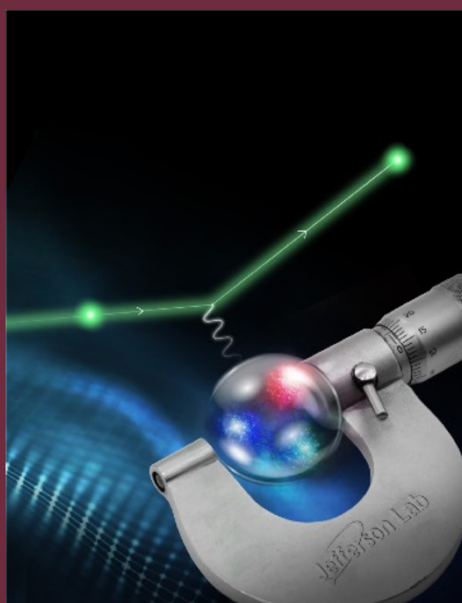
The Incredible Shrinking Proton and the PRad Experiment

Dipangkar Dutta

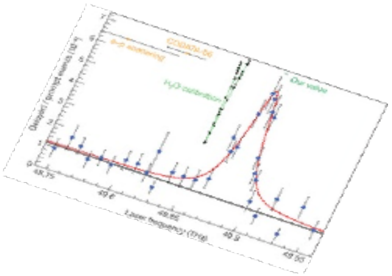
MISSISSIPPI STATE

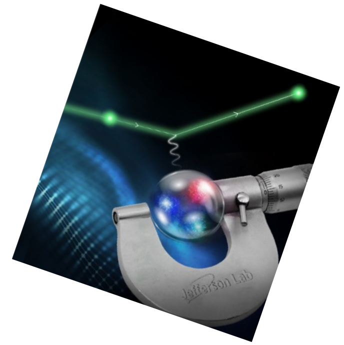


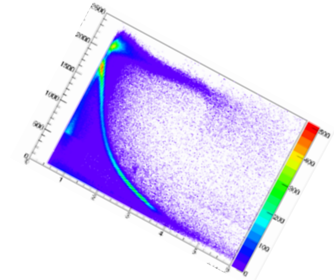
Jefferson Lab
Exploring the Nature of Matter

JLUO Meeting, June 22, 2020

Outline







- Introduction
- The Proton Charge Radius Puzzle
- A Novel Experiment (PRad) & Results
- Other Experiments & Future Prospects

PRoton Radius

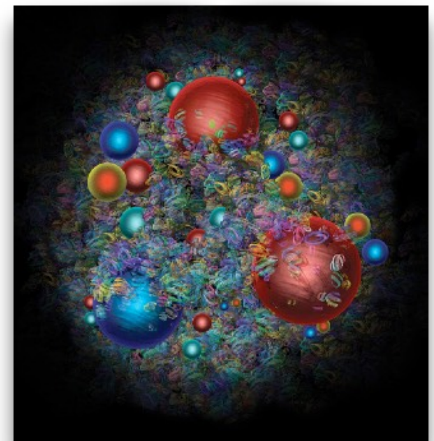
The study of the proton has revolutionized physics

The proton is the primary, stable building block of all visible matter in the Universe.

The proton played a leading role in the development of Quantum Chromo Dynamics (QCD): theoretical framework for strong interaction between quarks medicated by gluons.

In the last 100 yrs. since its discovery, the proton has evolved from

to



Positively charged structure-less point particle

Bag of quarks and gluons, with 99% of Its mass due to the quark gluon interaction (and hence 99% of the visible mass in the Universe).

The story of the proton has been in lock-step with many of the key advances in physics over the last 100 years.

It continues to surprise us time and again.

Proton's basic properties such as its RMS charge radius is interesting on its own right, but also needed for determining fundamental constants such as the Rydberg constant.

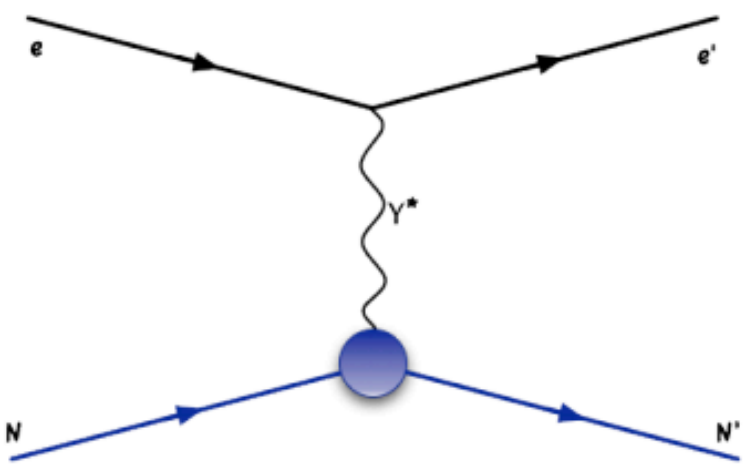
H - spectroscopy and elastic e-p scattering are the two traditional methods for determining proton charge radius

The forces defining the surface of a proton do not come to an abrupt end, its boundary is somewhat fuzzy.

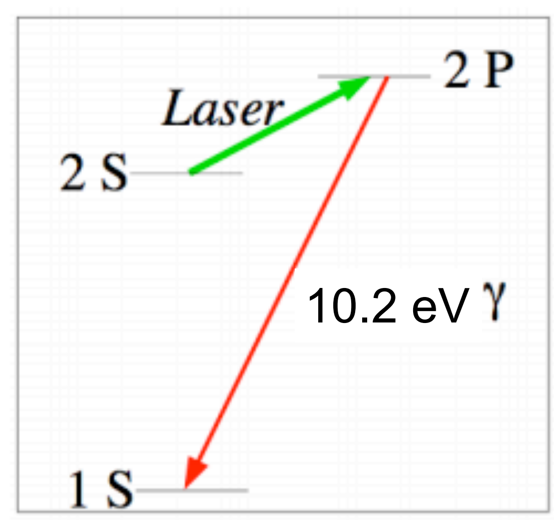
If the proton has no definite boundaries how do you define its radius?

RMS charge radius (r_p) is obtained from a consistent interpretation of hydrogen spectroscopy and electron-proton scattering experiments

e-p Scattering

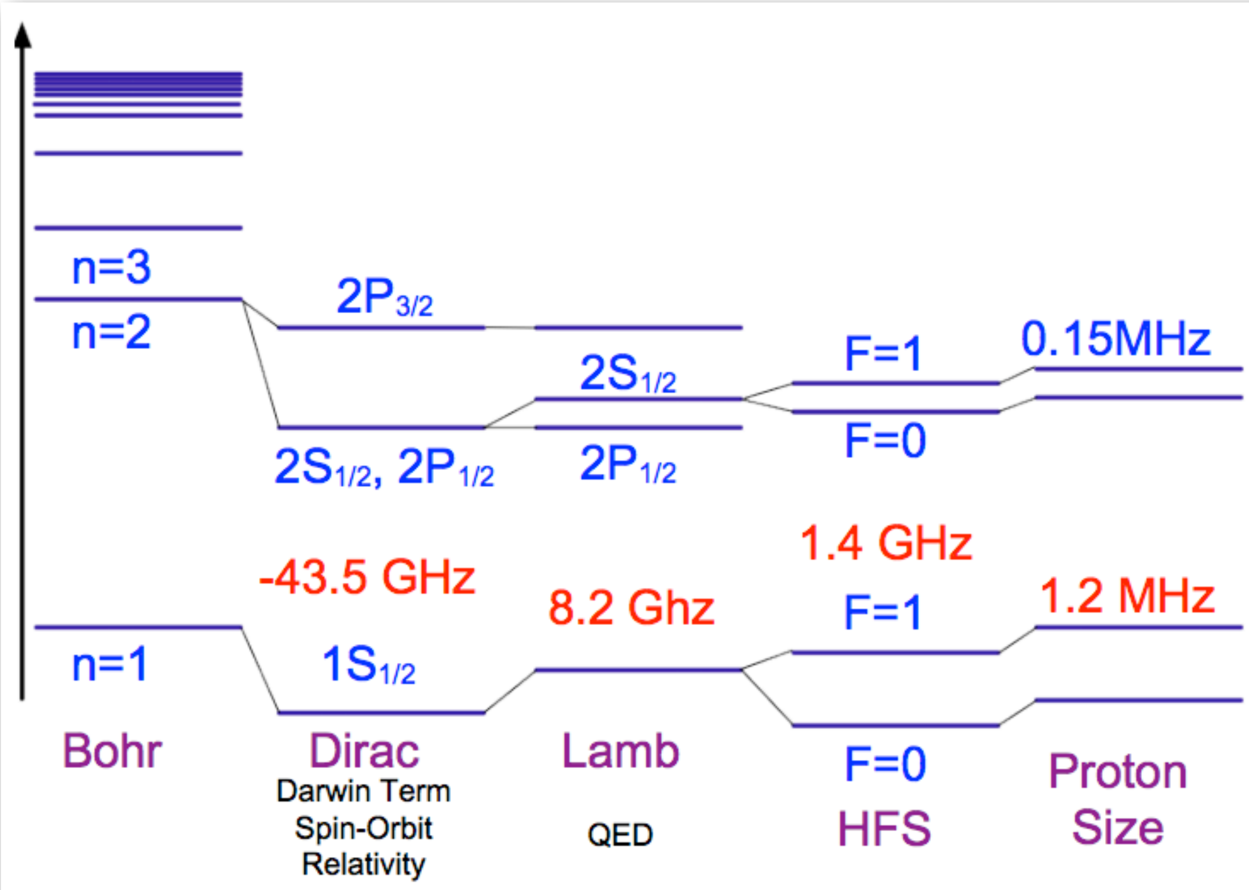


H-spectroscopy



This definition has been rigorously shown to be consistent for all types of experimental measurements. G. Miller, Phys. Rev., C 99, 035202 (2019)

Corrections to H - spectroscopy due to the extended charge distribution of the proton used to extract r_p

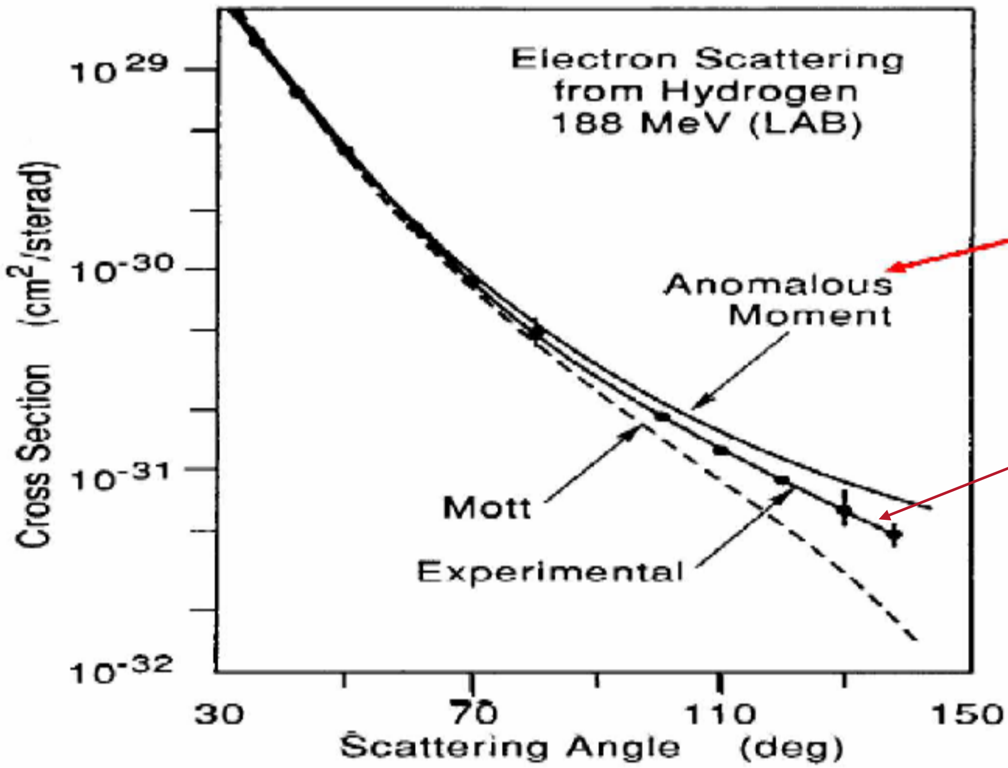


The absolute frequency of H energy levels has been measured with an accuracy of **1.4 part in 10^{14}** via comparison with an atomic Cs fountain clock as a primary frequency standard.

Comparing measurements to QED calculations that include corrections for the finite size of the proton provide a precise value of the rms proton charge radius.

Also, yields R_∞ (the most precisely known constant in Physics)

The slope of the electric form factor down to zero Q^2 used to extract r_p from elastic e-p scattering.



Point like proton with $G_E = 1$ and $G_M = \mu_p = 2.79$

Data show proton Has finite size

R. Hofstadter and R. W. McAllister, Phys. Rev., 98 (1955)

At very low Q^2, cross section dominated by G_E:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} G_E^2(Q^2)$$

$$G_E(Q^2) = 1 - \frac{Q^2}{6} < r^2 > + \frac{Q^4}{120} < r^4 > + \ldots.$$

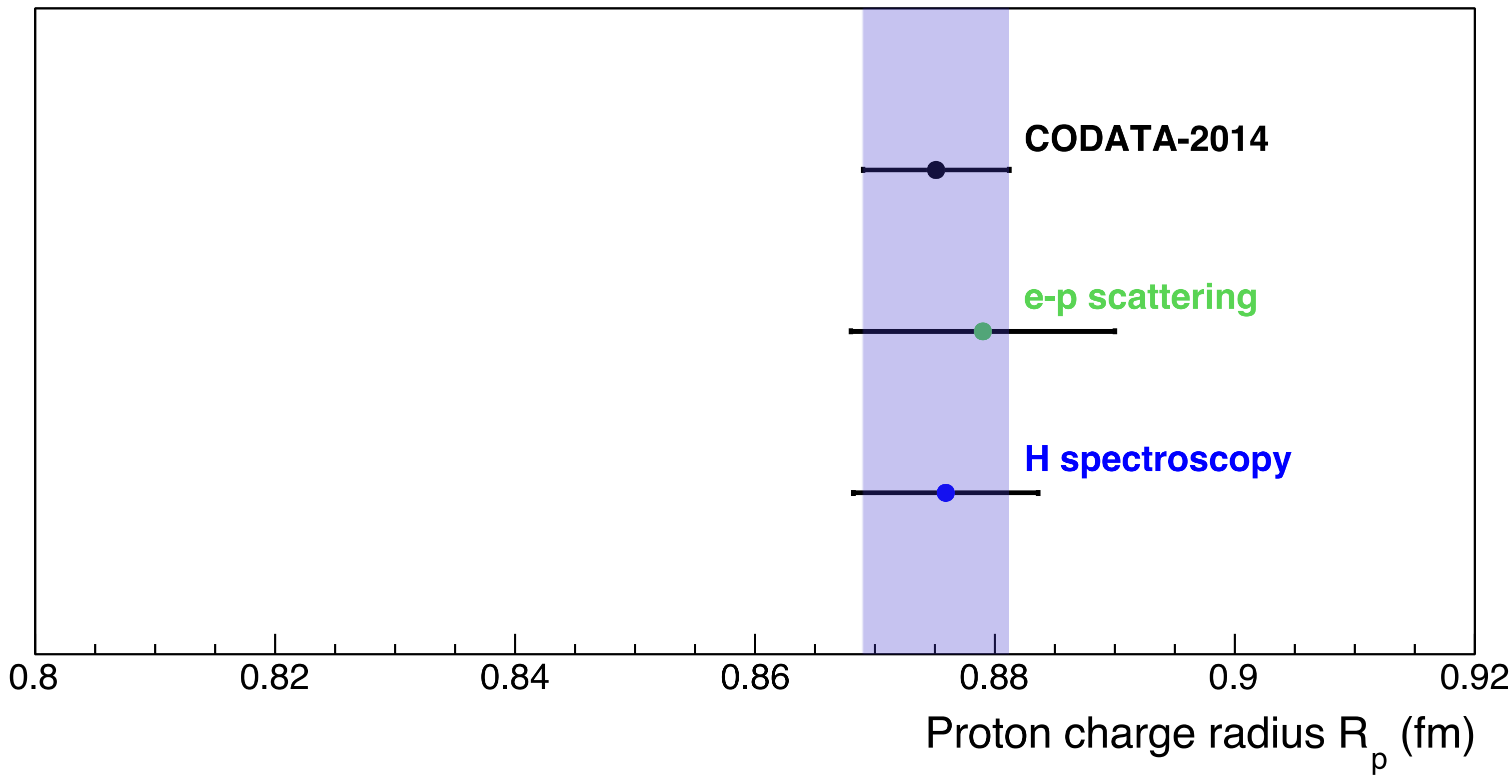
Charge radius given by the slope at $Q^2 = 0$:

$$< \mathbf{r^2} > = -6 \left| \frac{dG_E^2}{dQ^2} \right|_{Q^2=0}$$

This definition has been rigorously shown to be consistent with all experimental measurements.

G. Miller, Phys. Rev., C 99, 035202 (2019)

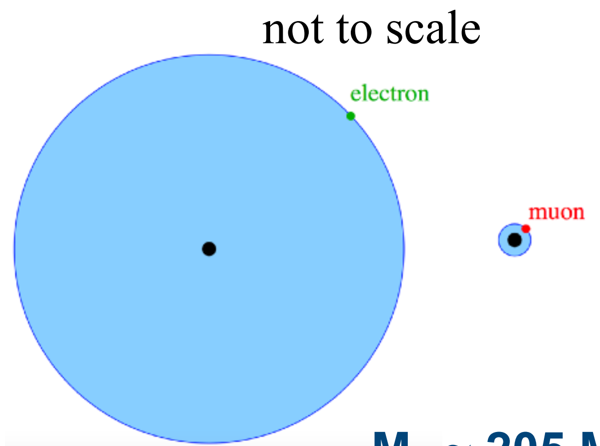
Prior to 2010 the r_p extracted from H - spectroscopy and elastic e-p scattering were consistent with each other.



CODATA average: **0.8751 ± 0.0061 fm**
ep-scattering average (CODATA): **0.879 ± 0.011 fm**
Regular H-spectroscopy average (CODATA): **0.859 ± 0.0077 fm**

The charge radius of the proton was considered a settled question.

