Proton Charge Radius and the PRad Experiment

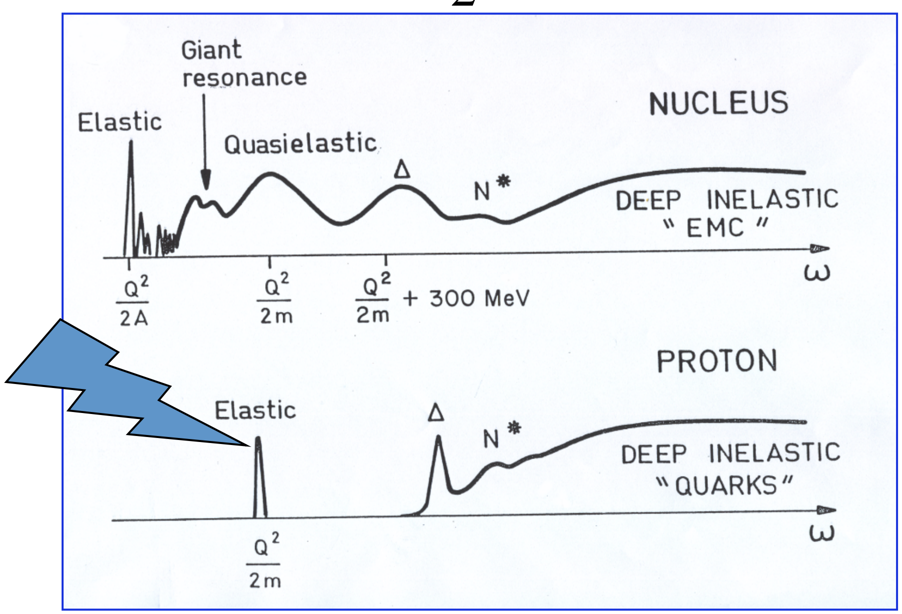
Haiyan Gao

Duke University and Duke Kunshan University

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***Vary the wave-length of the probe to view deeper inside***

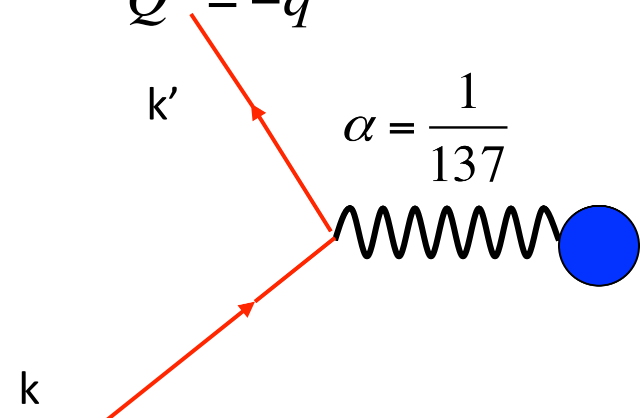
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right) \qquad \tau = -q^2 / 4M^2$$



Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$



$$\alpha = \frac{1}{137}$$

What is inside the proton/neutron?

1933: Proton's magnetic moment

Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic moment of the proton".

$g \neq 2$

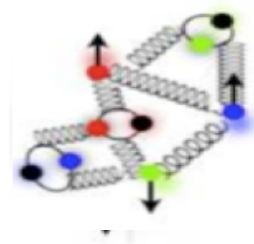
1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

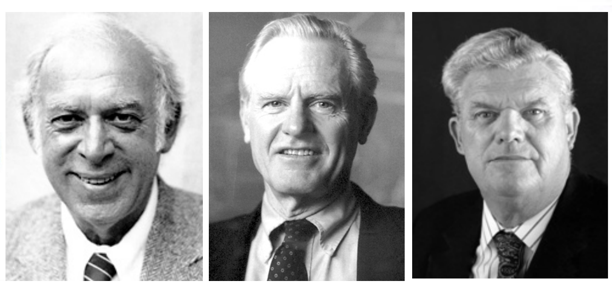
Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors → Charge distributions



1969: Deep inelastic e-p scattering



Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

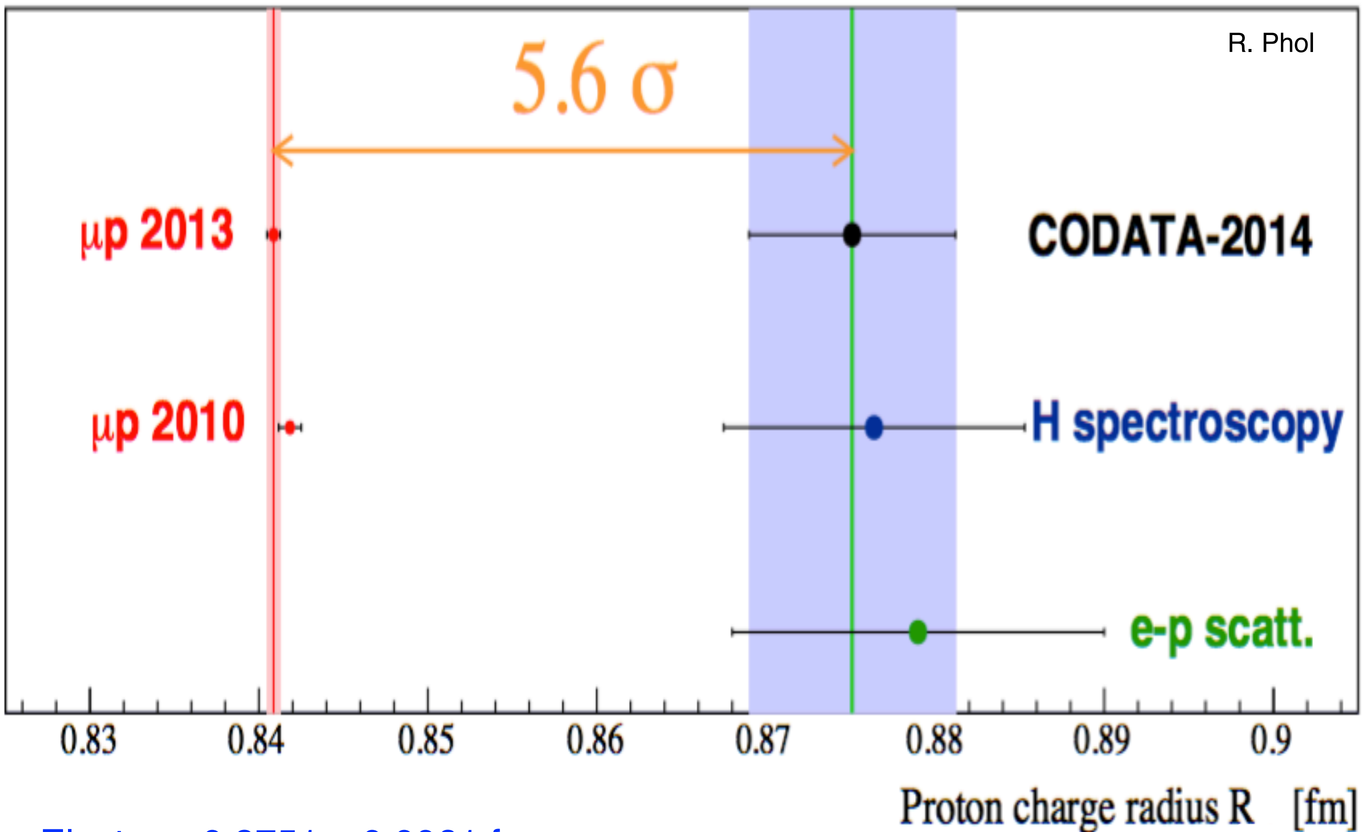
1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Proton Charge Radius Puzzle



Electron: 0.8751 ± 0.0061 fm
Muon: 0.8409 ± 0.0004 fm

- p Lamb shift measurements by CREMA (2010, 2013)
  - Unprecedented precision, <0.1%

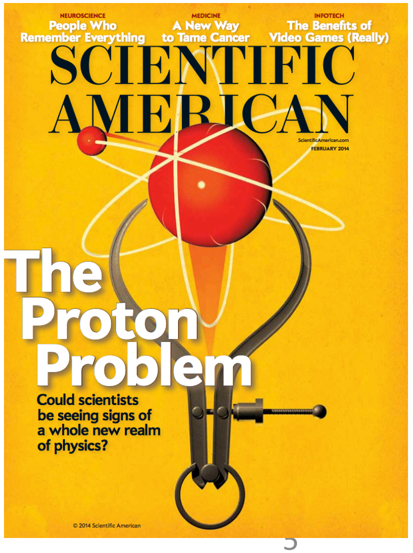
Proton Charge Radius

- 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)

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

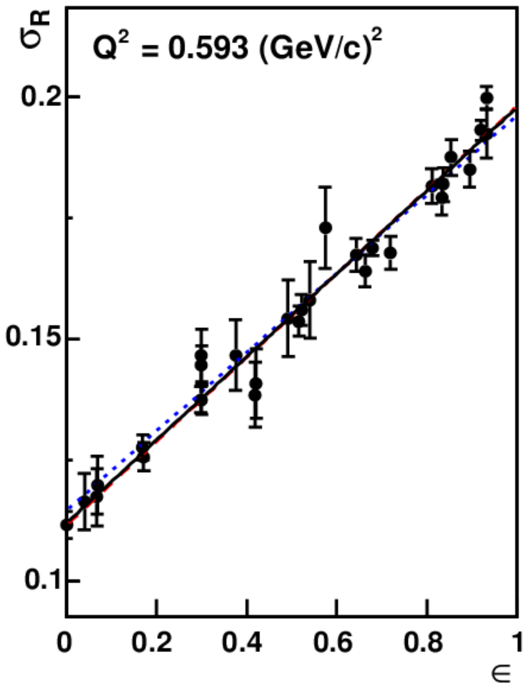
- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift



Unpolarized electron-nucleon scattering
(Rosenbluth Separation)

- Elastic e-p cross section

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



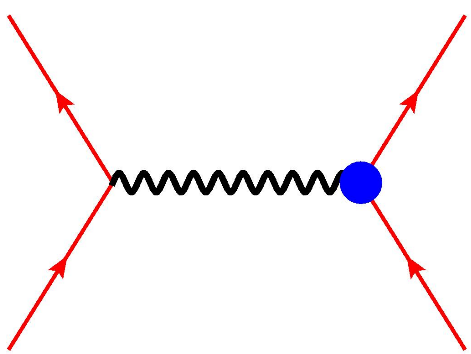
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - Low Q^2 by G_E
    - High Q^2 by G_M

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

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

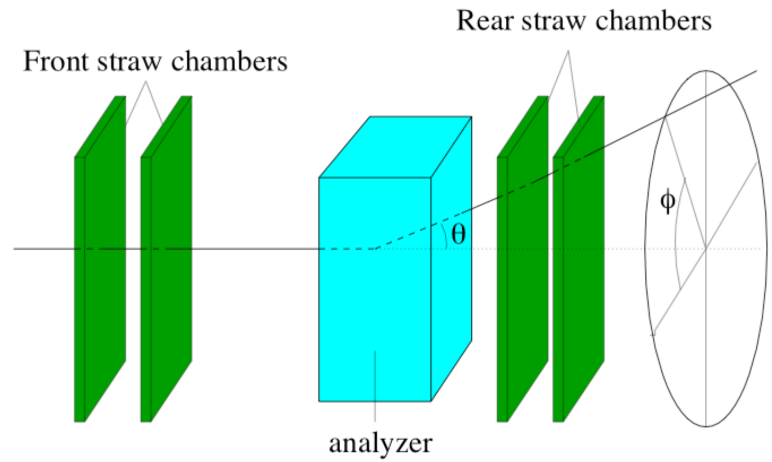
$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$

