Proton Charge Radius

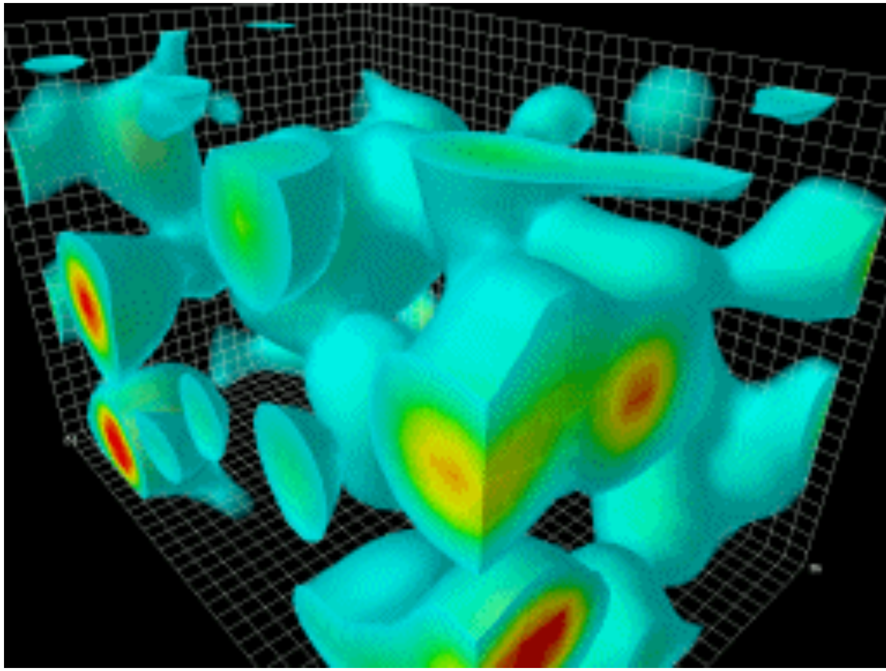
7[th] Workshop on Hadron Physics in China and Opportunities Worldwide

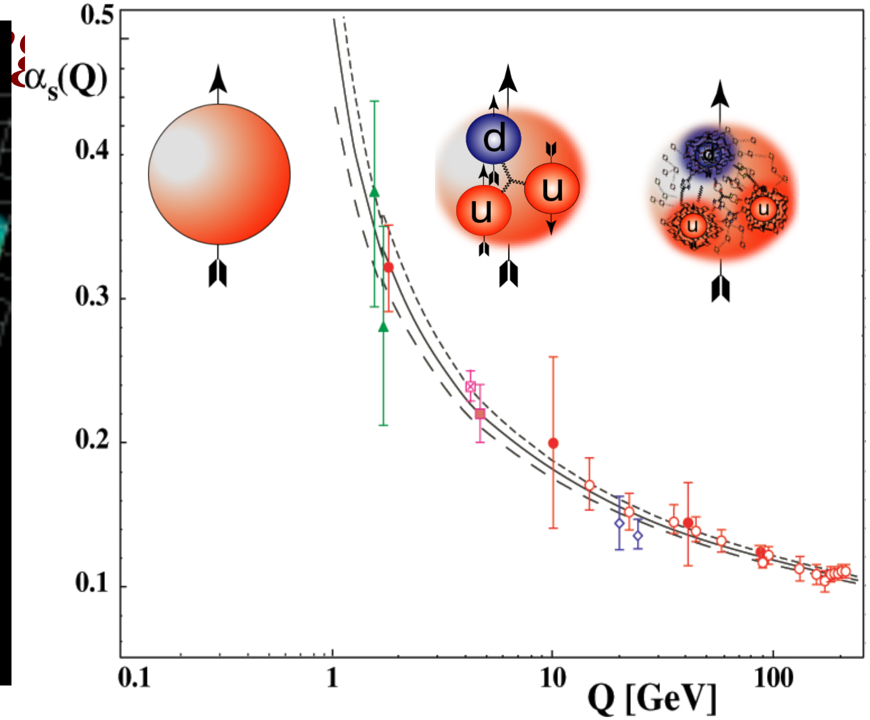
Kunshan, August 3-7, 2015

Haiyan Gao

Duke University and Duke Kunshan University

QCD: still unsolved in non-perturbative





Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom''*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

What is inside the proton/neutron?

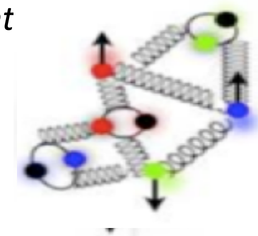
1933: Proton's magnetic moment

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

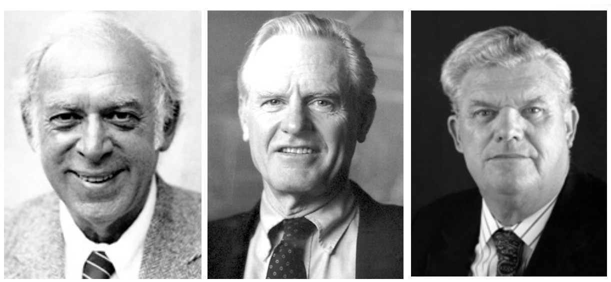
Nobel Prize
In Physics 1961

Robert Hofstadter

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

Form factors $\rightarrow$ 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

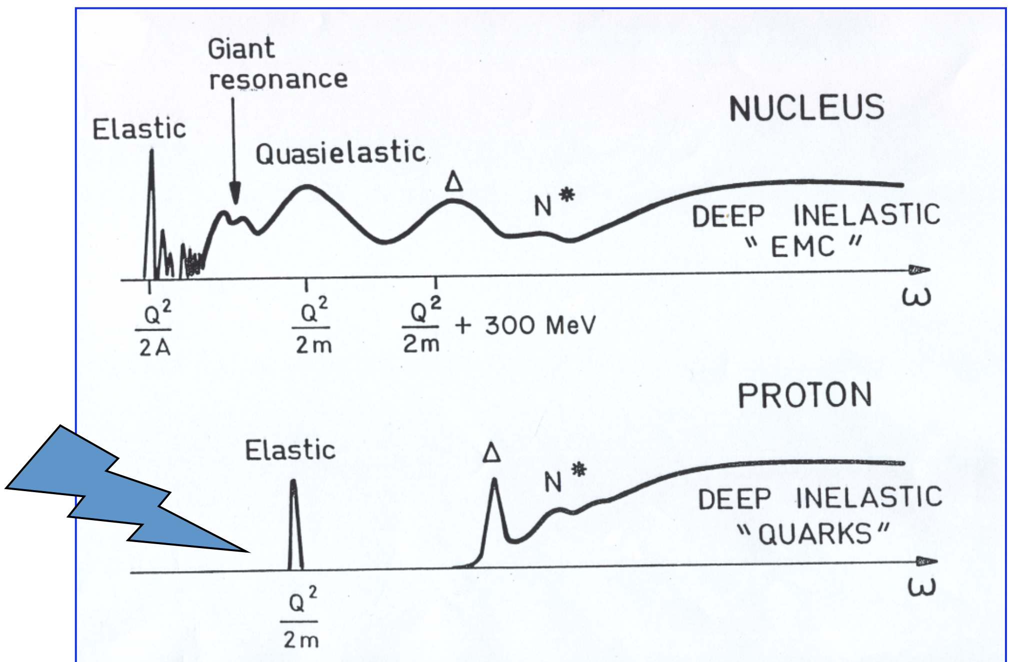
"for the discovery of asymptotic freedom in the theory of the strong interaction".

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- ***Vary probe wave-length to view deeper inside***

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

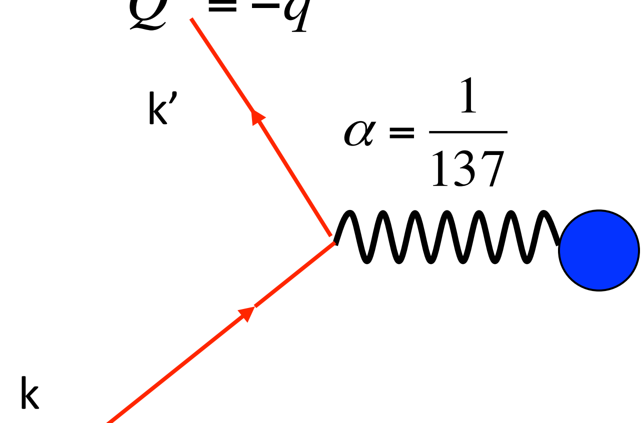
$$\tau = -q^2 / 4M^2$$



Virtual photon 4-momentum

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

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



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

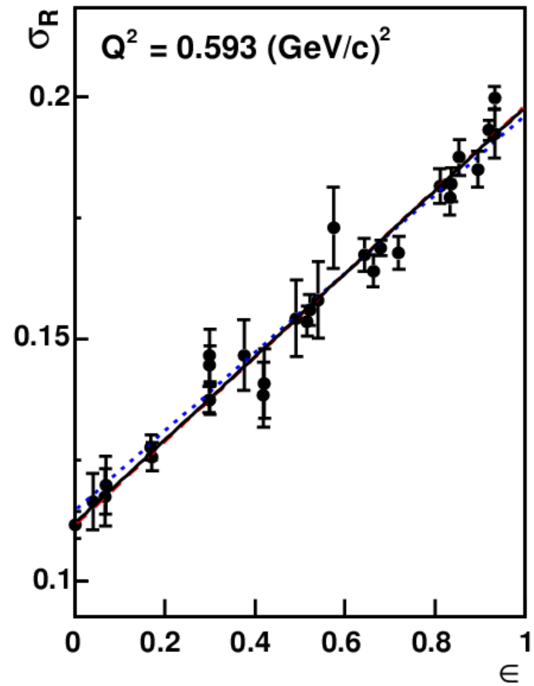
Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section