A new method based on muonic hydrogen spectroscopy was used to extract r_p for the first time in 2010.



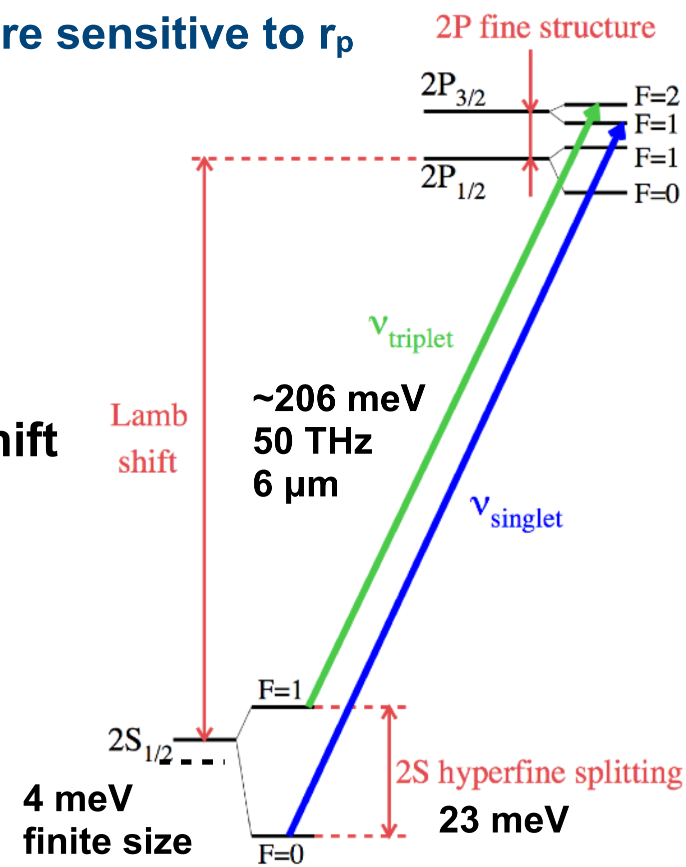
Probability of lepton to be inside proton

$$\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p \alpha)^3 m^3$$

m = reduced mass
~ 186 M_e

μH is ~ 6×10^6 times more sensitive to r_p

$M_\mu \sim 205\ M_e$

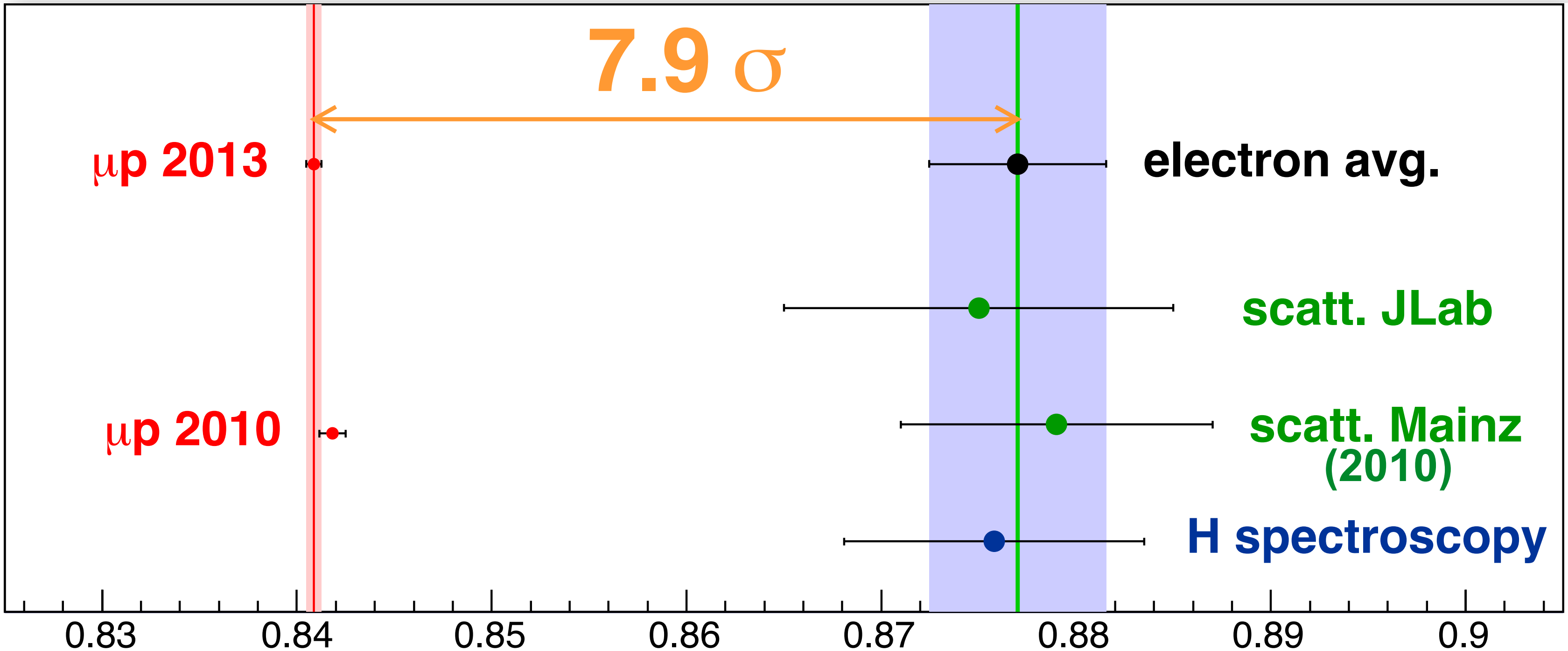


Lamb shift in μH:
ΔE = 206.0668(25) – 5.2275(10) r_p^2 [meV]
finite proton size is ~2% correction to μH Lamb shift

r_p was extracted with
10 times higher precision (~0.1 %)
compared to all previous measurements

The results from the muonic hydrogen spectroscopy led to the so called “proton radius puzzle.”

~8σ discrepancy between muon and electron based measurements



Pohl et al., Nature 466, 213 (2010
Antognini et al., Science 339, 417 (2013)

Proton rms charge radius measured using

electrons: 0.8770 ± 0.0045 (CODATA2010 + Zhan et al.)

muons: 0.8409 ± 0.0004

- unprecedented precision ~0.08%
- $Q^2 \sim 10^{-6}$ GeV^2

There was a world wide effort to explore numerous possible resolutions to the "proton radius puzzle."

★ **Are the state of the art QED calculations incomplete?**

- E. Borie, Phys. Rev. A 71, 032508 (2005)
- U. D. Jentschura, Ann. of Phys. 326, 500 (2011)
- F. Hagelstein, V. Pascalutsa, Phys. Rev. A 91, 040502 (2015)

★ **Are there additional corrections to the muonic Lamb shift due to proton structure (such as proton polarizability of $\mathcal{O}(\alpha^5)$)?**

- C. E. Carlson, V. Nazaryan and K. Griffioen, Phys. Rev. A 83, 042509 (2011)
- R. J. Hill and G. Paz, Phys. Rev. Lett. 107, 160402 (2011)

★ **Are higher moments of the charge distribution accounted for in the extraction of rms charge radius?**

- M. O. Distler, J. C. Bernauer and T. Walcher, Phys. Lett. B 696, 343 (2011)
- A. de Rujula, Phys. Lett. B 693, 555 (2010), and 697, 264 (2011)
- I. Cloet, and G. A. Miller, Phys. Rev. C. 83, 012201(R) (2011)

★ **Is there an extrapolation problem in electron scattering data?**

- D. W. Higinbotham et al., Phys. Rev. C 93, 055207 (2016)
- K. Griffioen, C. Carlson, S. Maddox, Phys. Rev. C 93, 065207 (2016)

★ **Has new physics been discovered (violation of Lepton Universality)?**

- V. Barger, et al., Phys. Rev. Lett. 106, 153001 (2011)
- B. Batell, D. McKeen, M. Pospelov, Phys. Rev. Lett. 107, 011803 (2011)
- D. Tucker-Smith, I. Yavin, Phys. Rev. D 83, 101702 (2011).

★ **New force carriers?**

- C. E. Carlson, Prog. Part. Nucl. Phys. 82, 59–77 (2015).
- Y. S. Liu and G. A. Miller, Phys. Rev. D 96, 016004 (2017).

Clearly more experiments were needed !

- ✦ Redo atomic hydrogen spectroscopy (3 different groups)
- ✦ Muon-proton scattering (MUSE experiment-2020)
- ✦ Electron scattering experiments (PRad-2016, ISR, ProRad, ULQ²…)

The status of "proton radius puzzle" in 2018

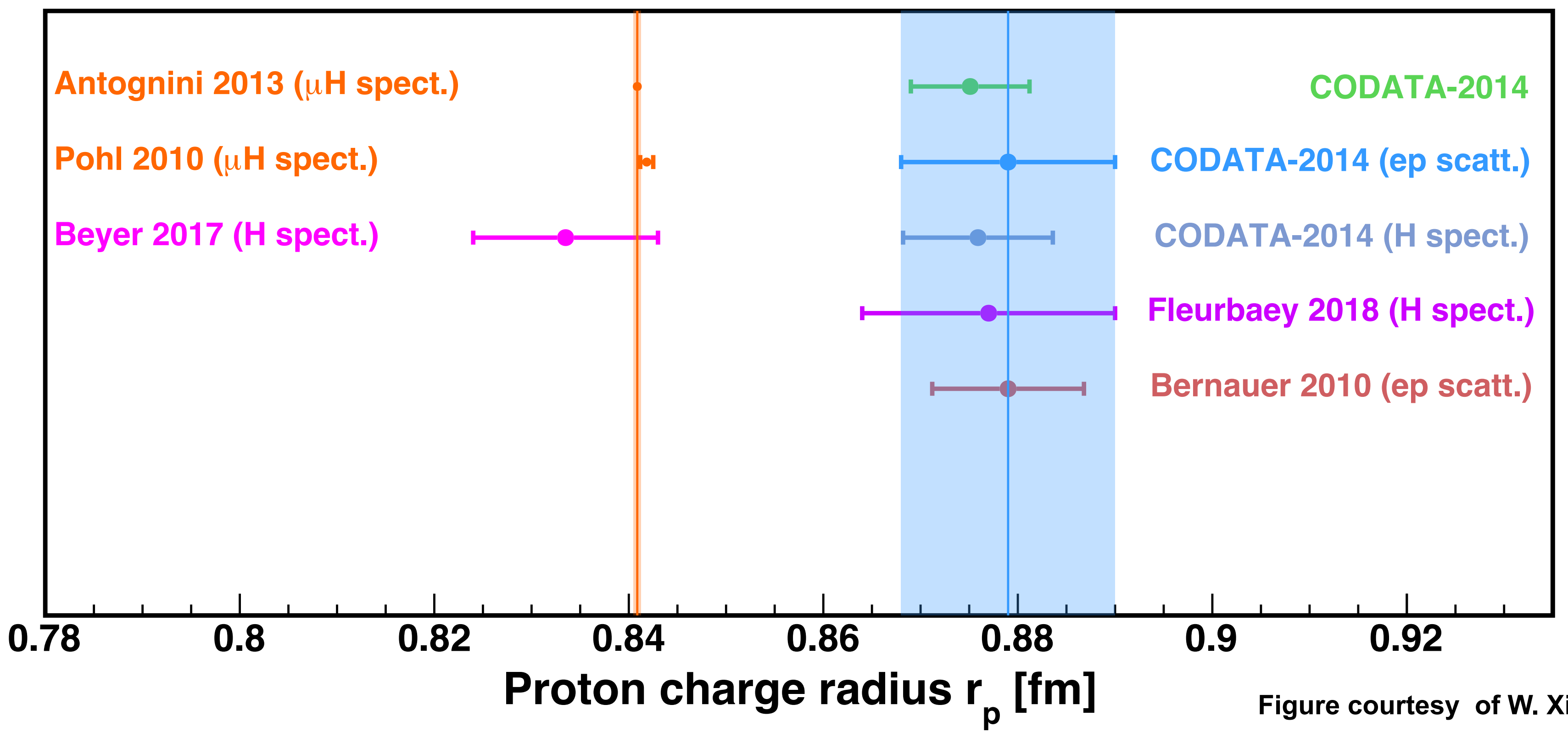
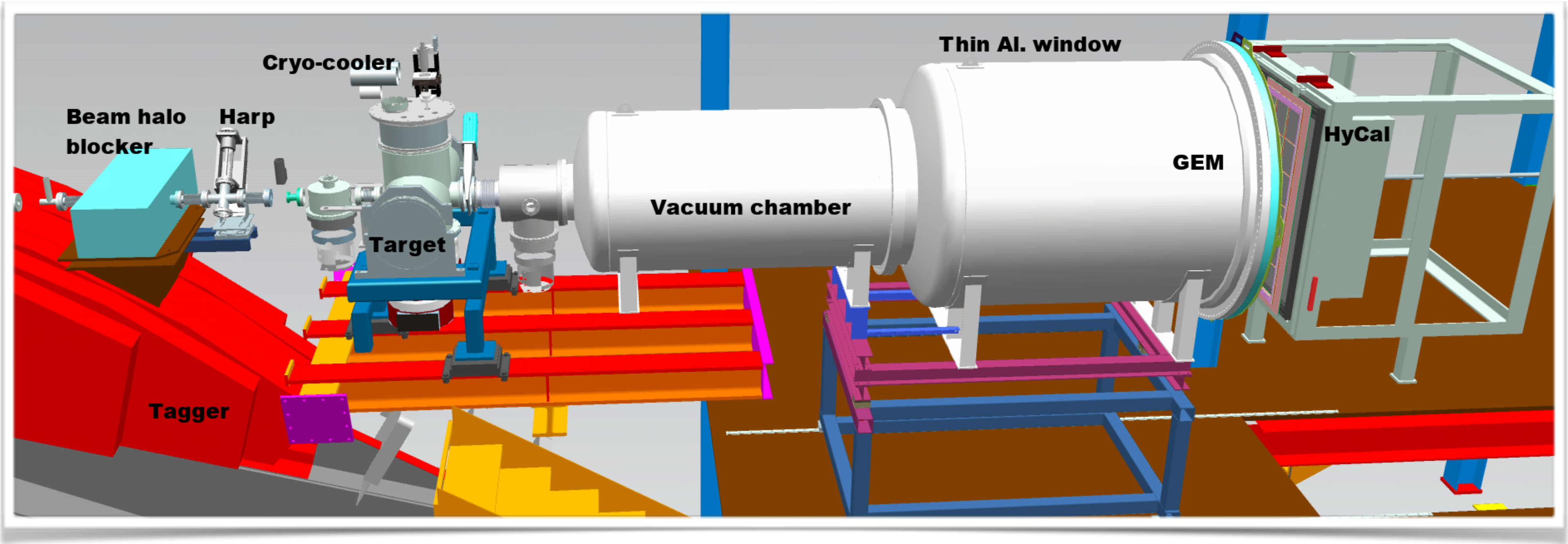


Figure courtesy of W. Xiong

PRad: a novel electron scattering experiment



Spokesperson: A. Gasparian,
Co-spokespersons: D. Dutta, H. Gao, M. Khandaker

- **High resolution, Hybrid calorimeter (magnetic spectrometer free)**
- **Windowless, high density H_2 gas flow target (reduced backgrounds)**
- **Simultaneous detection of elastic and Møller electrons (control of systematics)**
- **Vacuum chamber, one thin window, large area GEM chambers (better resolution)**
- **Q^2 range of 10^{-4} – 6×10^{-2} GeV^2 (lower than all previous electron scattering expts.)**

Ran in Hall-B at JLab in 2016, using 1.1 GeV and 2.2 GeV electron beam

The first experiment to use a magnetic spectrometer free method to measure r_p

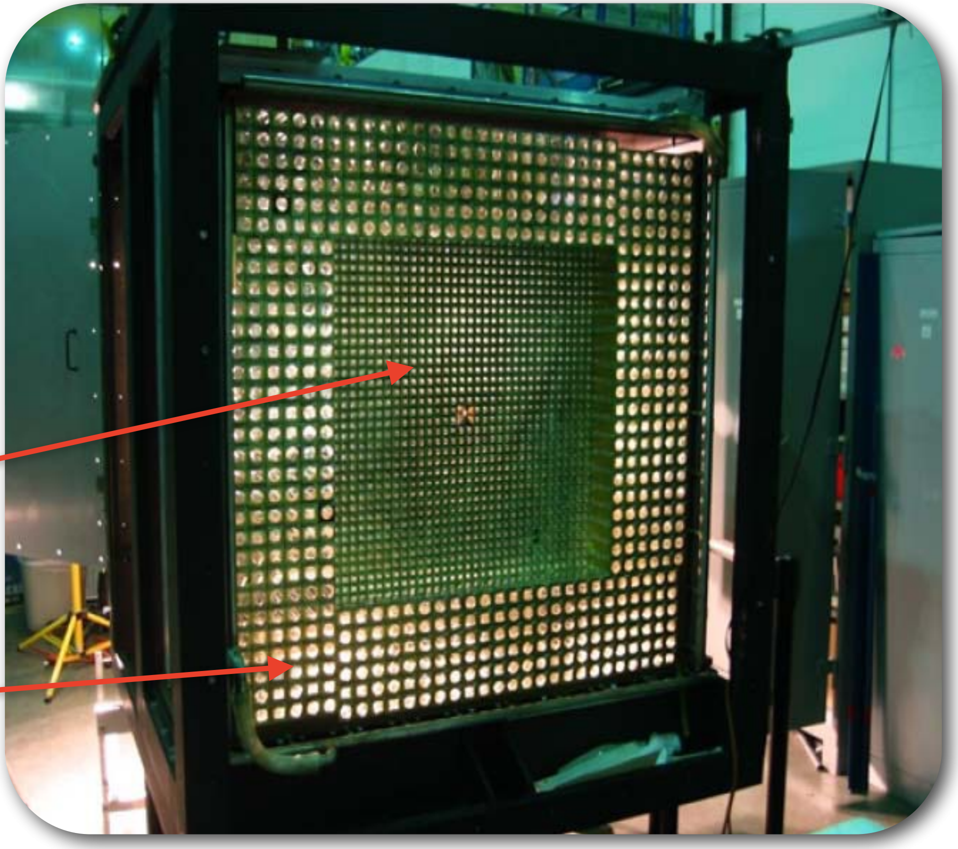
Reused PrimEx Hybrid Calorimeter

- $PbWO_4$ and Pb-glass calorimeter (118x118 cm^2)
- 34x34 matrix of 2.05 x 2.05 cm^2 x18 cm $PbWO_4$
- 576 Pb-glass detectors (3.82x3.82 cm^2 x45 cm)
- 5.5 m from the target,
- 0.5 sr acceptance