G_E or G_M



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

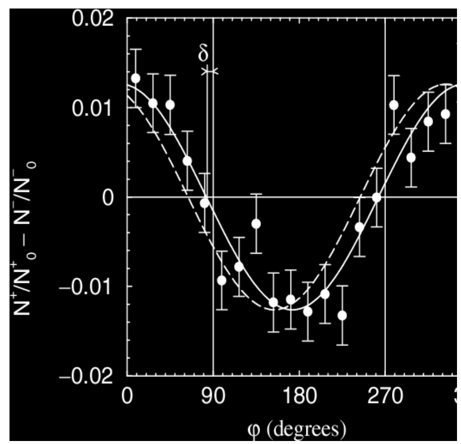
Polarization Transfer → $\frac{G_E^p}{G_M^p}$

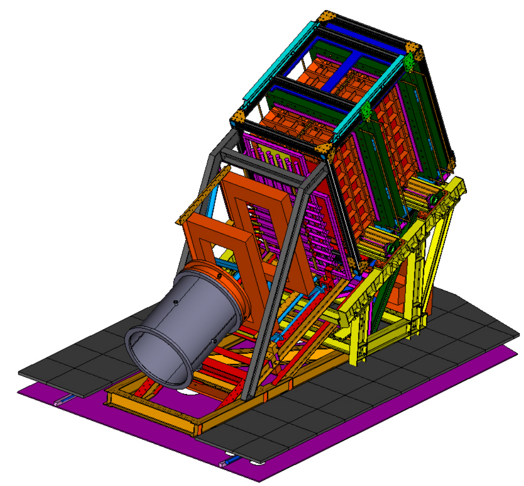


- Recoil proton polarization

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

- 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





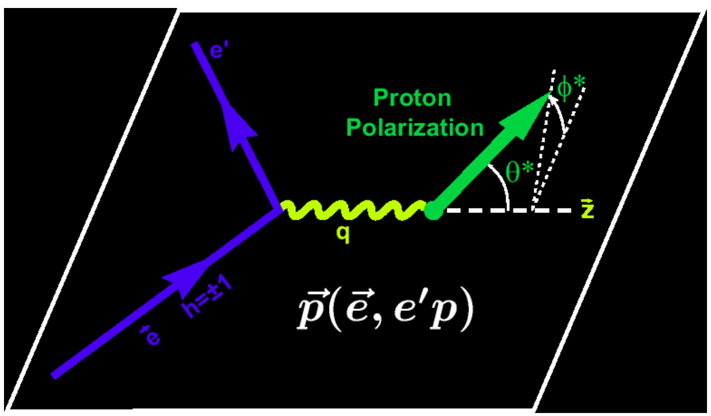
Focal-plane polarimeter

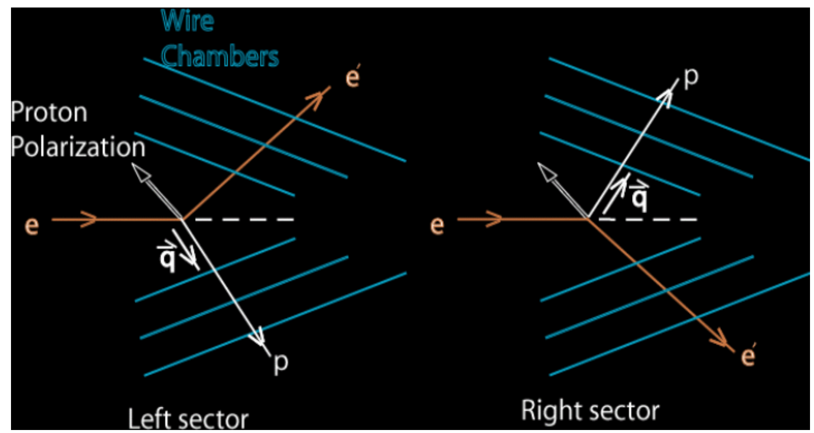
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

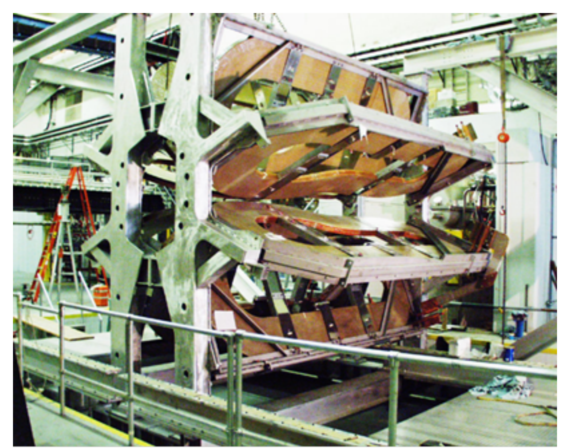
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)}\, v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





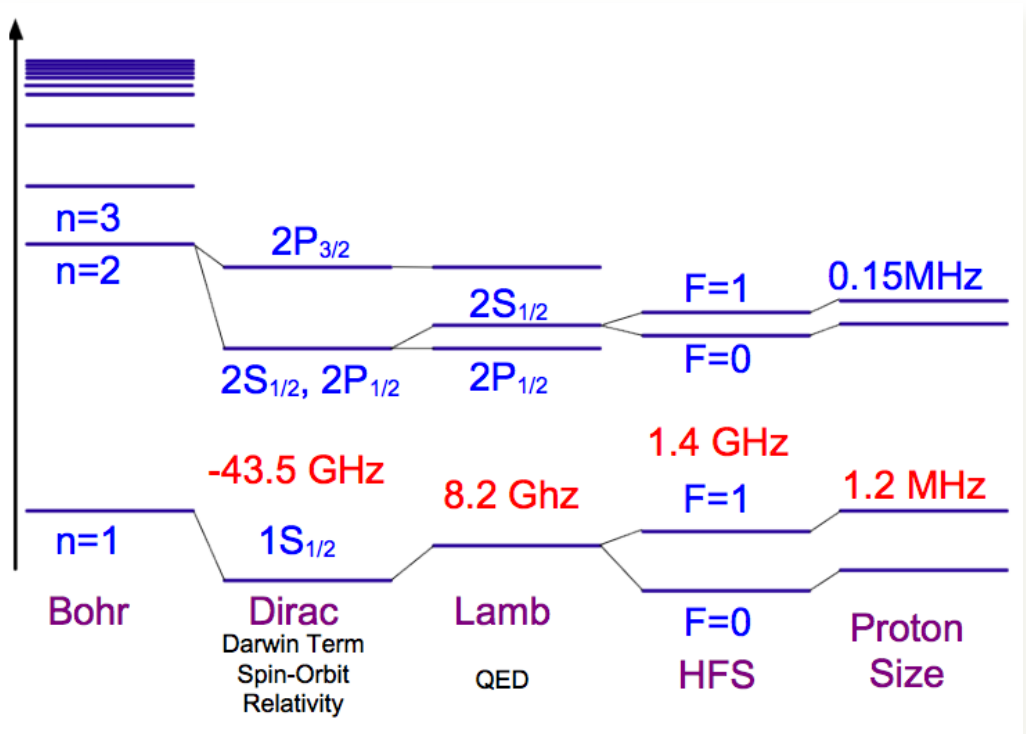
- Super-ratio

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



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.

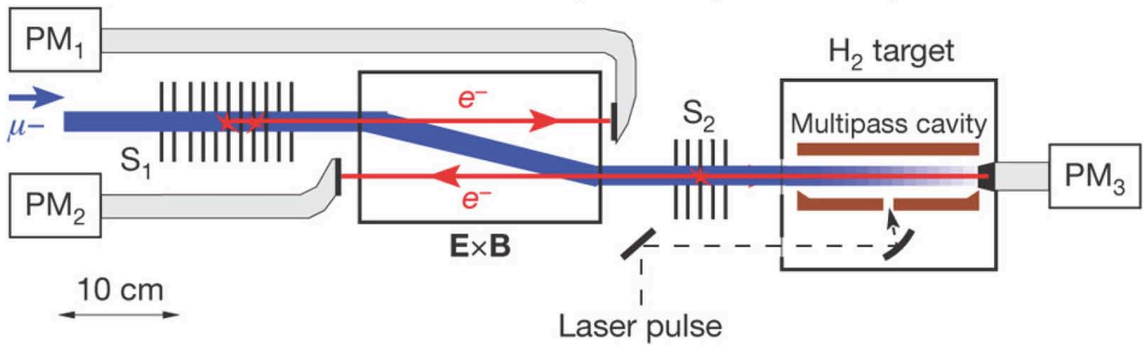
Yields R_∞ (the most precisely known constant)

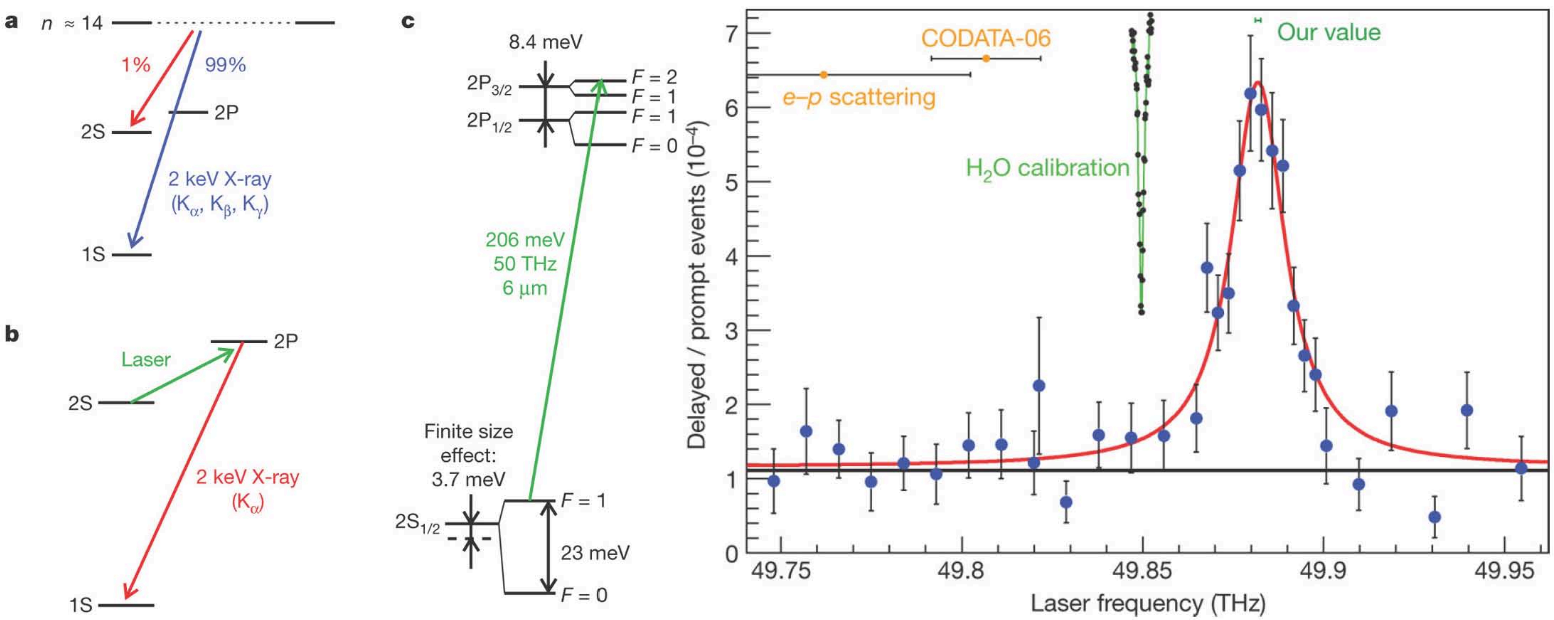
Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius

