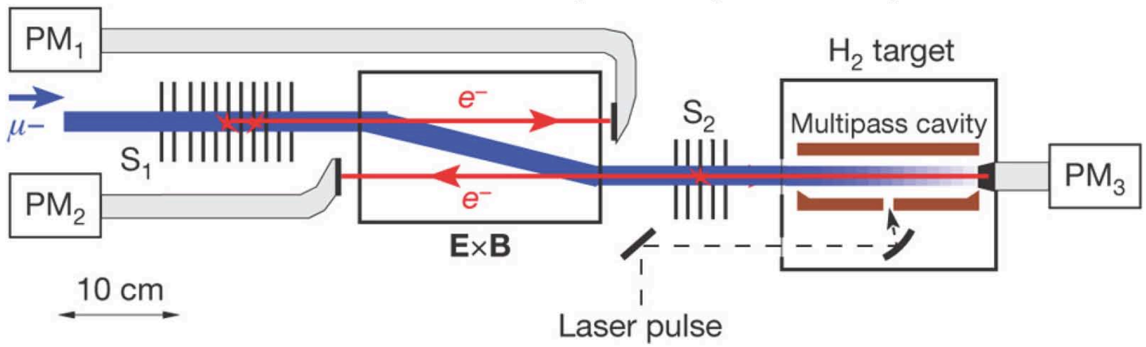
Yields R_∞ (the most precisely known constant)

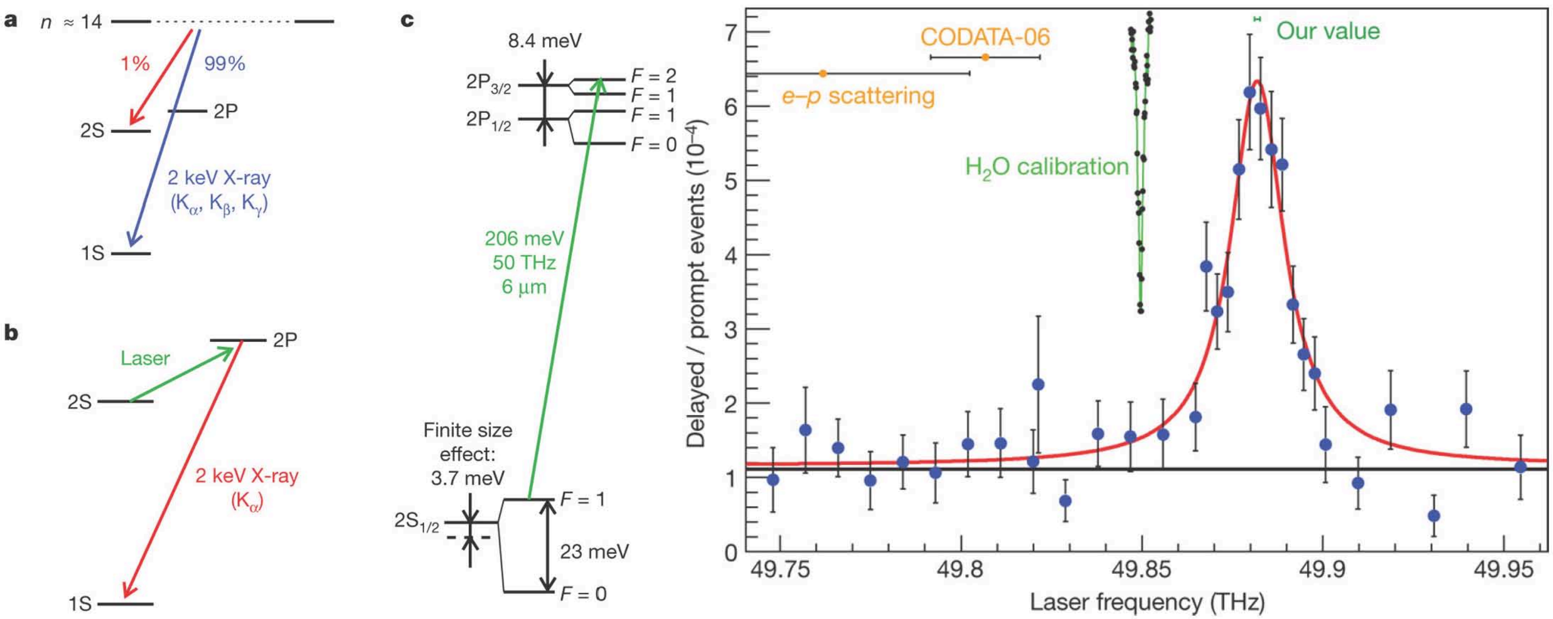
Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius

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

Muonic hydrogen Lamb shift at PSI (2010, 2013)

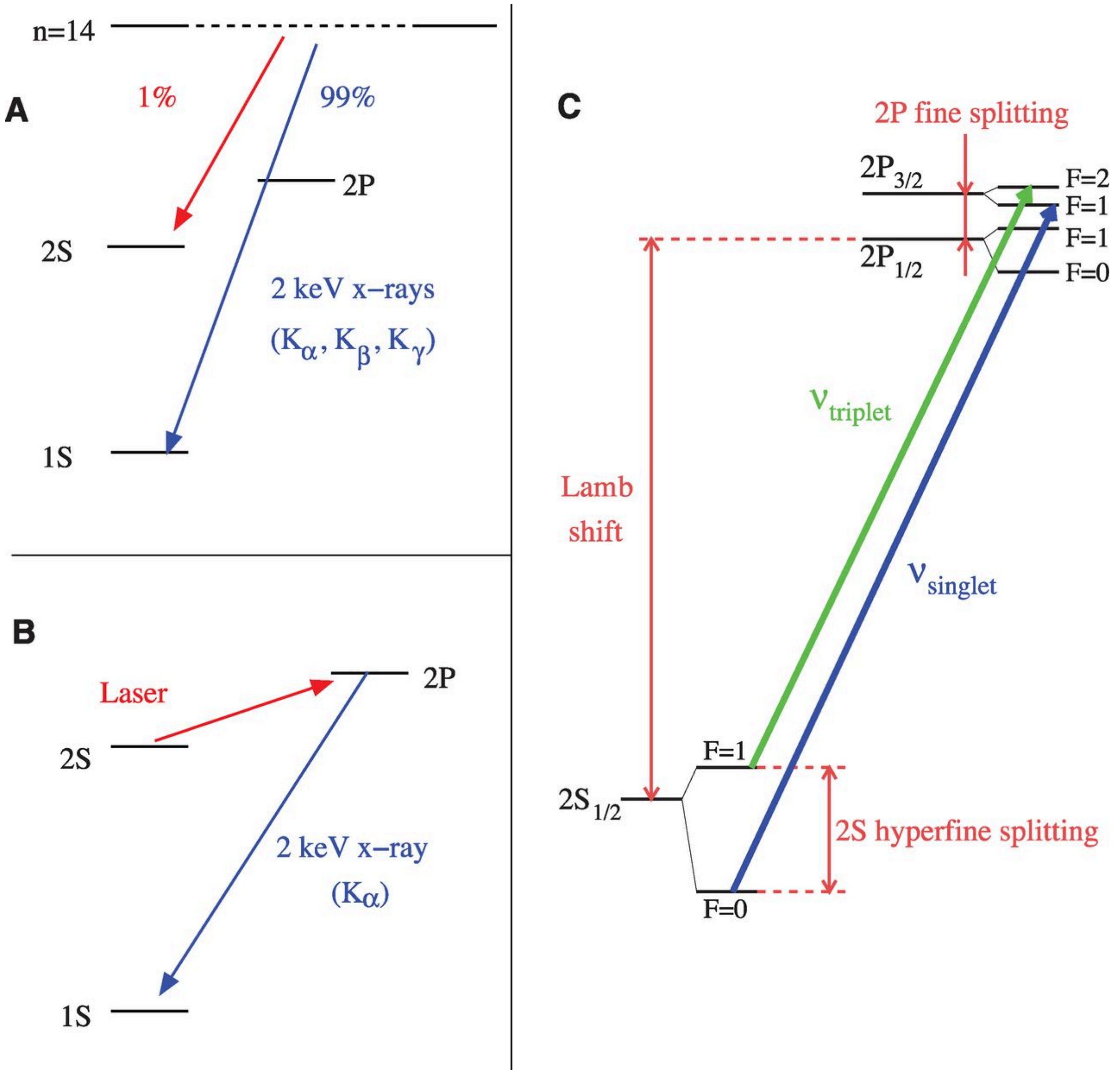
Nature **466**, 213-216 (8 July 2010)