Allows coverage of extreme forward angle (0.7^o - 7.5^o) in a single setting and complete azimuthal angle coverage

$PbWO_4$ resolution:
$\sigma_E/E = 2.6\%/\sqrt{E}$
$\sigma_{xy} = 2.5\ mm/\sqrt{E}$

Pb-glass:
2.5 times worse

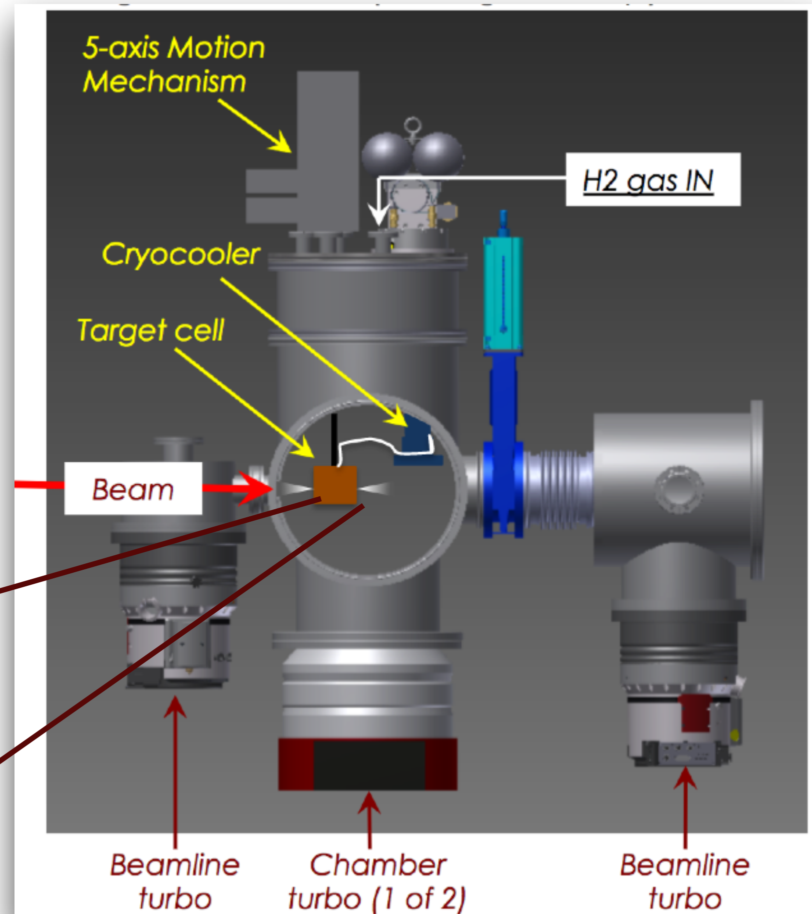


The first experiment to use a windowless target to measure r_p

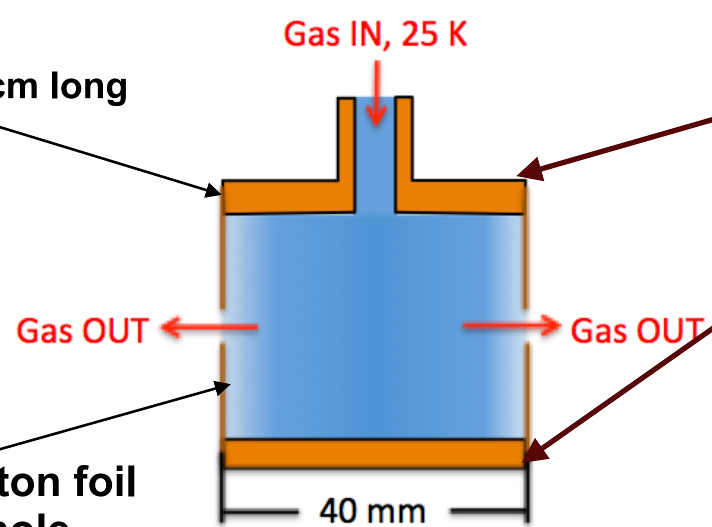
Used a cryo-cooled windowless gas flow hydrogen target.

density:
~2x10[18] atoms/cm[2]

cell / chamber/ tank pressure:
470 / 2.3 / 0.3 mtorr



Target cell (8 cm dia x 4 cm long copper)

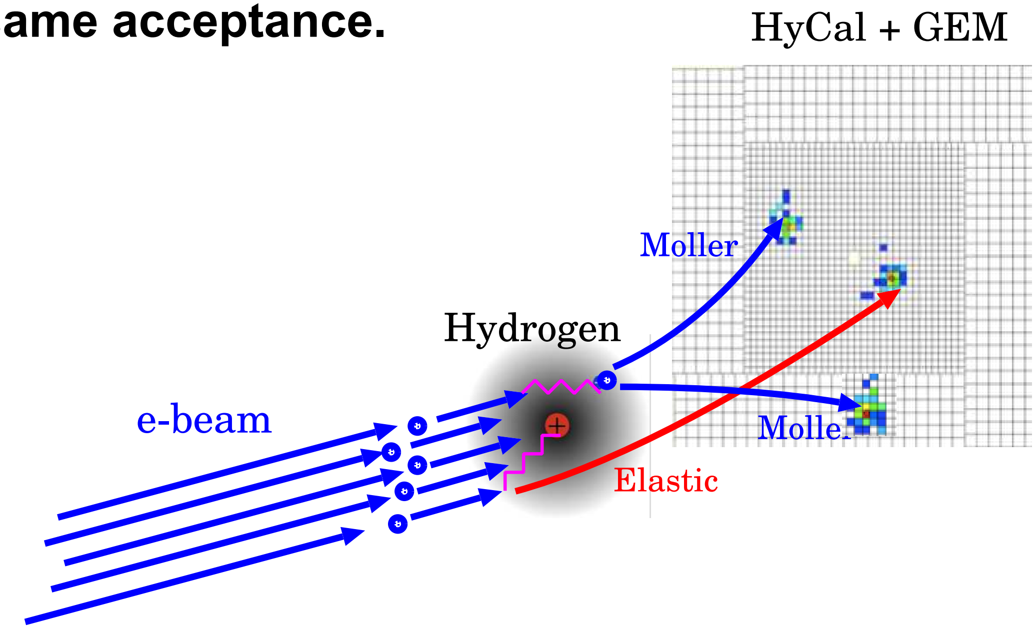


7.5 µm kapton foil with 2mm hole

Empty target runs used to subtract background

Key innovations in the design allowed a unique high precision measurement.

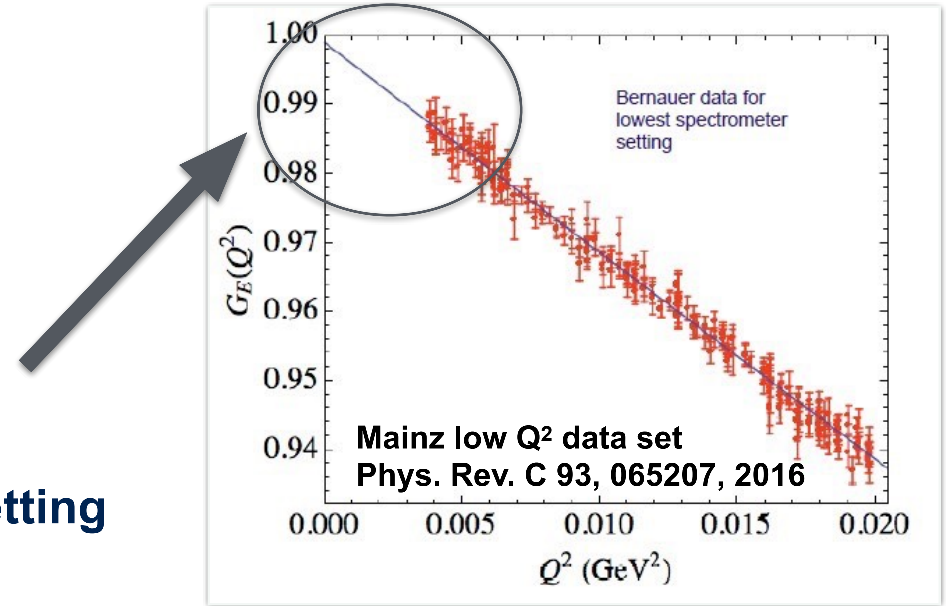
Simultaneous detection of the Møller *(e-e)* and *e-p* elastic events within the same acceptance.



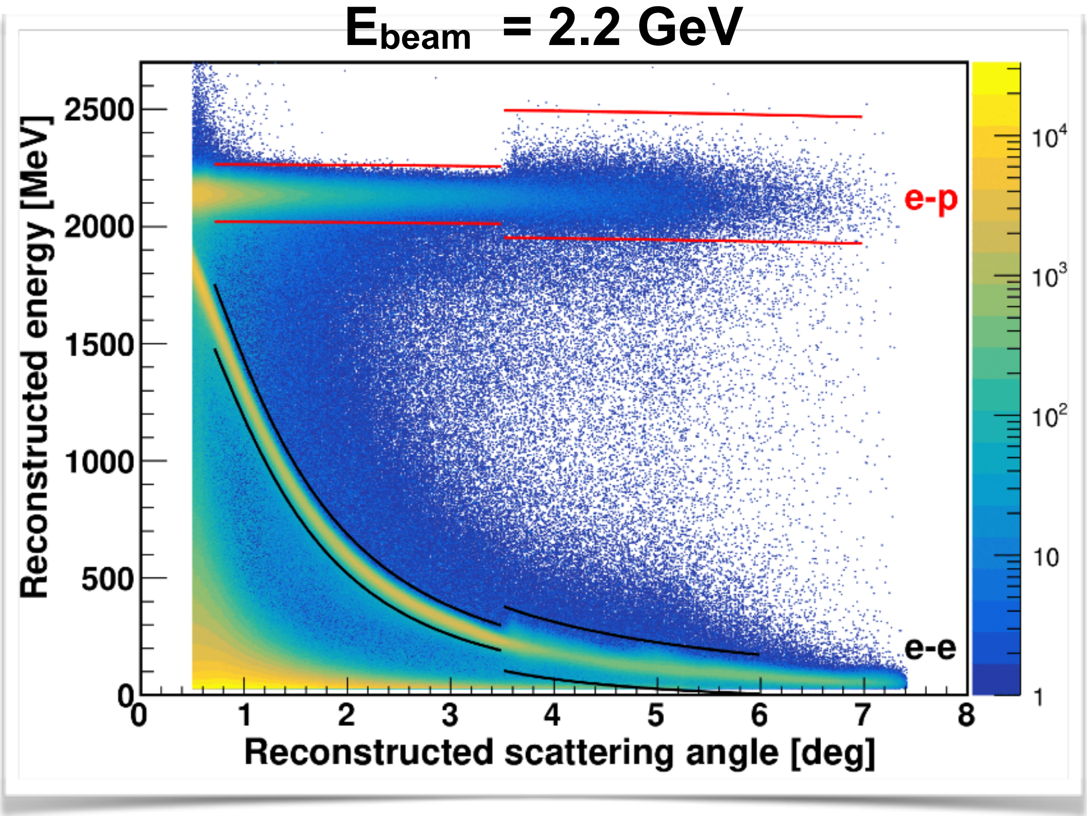
- **Experimental design allows:**
  - **control of systematics**
  - **eliminates need to monitor luminosity**

Large forward angle acceptance with high energy resolution (HyCal) and 72 μm position resolution (GEM).

- **Experimental design allows:**
  - **fill in the very low Q^2 range**
  - **large Q^2 range in a single setting (~2×10^{-4} - 6×10^{-2} GeV^2)**



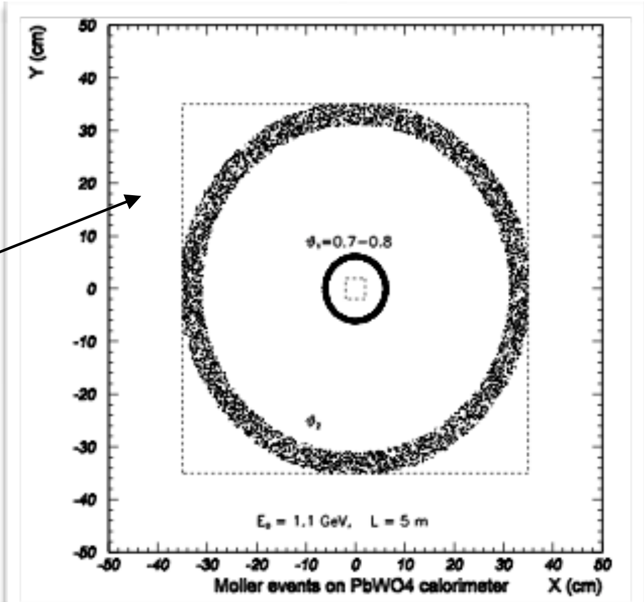
Angle dependent energy cuts are used to select the Møller (*e-e*) and *e-p* elastic events.



GEM and HyCal detector hits must match for all (*e-p*) and (*e-e*) events

Angle dependent energy cuts for (*e-p*) and (*e-e*) events based on kinematics with the cut size based on local resolution.

Additional constraints for double arm Møller events on: co-planarity, elasticity, z-vertex



e-p elastic cross section extracted by normalizing to Møller cross section.

bin-by-bin normalization (double arm Møller)

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{ep}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{ep}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

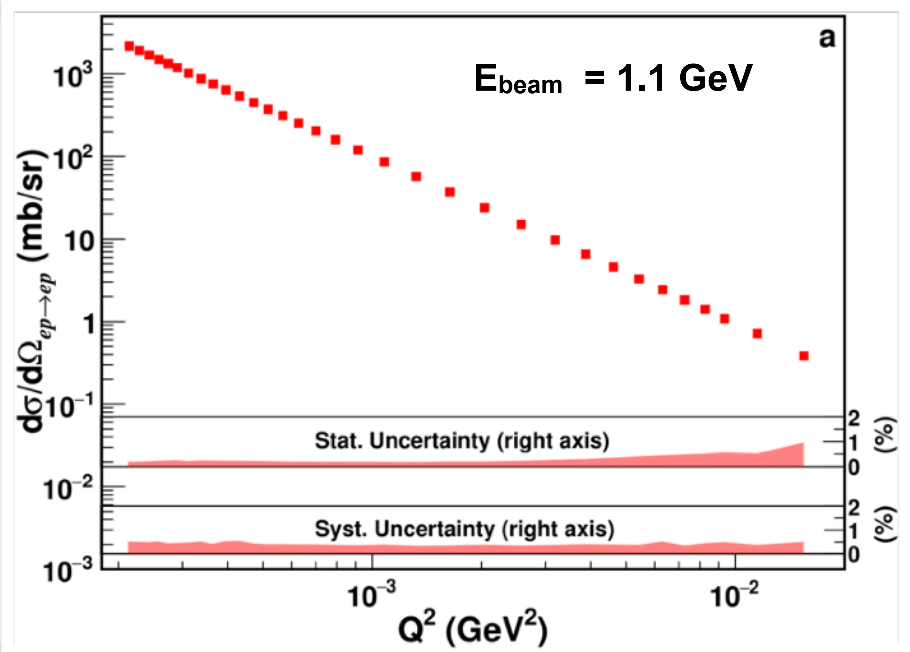
or

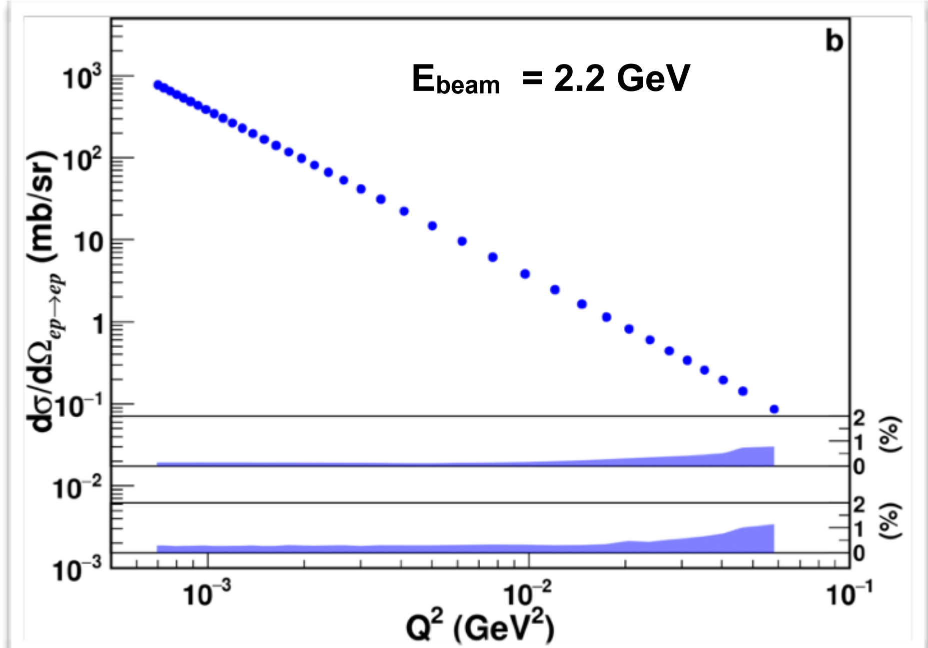
integrated over HyCal acceptance

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ep,\ \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^-,\ \text{on PWO})}\right]\frac{\varepsilon_{\text{geom}}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\text{geom}}^{ep}(\theta_i \pm \Delta\theta)}\,\frac{\varepsilon_{\text{det}}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\text{det}}^{ep}(\theta_i \pm \Delta\theta)}\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

Event generator for *e-p* elastic and Møller include radiative corrections beyond the ultra-relativistic approximation & two photon exchange (used iteratively within a Geant4 simulation)

1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41, 115001 (2014).
2. I. Akushevich et al., Eur. Phys. J. A 51, 1 (2015).
3. O. Tomalak, Few Body Syst. 59, 87 (2018). (two photon exchange formalism)