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

Muonic hydrogen Lamb shift at PSI (2010, 2013)

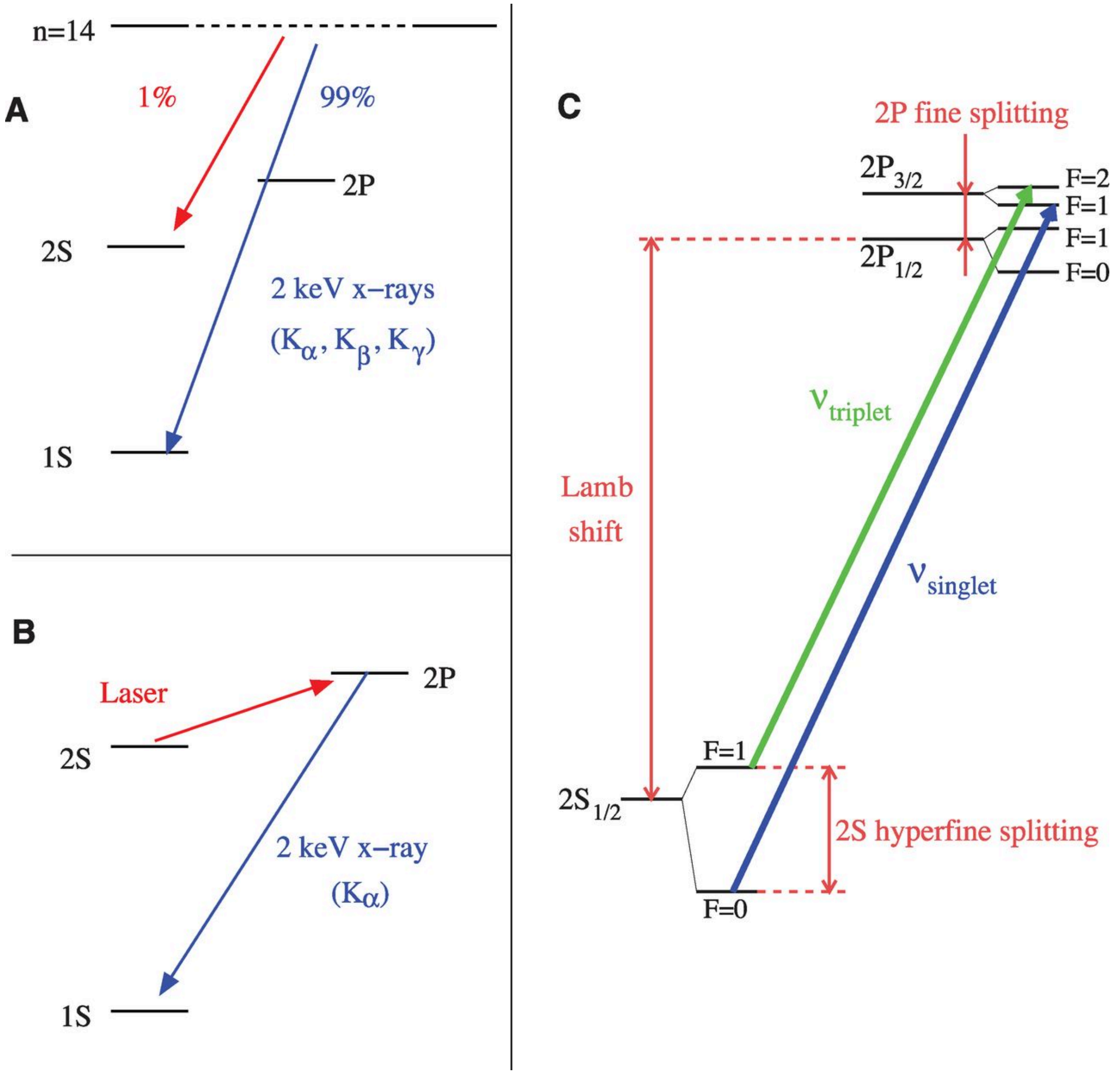
Nature **466**, 213-216 (8 July 2010)





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

New PSI results reported in Science 2013

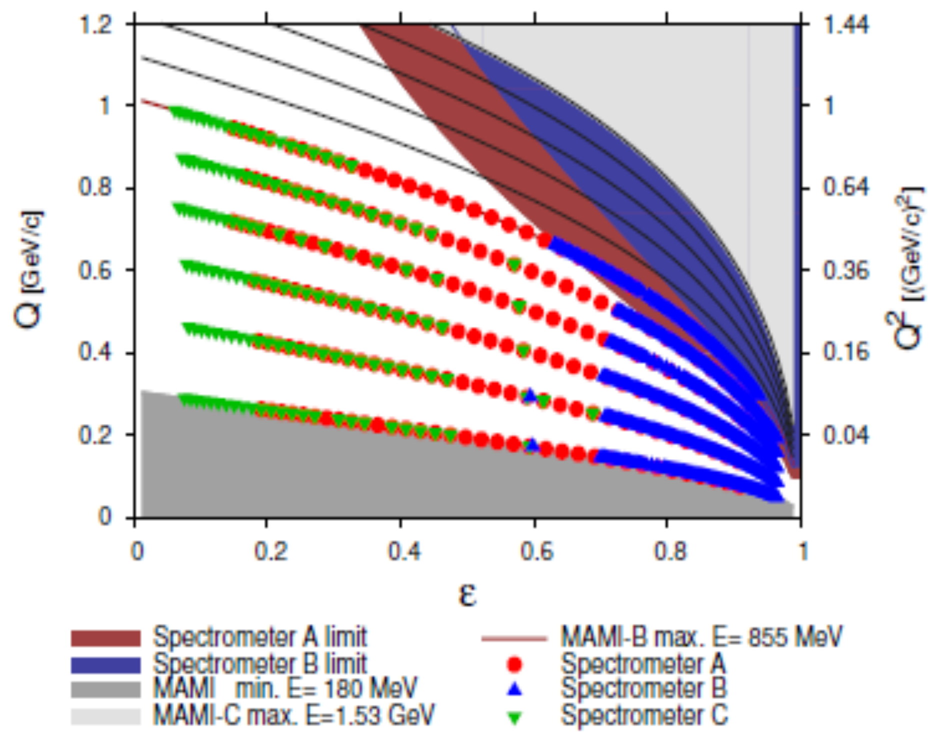


2013: r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

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

- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

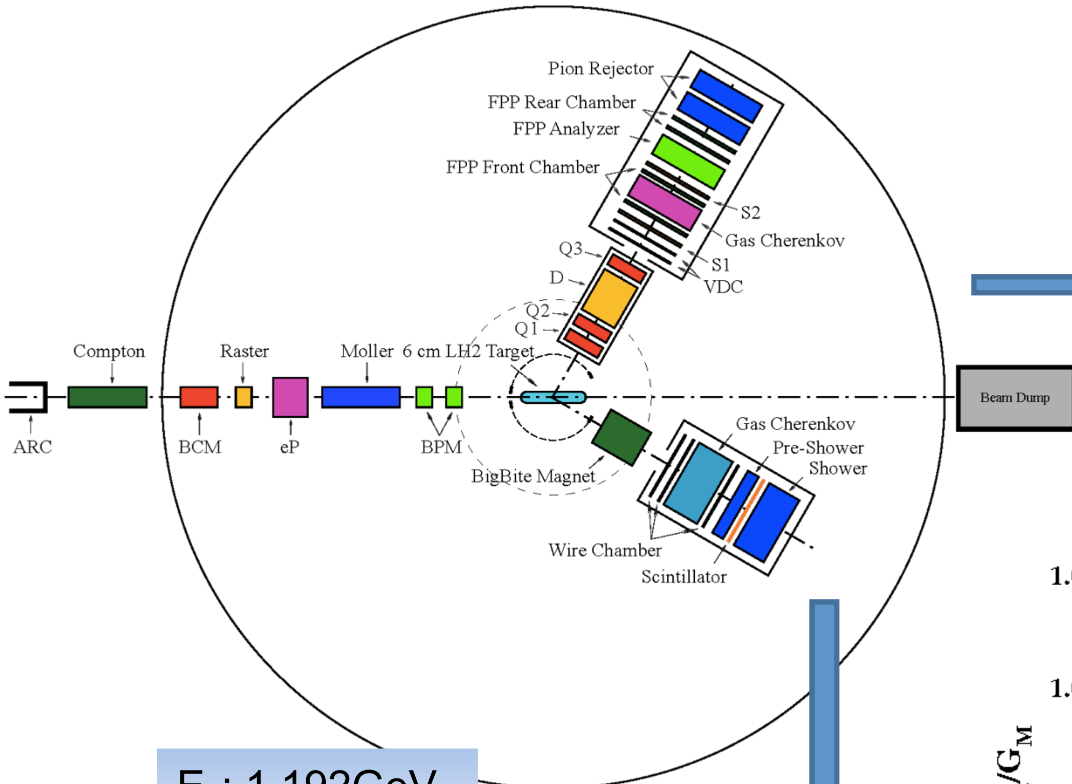
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