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

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

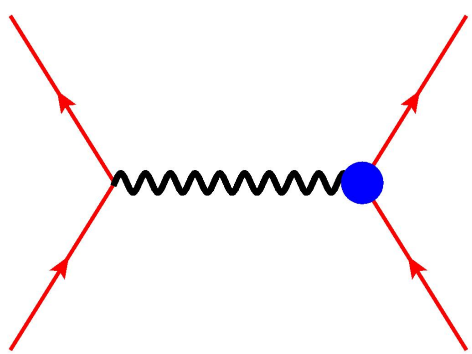


$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

- 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**

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

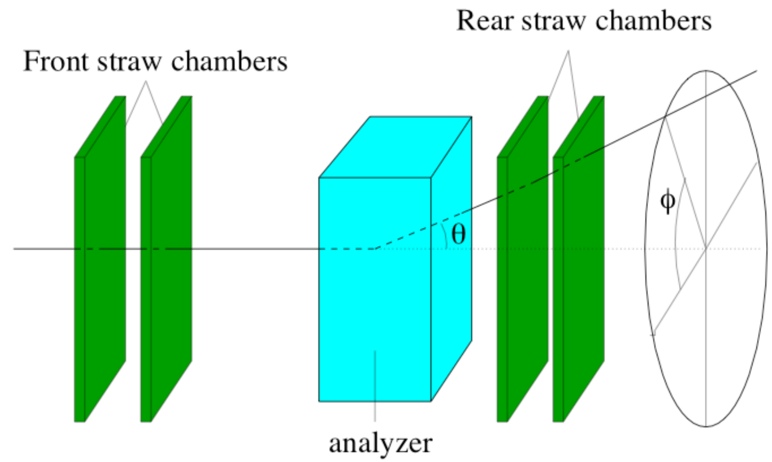
$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$



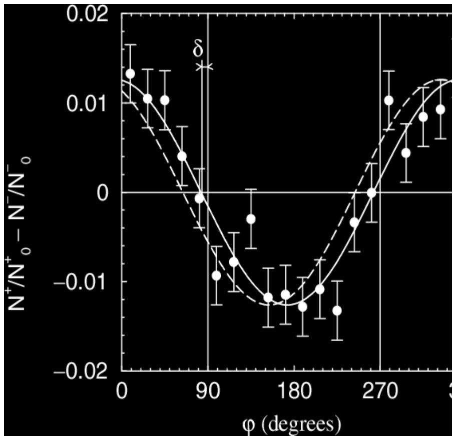
super Rosenbluth Separation (Jlab Hall A experiment)

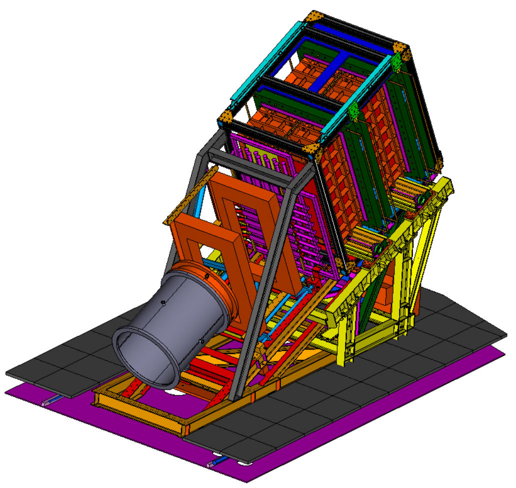
Recoil proton polarization measurement from e-p elastic scattering

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



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





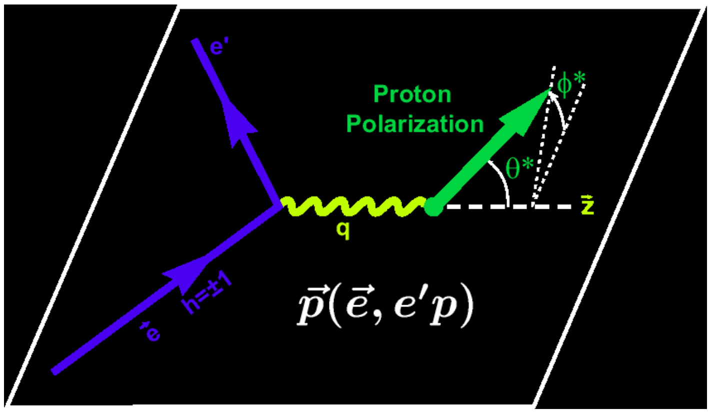
Focal-plane polarimeter

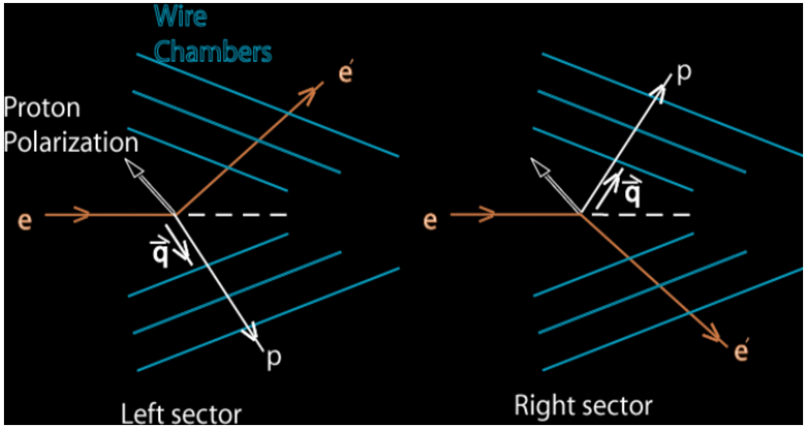
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

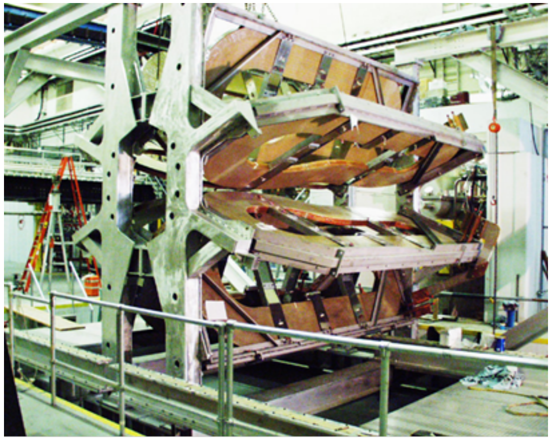
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





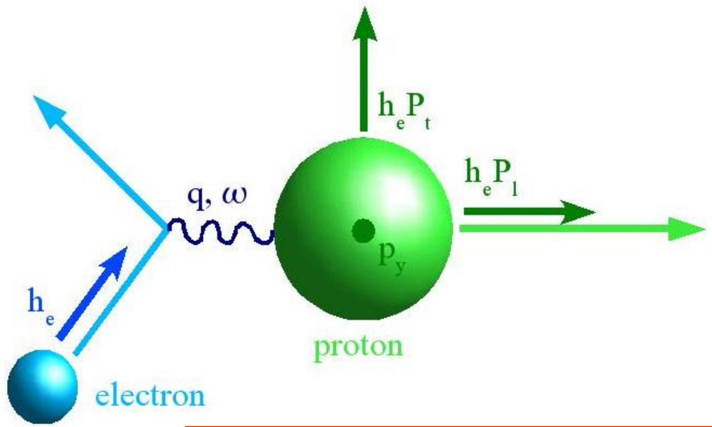
- Super-ratio

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

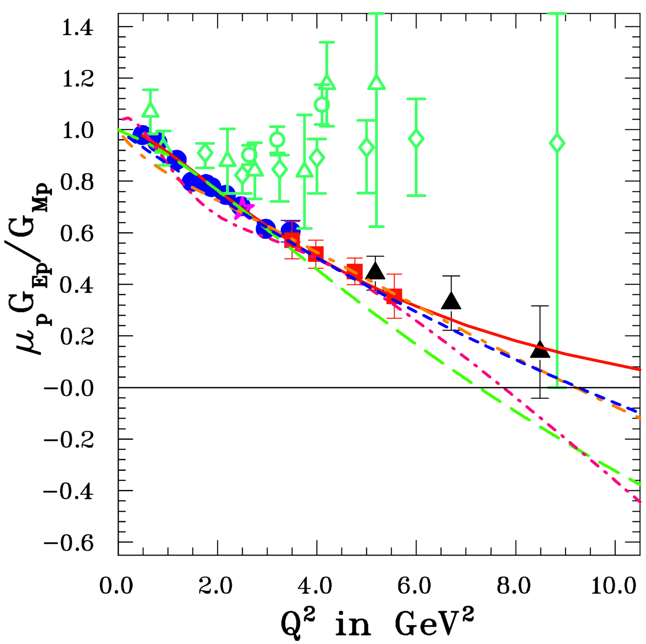


BLAST pioneered this technique, later also used in Jlab Hall A experiment

Tremendous advances in electron scattering



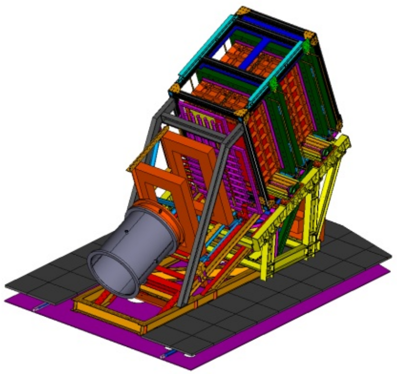
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M}\tan(\frac{\theta_e}{2})$$