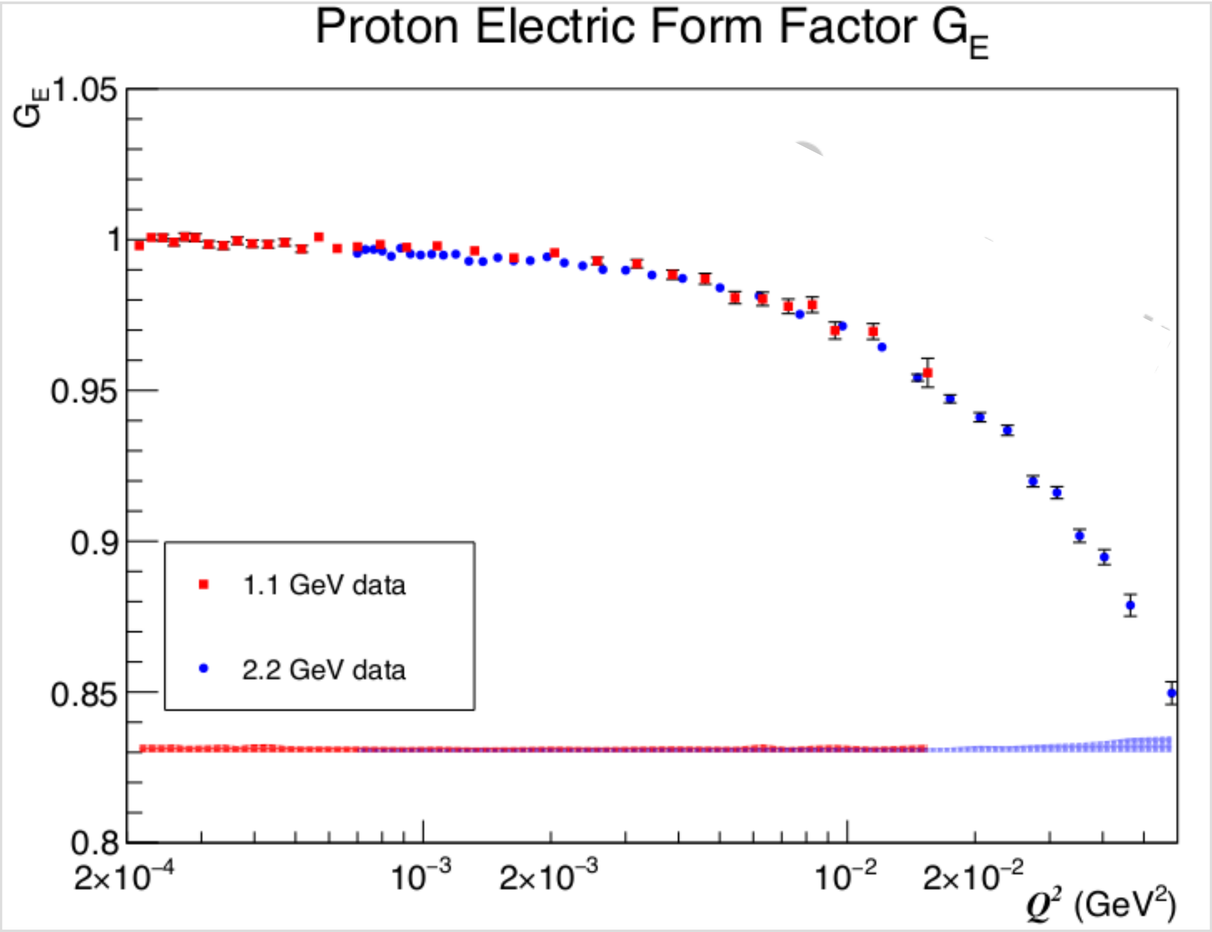




Systematic uncertainties: 0.3% - 0.5% at 1.1 GeV and 0.3% - 1.1% at 2.2 GeV

Figures courtesy of W. Xiong

The proton electric form factor was extracted at the lowest Q^2 ever achieved in electron scattering.



The slope of $G_E(Q^2)$ as $Q^2 \rightarrow 0$ is proportional to r_p^2.

Typically r_p is obtained by fitting $G_E(Q^2)$ to a functional form and extrapolating to $Q^2 = 0$.

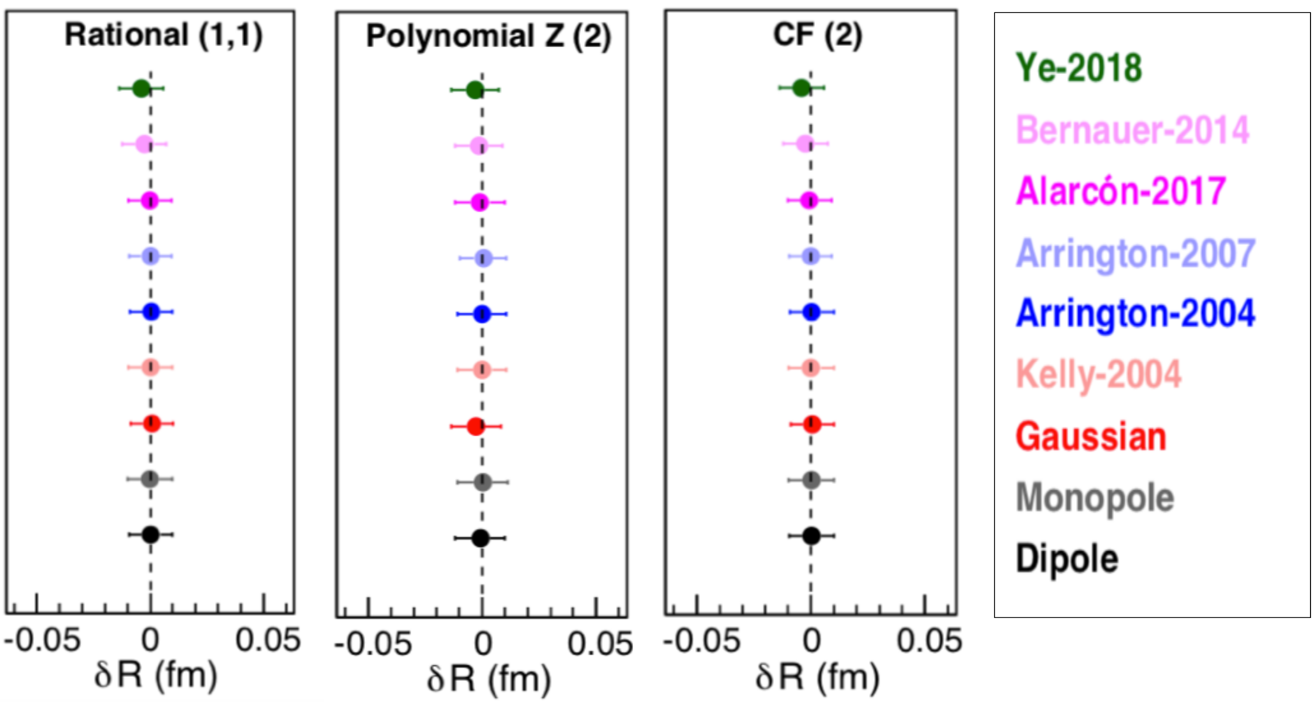
The truncation of the higher-order moments of $G_E(Q^2)$ introduces a model dependence which can bias the determination of r_p.

Figure courtesy of W. Xiong

A wide range of functional forms were systematically tested for their robustness in extracting r_p.

- **Numerous functional forms were tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties**: X. Yan *et al.* Phys. Rev. C98, 025204 (2018)

- **Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties**



Rational (1,1)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order *z* transformation

$$p_0(1 + p_1 z + p_2 z^2)$$

$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

2nd order continuous faction

$$p_0 \frac{1}{1 + \frac{p_1 Q^2}{1 + p_2 Q^2}}$$

The robustness = root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{(\delta R)^2 + \sigma^2},$$

δR = difference between the input and extracted radius
σ = statistical variation of the fit to the mock data

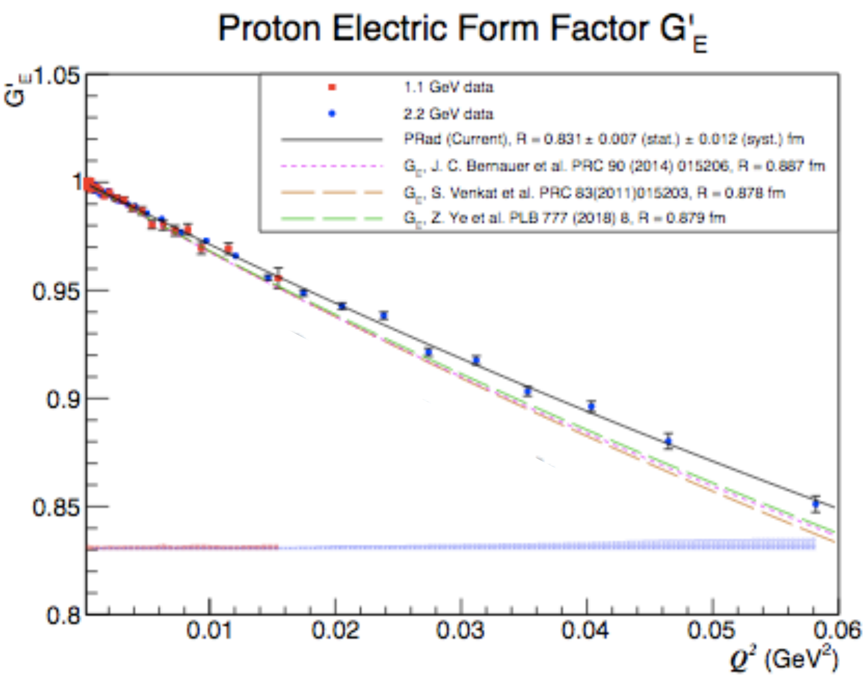
Figure courtesy of W. Xiong

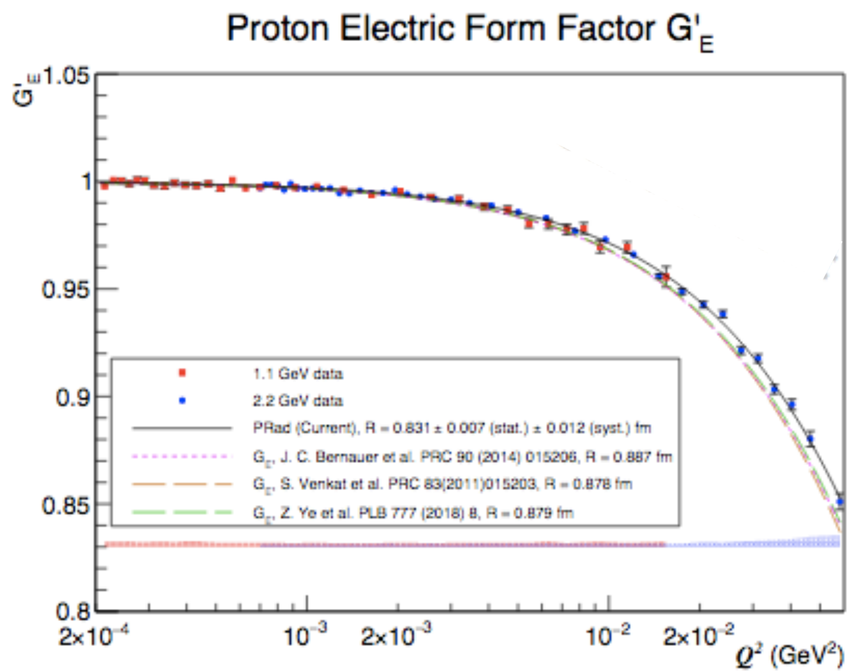
The rational (1,1) functional forms provides the most robust extraction of r_p from the PRad data.

- n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$
- G'_E as normalized electric Form factor: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$
- PRad fit shown as $f(Q^2)$ $\quad r_p$ = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

Using rational (1,1)

$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$



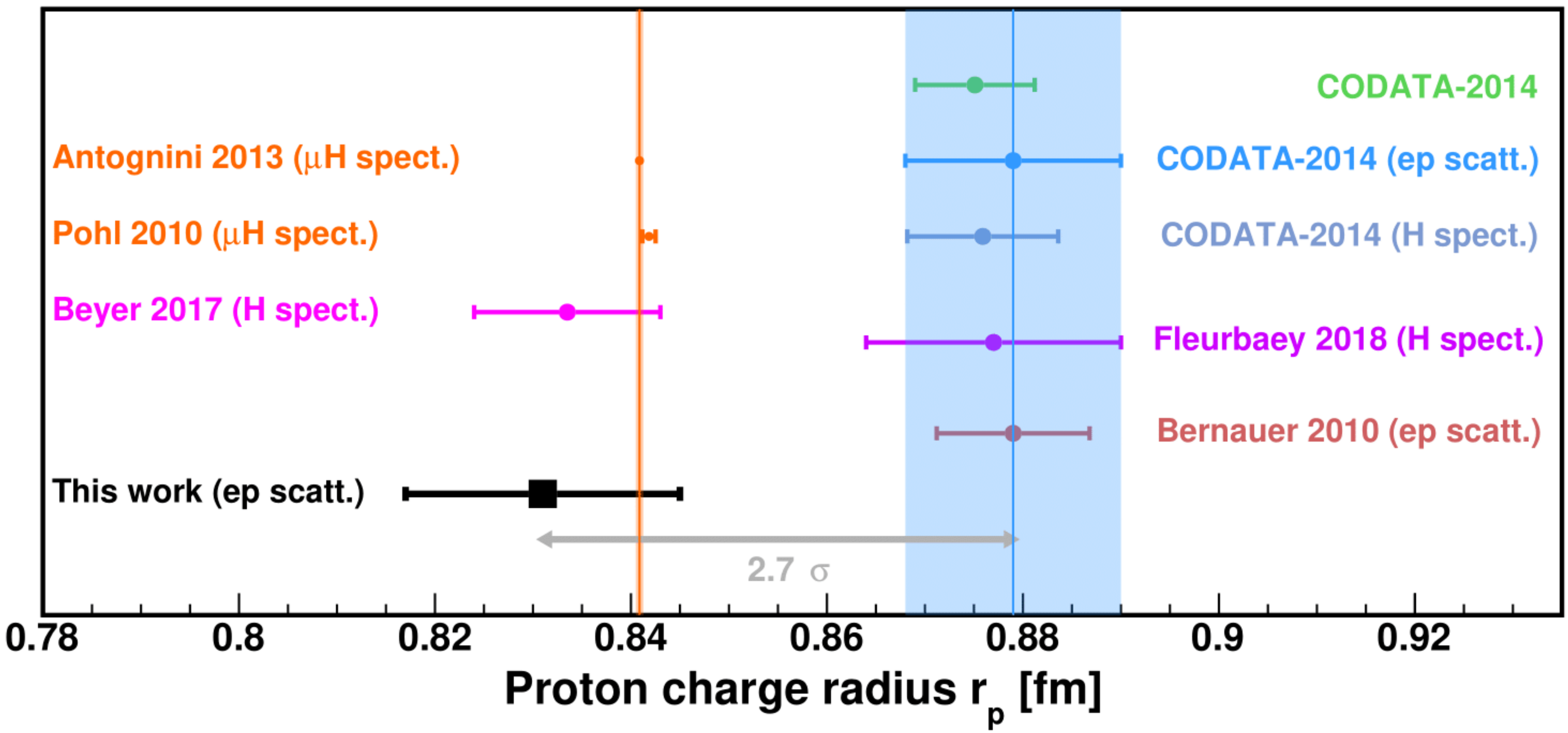


n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), $\quad n_2$ = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

Figures courtesy of W. Xiong

The PRad result for the proton charge radius.

PRad result: 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm



W. Xiong et al., Nature, 575, 147 (2019)

There has been some rapid and dramatic development over the last few months.

A new H-spectroscopy results was reported in Science Magazine in November.