JLab Recoil Proton Polarization Experimental



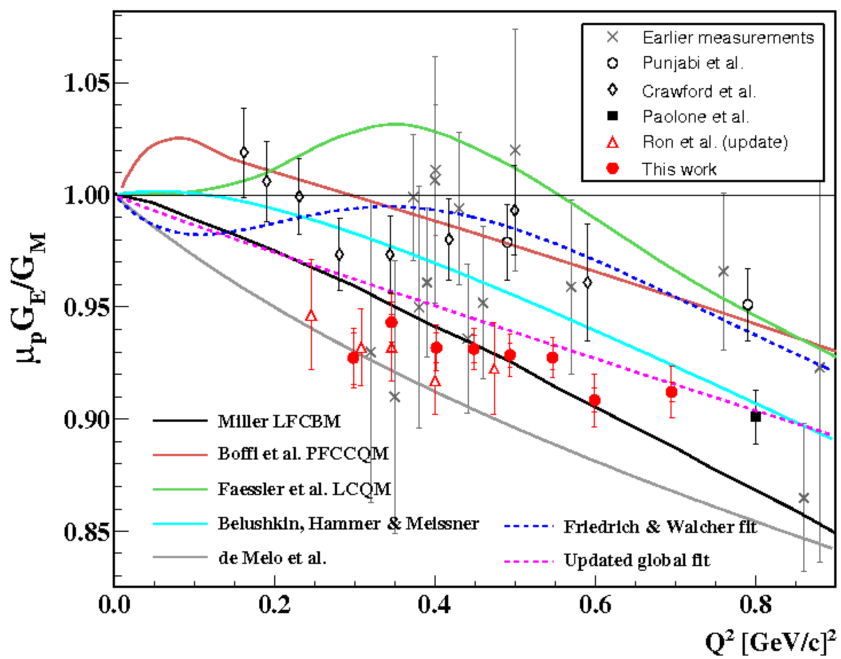
LHRS

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

E_e: 1.192GeV
P_b: ~83%

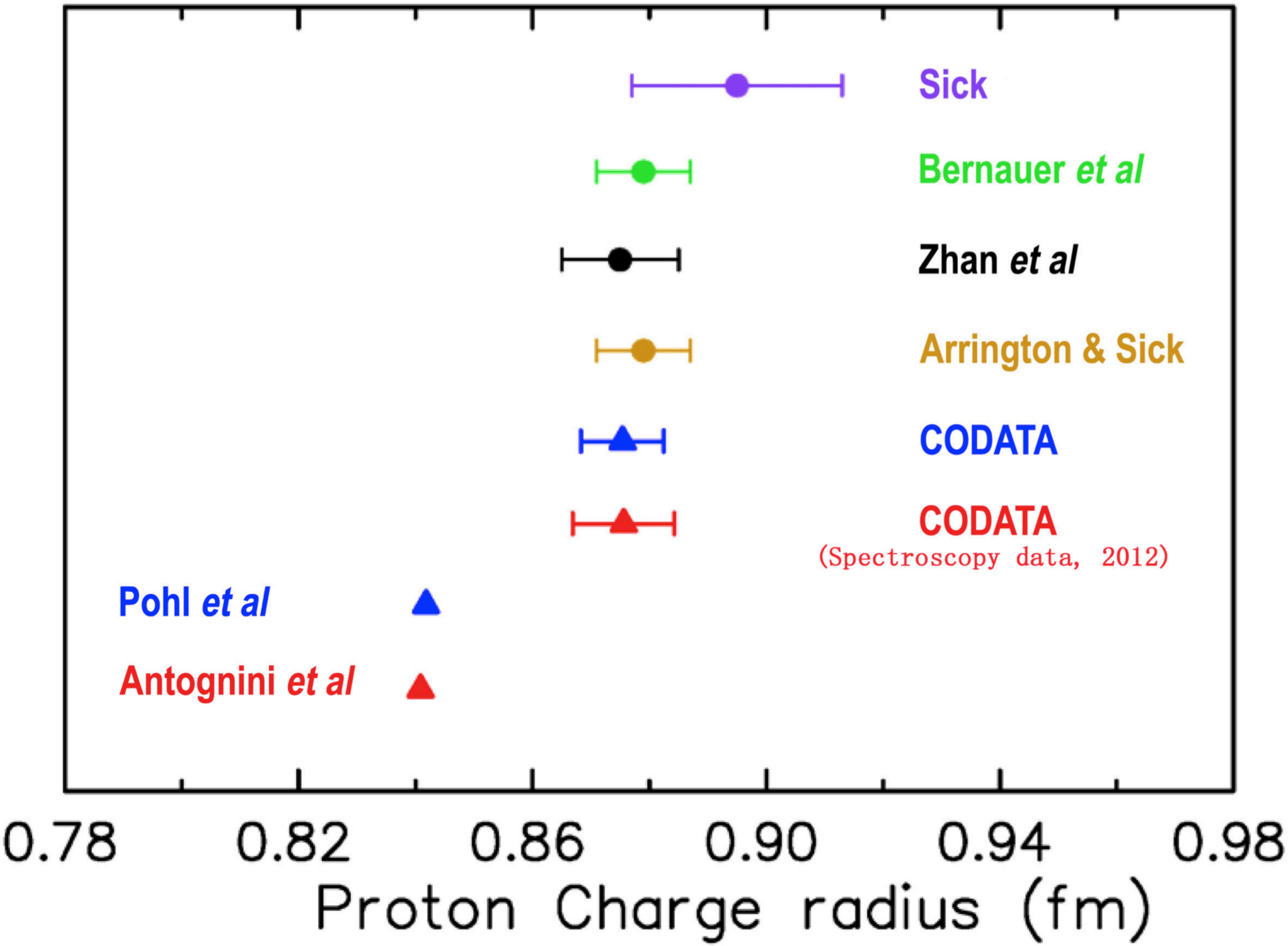
BigBite

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



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

Proton Charge Radius from recent experiments and analyses



Revisits QED Calculations….

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

An additional 0.31 meV to match CODATA value

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

Revisits of e-p scattering data (just 2015)

- 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.
  - Distler, Walcher, and Bernauer, arXiv1511.00479

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

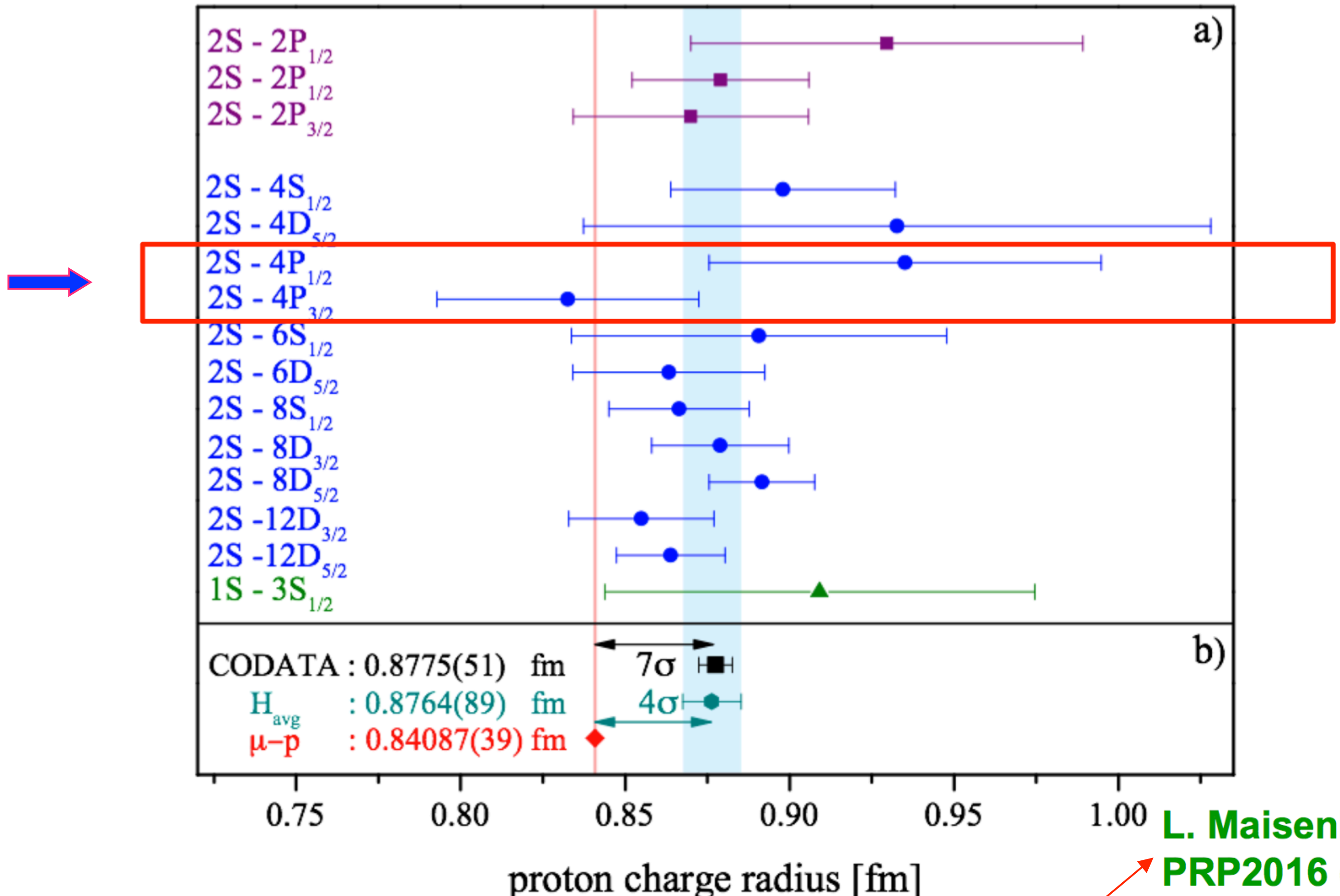
New Physics or what? - Incomplete list

- New physics: new particles, Barger et al., Carlson and 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**

The Proton Radius Puzzle (June 2016)



L. Maisenbacher, PRP2016 (Trento)

- New, preliminary value for r_p was reported in PRP-2016 Workshop (Trento, Italy) from ordinary hydrogen
- Consistent with the muonic-hydrogen result !
- Is the Puzzle solved? No, new measurements are needed (spectroscopy, ep-scattering)

Update on proton radius puzzle

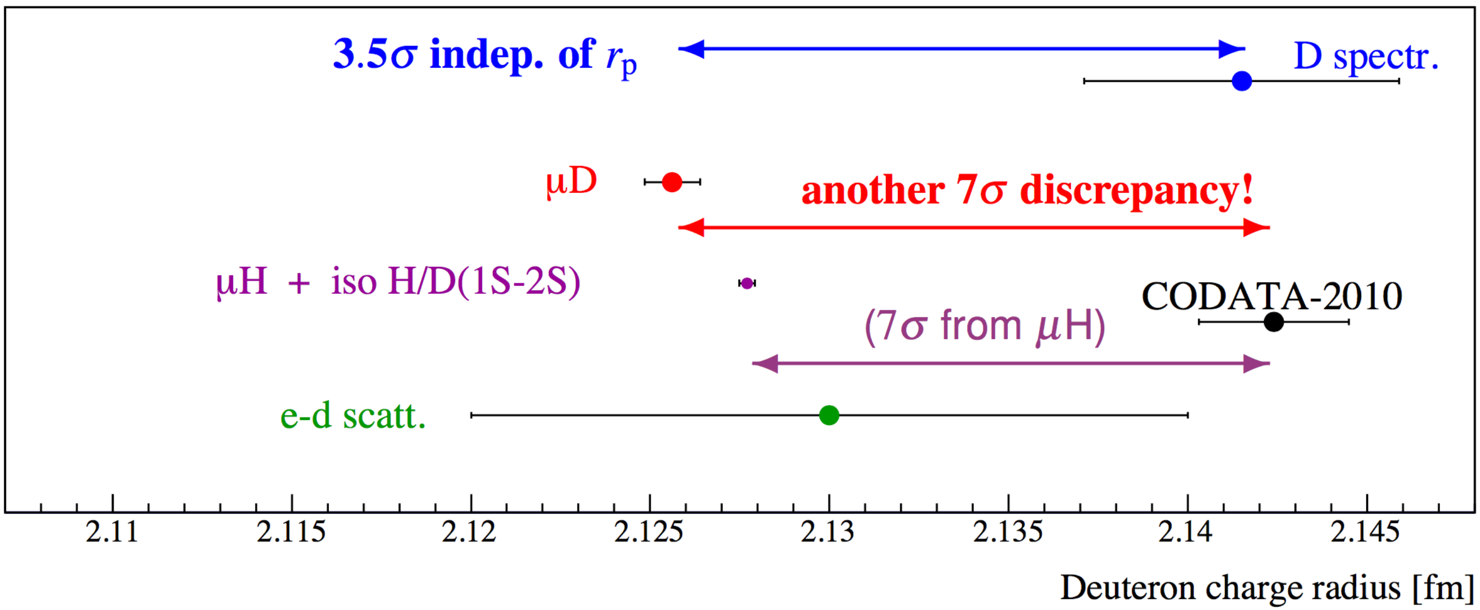
- Deuteron radius puzzle
  - Deuteron rms charge radius from muonic deuterium spectroscopy (R. Pohl et al., Science 353, 6300, 669, 2016)
  - 7.5σ smaller than the CODATA-2010 value, and 3.5σ smaller than the value from electronic deuterium spectroscopy (R. Pohl et al., Metrologia 54, L1, 2017)
  - Confirms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