Unprecedented capabilities:

- High Intensity and duty factor
- High quality polarized beams
- Large acceptance detectors
- State-of-the-art polarimetry, polarized targets

Polarized ^{3}He target



Focal plane polarimeter – Jefferson Lab

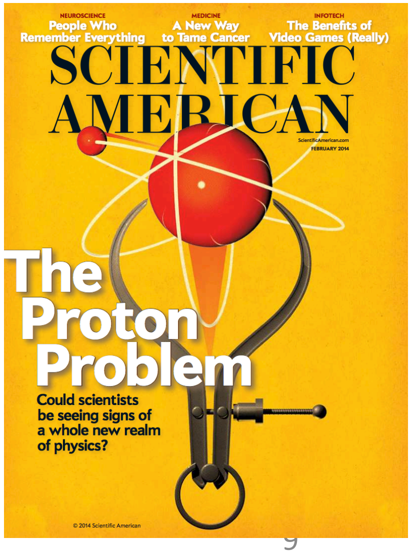
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - An important input to bound state QED calculations, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%

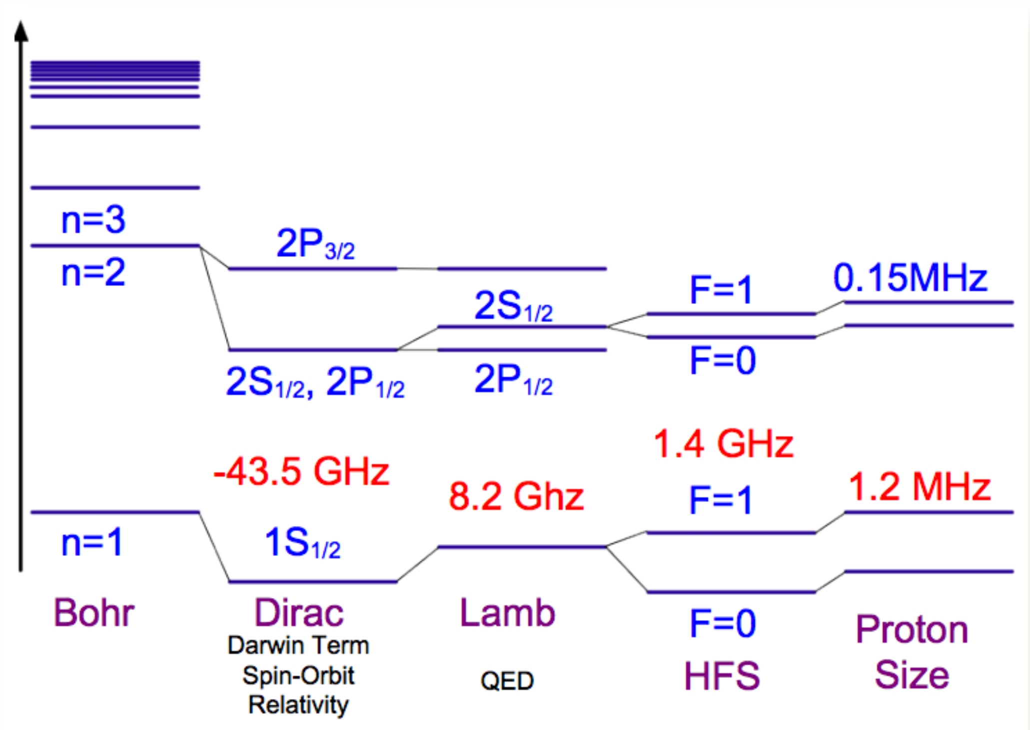
- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

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

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



Hydrogen Spectroscopy



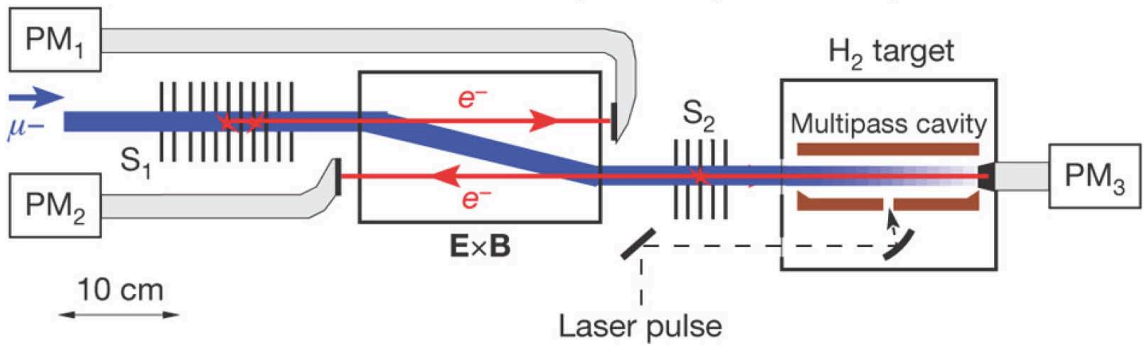
The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in 10^{14} via comparison with an atomic cesium fountain clock as a primary frequency standard.

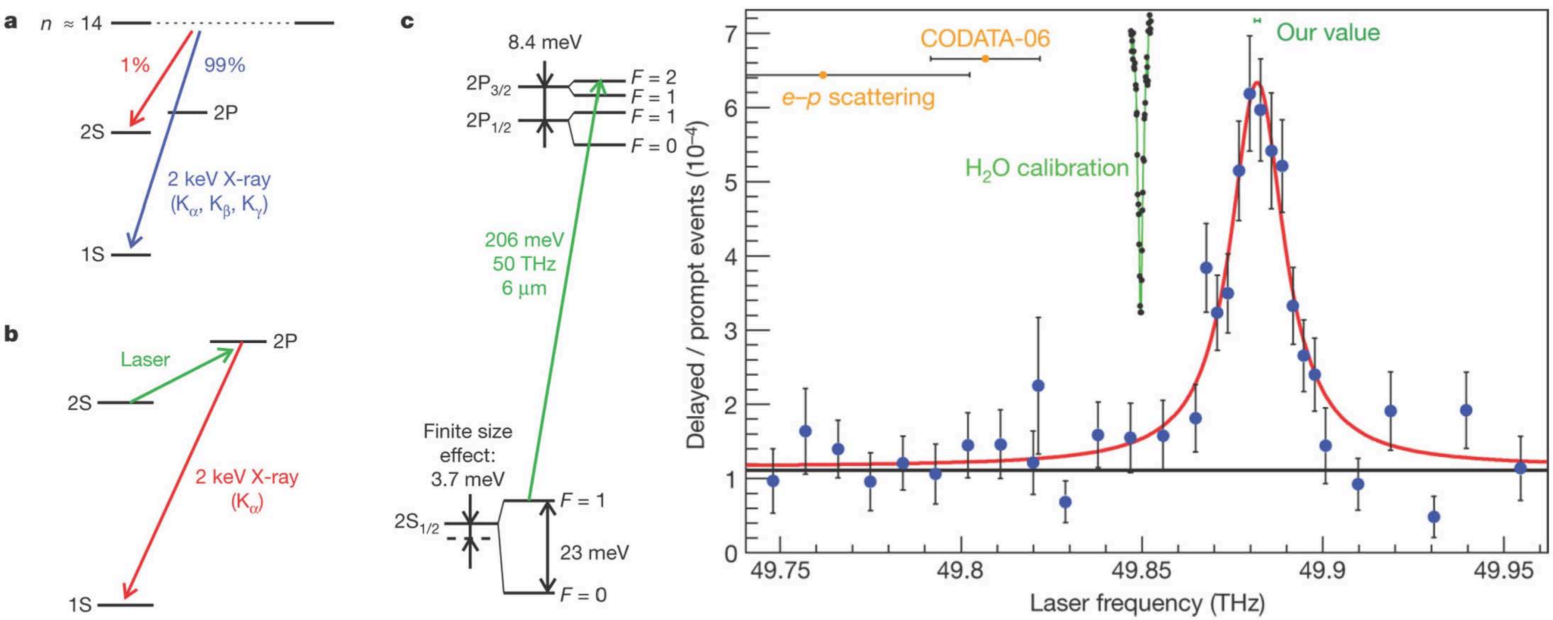
Yields R_∞ (the most precisely known constant)

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

Muonic hydrogen Lamb shift at PSI (2010, 2013)