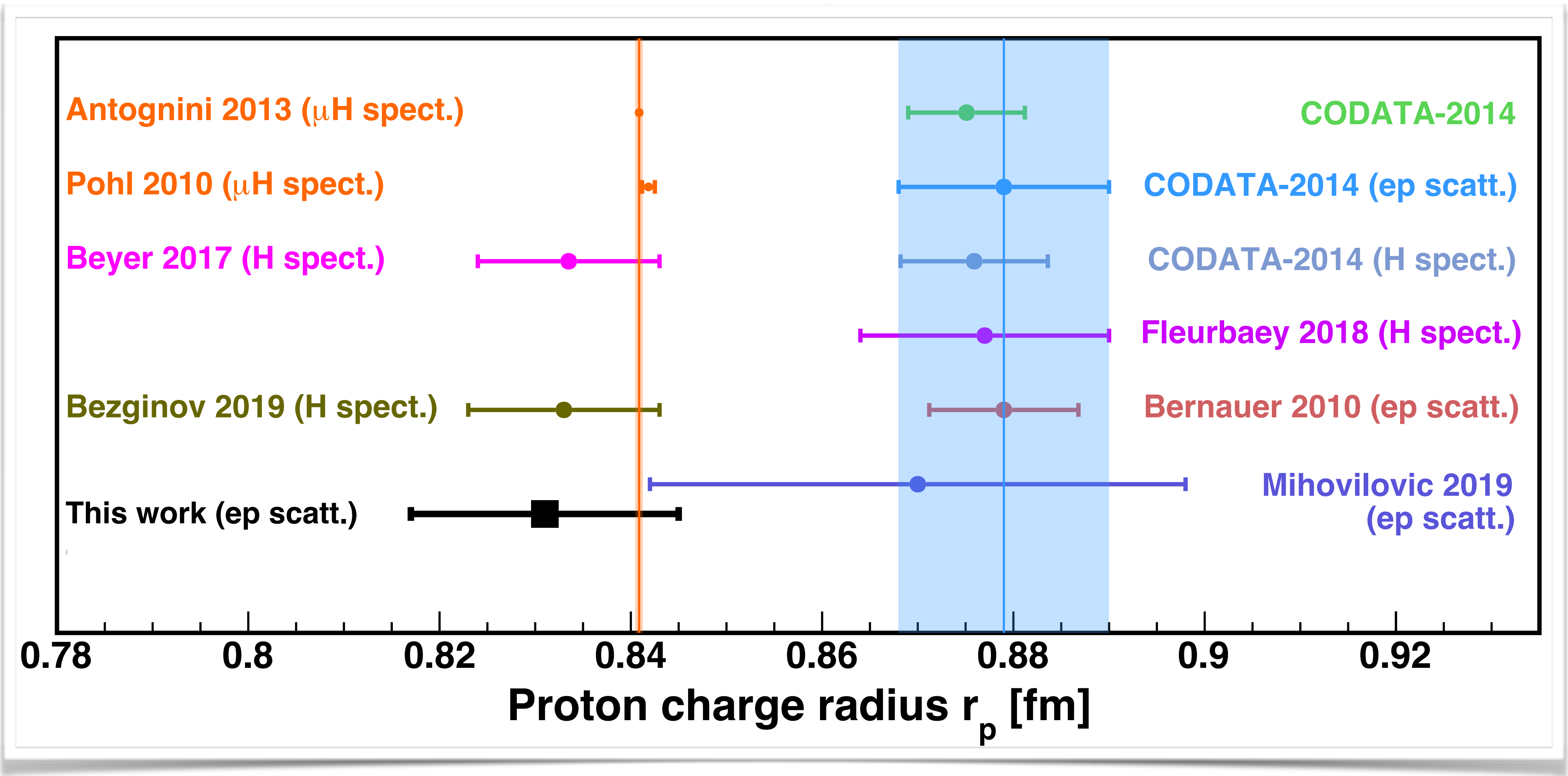
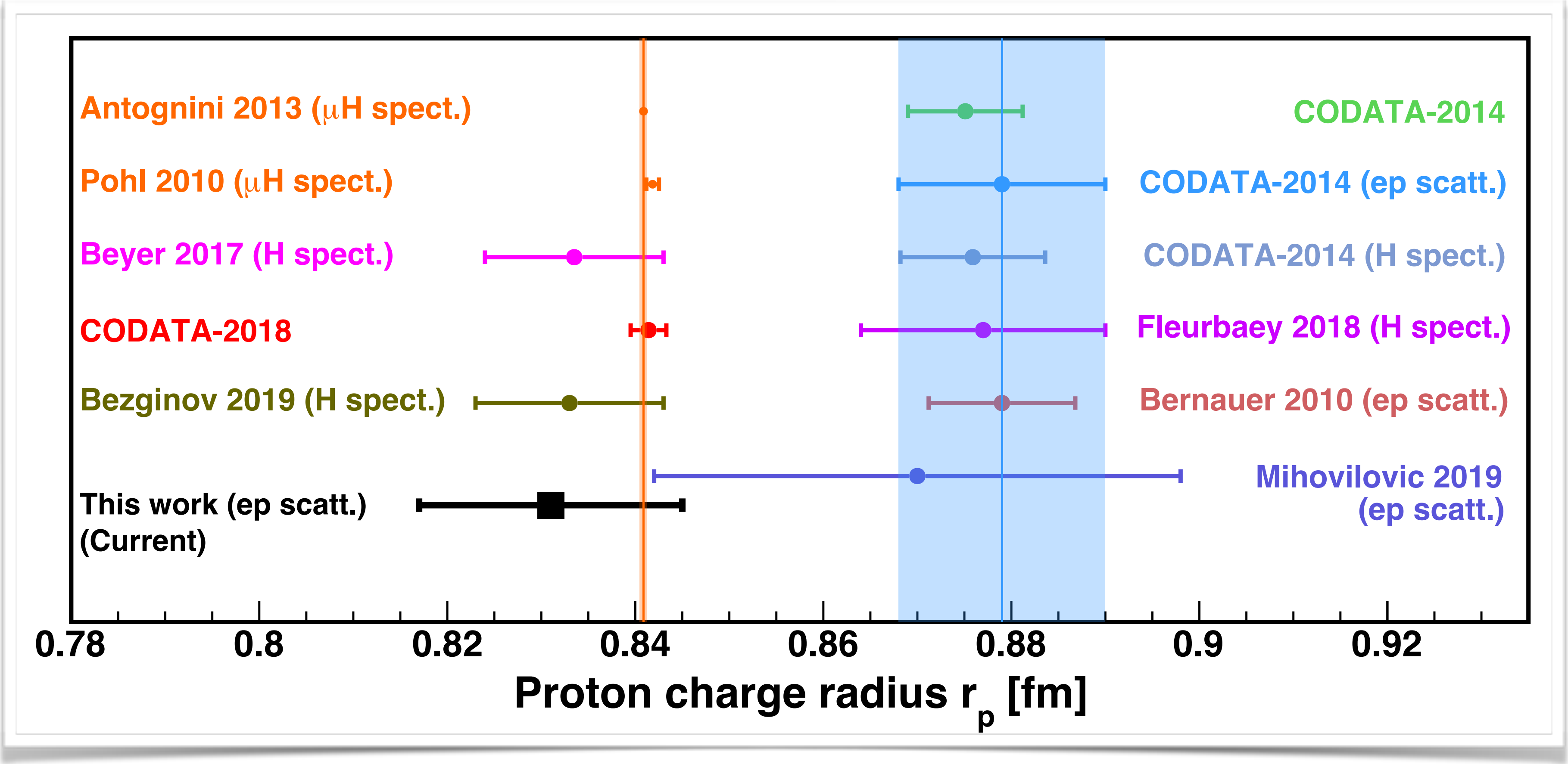


Figure courtesy of W. Xiong

There has been some rapid and dramatic development over the last few months.

Recently, CODATA released, online, their revised value of r_p



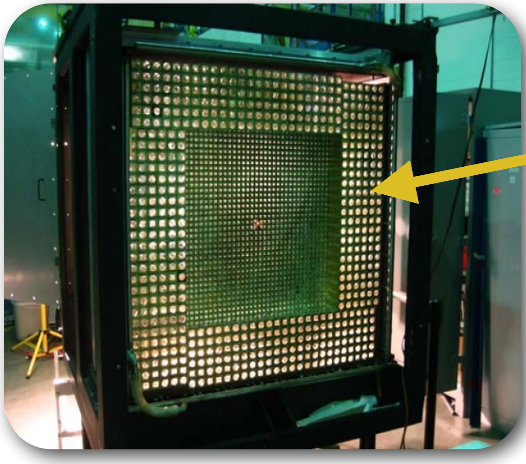
CODATA has also revised the value of the Rydberg constant.

2020 Review of Particle Physics claims - "…the puzzle appears to be resolved"

P.A. Zyla *et al.* (Particle Data Group), to be published in Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Figure courtesy of W. Xiong

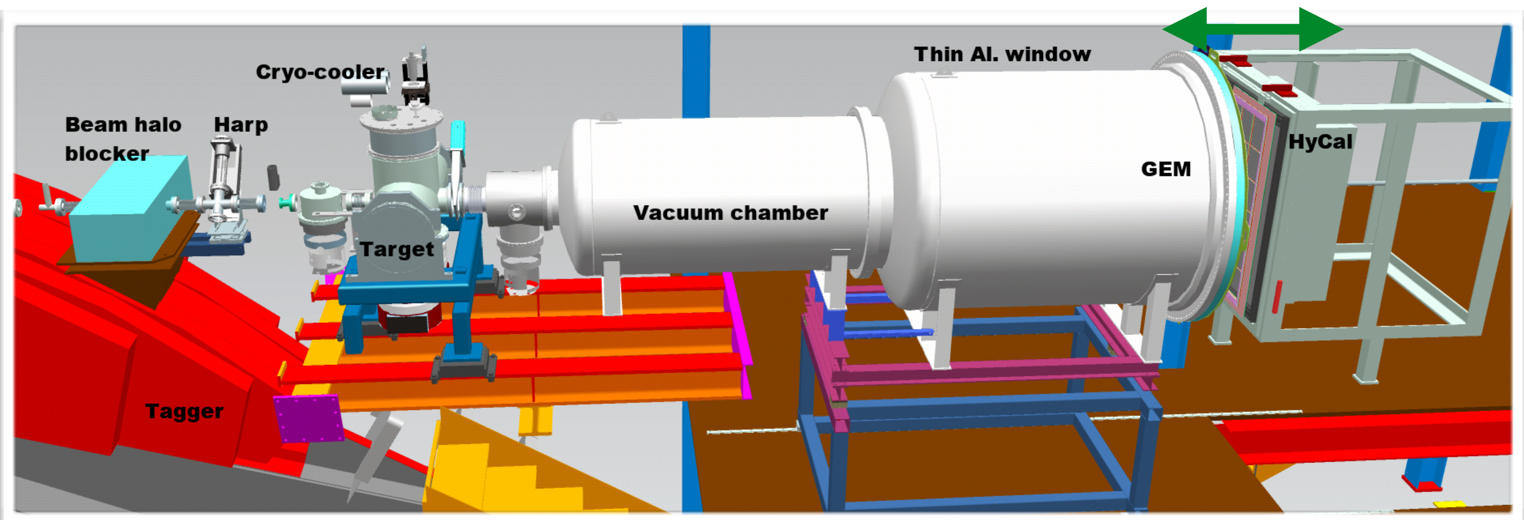
A new proposal - PRad-II was submitted to push the precision frontier of electron scattering.



Upgrade HyCal to be replace all lead-glass modules with $PbWO_4$ modules to have uniform high resolution.

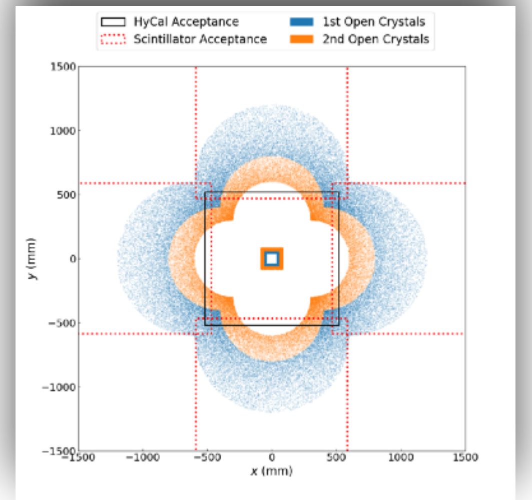
Convert to FADC based readout of HyCal

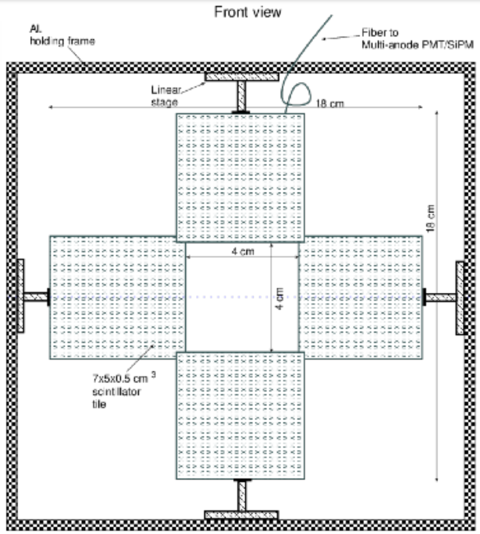
Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.



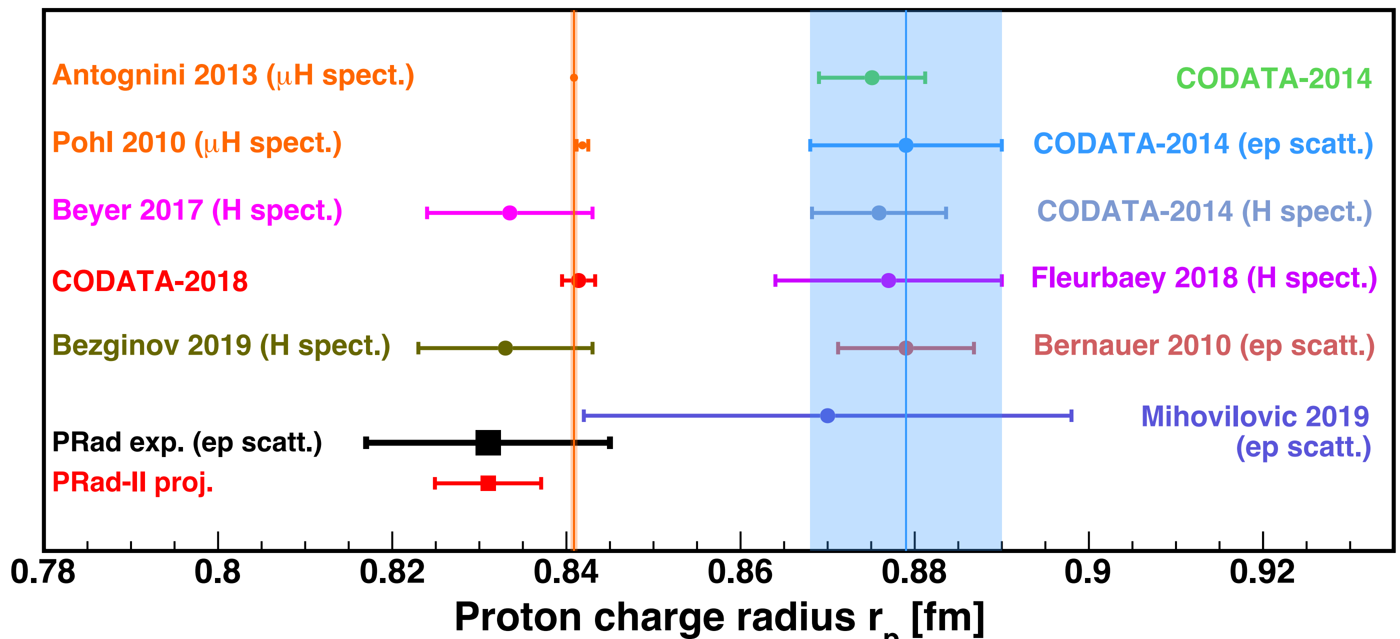
Will improve the precision of r_p measurements and start a new program of high precision measurements using the PRad method

PRad-II is projected to be 2.5 times more precise than PRad





A new scintillator detector will help reach the smallest scattering angles and the lowest Q^2 range (10^{-5} GeV^2) in lepton scattering.



The PRad Collaboration

Duke University, NC A&T State University,
Mississippi State University, Idaho State University,
University of Virginia, Jefferson Lab,
Argonne National Lab,
University of North Carolina at Wilmington,
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MIT, Old Dominion University, ITEP,
University of Massachusetts, Amherst
Hampton University, College of William & Mary,
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Summary

- **The proton charge radius is a fundamental quantity in Physics**
  - ✓ Important for precision atomic spectroscopy
  - ✓ Precision tests of future lattice QCD calculations
  - ✓ "New Physics"

- **The "proton radius puzzle" arose in 2010 with the first μH spectroscopy measurement of r_p.**

- **A novel electron scattering experiment (PRad) was completed at JLab Hall-B in 2016**
  - ✓ lowest Q^2 (~2×10^{-4} GeV/C^2) in ep-scattering experiments was achieved;
  - ✓ simultaneous measurement of the Møller and elastic scattering processes was demonstrated to control systematic uncertainties;
  - ✓ data in a large Q^2 range (2×10^{-4} - 6×10^{-2} GeV^2) was recorded in the same experimental setting, for the first time in ep-scattering experiments.

- **The PRad result found a small proton charge radius.**
- **Several other recent results seem to confirm the small proton radius.**
- **Several new experiments are being prepared to help further establish these results.**

This work was supported by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-07ER41528

The PRad results received some press coverage.

SUMMARY | News | Blogs | Twitter | Facebook | Wikipedia | Misc.

So far, Altmetric has seen **27** news stories from **27** outlets.

bild der wissenschaft

Bild der wissenschaft 01-2020 - wissenschaft.de

wissenschaft.de, 16 Dec 2019

Zu den Nachrichten in der Rubrik „Magazin" in der bild der wissenschaft-Ausgabe 01/2020, finden Sie hier die Quellen und weiterfü...

Daily Press

Jefferson Lab helping to resolve the "proton radius puzzle"

Daily Press, 15 Nov 2019

How do you measure the width of a proton? A ruler won't help and neither will a microscope. Instead, it involves smashing...

madrid

Científicos confirman que el protón ha menguado

Madrid , 13 Nov 2019

La medida más precisa hasta la fecha le otorga un radio de 0,8331 fentómetros, menos que lo asignado por mediciones anteriores...

physicsworld

Electron scattering experiment is first to point to a small proton radius Physics

About this Attention Score

In the top 5% of all research outputs scored by Altmetric

MORE...

Mentioned by

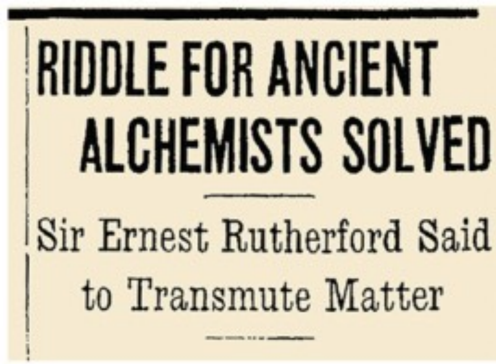
- **27** news outlets
- **1** blog
- **91** tweeters
- **5** Facebook pages
- **2** Wikipedia pages

Rutherford discovers the hydrogen nucleus is produced in α-scattering from air.

$^{14}N + \alpha \rightarrow {}^{17}O + p$

when α-particles were shot into air, hydrogen nuclei were detected as a product.

α-scattering on other atoms produced hydrogen nuclei in every case.



RIDDLE FOR ANCIENT ALCHEMISTS SOLVED

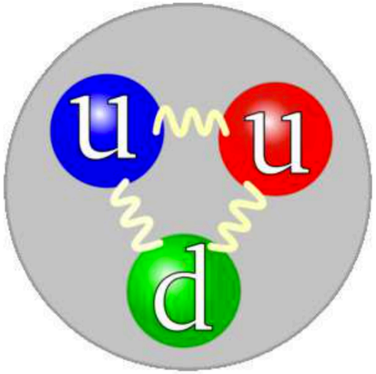
Sir Ernest Rutherford Said to Transmute Matter

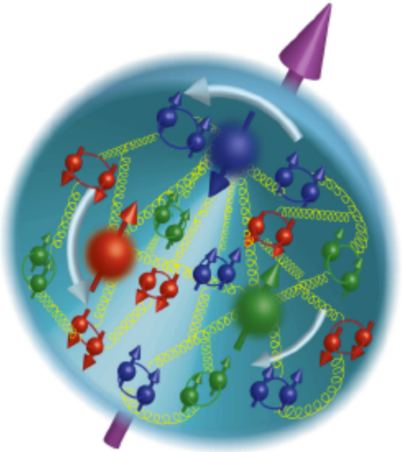
Rutherford concluded that hydrogen nucleus played a fundamental role in atomic structure, and called it a proton (proton appears in literature for the first time in 1920).