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

New PSI results reported in Science 2013

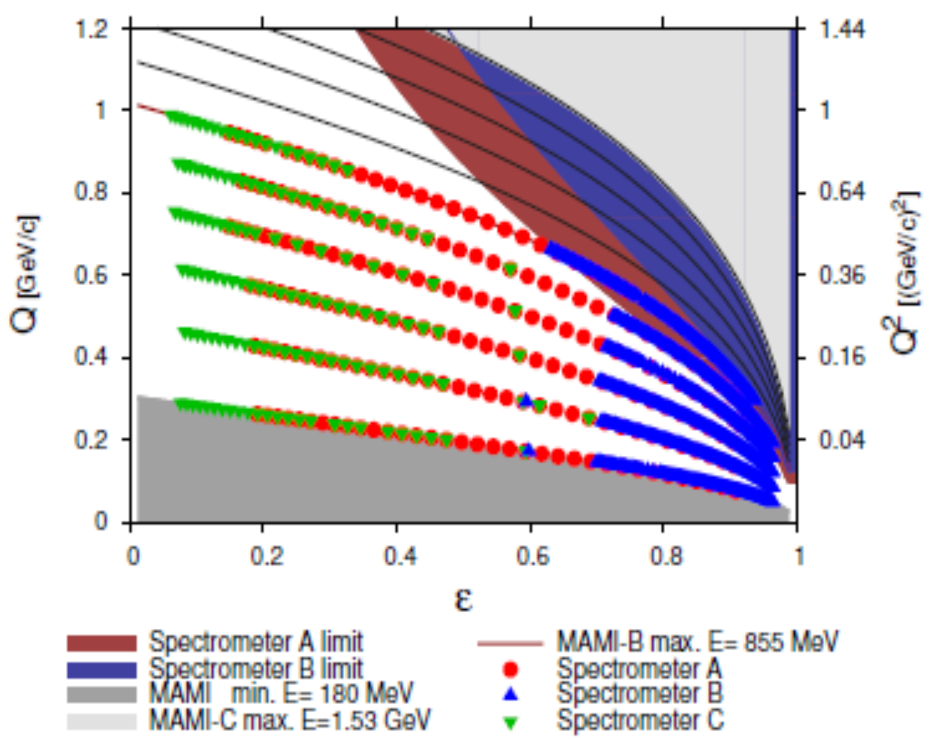


2013: r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



– Large amount of overlapping data sets

– Statistical error ≤ 0.2%

– Luminosity monitoring with spectrometer

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

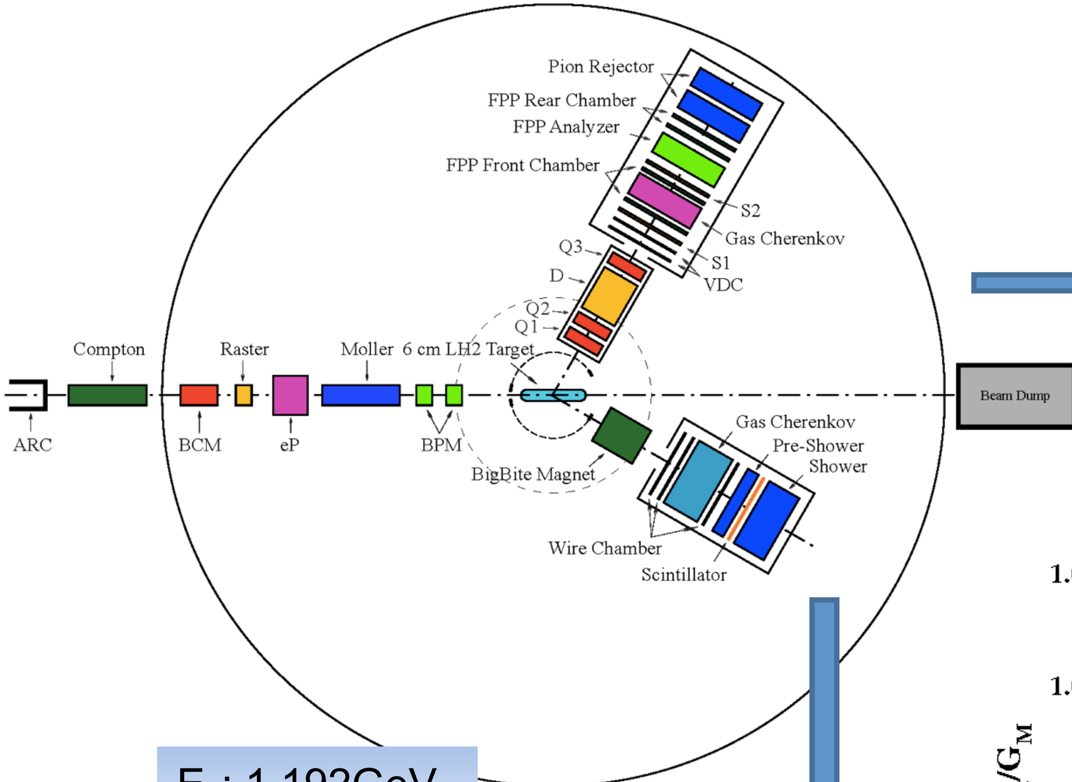
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