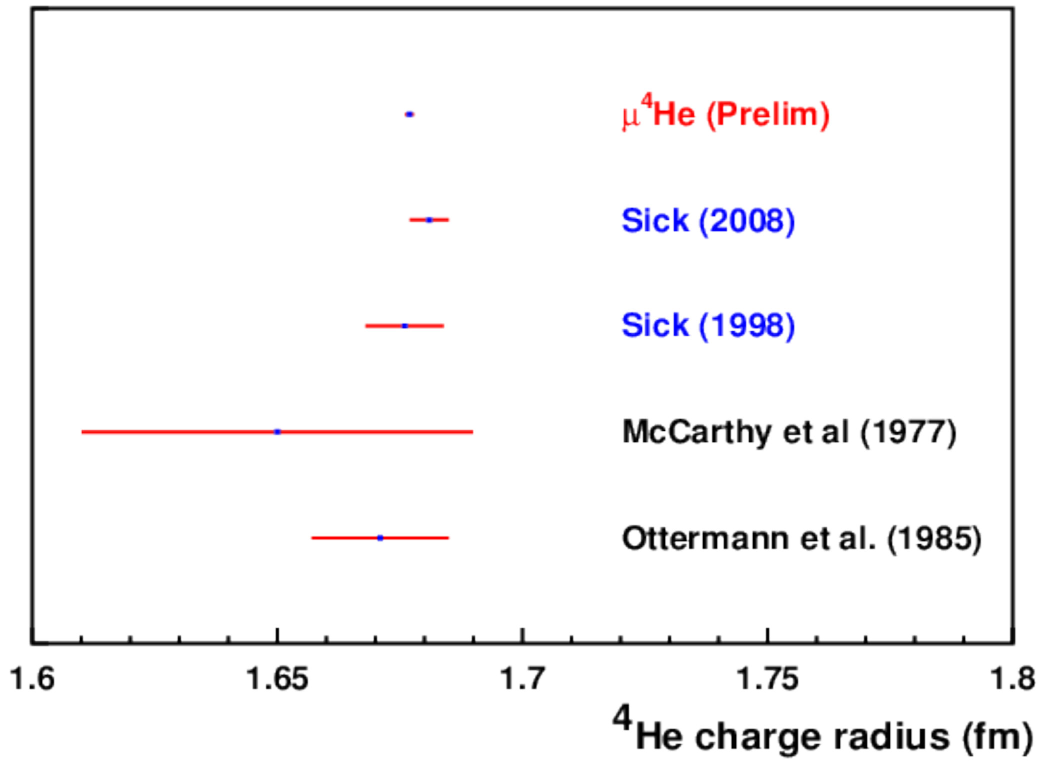


(R. Pohl, 2017)

- Calls for new independent experiments with possible highest accuracy!
- New ed- cross sections at low Q^2 will be a critical input to reduce theory error in r_d extracted from μD spectroscopy.

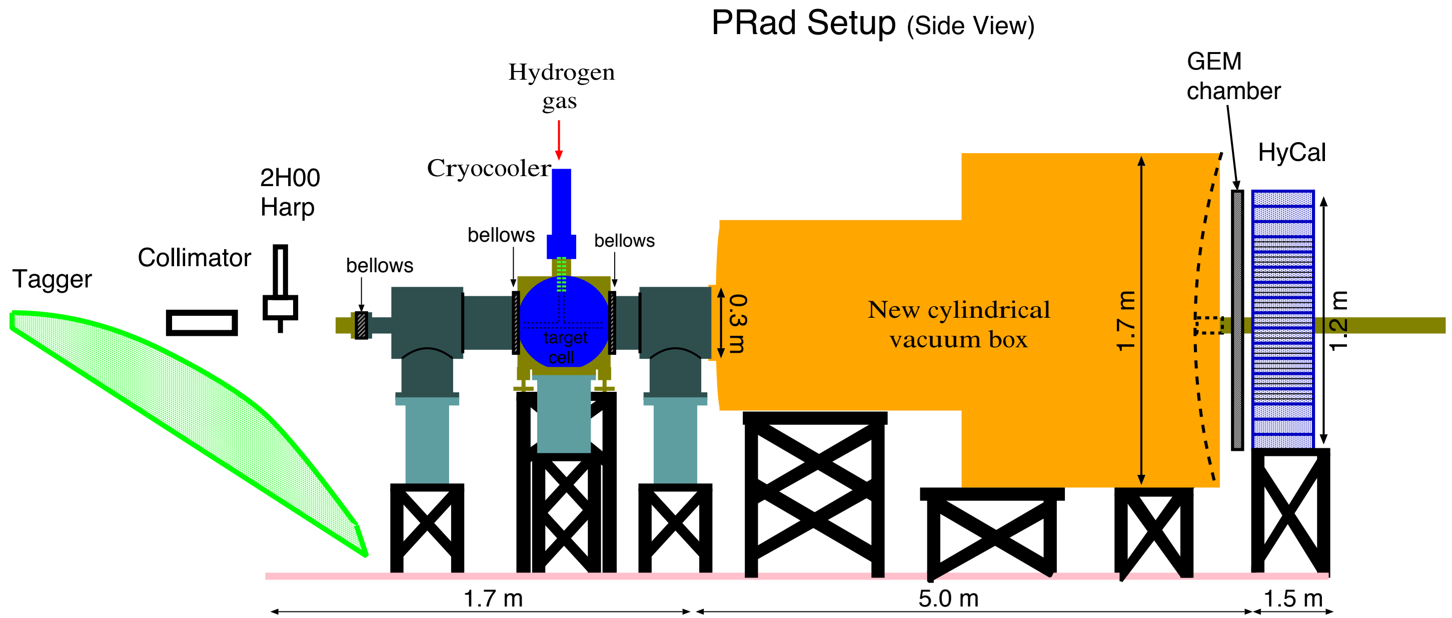
Charge Radius of Helium Nuclei

Helium



Electron scattering consistent with μ-spectroscopy

PRad Experimental Setup in Hall B at JLab



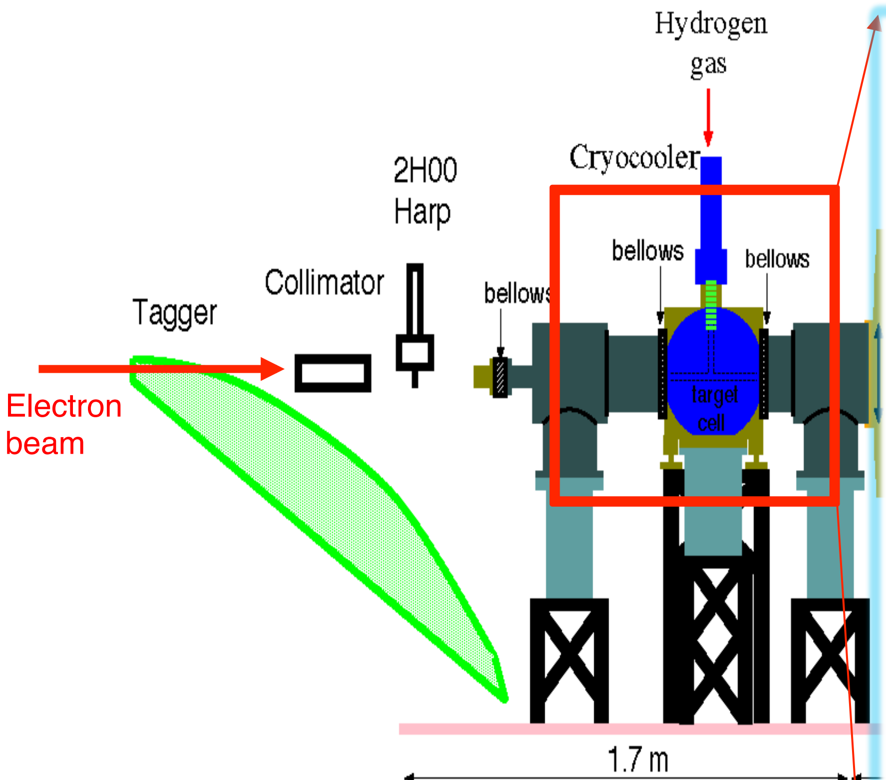
- **High resolution, large acceptance, hybrid HyCal calorimeter ($PbWO_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2x10^{-4}$ – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum chamber**

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

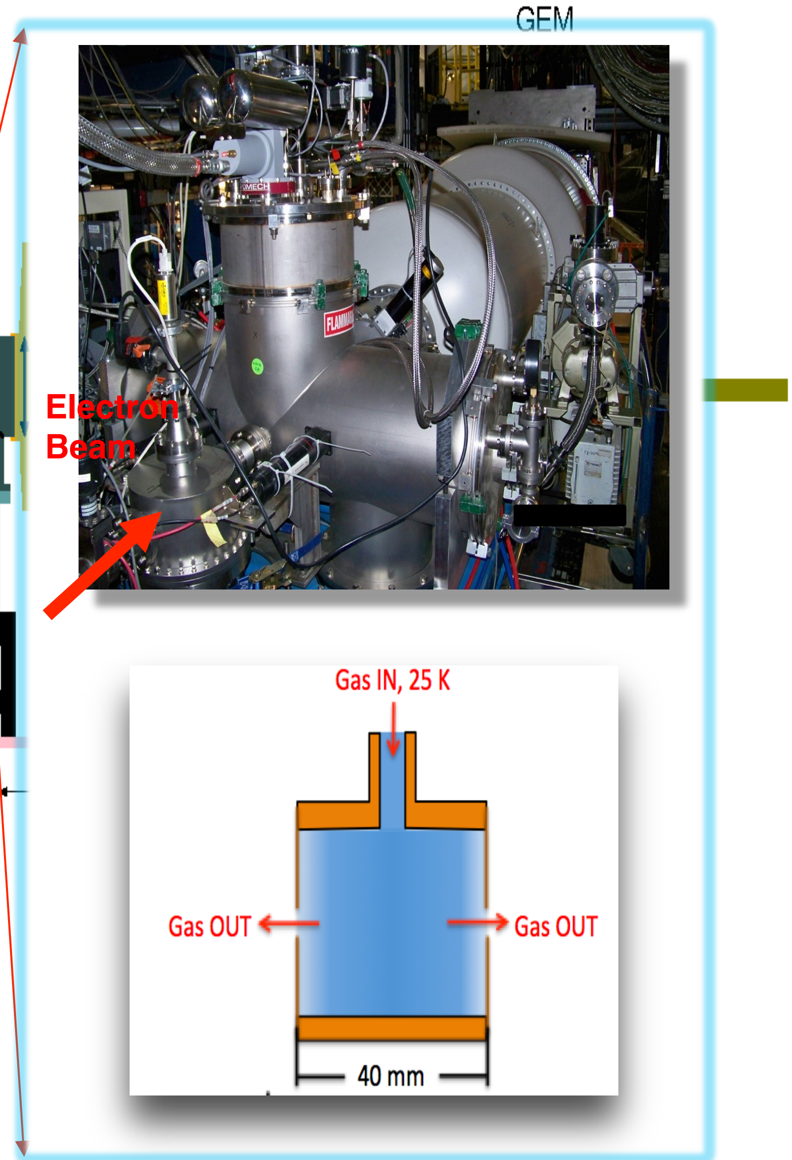
Sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