In 1933 Stern measured the anomalous magnetic moment of the proton $\mu_p = 2.79$

Showing that the proton is NOT an elementary point like particle.

The proton proved to be an ideal laboratory to study the strong interaction.



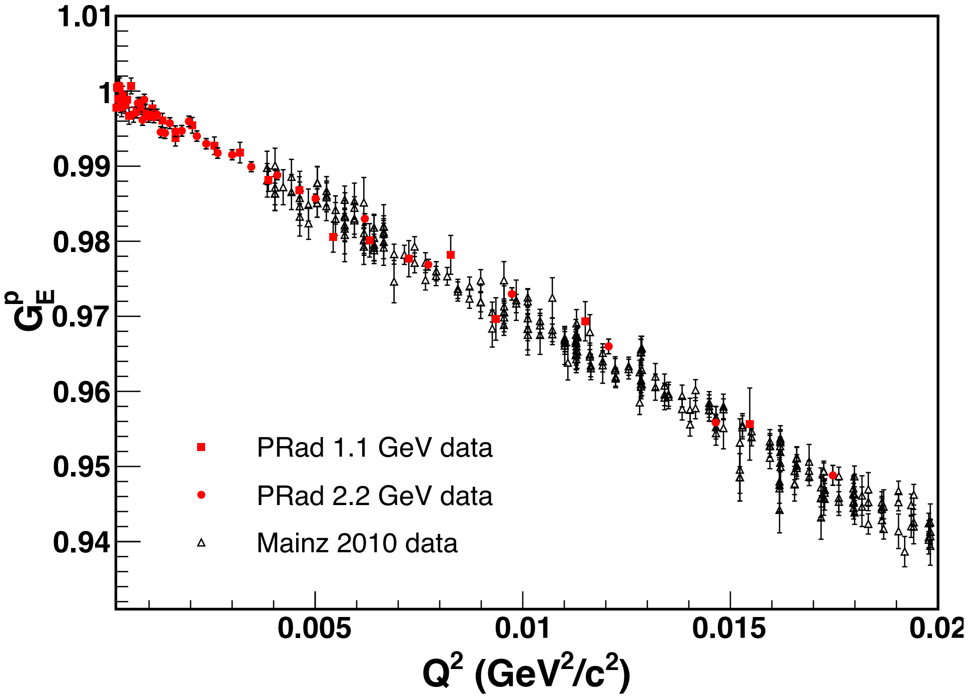


Many questions still left to answer:

- **How does proton acquire its mass: only 1% of proton mass comes from Higgs.**
- **What are the different contributions to nucleon spin (especially the gluons)?**
- **How does the confinement come about and does the proton decay?**

But we thought we at least understood the ground state bulk properties of the proton, such as the charge radius….

The proton electric form factor was extracted at the lowest Q^2 ever achieved in electron scattering.



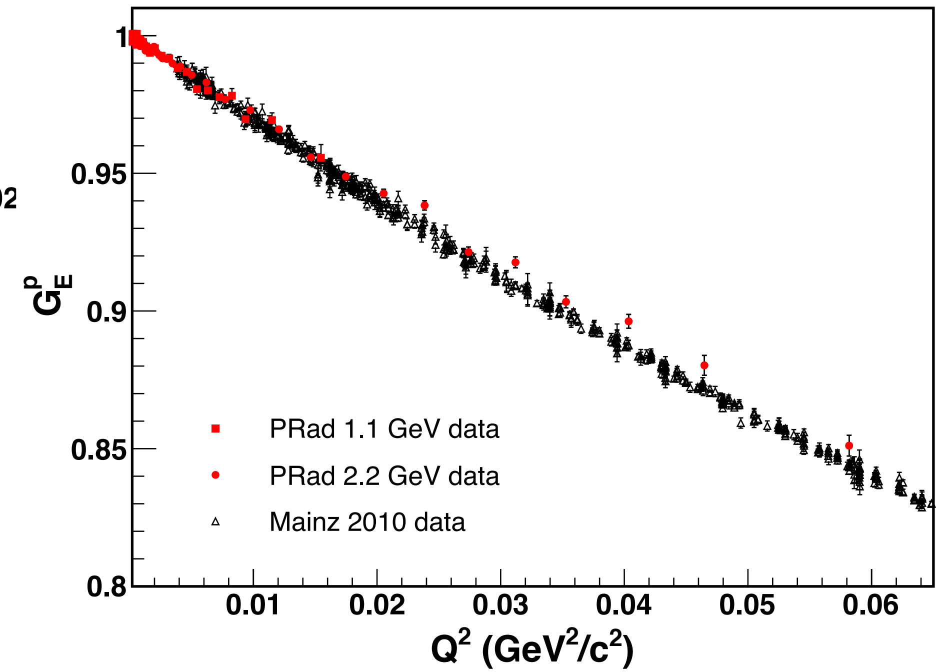
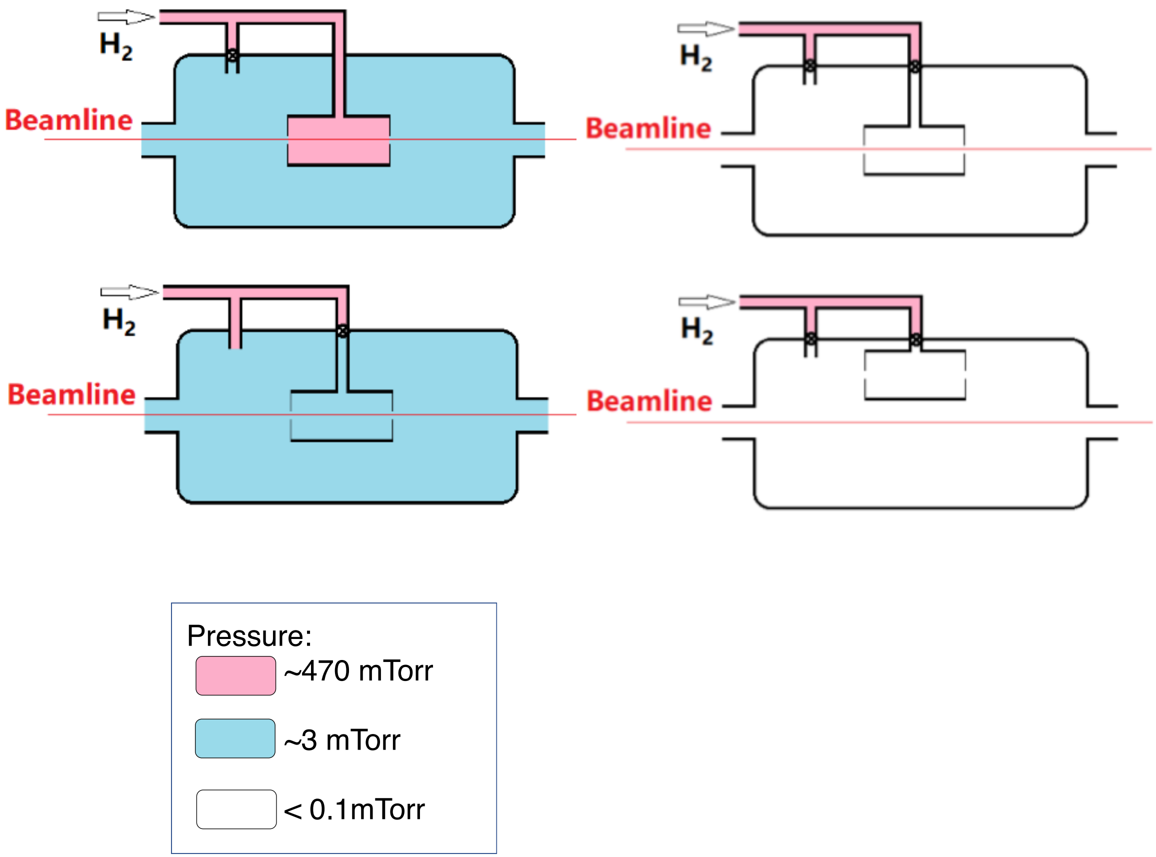
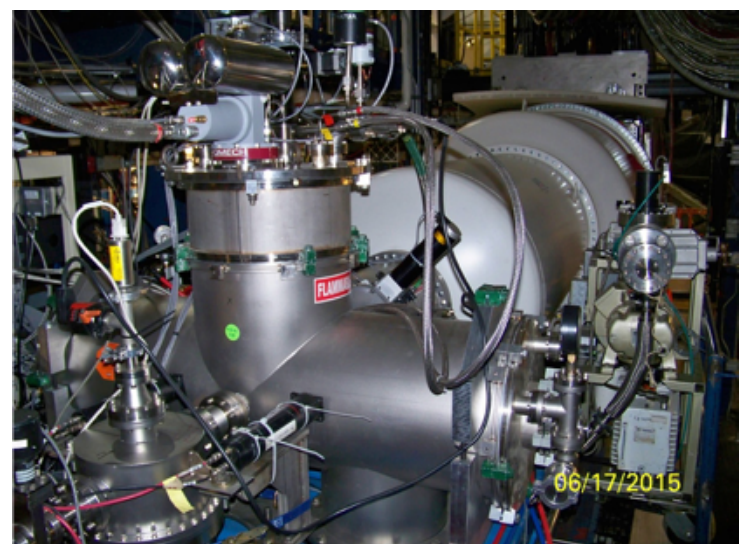


Figure courtesy of W. Xiong

Empty target runs were taken for background subtraction.

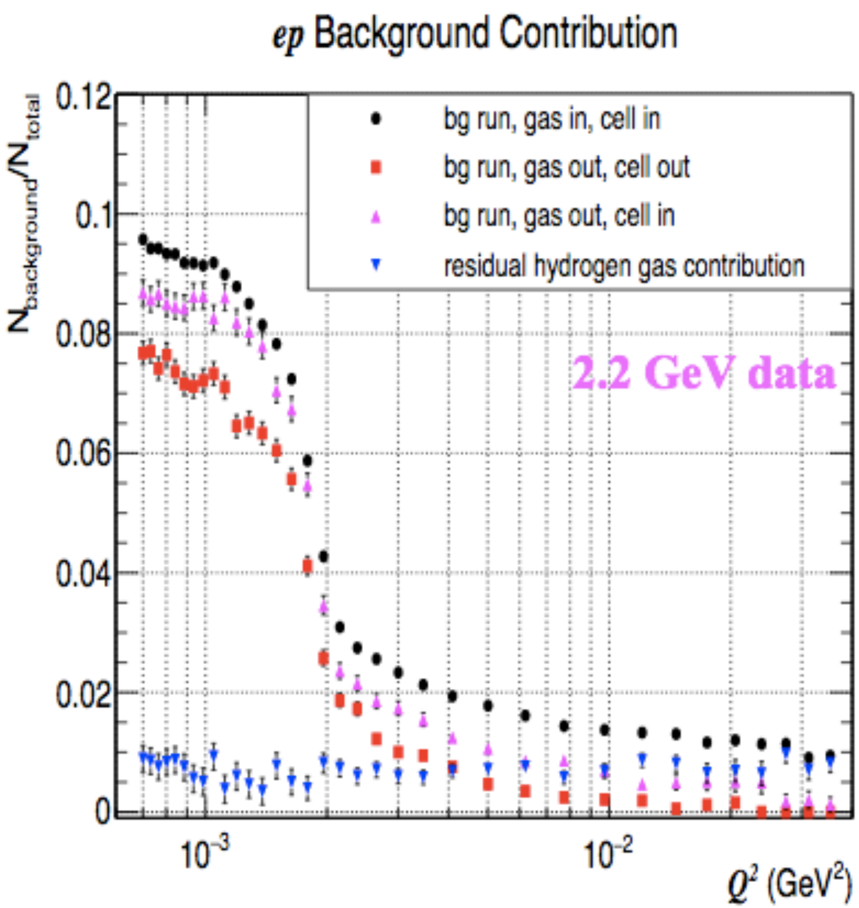
- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)

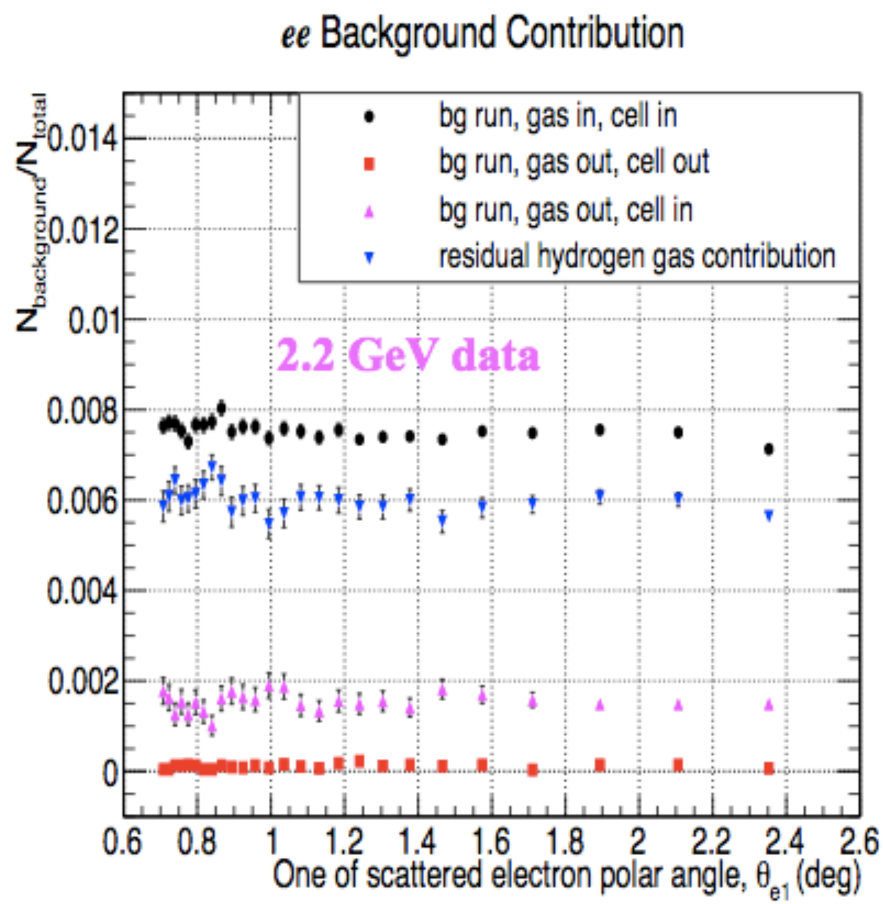




Empty target runs were used for background subtraction.

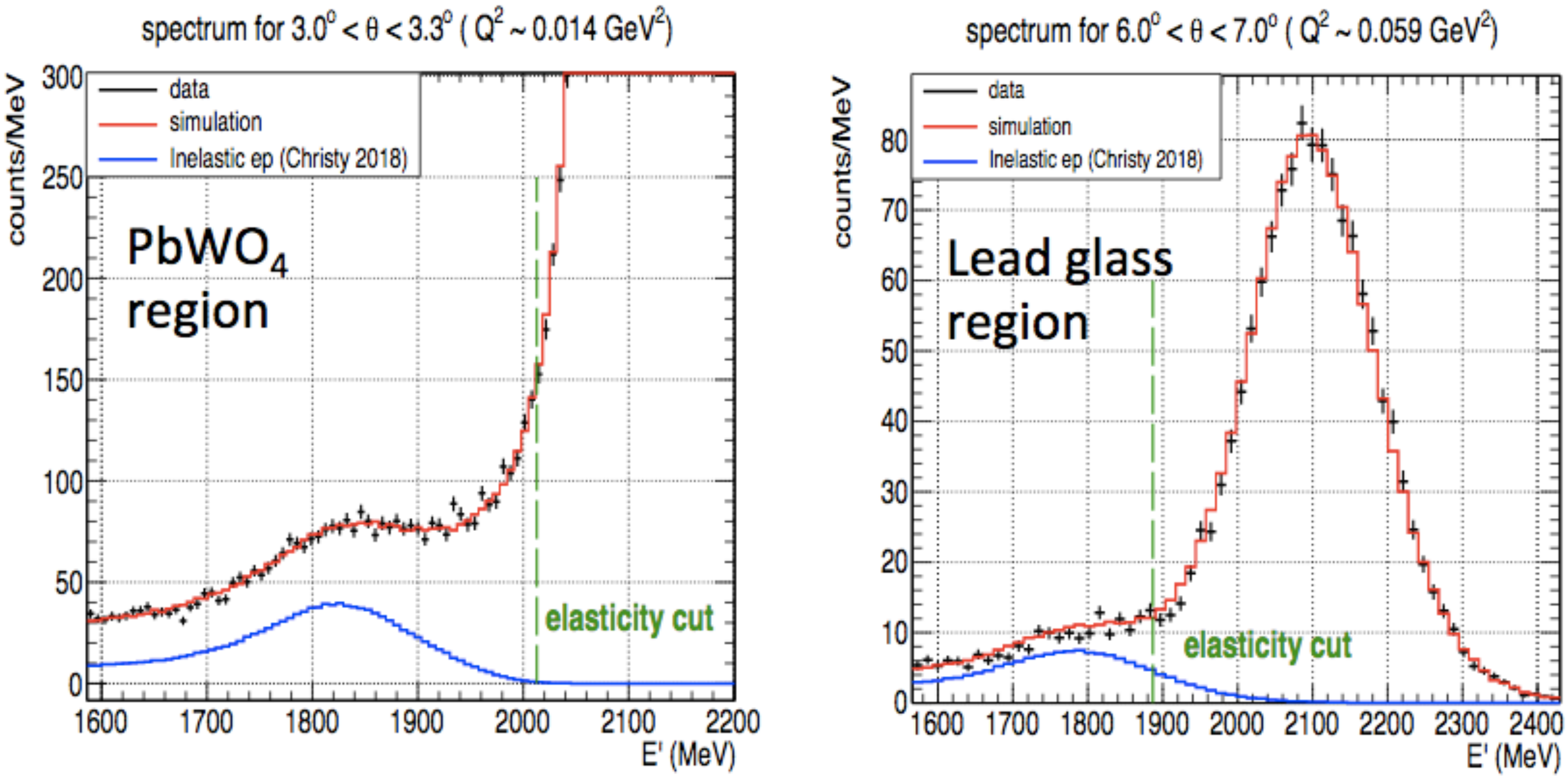
- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~ 0.8% at all angles