JLab Recoil Proton Polarization Experimental



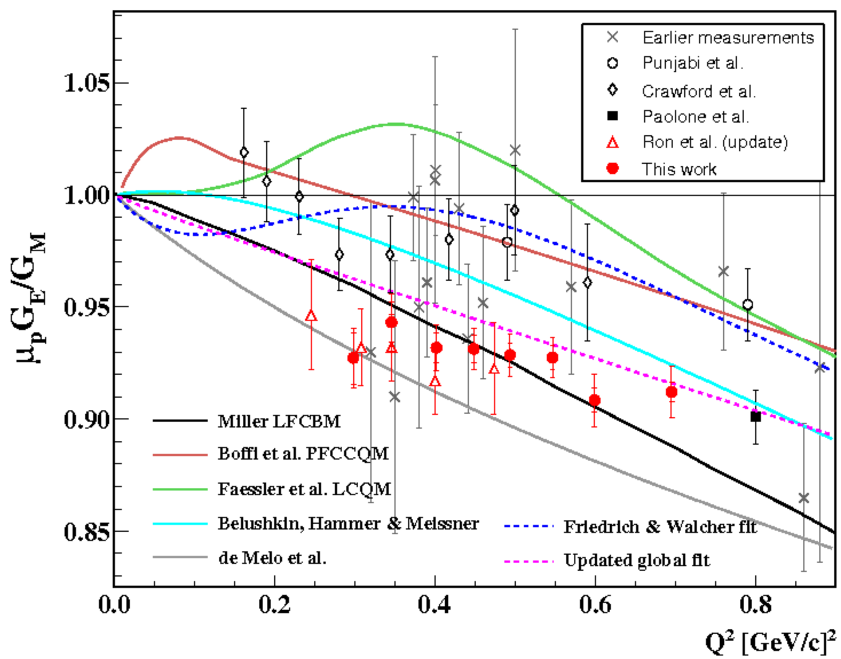
LHRS

- 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%

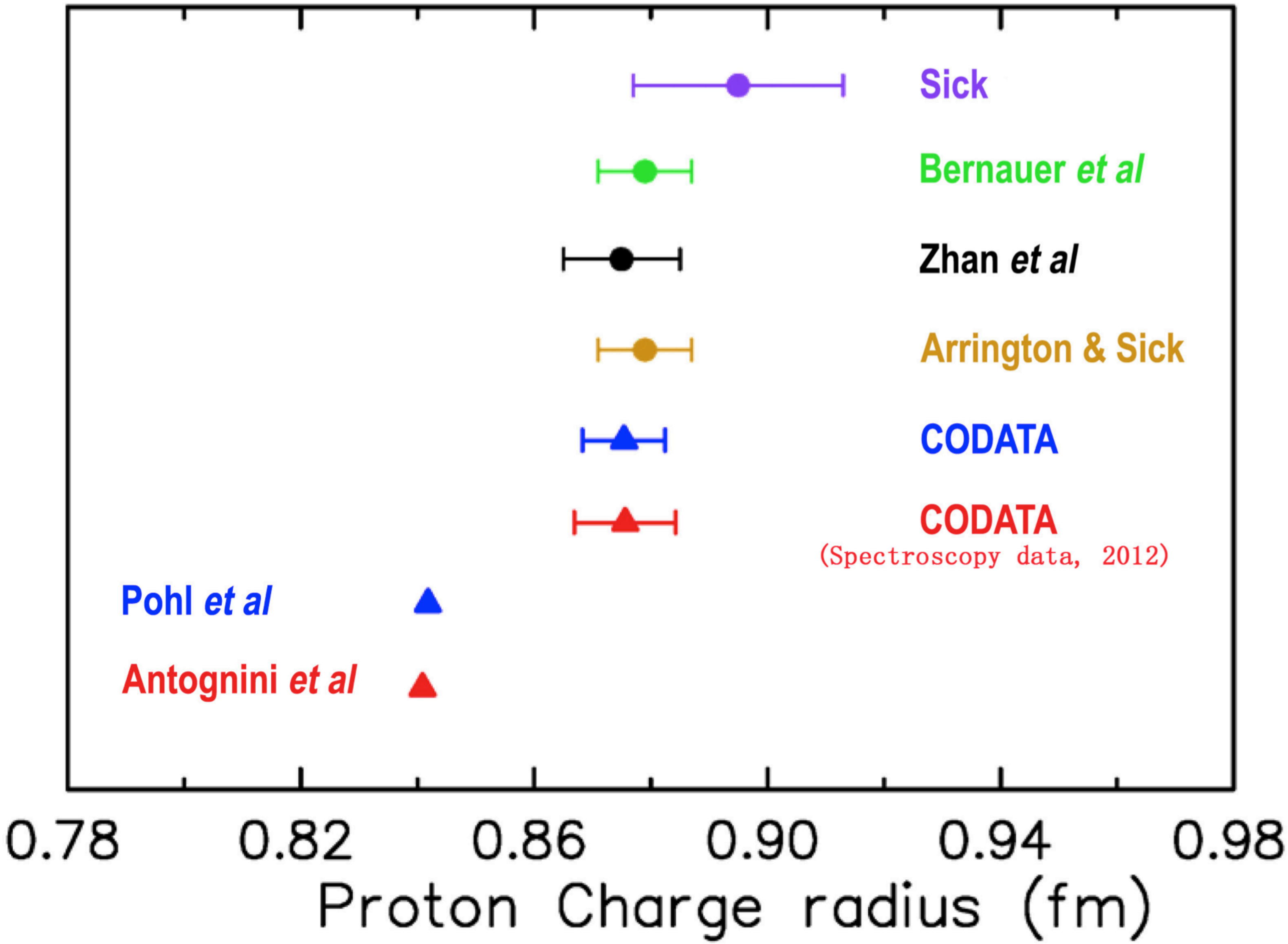
BigBite

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



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

The situation on the Proton Charge Radius several years ago



Revisits 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]	$-5.1975(1)\, r_p^2$	−3.979	(620)
Finite size of order $(Z\alpha)^5$	$0.0347(30)\, r_p^3$	0.0232	(20)
Finite size of order $(Z\alpha)^6$		−0.0005	
Correction to VP	$-0.0109\, r_p^2$	−0.0083	
Additional size for VP [19]	$-0.0164\, r_p^2$	−0.0128	
Proton polarizability [18,33]		0.015	40
Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$		8.352	10
$2P_{3/2}^{F=2}$ 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)
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

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

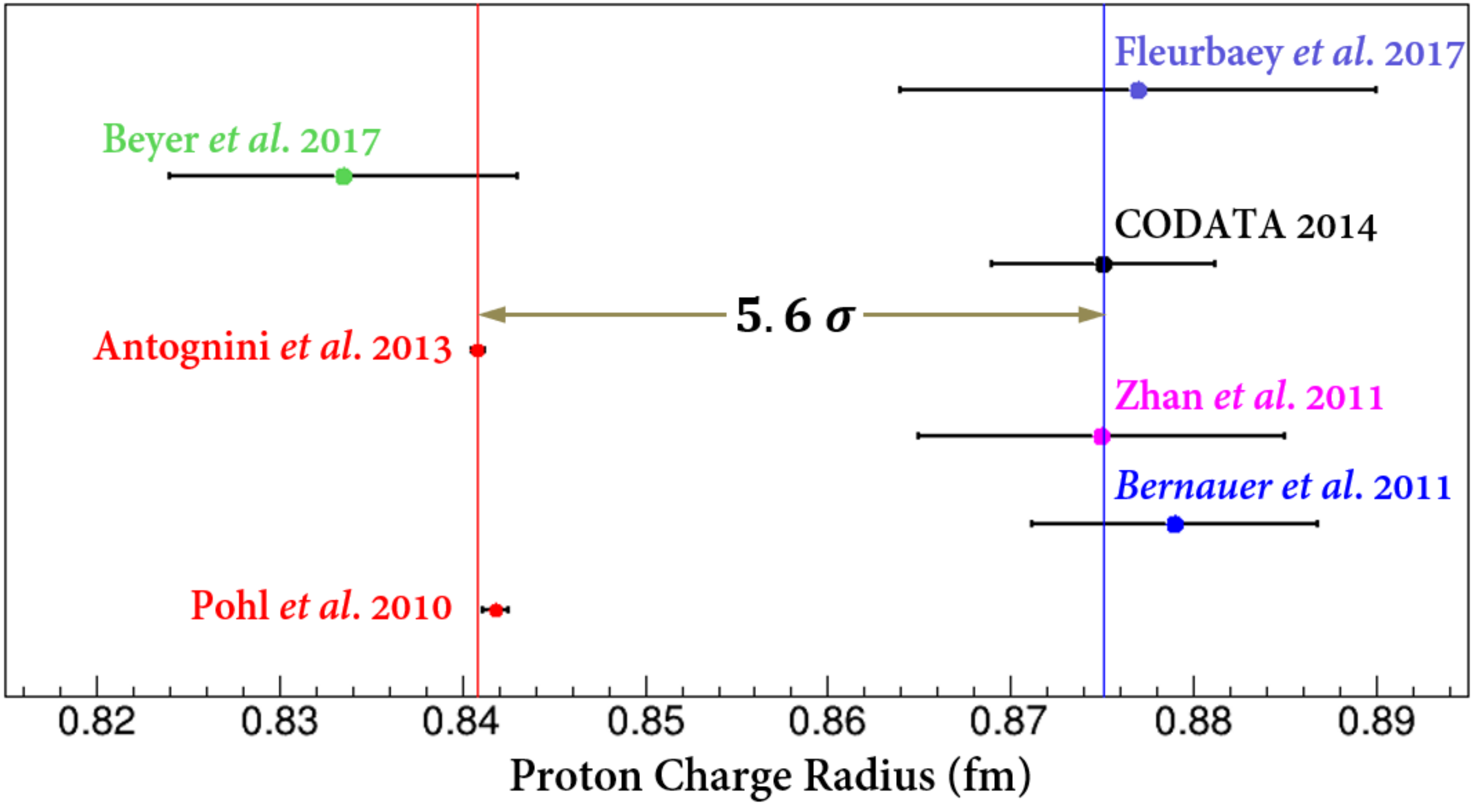
- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H_2 Lamb shift (spectroscopy), and others**