PRad Experimental Apparatus

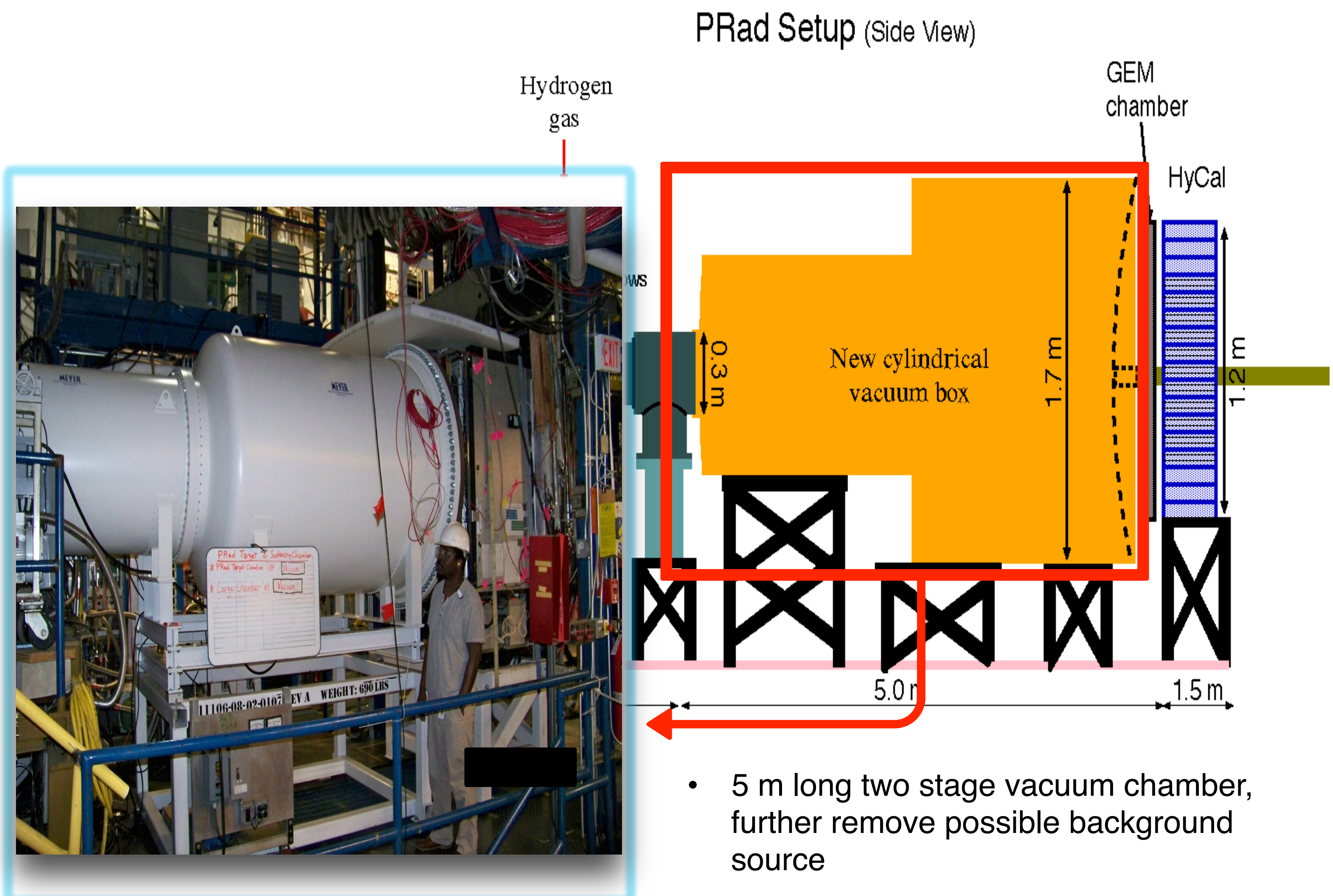


PRad Setup (Side View)



- 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

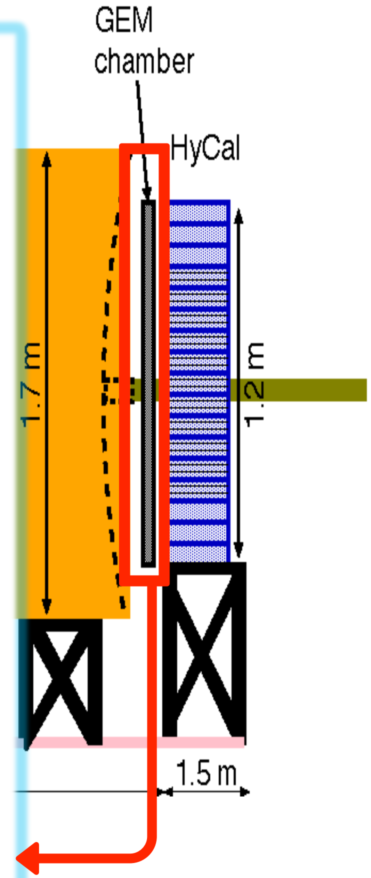


- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum tank pressure: 0.3 mTorr

PRad Experimental Apparatus

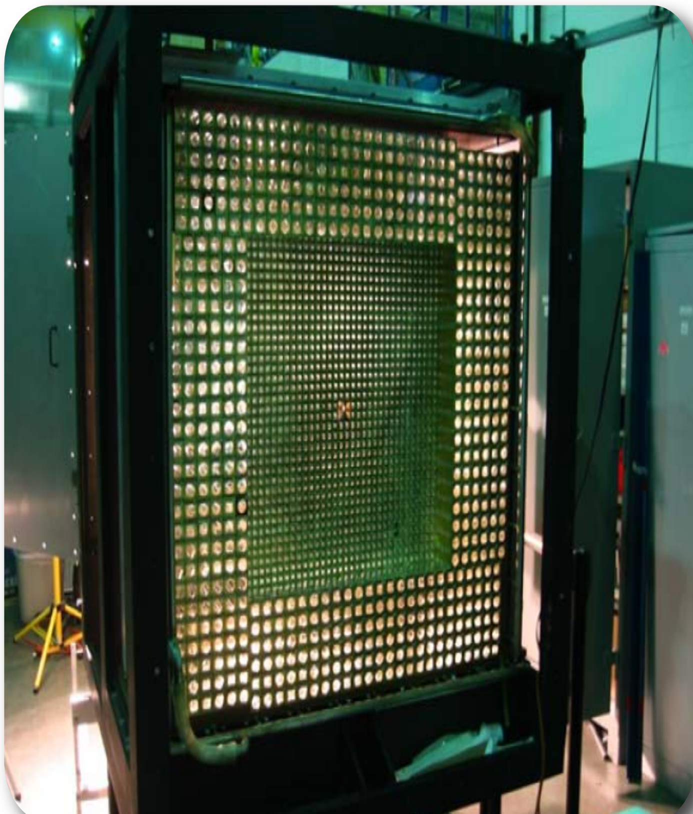
PRad Setup (Side View)

- 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



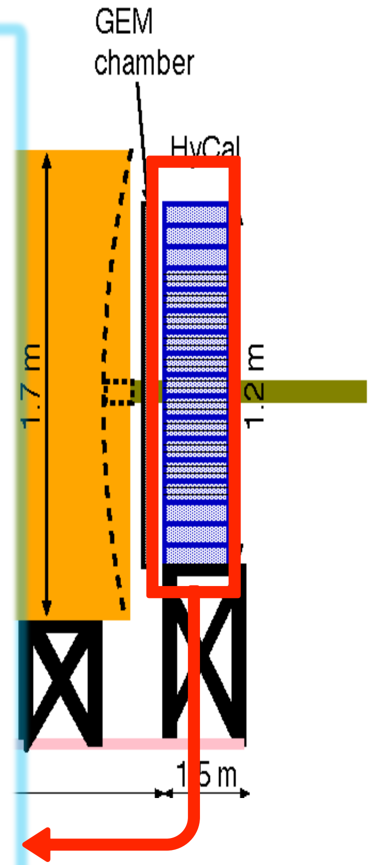
More details see presentation of X. Bai in session E12

PRad Experimental Apparatus



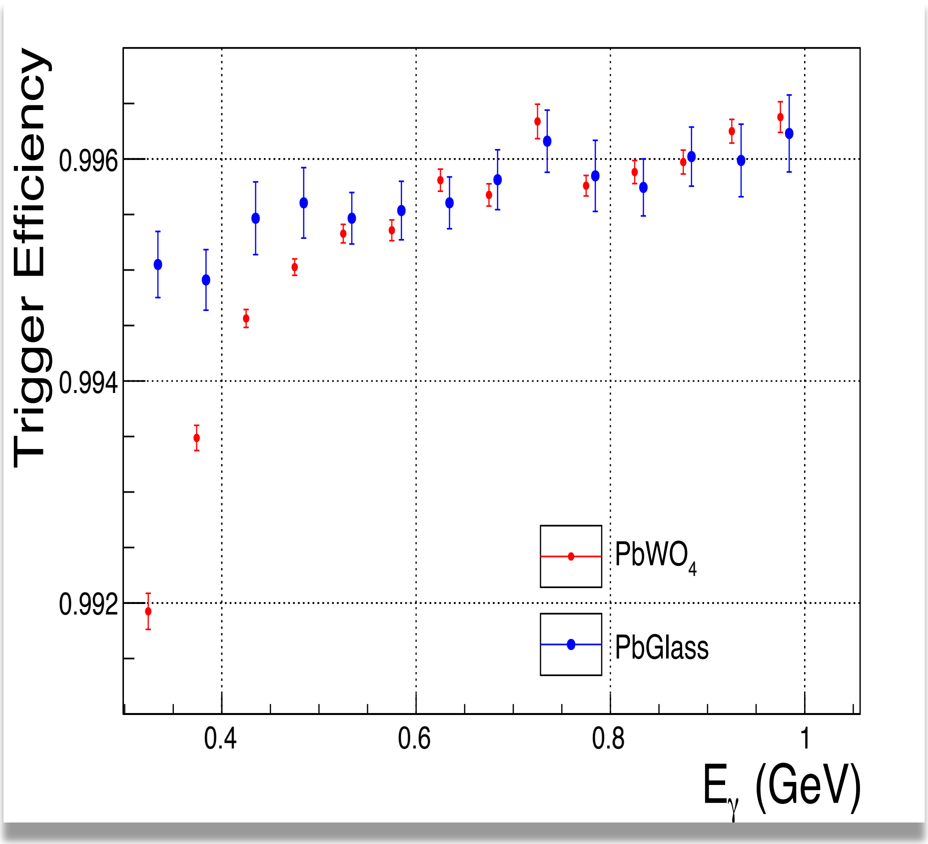
- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO_4 modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~ 0.6° to 7.5°
- Full azimuthal angle coverage
- High resolution and efficiency

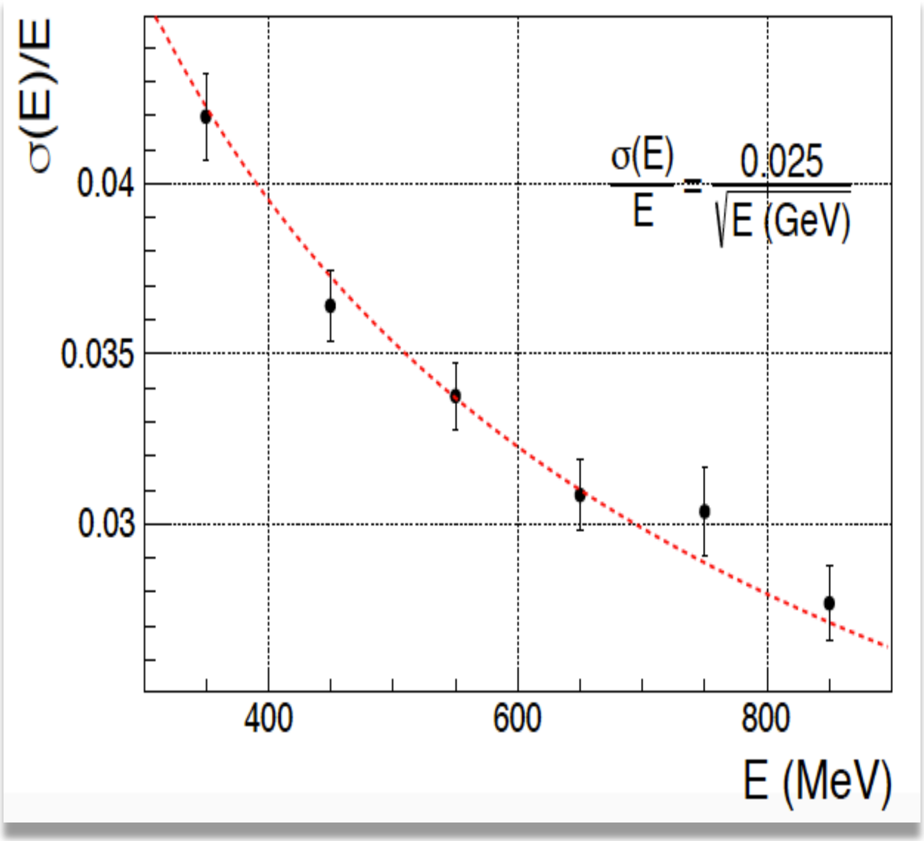
PRad Setup (Side View)