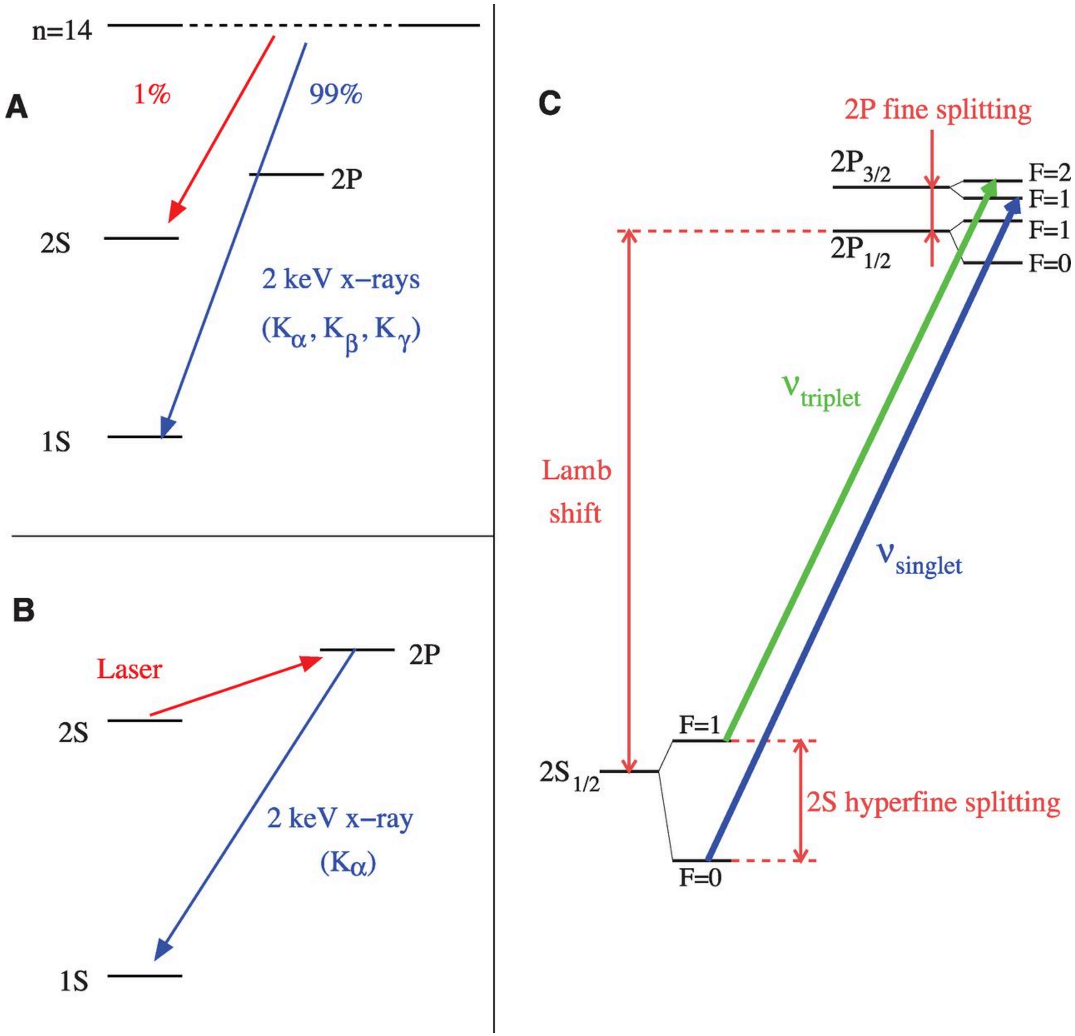
Nature **466**, 213-216 (8 July 2010)





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

New PSI results reported in Science 2013

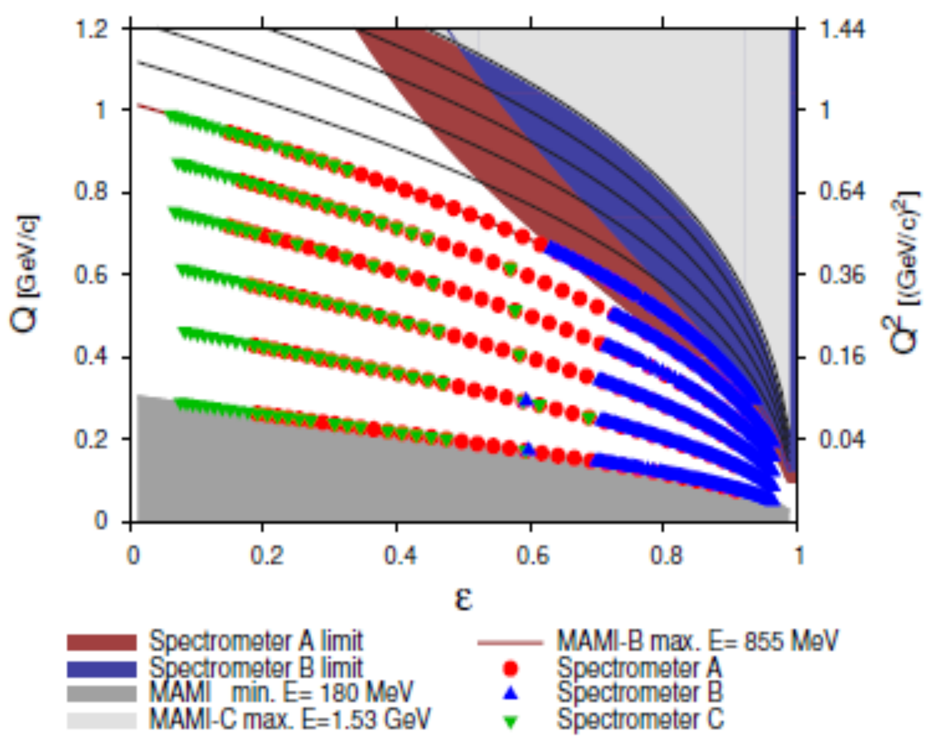


r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



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

- $Q^2 = 0.004 – 1.0\ (GeV/c)^2$

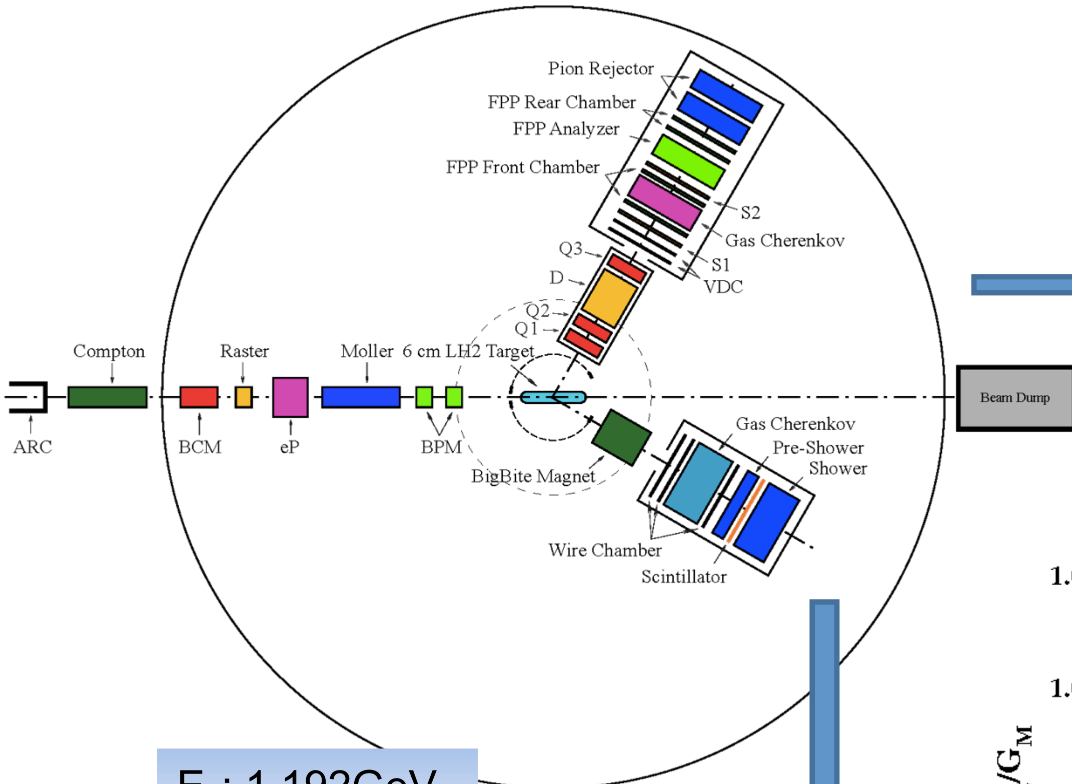
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

Jlab Recoil Proton Polarization Experiment



LHRS

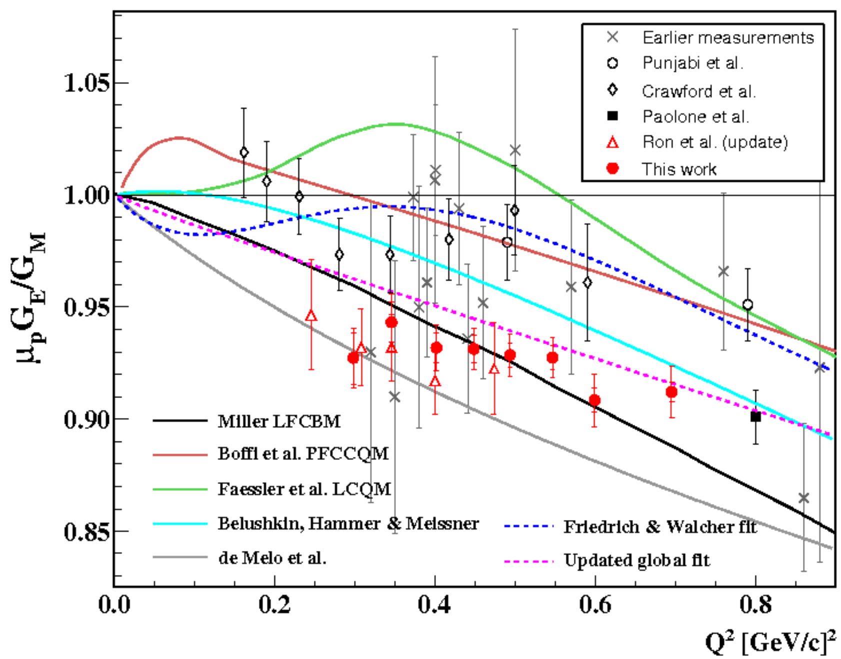
- Δp/p0: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7msr
- QQDQ
- Dipole bending angle 45^o
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