Revisits of e-p scattering data (selected)

- **Analysis of existing and upcoming proton form factor data**
  - X. Yan, D. Higinbotham *et al*., arXiv:1803.01629: robust method of radius extraction discussed for the kinematic range of PRad experiment
  - T. Hayward, K. Griffioen, arXiv:1804.09150: re-examination of several low-Q2 data sets from *ep* scattering measurements – result consistent with PSI value but with large uncertainty
  - M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, several simple fits for low Q^2 data, spline extension to high Q2 data – fits describe data well with extracted radius varies from 0.84 ~ 0.89 fm.
  - 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

Proton Radius Puzzle



- CODATA recommended value
- Recent experimental results
  - Muonic hydrogen spectroscopy (Antognini, Pohl)
  - Ordinary hydrogen spectroscopy (Beyer, Fleurbaey)
  - Elastic ep-scattering measurements (Bernauer, Zhan)
  - **Latest from York University on hydrogen spectroscopy (this week!)**

Proton radius puzzle and deuteron also?

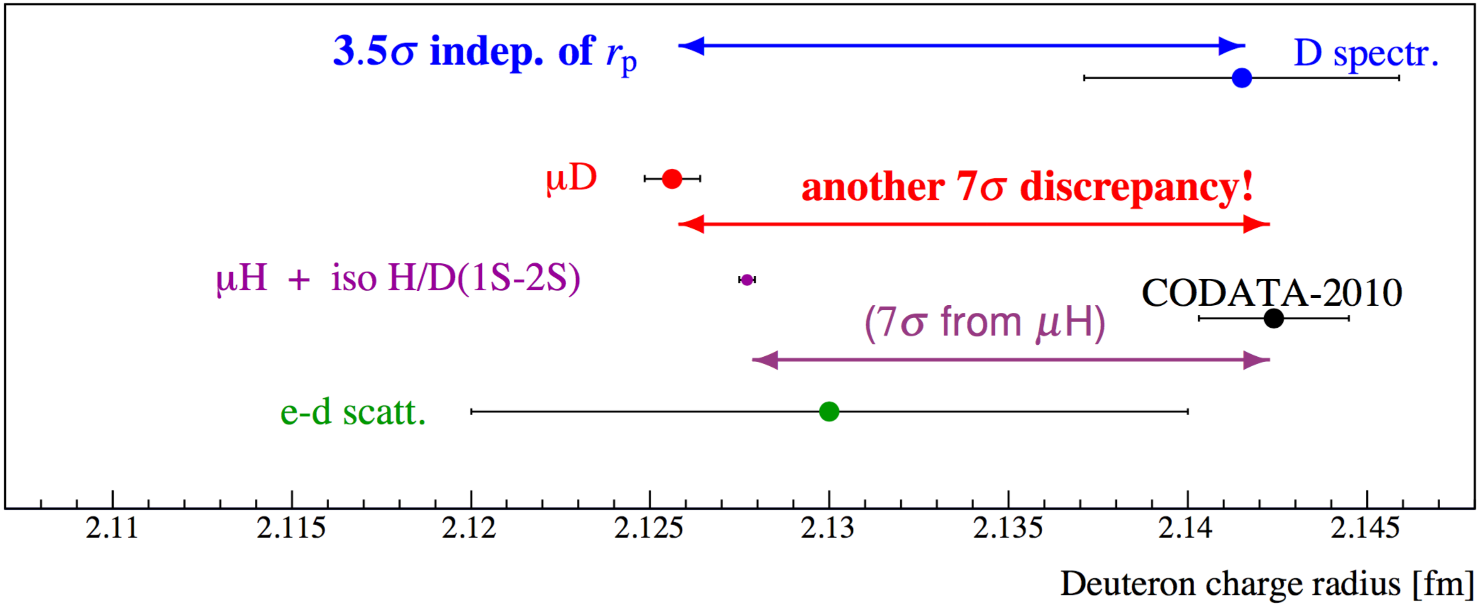
- Deuteron radius puzzle
  - Deuteron rms charge radius from muonic deuterium spectroscopy (R. Pohl et al., Science 353, 6300, 669, 2016)
  - 7.5σ smaller than the CODATA-2010 value, and 3.5σ smaller than the value from electronic deuterium spectroscopy (R. Pohl et al., Metrologia 54, L1, 2017)
  - Confirms proton radius puzzle

- Analysis of electron scattering data
  - Focusing on the low-q data yields a consistent result with CREMA's value
    K. Griffioen, C. Carlson, and S. Maddox. (Phy. Rev. C 93, 065207, 2016)
    D. Higinbotham, A.A. Kabir, V. Lin, D. Meekins, B. Norum, and B. Sawatzky. (Phys. Rev. C 93, 055207, 2016)
    M. Horbatsch and E.A. Hessels. (Phys. Rev. C 93, 015204, 2016)
  - However, I. Sick and D. Trautmann (Phys. Rev. C 95, 012501(R), 2017) claim that the above analyses led to a systematically smaller proton rms-radius because of the ignorance of the correlations from higher moments $< r^{2n} >$

Deuteron Charge Radius?

- *"Proton Charge Radius Puzzle"* is still unsolved after seven years.
- There is a newly developing *"Deuteron Charge Radius Puzzle"*