HyCal Resolution and Efficiency

- HyCal energy resolution and trigger efficiency extracted using high energy photon beam from Hall B at Jlab
  - > 99.5% trigger efficiency obtained for E_γ > 500 MeV, for various parts of HyCal
  - Energy resolution ~2.5% for PWO_4 part, lead glass part about 2.5 time worse

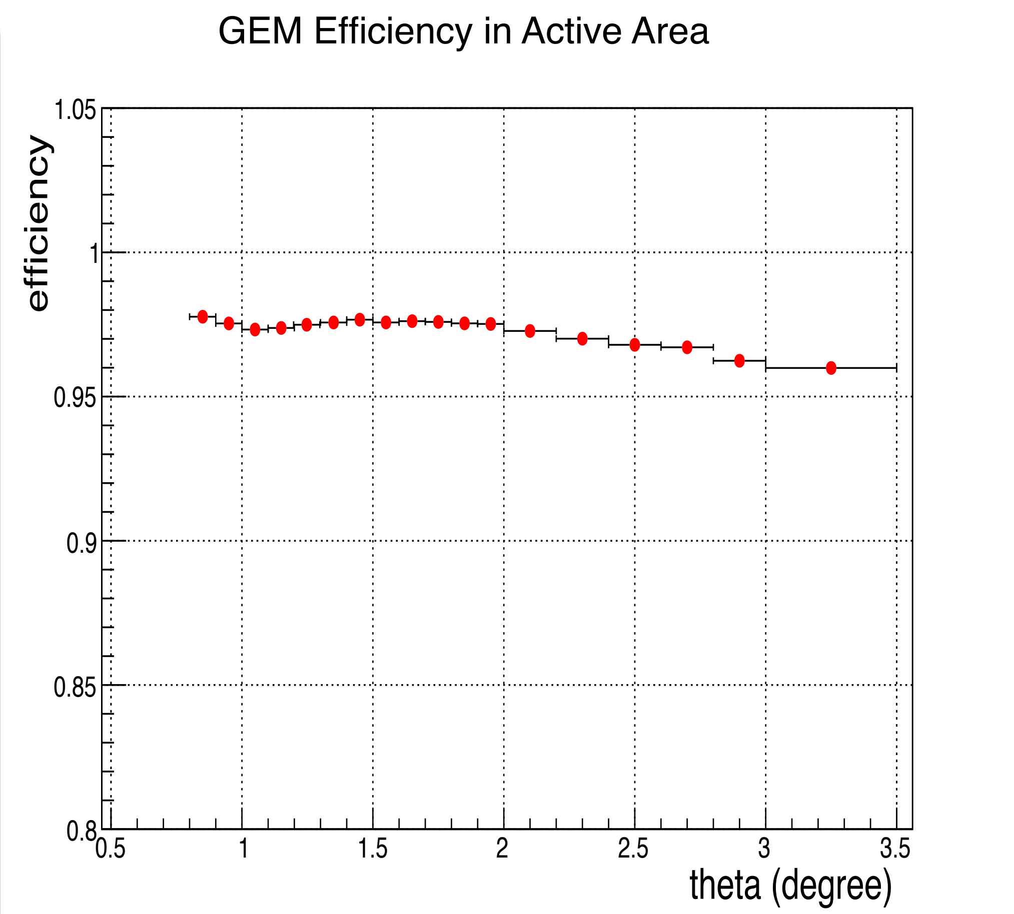


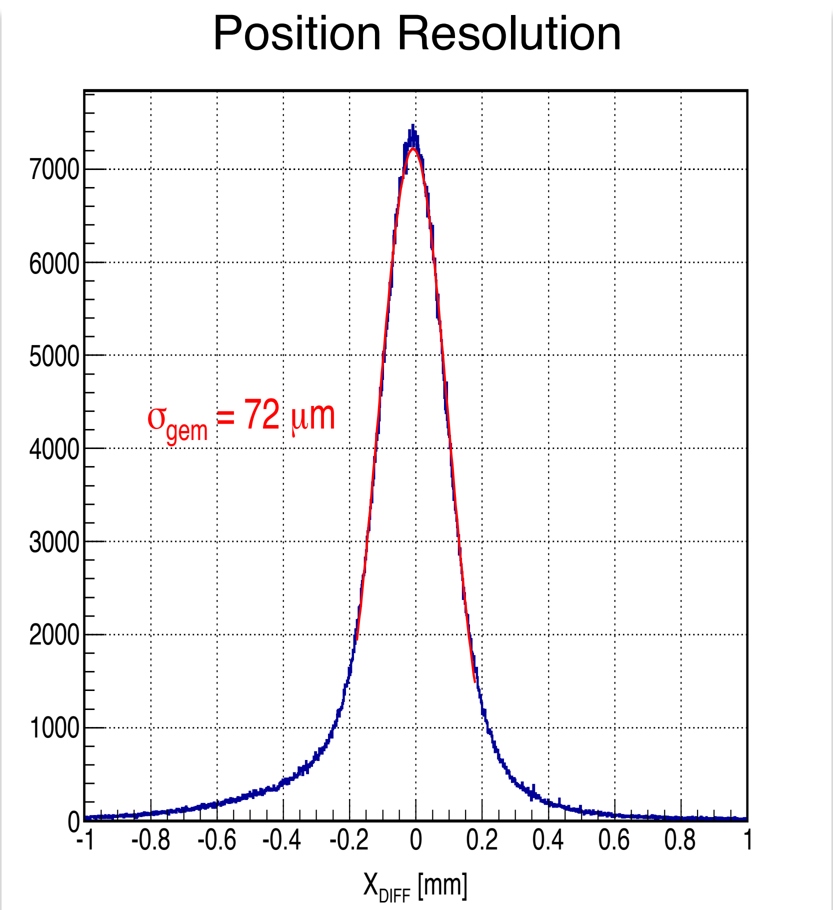


Plots courtesy of M. Levillain

Performance of GEM Detectors

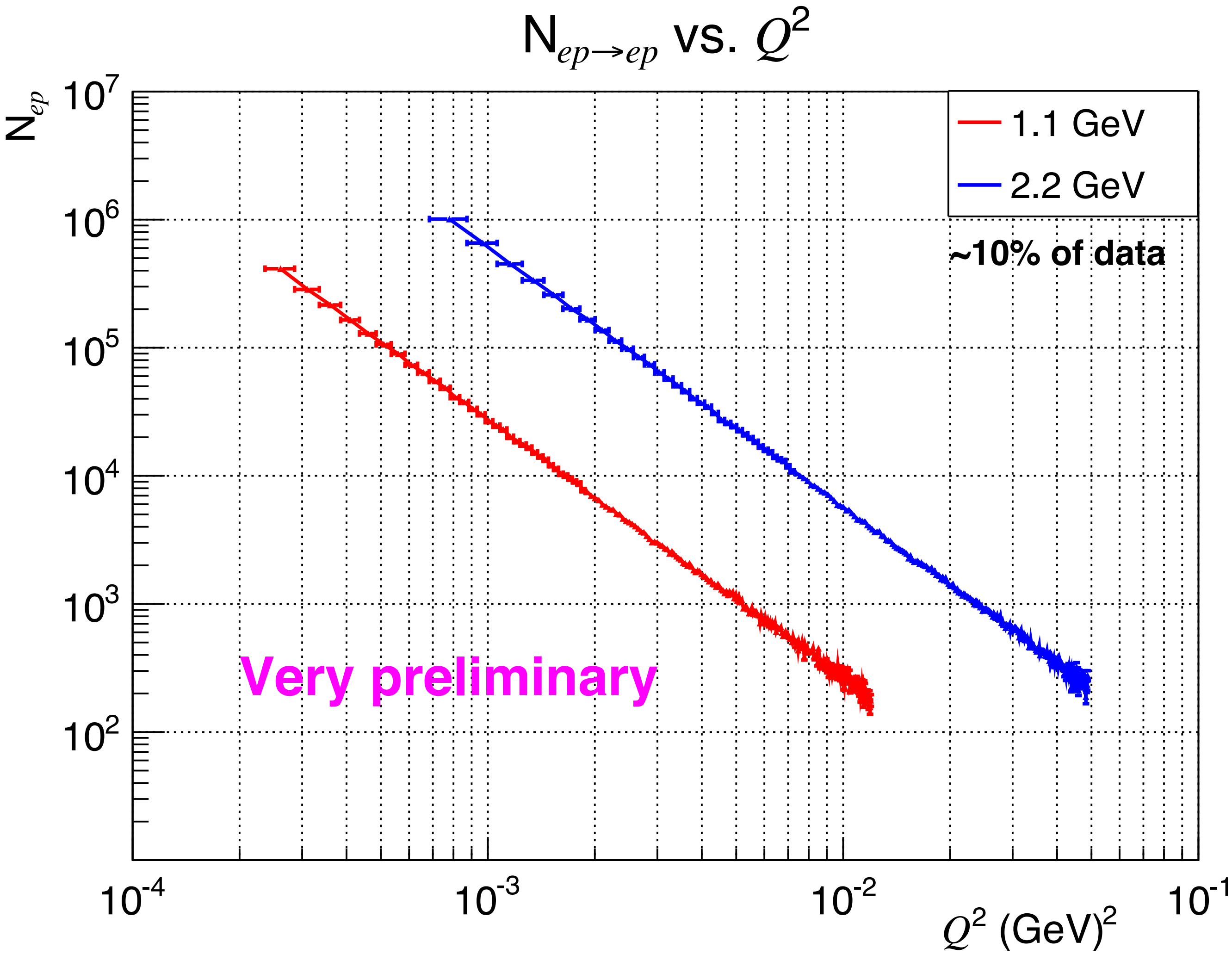
- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (*ep* and *ee*)
- Using overlap region of GEMs to measure position resolution (72 μm)