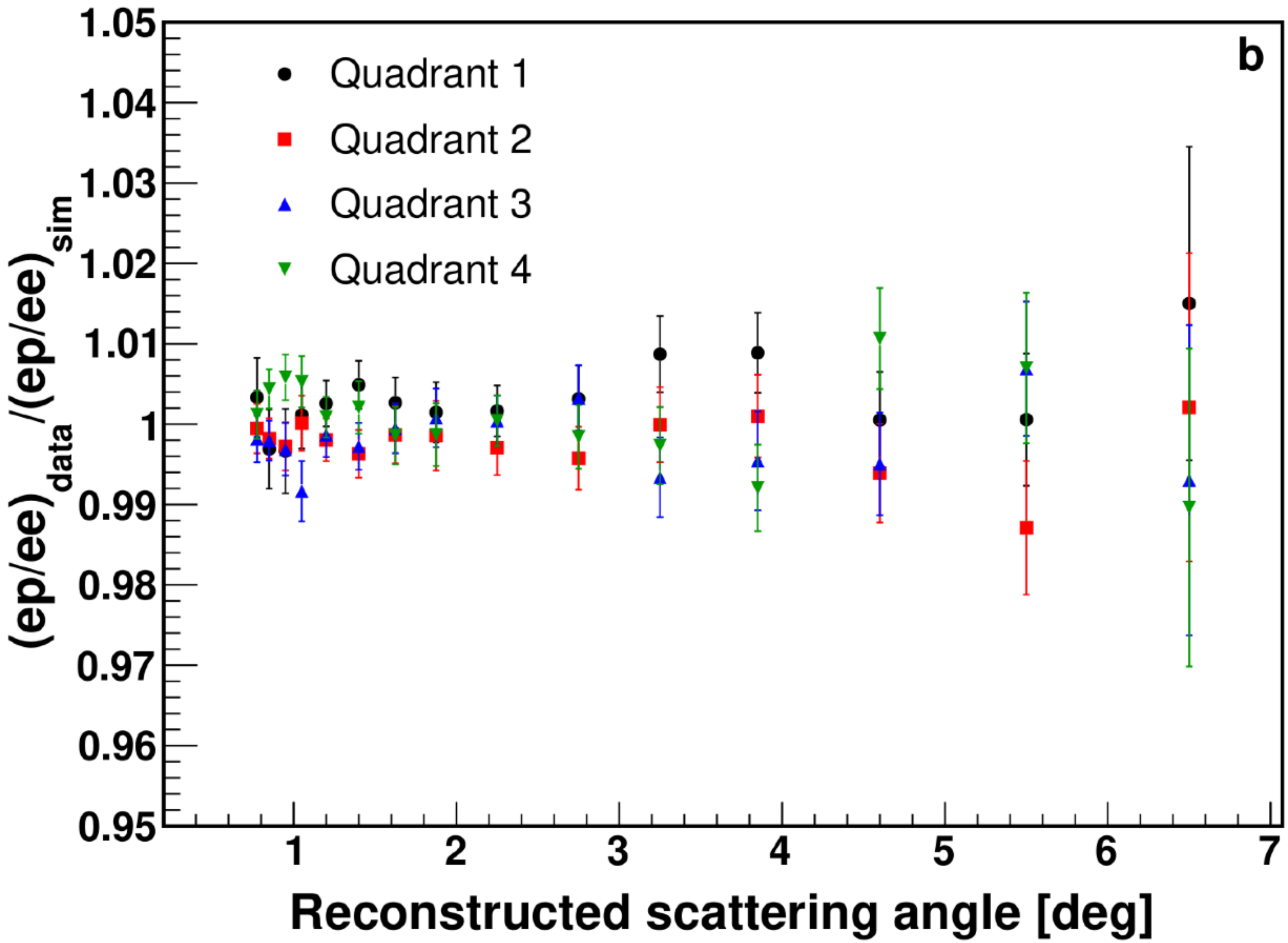
Contribution from inelastic scattering was simulated and compared to data.

- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region

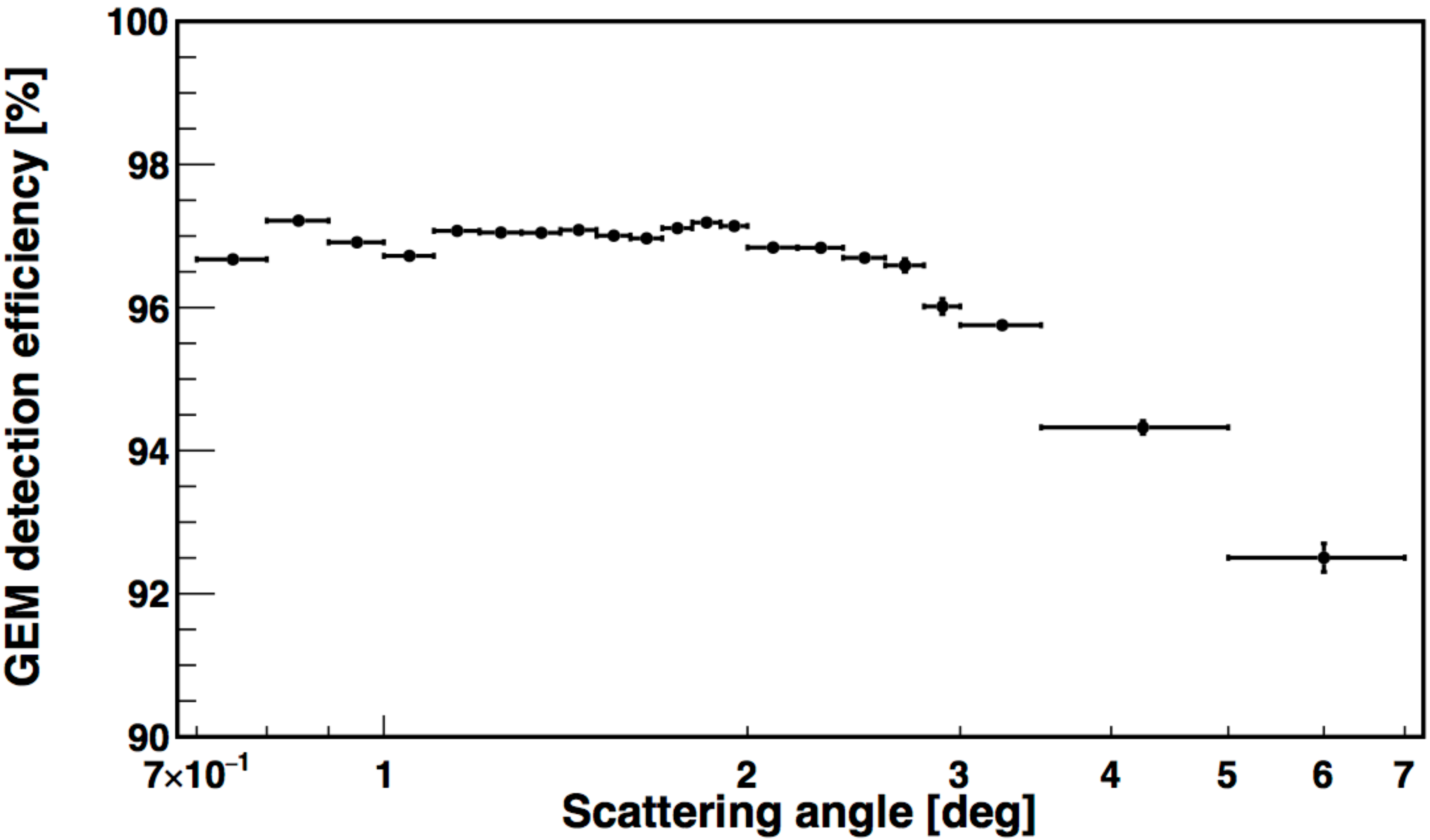


M.E. Christy and P.E. Bosted. PRC 81, 055213 (2010)

4-quadrant test demonstrated azimuthal symmetry



GEM efficiency



Simultaneous detection of *ep* elastic and *ee* Moller events

- ***ep*** **cross section measured related to Moller:**

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ep}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm det}^{ep}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

Two major sources of systematic errors, N_e and N_{tgt}, cancel

ε_{det} will be measured for [0.5 – 2.0] GeV range

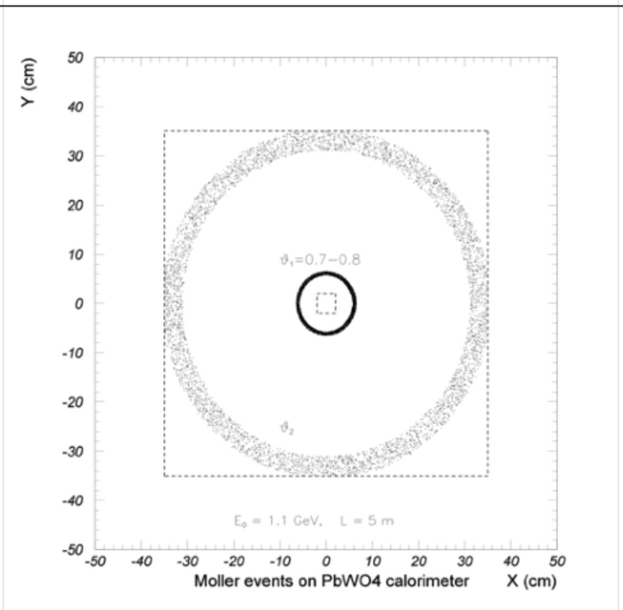
Relative ε_{det} are needed for this experiment

A. Gasparian

Alternative Moller analysis methods possible

Detect both Moller electrons in coincidence

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ep}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm det}^{ep}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$



Integrated over HyCal acceptance

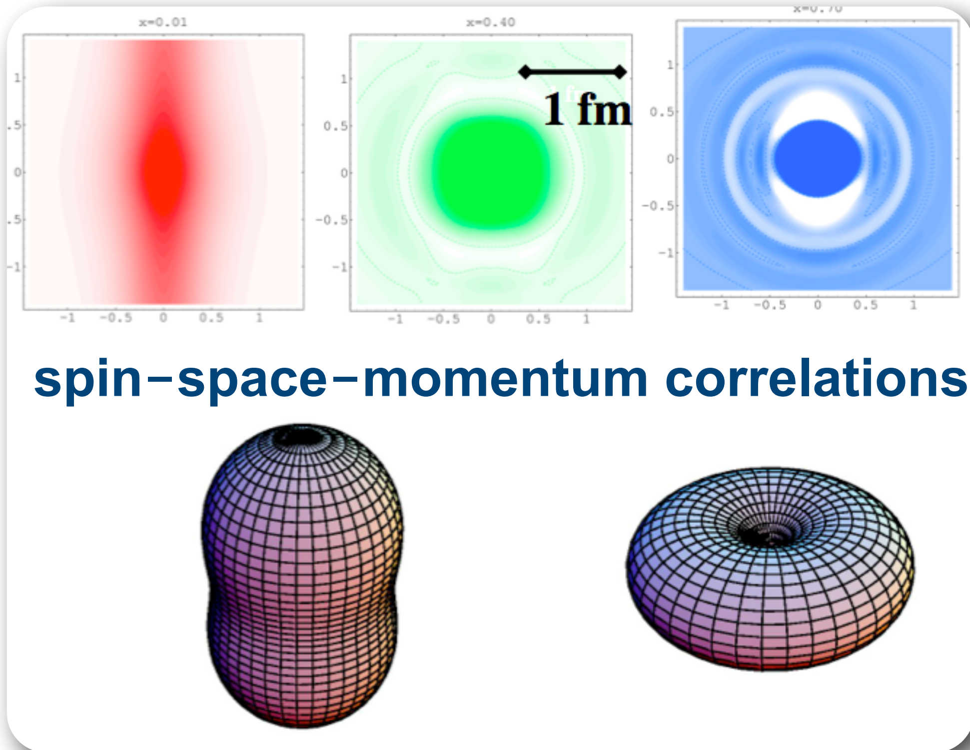
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep,\ \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^-,\ \text{on PWO})}\right]\frac{\varepsilon_{\rm geom}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm geom}^{ep}(\theta_i \pm \Delta\theta)}\,\frac{\varepsilon_{\rm det}^{e^-e^-}(\text{all PWO})}{\varepsilon_{\rm det}^{ep}(\theta_i \pm \Delta\theta)}\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

Over the last decade a new framework has been developed to map the 3D structure of the proton.

Generalized Parton Distributions (GPDs): a 3D map of the proton

GPDs provide connection between the formfactors and the parton distributions

the shape of the proton in the GPD framework



M. Burkardt ; A.Belitsky, X.Ji, F.Yuan PRD69, 074014 (2004) ; G.Miller, PRC68, 022201 (2003)

The PRad Collaboration

nature

Article | Published: 06 November 2019

A small proton charge radius from an electron–proton scattering experiment

W. Xiong, A. Gasparian, H. Gao, D. Dutta, M. Khandaker, N. Liyanage, E. Pasyuk, C. Peng, X. Bai, L. Ye, K. Gnanvo, C. Gu, M. Levillain, X. Yan, D. W. Higinbotham, M. Meziane, Z. Ye, K. Adhikari, B. Aljawrneh, H. Bhatt, D. Bhetuwal, J. Brock, V. Burkert, C. Carlin, A. Deur, D. Di, J. Dunne, P. Ekanayaka, L. El-Fassi, B. Emmich, L. Gan, O. Glamazdin, M. L. Kabir, A. Karki, C. Keith, S. Kowalski, V. Lagerquist, I. Larin, T. Liu, A. Liyanage, J. Maxwell, D. Meekins, S. J. Nazeer, V. Nelyubin, H. Nguyen, R. Pedroni, C. Perdrisat, J. Pierce, V. Punjabi, M. Shabestari, A. Shahinyan, R. Silwal, S. Stepanyan, A. Subedi, V. V. Tarasov, N. Ton, Y. Zhang & Z. W. Zhao - Show fewer authors

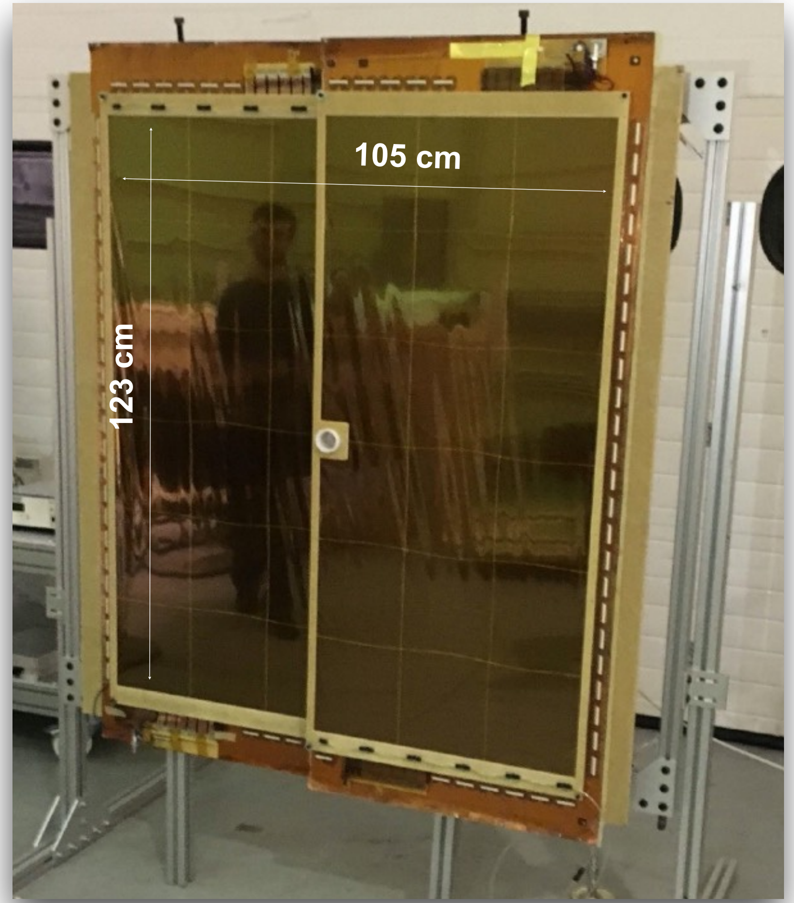
Nature **575**, 147–150(2019) | Cite this article

13 of the 58 authors from MSU
3 faculty, 3 post-docs (former)
6 graduate students (1 thesis student) & 1 undergraduate

Large area GEM coordinate detectors

- Two large GEM based X and Y- coordinate detectors with 100 μm position resolution

- Designed and built at University of Virginia (UVa)



- The GEM detectors provided:
  - factor of >20 improvements in coordinate resolutions
  - similar improvements in Q^2 resolution
  - unbiased coordinate reconstruction (including HyCal transition region)
  - increase Q^2 range by enabling use of Pb-glass part of calorimeter