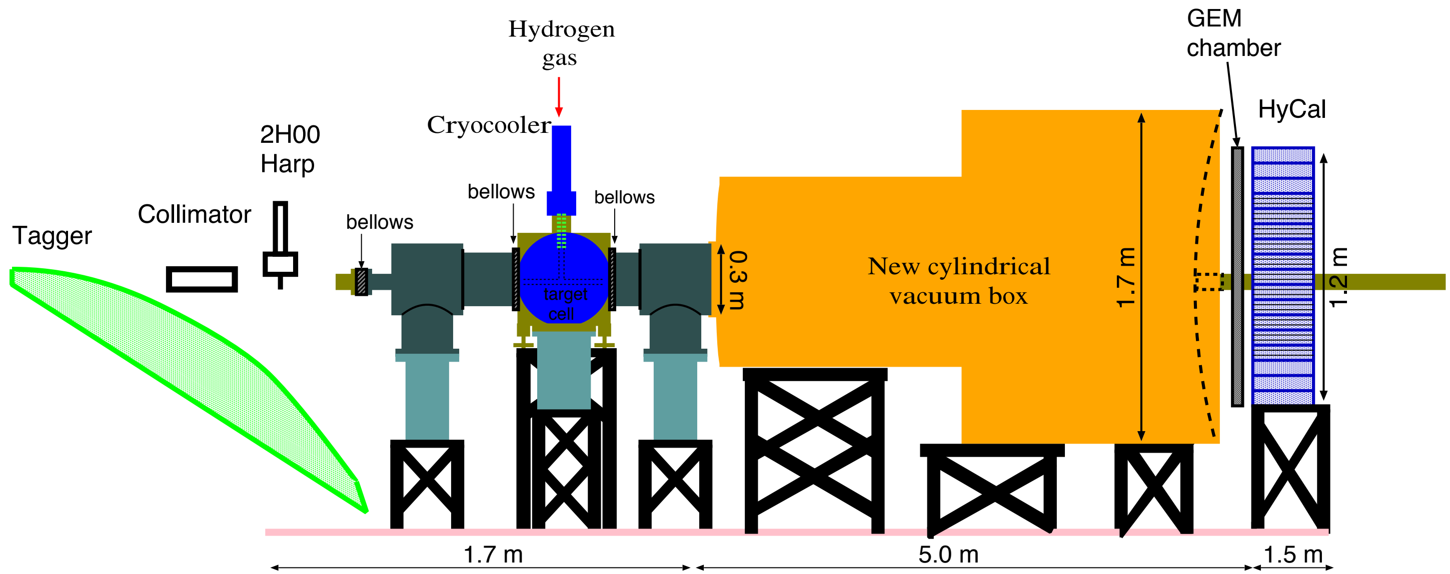
H/D isotope shift:	$r_d^2 - r_p^2$ = 3.82007(65) fm2
Muonic deuterium:	$r_d = 2.12562(13)_{exp}(77)_{theory}$ fm
Electronic deuterium:	r_d = 2.14150(450) fm



(R. Pohl, 2017)

- Deuteron rms charge radius from muonic deuterium spectroscopy (R. Pohl et al., Science, 353, 6300, 669 (2016))
- 7.5σ smaller than the CODATA-2010 value, 3.5σ smaller than the value from electronic deuterium spectroscopy (R. Pohl, et al, metrologia 54, L1, (2017))

PRad Experimental Setup in Hall B at JLab



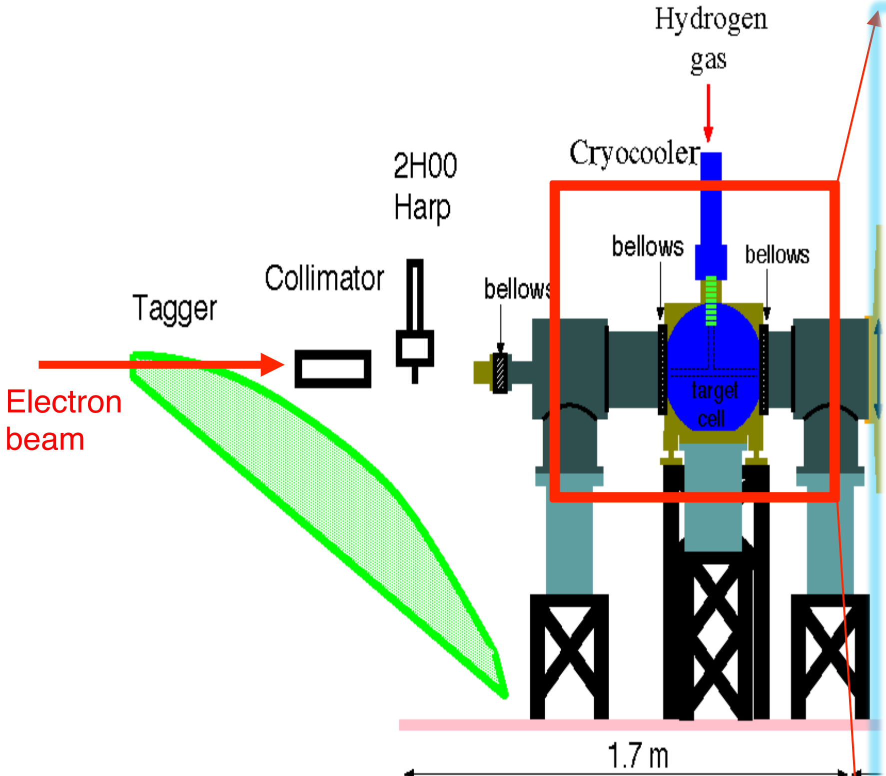
- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2×10^{-4} – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum chamber**

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

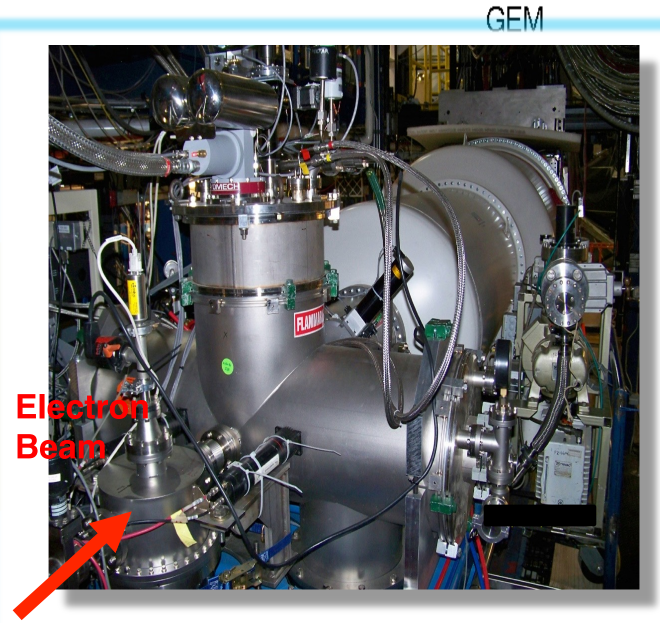
Sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