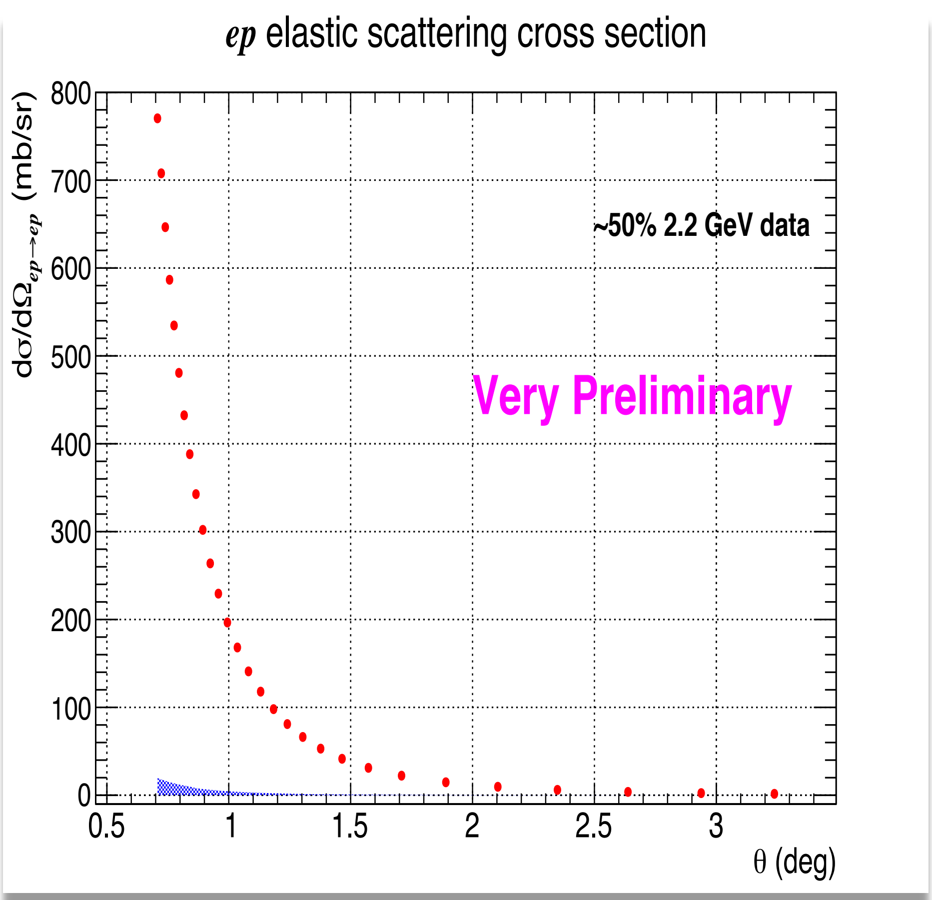
Plots courtesy of X. Bai

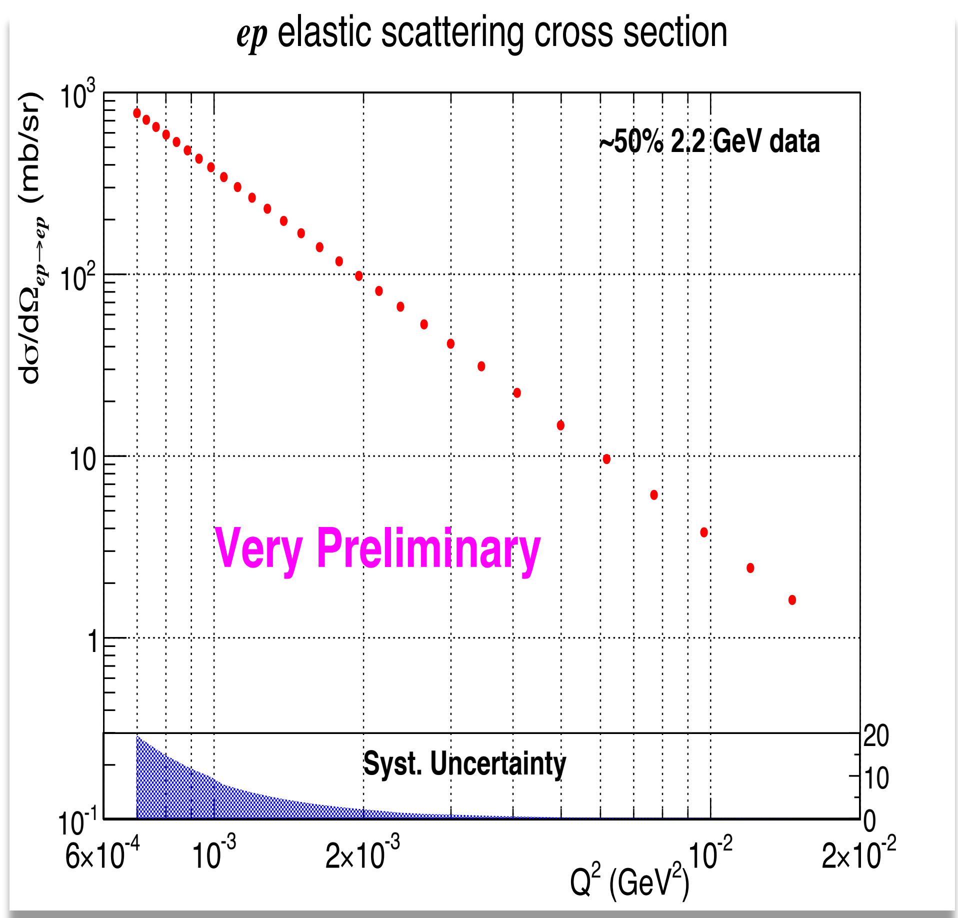
Preliminary Results:



Preliminary Elastic *ep* Cross Section

- Plots show the extracted differential cross section v.s. scattering angle and Q^2, with 2.2 GeV data in 0.7 ~ 3.5 deg range (very preliminary)
- Statistical error at this stage: ~0.2% per point
- Systematic errors are conservatively assigned at ~2% at current stage (shown as shadow area)



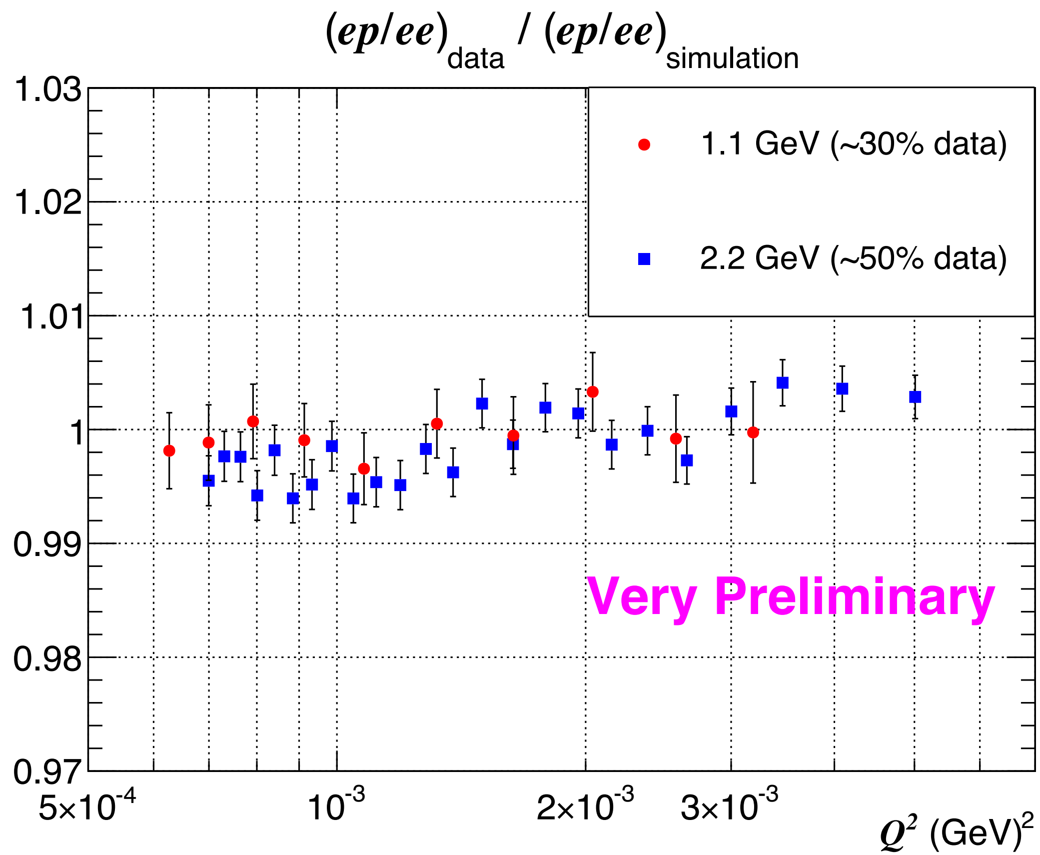


PRad Analysis Status: Event Selection Quality

- Control of background in the PRad experiment.

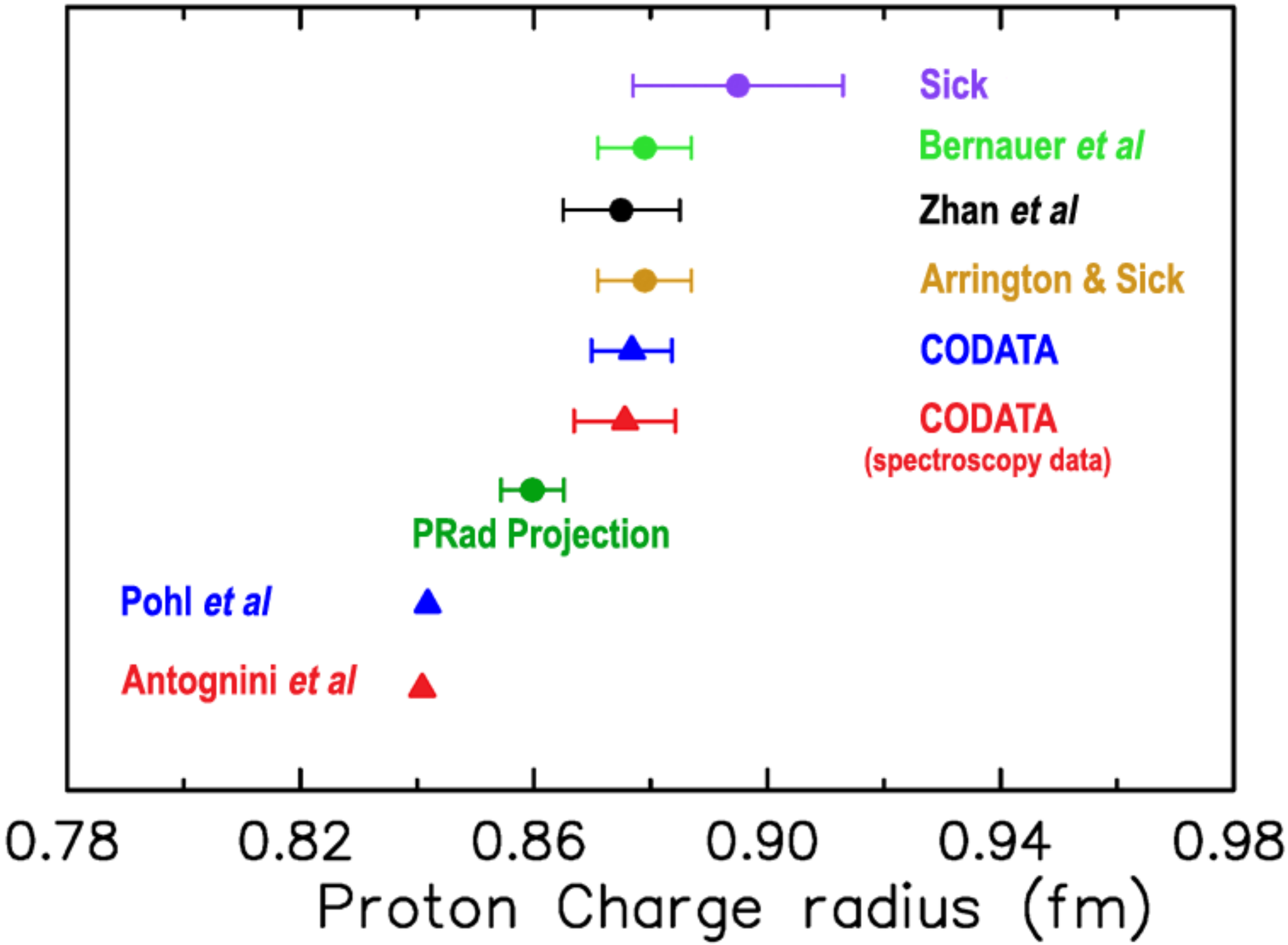
- Consistency of two practically independent measurements (within the ~ 0.2% statistical errors)demonstrates that we control the background, and

PRad will reach its goal of sub-percent extraction of the Proton Radius!!!



for both 1.1 GeV and 2.2 GeV

PRad Projected Result with world data



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 cross section results (partial data) announced in June 2017
- Preliminary radius result is anticipated in the fall 2017 –Stay tuned!

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