BigBite

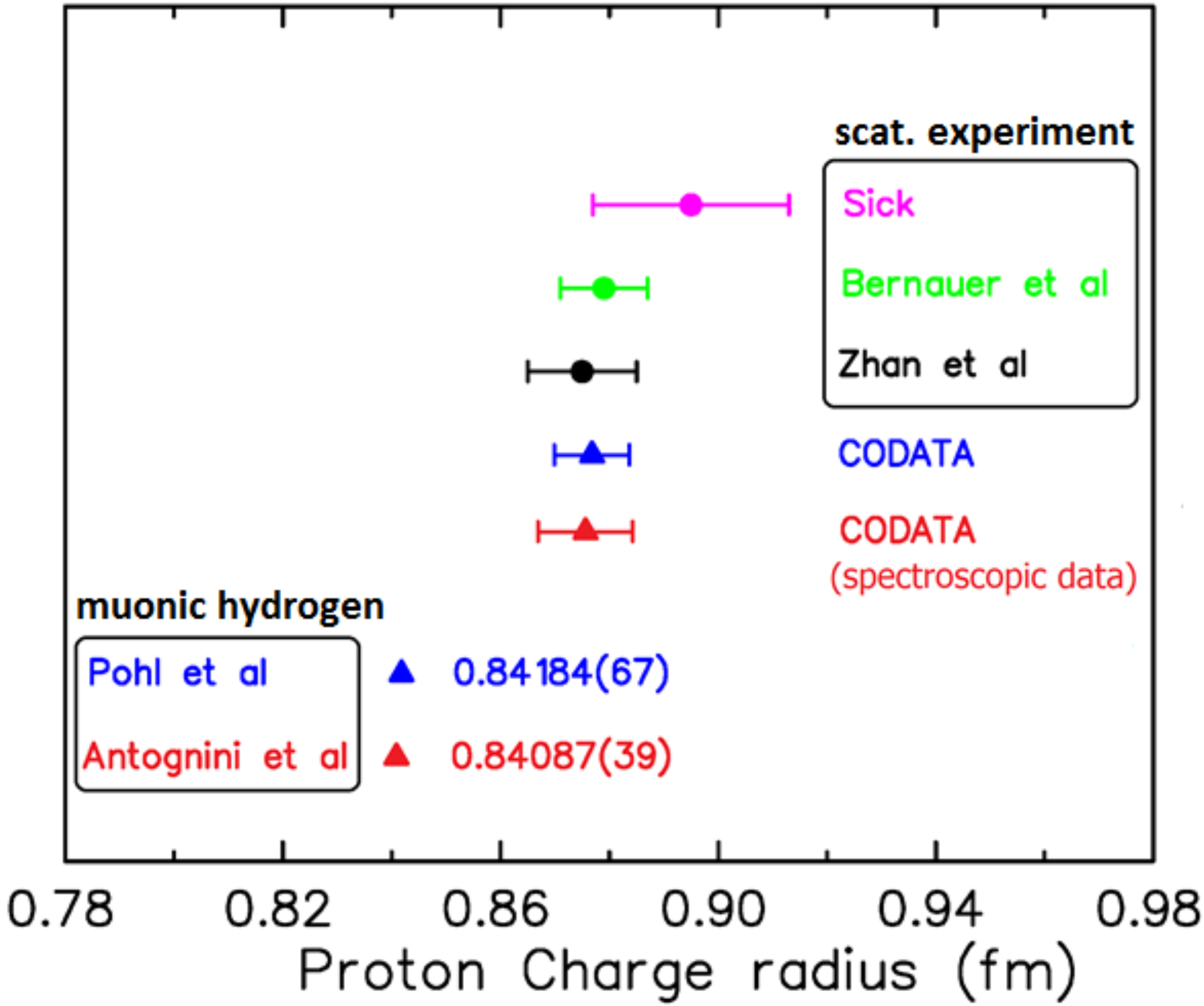
- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - ΔΩ: 96msr
- PS + Scint. + SH

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)

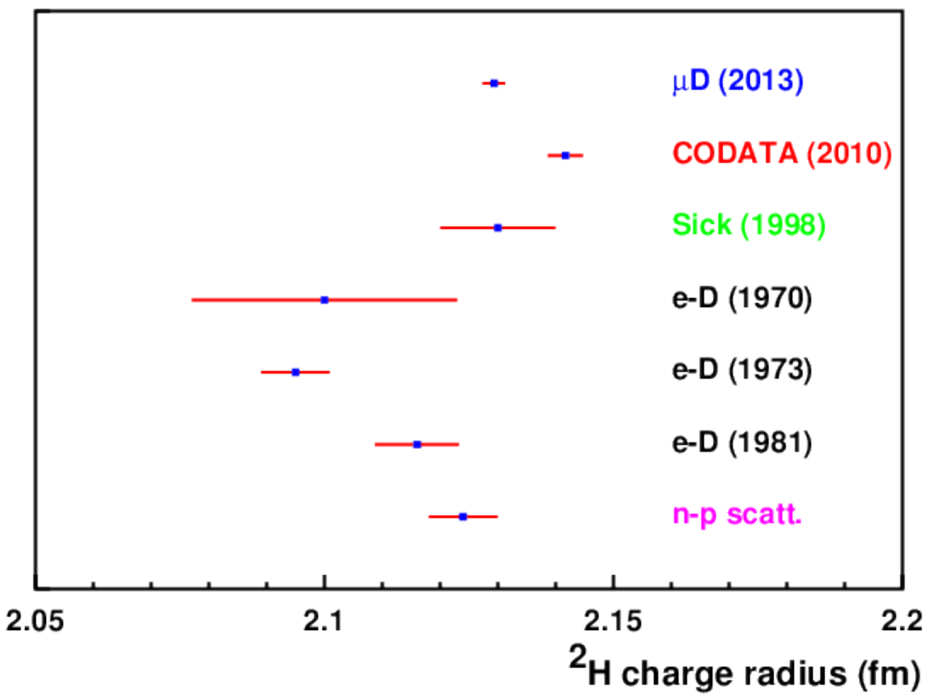
The proton radius puzzle intensified



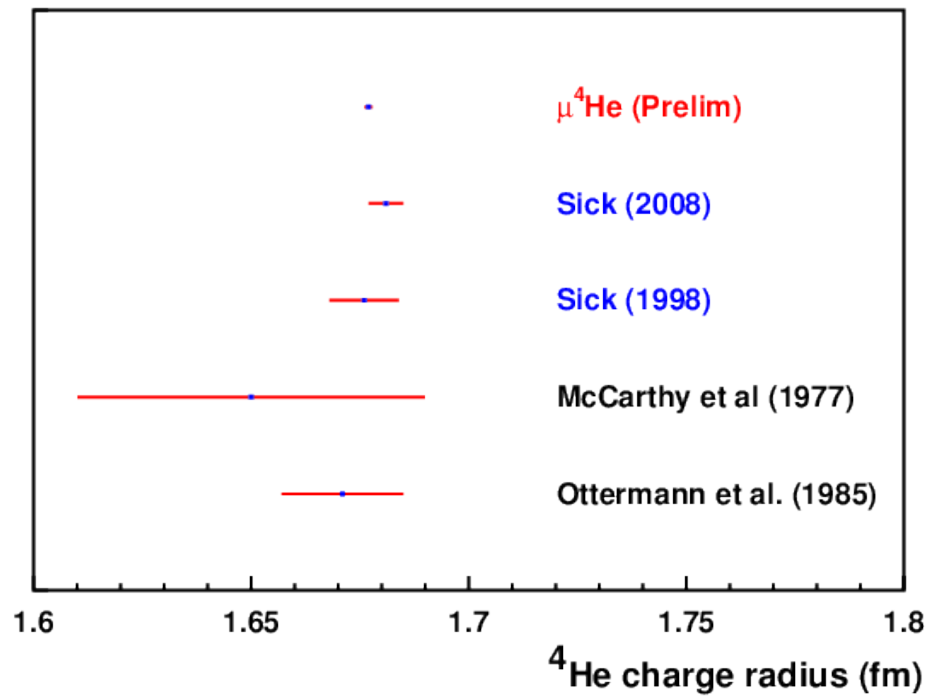
r_p = 0.879(11) fm by Arrington and Sick (2015) from reanalysis of ep data

Charge Radius of Other Light Nuclei

Deuterium



Helium



Electron scattering consistent with μ-spectroscopy

Revisits of 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

Incomplete list

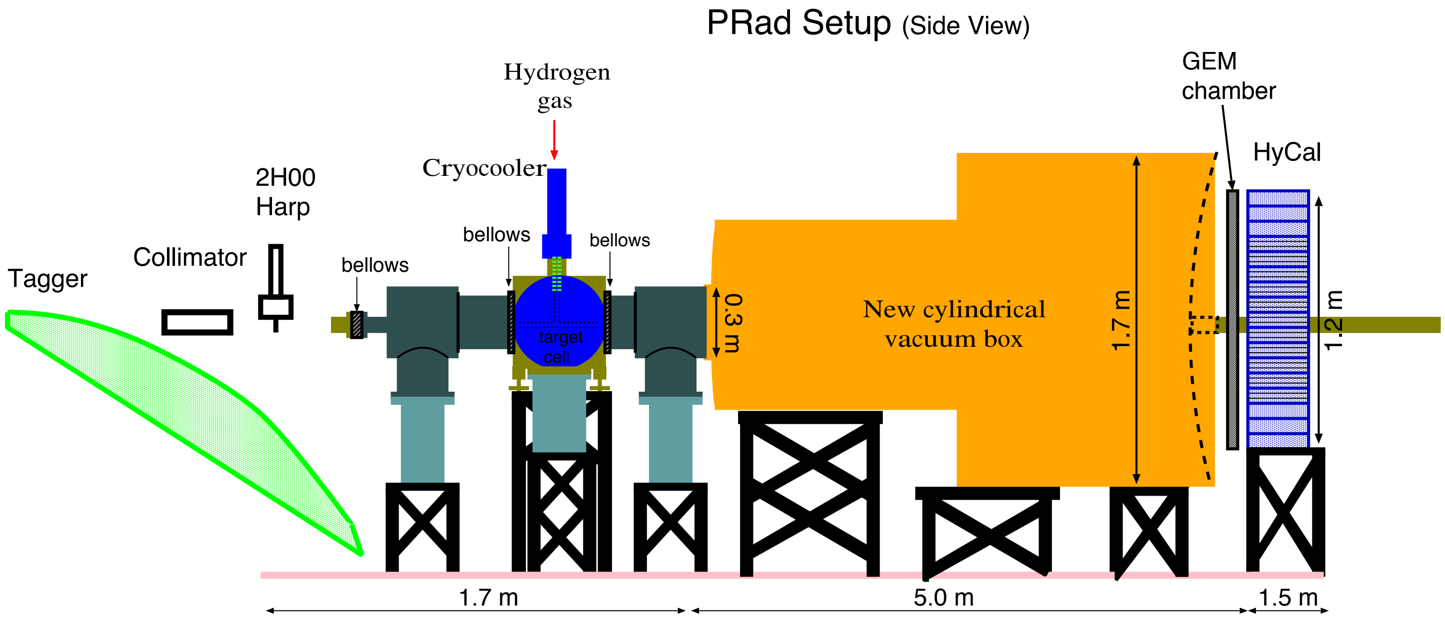
- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….