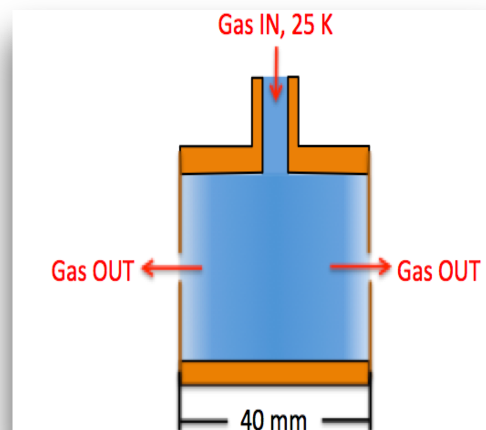
H spectroscopy experiments

PRad Experimental Apparatus



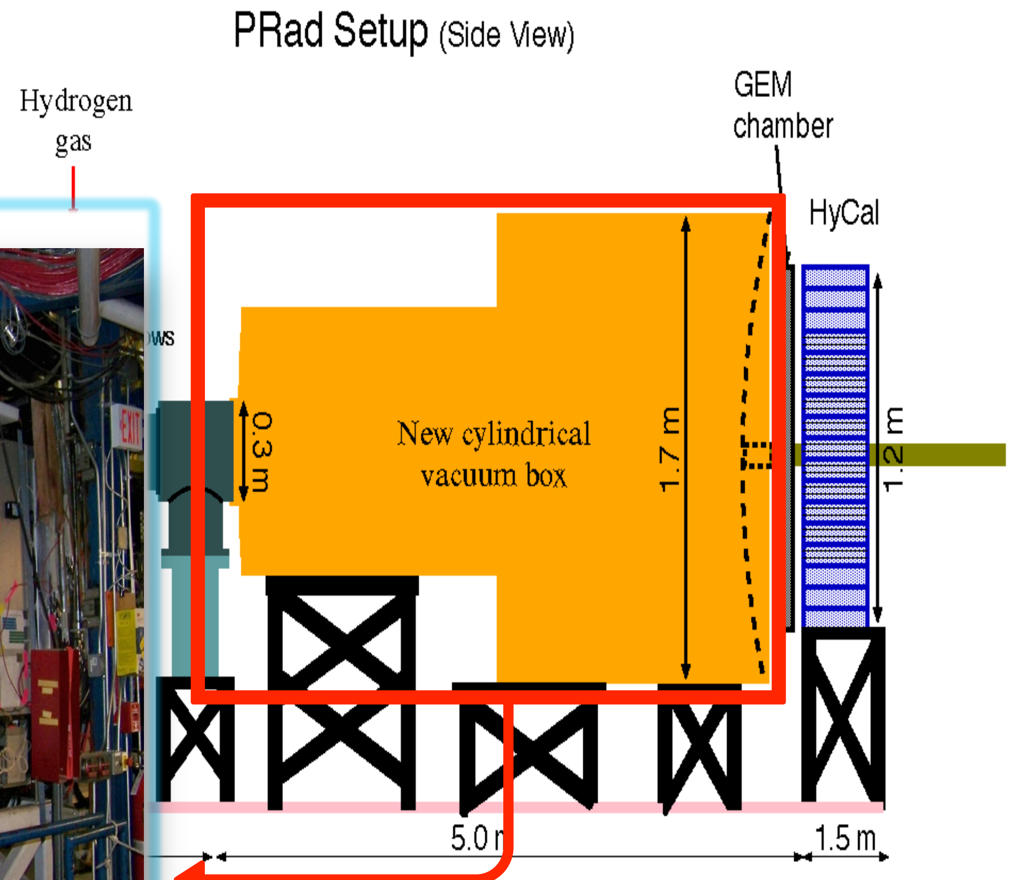
PRad Setup (Side View)





- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2

PRad Experimental Apparatus

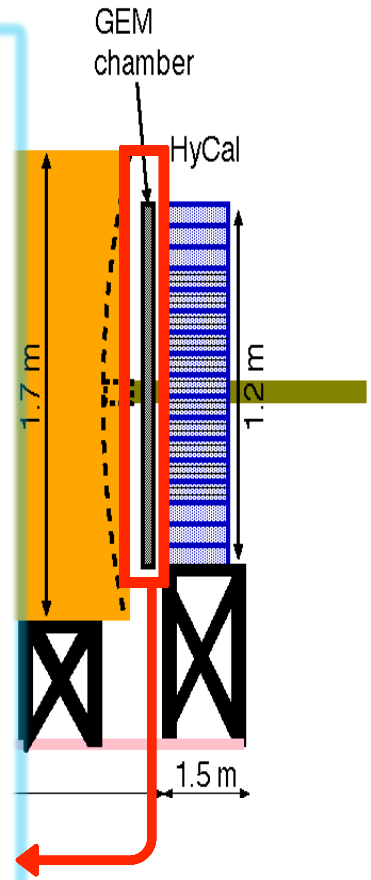


- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum tank pressure: 0.3 mTorr

PRad Experimental Apparatus

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Similar improvement for Q^2 determination at small angle

PRad Setup (Side View)



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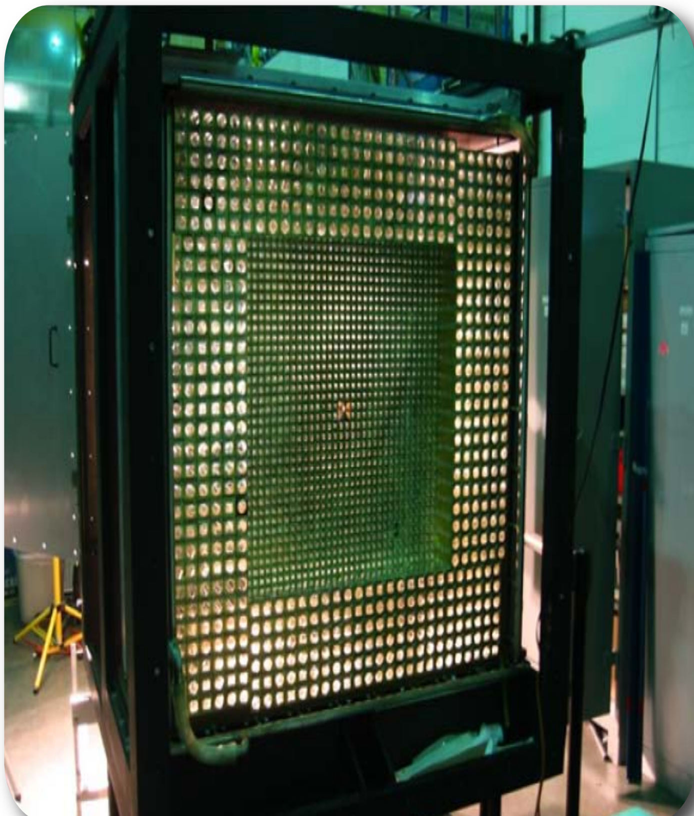
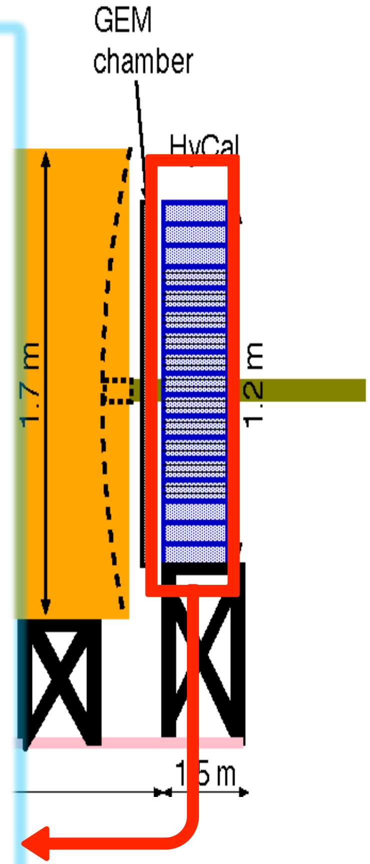


- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO_4 modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~ 0.6˚ to 7.5˚
- Full azimuthal angle coverage
- High resolution and efficiency

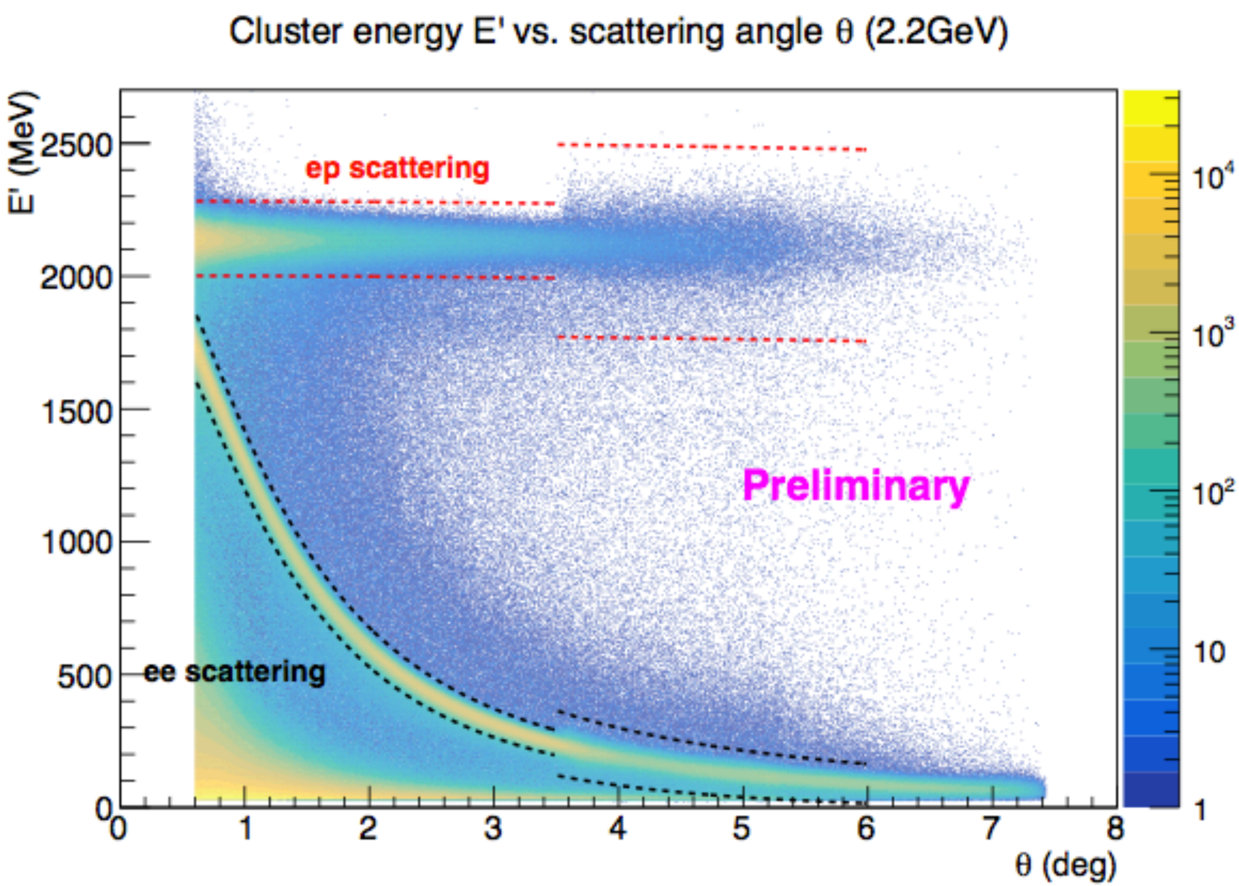
PRad Setup (Side View)



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:

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

- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections
  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 (fully beyond ultra relativistic approximation)

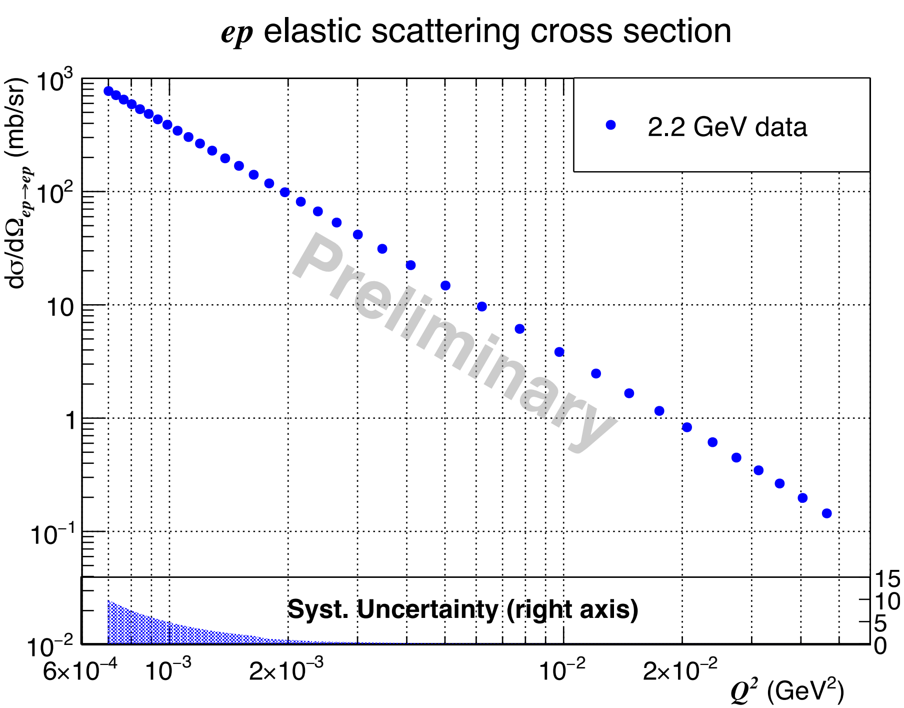
- A Geant4 simulation package is used to study the radiative effects:

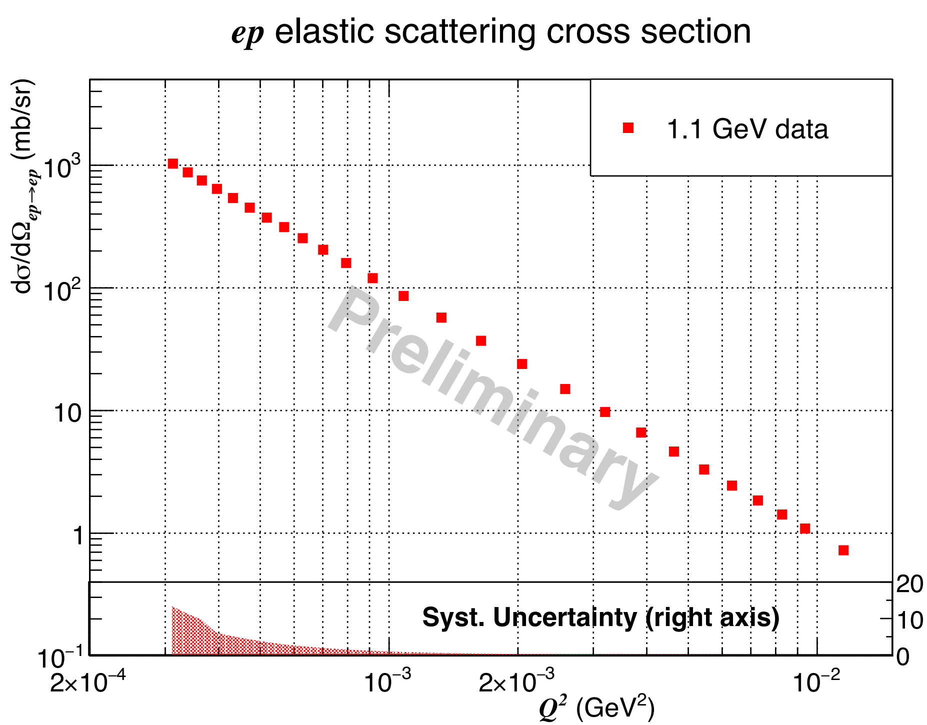
$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

- Iterative procedure applied for radiative correction

Differential Cross Sections (Preliminary)