  New PV muonic force, Batell et al.; Carlson and Freid; 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,….
- 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**

PRad Experimental Setup in Hall B at JLab

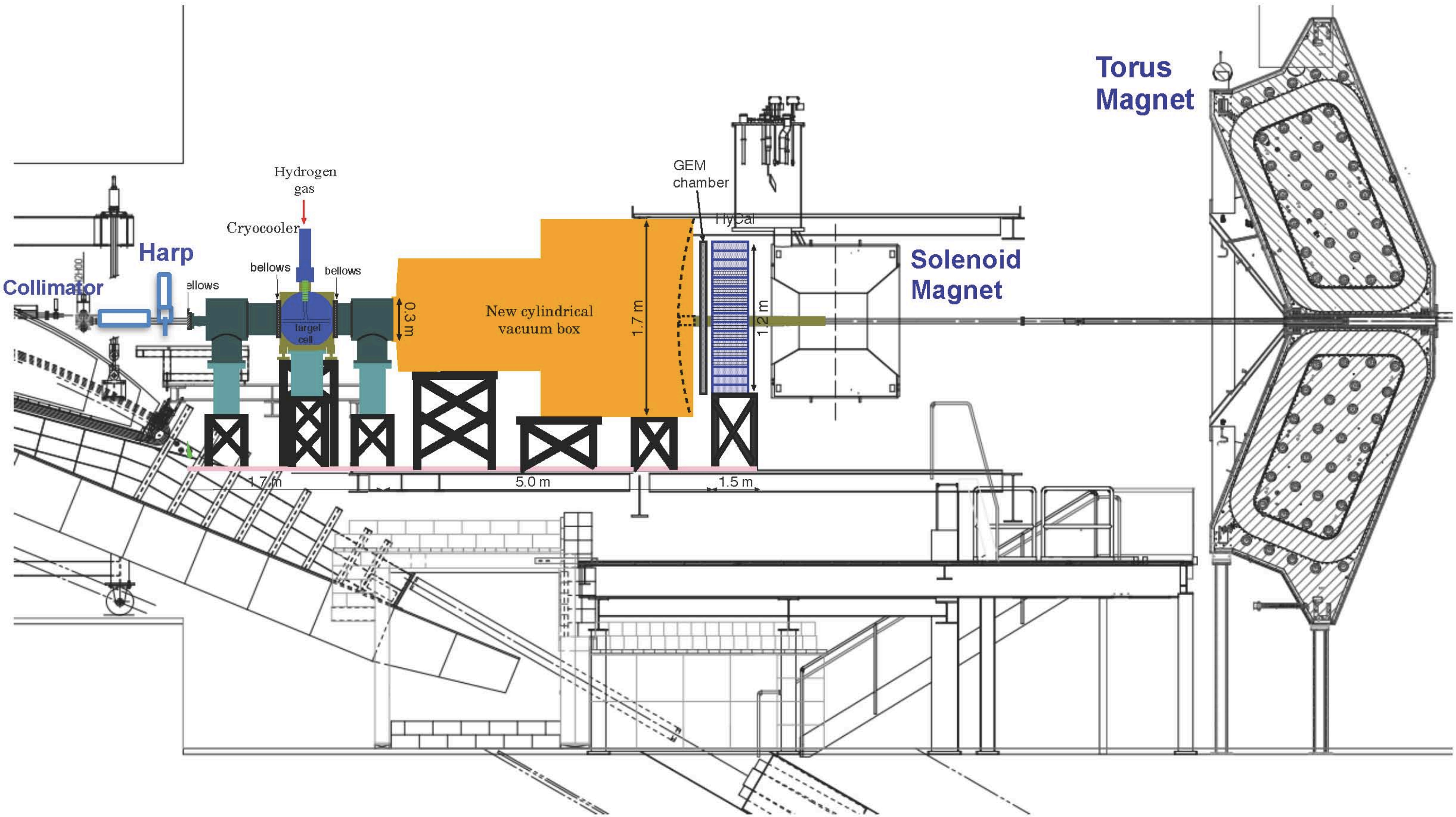


- **High resolution, large acceptance calorimeter**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **GEM detectors**
- **Q^2 range of $2x10^{-4}$ – 0.14 GeV^2**

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

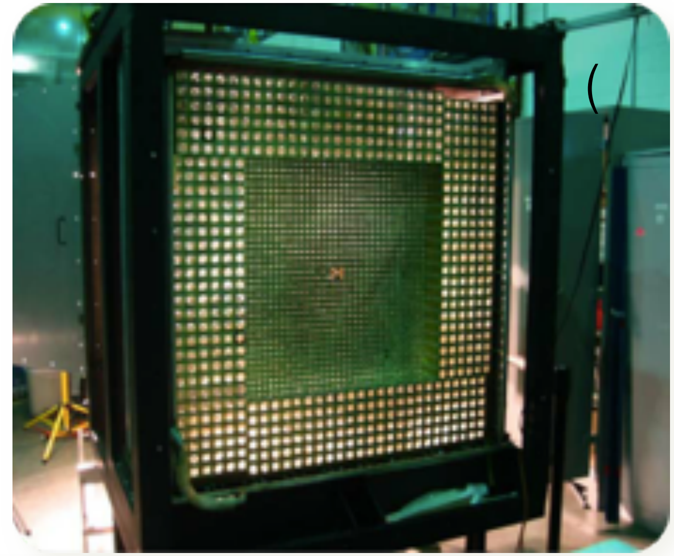
PRad Running Setup

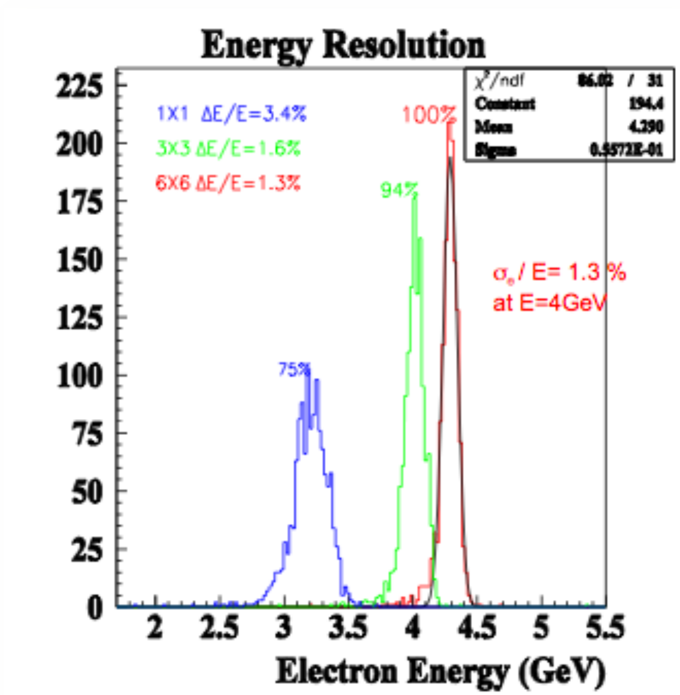


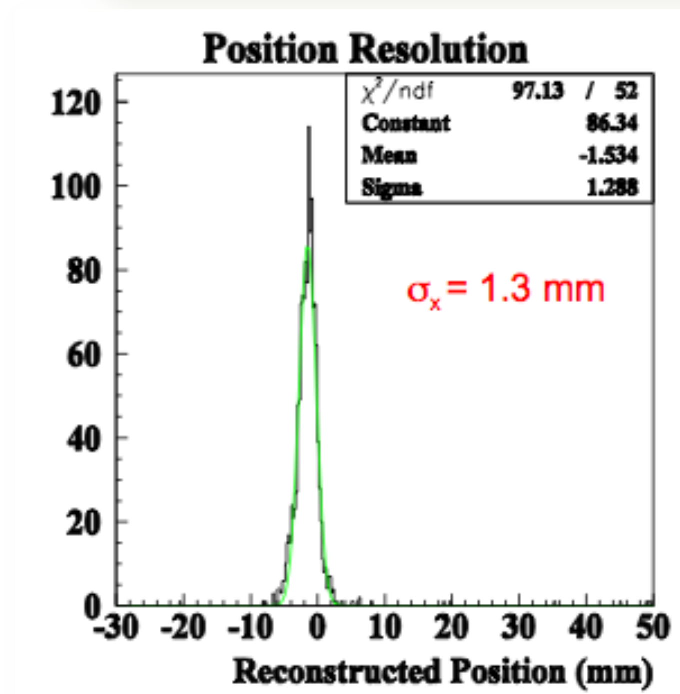
Distance: 2H00 wire harp to Solenoid support frame ~13.7 m