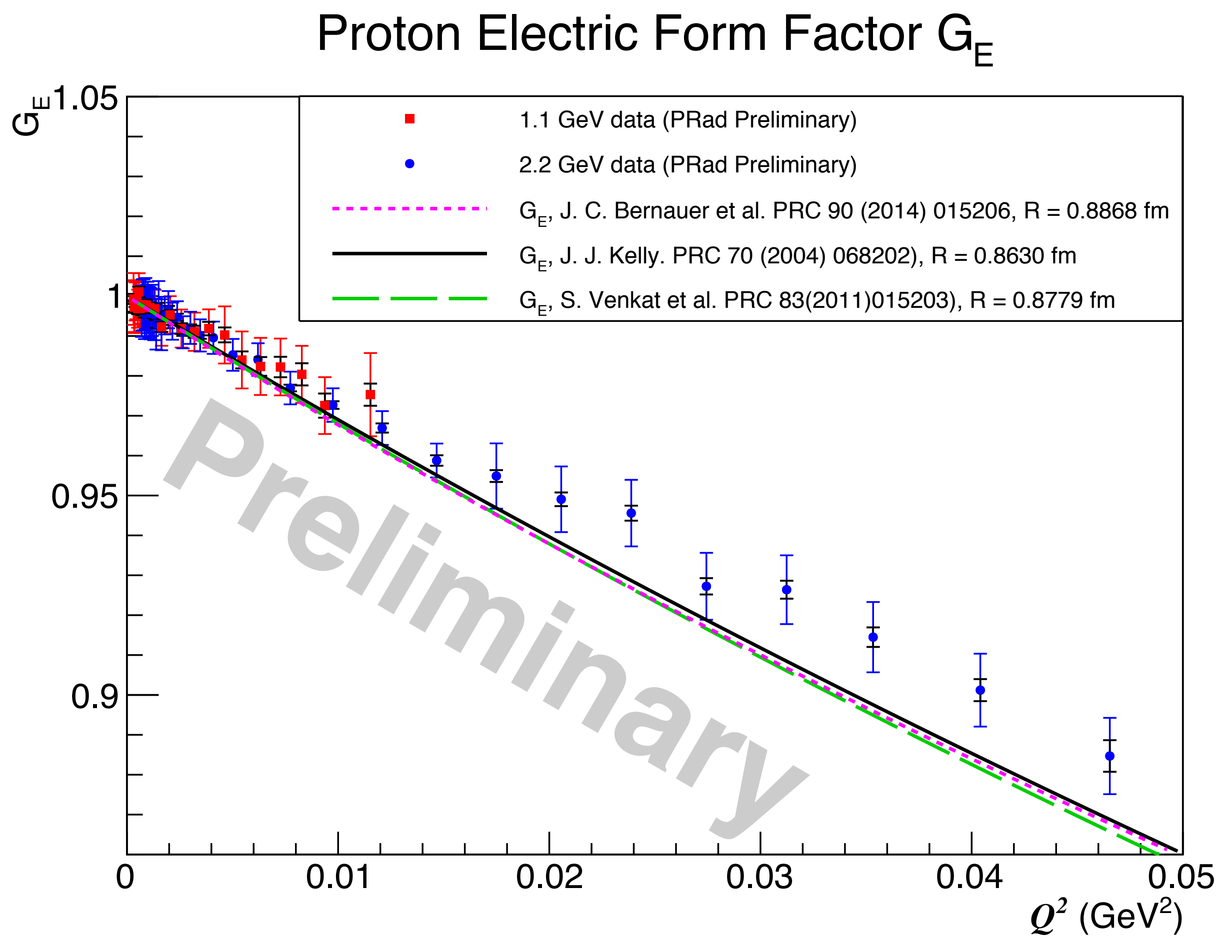
- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Statistical uncertainties at current stage: ~0.18% for 2GeV, ~0.3% for 1GeV per point
- Systematic uncertainties at current stage: 0.8% ~ 2.0% for 2GeV, 0.9% ~2.0% for 1GeV (shown as shadow area)





Form Factor G_E (Preliminary)

- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slope seems to favor smaller radius



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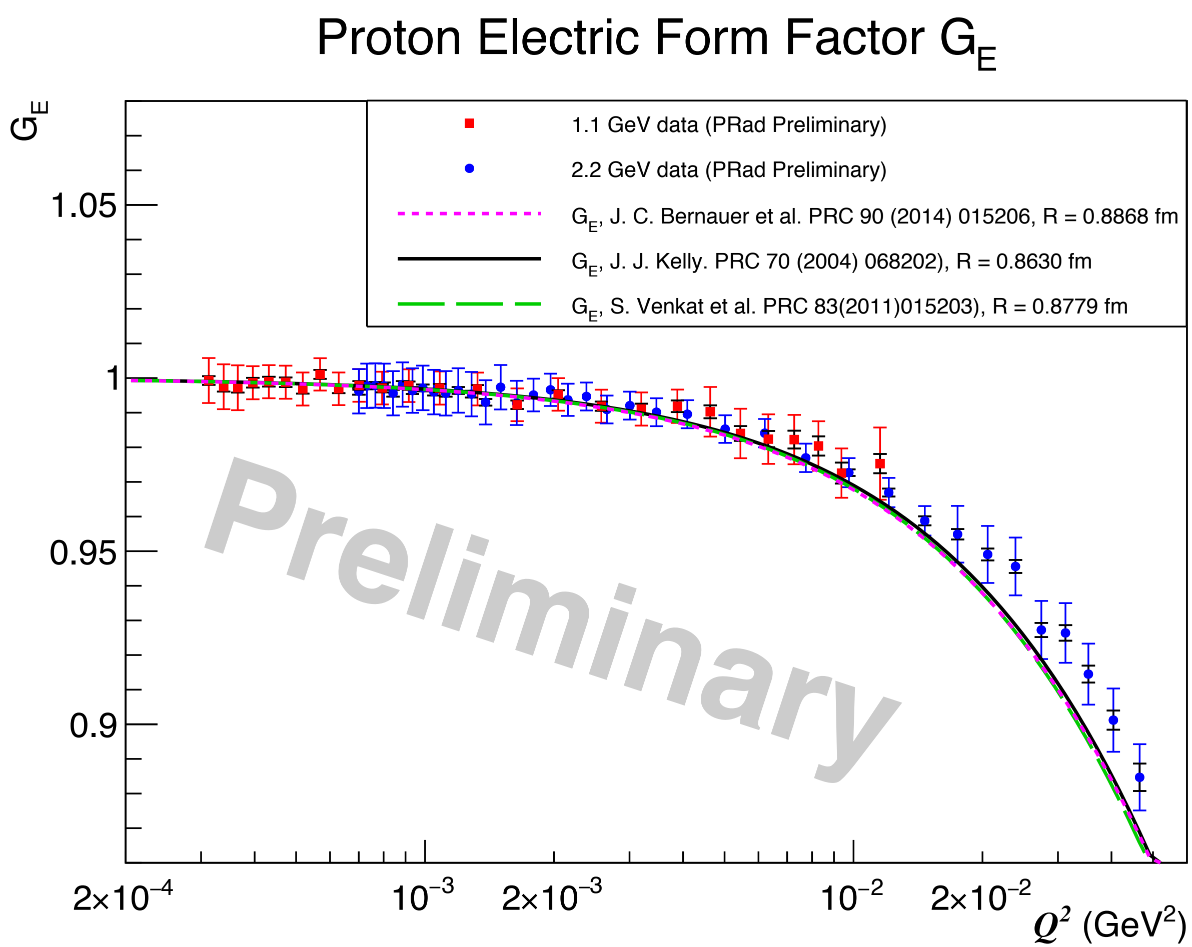

Summary and outlook

- After several years, the proton charge radius remains puzzling, and perhaps also the deuteron charge radius
- PRad experiment had a successful data taking in May/June 2016
- PRad collaboration is making good progress in data analysis and preliminary form factor results (partial data) presented in April 2018
- Preliminary radius result is anticipated in the fall 2018 –Stay tuned!

Acknowledgement: the PRad Collaboration (supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231, NSF MRI PHY-1229153)