High Resolution Calorimeter

- HyCal is a $PbWO_4$ and Pb-glass calorimeter
- 2.05 x 2.05 cm^2 x18 cm (20 rad. Length)
- 1152 modules arranged in 34x34 matrix
- ~5 m from the target,
- 0.5 sr acceptance

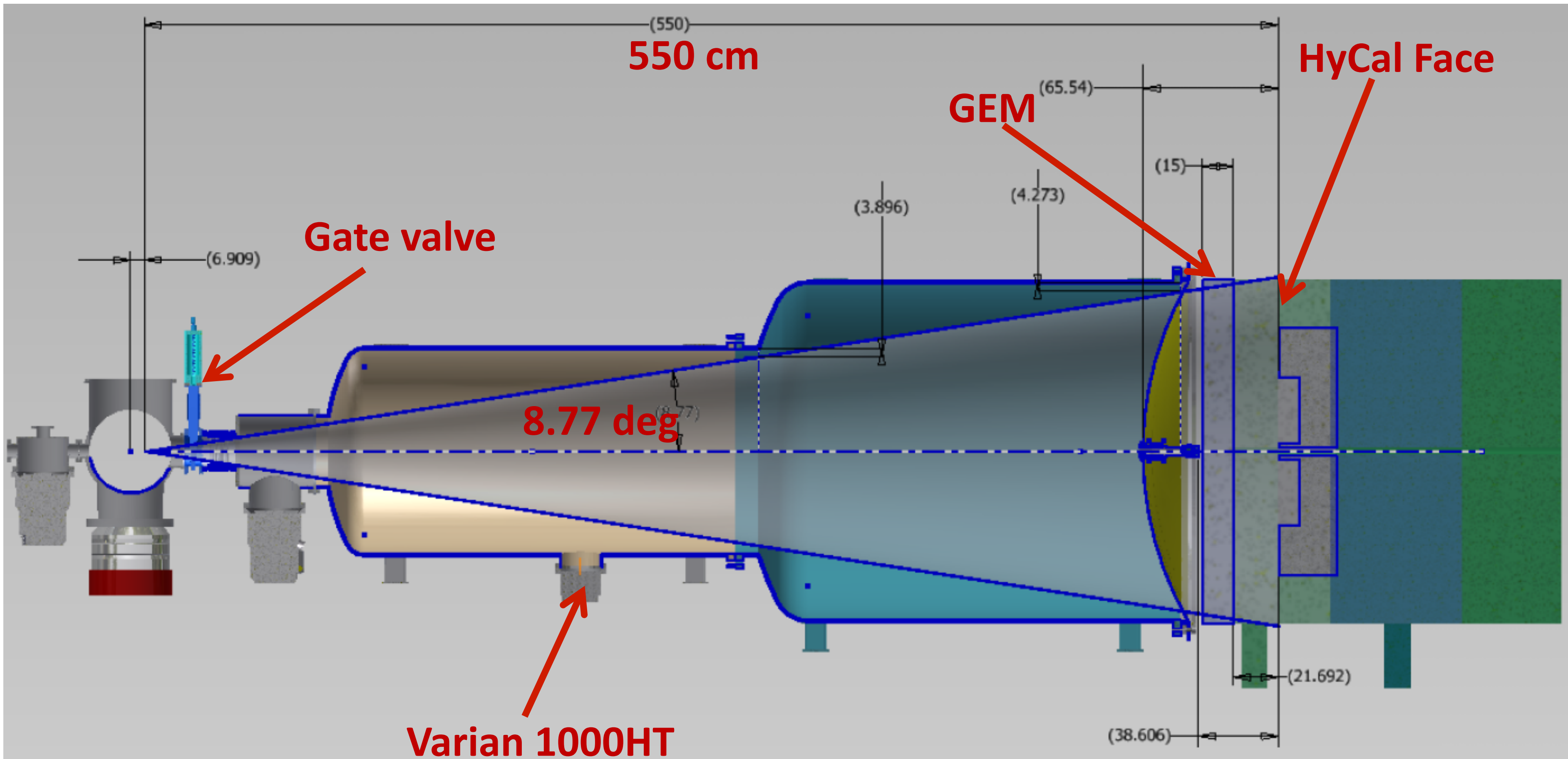






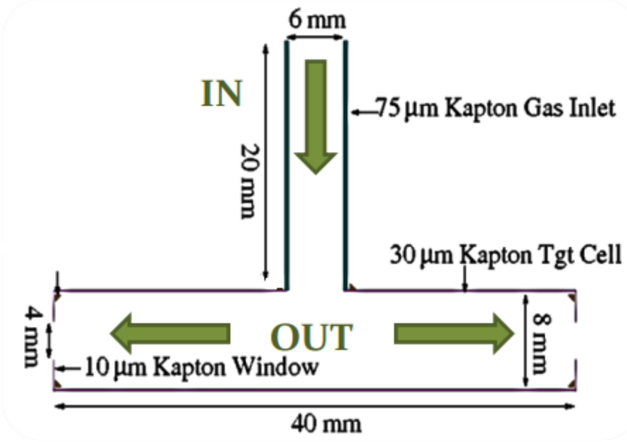
Vacuum Box and GEM

Two-cylinder design for vacuum box
GEM detector to replace veto counter to improve Q2 resolution (particularly with using lead blocks)



▪ **GEM detector funded by DOE**

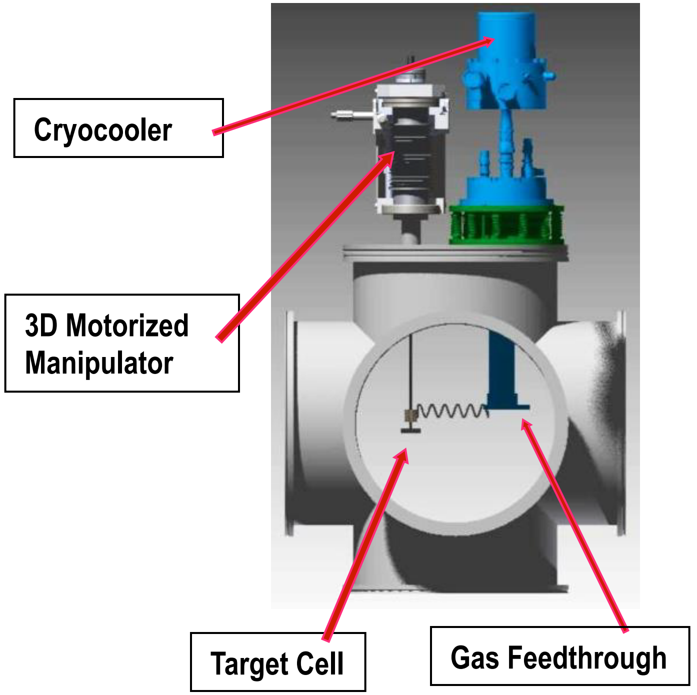
Windowless H_2 Gas Flow Target



- **Target cell (original design):**
  - cell length 4.0 cm
  - cell diameter 8.0 mm
  - cell material 30 µm Kapton
  - input gas temp. 25 K
  - target thickness 1×10^{18} H/cm^2
  - average density 2.5×10^{17} H/cm^3
  - gas mass-flow rate 6.3 Torr-l/s ≈ 430 sccm

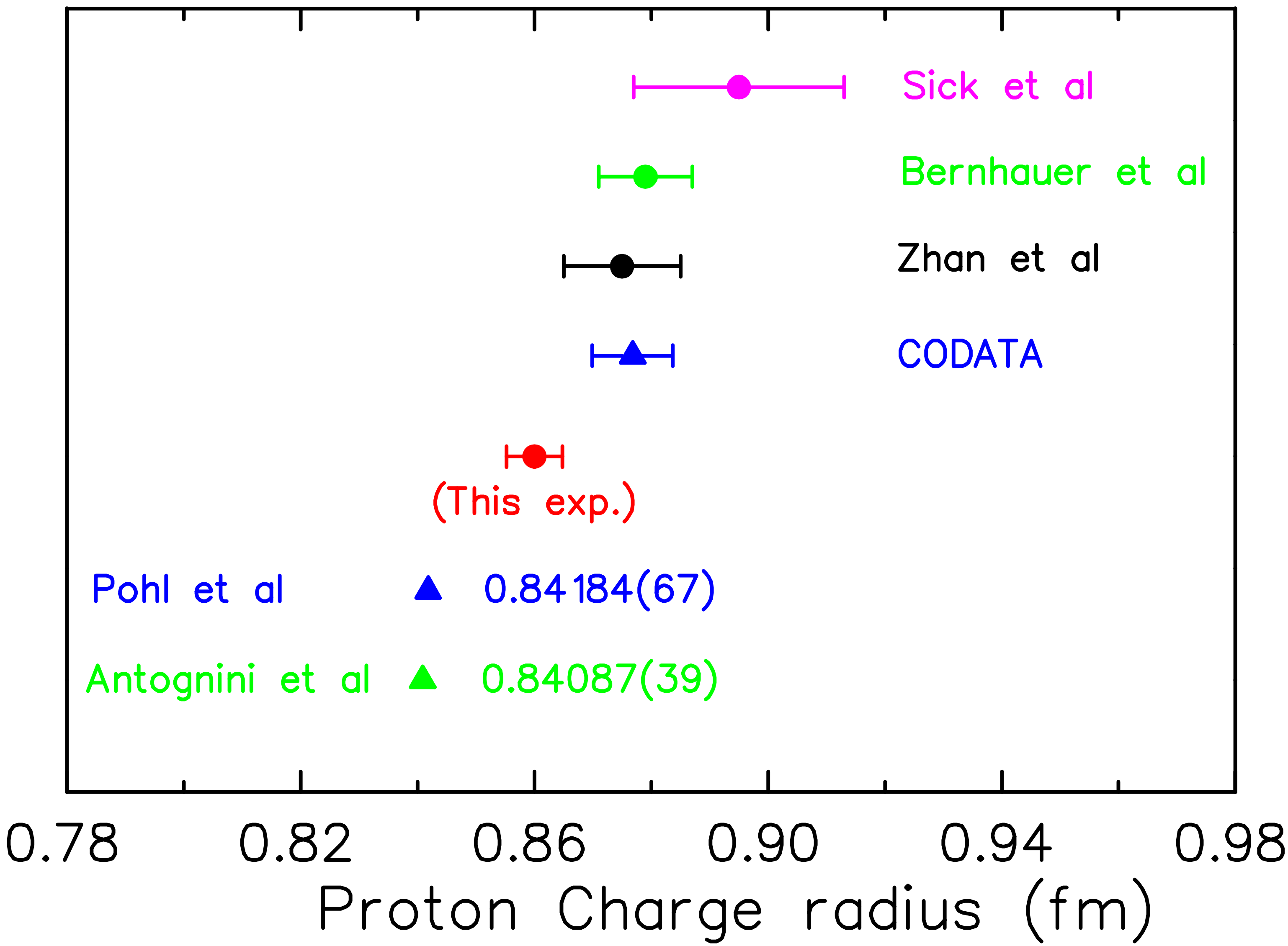
- **Target components:**
  - pumping system
  - cryocooler
  - motorized Manipulator
  - chillers for pumps and cryocooler
  - Target and secondary chambers

- **Kapton cell**

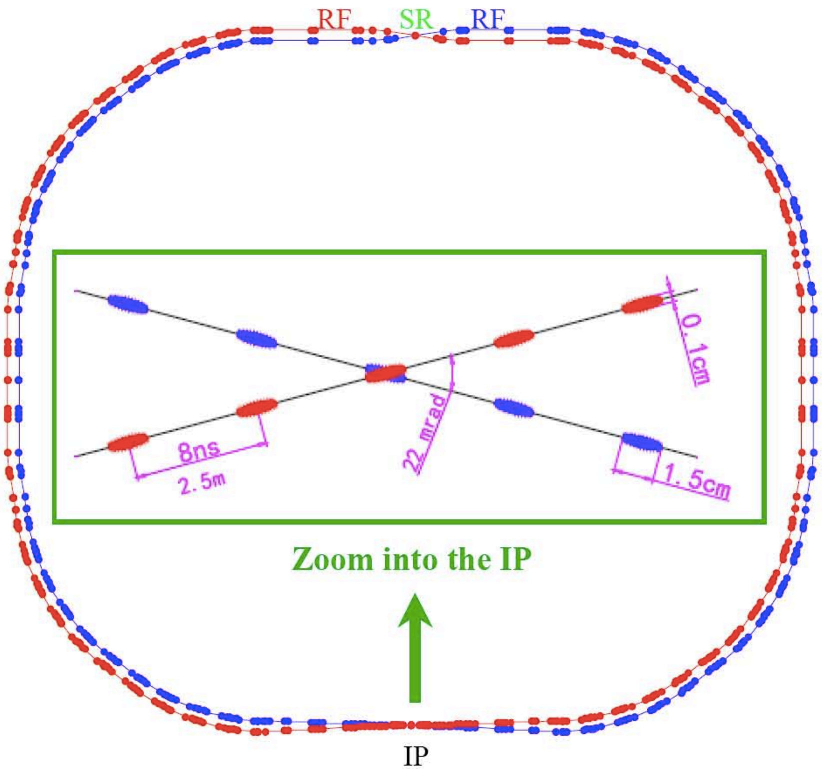


Target supported by NSF - MRI grant and is complete

PRad Projected Result



The BEPCII electron-positron double storage rings



Beam energy:	1.0-2.3 GeV
Design Luminosity:	1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:	1.89 GeV
Energy spread:	5.16×10^{-4}
No. of bunches:	93
No. e^+ or e^-/bunch	4.5×10^{12}
Bunch length:	1.5 cm
Bunch distance	2 m
Beam size σ_x/σ_y	380/5.7 μm
Current/bunch	9.8 mA
Total current:	0.91 A
Circumference:	237m
Injection rate for e+	50 mA/s
Injection rate for e-	200 mA/s

Only running experiment: BESIII
Start data taking: 2009
Estimated end of BESIII life time: 2022
Can we do more experiments with BEPCII?

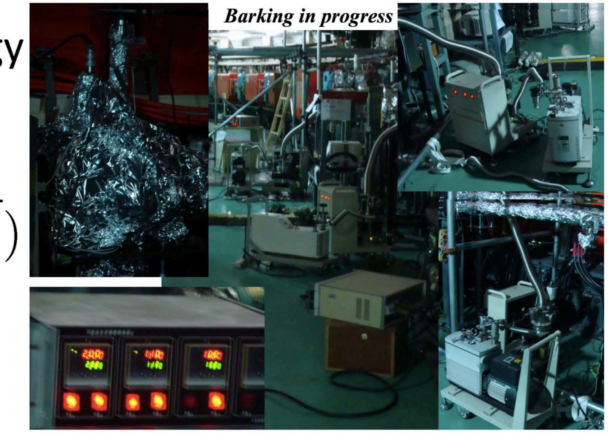
PRad at BEPCII?

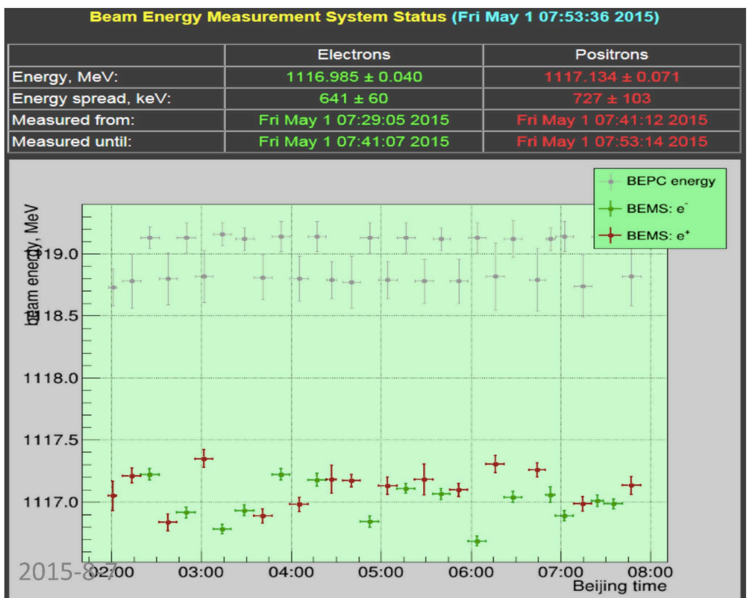
Beam energy measurement

- Reconstruction of the beam energy from an energy spectrum of laser photons backscattered on beam particles:

$$E_{beam} = \frac{\omega_{max}}{2} \times \left(1 + \sqrt{1 + m_e^2/\omega_0\omega_{max}}\right)$$

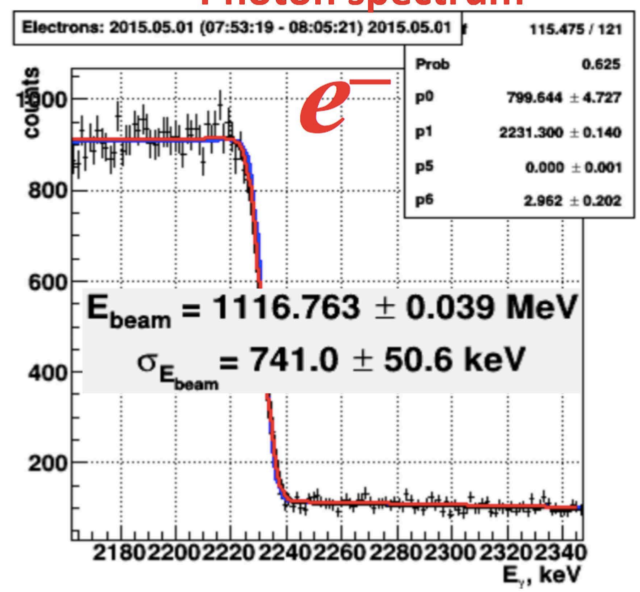
- Achieved accuracy is $\Delta E/E \approx 4 \times 10^{-5}$
- This allows us to tune the BEPCII operation regimes, to monitor the beam energy, and to apply corrections during data analysis .




Beam Energy Measurement System Status (Fri May 1 07:53:36 2015)

	Electrons	Positrons
Energy, MeV:	1116.985 ± 0.040	1117.134 ± 0.071
Energy spread, keV:	641 ± 60	727 ± 103
Measured from:	Fri May 1 07:29:05 2015	Fri May 1 07:41:12 2015
Measured until:	Fri May 1 07:41:07 2015	Fri May 1 07:53:14 2015

Photon spectrum



Summary

- Proton charge radius puzzle still unresolved awaiting new results
- The PRad Experiment at Jefferson Lab will be ready to take data by the end of 2015
- Potential opportunities: Mainz, and BEPII?
- Stay tuned

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