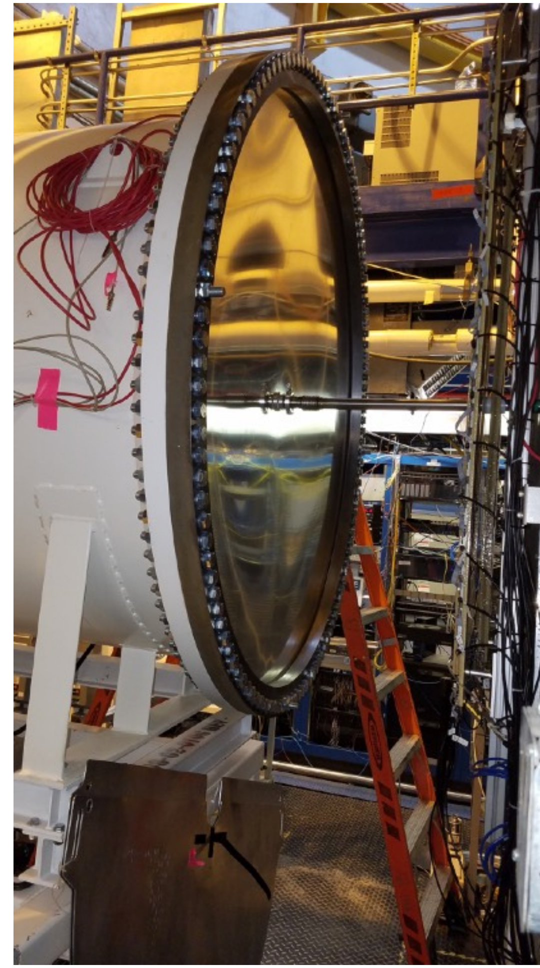
HyCal and GEMs on the beamline

beam view

downstream view

Vacuum chamber with one thin window

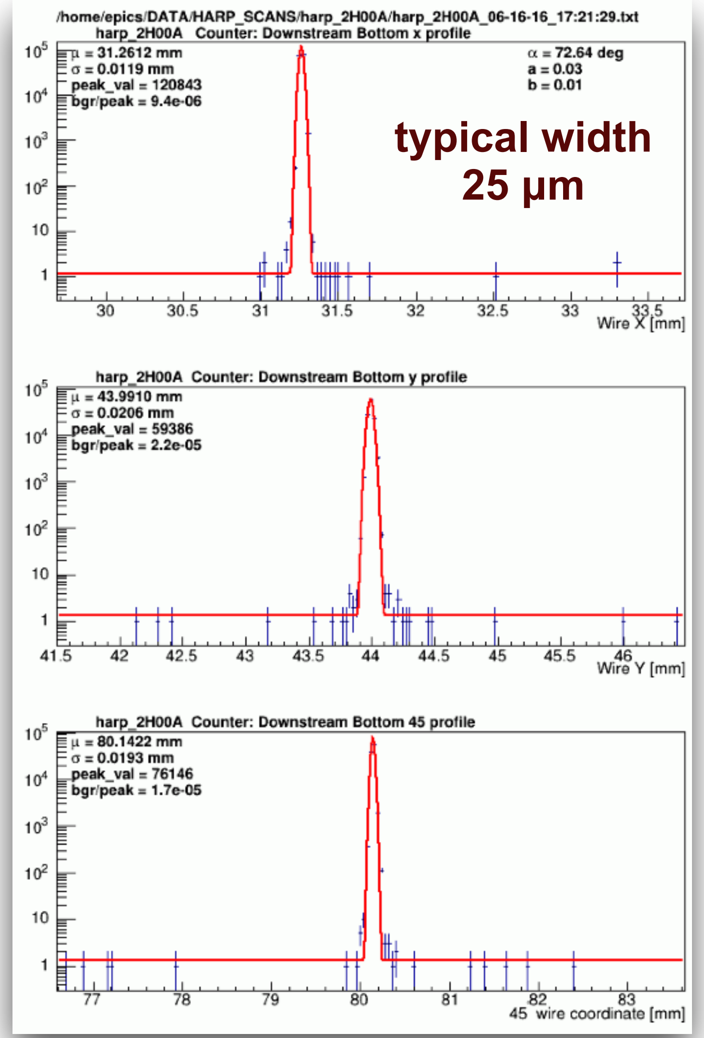
two stage, 5 m long vacuum chamber



1.7 m dia, 2 mm thick
Al window

High quality, stable CEBAF electron beam

electron beam profile at target
(measured with harp scan)



position stability : ± 250 μm

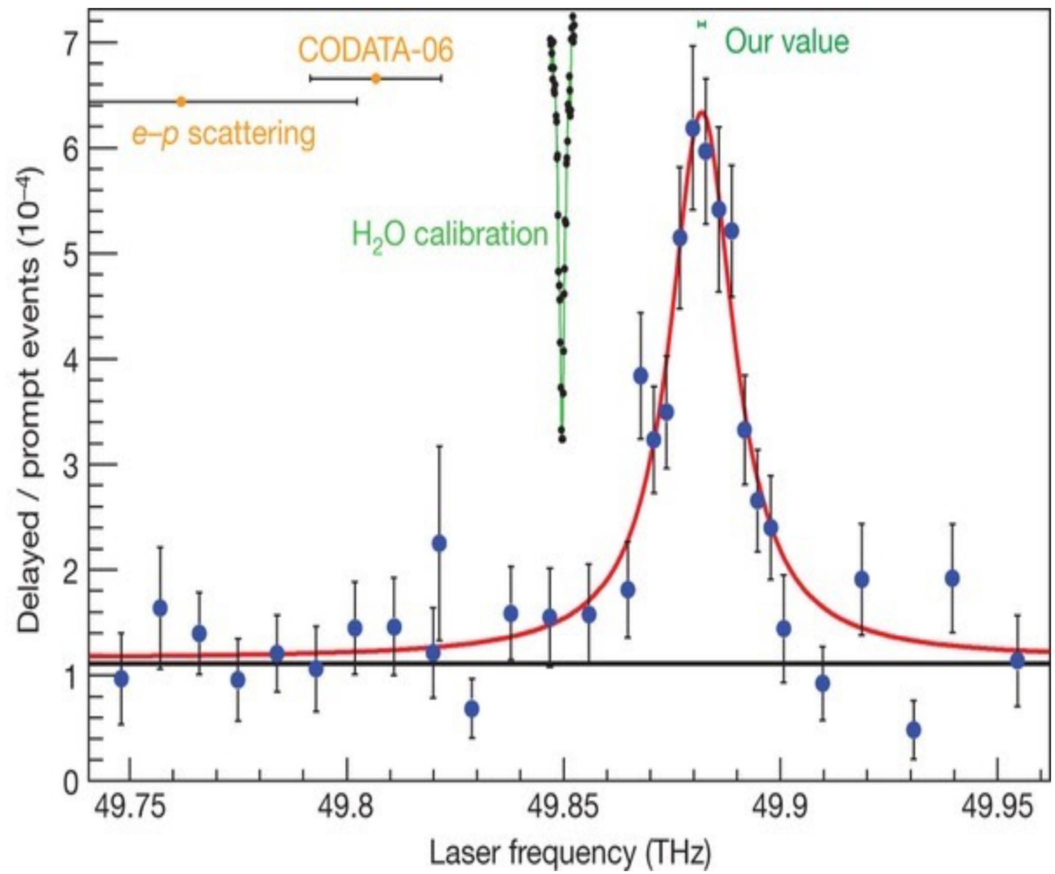
Experiment ran during May/June 2016

With E_e = 1.1 GeV beam
collected 4.2 mC on target (2x10^{18} H atoms/cm^2)
604 M events with H and
53 M events without H in target
25 M events on 1μm Carbon foil target

With E_e = 2.2 GeV beam
collected 14.3 mC on target (2x10^{18} H atoms/cm^2)
756 M events with H and
38 M events without H in target
10.5 M events on 1μm Carbon foil target

The muonic hydrogen spectroscopy results had unprecedented precision and were very surprising.

R. Pohl et al, Nature, 466, 213 (2010).

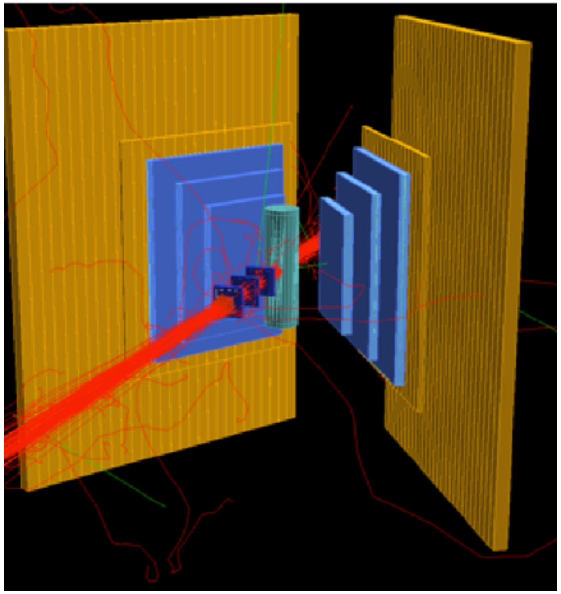


- Muonic hydrogen Lamb shift experiment at PSI: *$Q^2 \sim 10^{-6}$ GeV^2*
- r_p = 0.84184(67) fm ➡ unprecedented precision ~0.08%
- Different from most previous experimental results and analysis.

Several new experiments are currently being prepared and some are expected to run as soon as Fall 2019.

The MUon proton Scattering *Experiment* (*MUSE*) at the PSI will simultaneous measure elastic *μ*±*-p* and elastic *e*±*-p* scattering to determine r_p.

Spokespersons: R. Gilman, E. Downie, & G. Ron



θ ≈ 20° – 100°

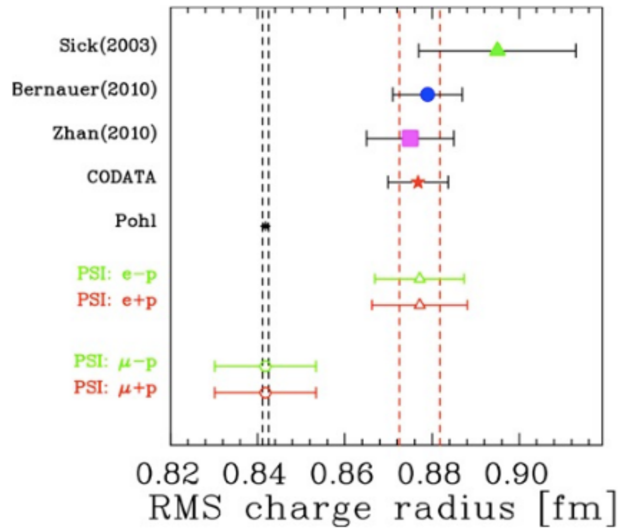
Q^2 ≈ 0.002 - 0.07 GeV^2

3.3 MHz total beam flux

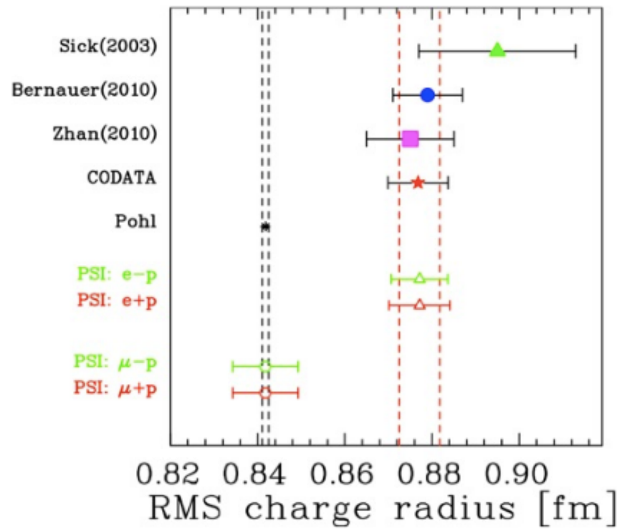
≈ 2-15% μ's

≈ 10-98% e's

≈ 0-80% π's



Absolute errors



Relative errors

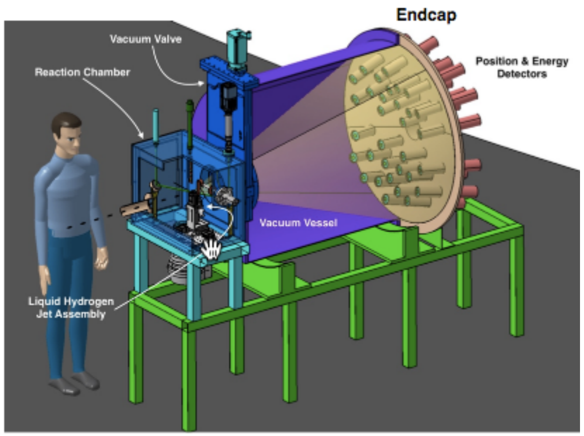
Individual radius extractions from e±, μ± each to 0.01 fm

➔ Test of lepton universality

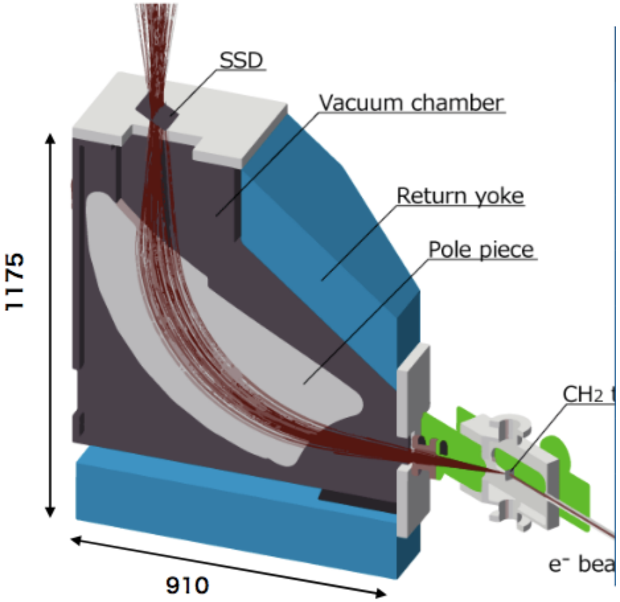
➔ Determination contribution of two-photon exchange in μ-p scattering.

Figures courtesy of J. Arrington and PSI

The ProRad and ULQ^2 experiments will use very low energy electron beams to reach ultra low Q^2.



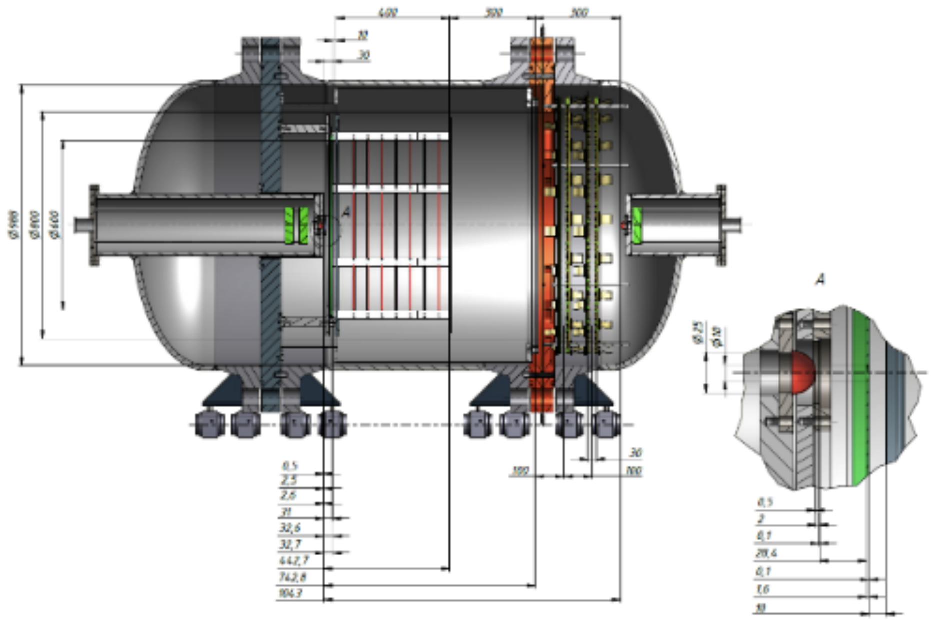
ProRad at IPNO will use a **30-70 MeV** electron beam on a laminar liquid hydrogen jet target to measure the cross section in the **6^o - 15^o** angular range with a 32 cell detector where each cell consists of a sci-fi coordinate detector and a BGO crystal. ProRad plans to cover a Q^2 range of **10^{-6} - 10^{-4}** (GeV/c)^2.
Spokesperson: **E. Voutier**



ULQ^2 collaboration at Tohoku U, will use a **20-60 MeV** electron beam on a CH_2 target to measure the cross section in the **30^o - 150^o** angular range with double arm high resolution spectrometers. ULQ^2 plans to cover a Q^2 range of **3x10^{-4} - 8x10^{-3}** (GeV/c)^2.
Spokesperson: **T. Suda**

Proton charge radius will be measured at COMPASS and at Mainz using a hydrogen gas TPC.

μ^--p scattering will used to measure r_p at COMPASS using a high pressure hydrogen gas TPC as an active target and recoil proton detector. COMPASS plans to cover a Q^2 range of **10^{-4} - 1** $(GeV/c)^2$.



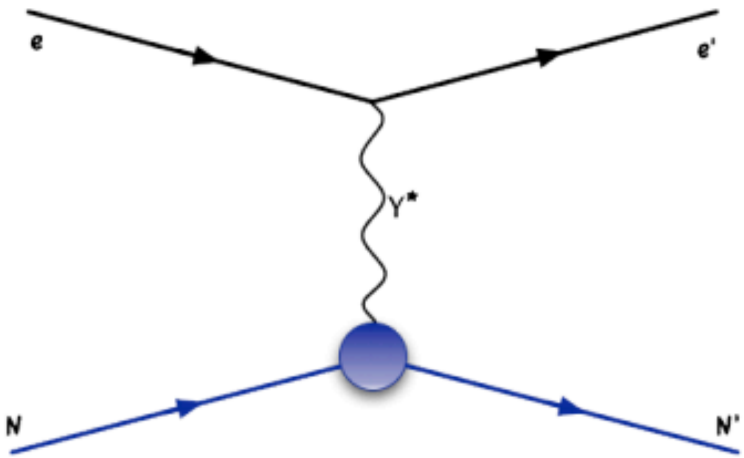
The same high pressure hydrogen gas TPC will be used as an active target and recoil proton detector for an *e-p* scattering experiment at Mainz to determine r_p

H - spectroscopy and elastic e-p scattering are the two traditional methods for determining proton charge radius

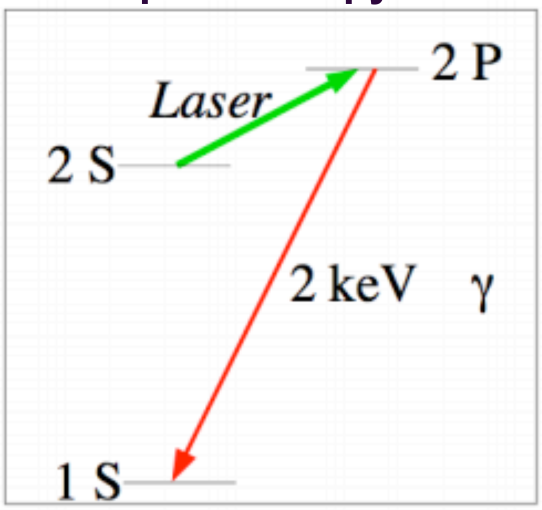
The forces defining the surface of a proton do not come to an abrupt end, its boundary is somewhat fuzzy.

RMS charge radius (r_p) is obtained from a consistent interpretation of hydrogen spectroscopy and electron-proton scattering experiments

e-p Scattering



H-spectroscopy



For all types of experiments: r.m.s. charge radius given by the slope at $Q^2 = 0$:

$$\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

This definition has been rigorously shown to be consistent with all experimental measurements. G. Miller, Phys. Rev., C 99, 035202 (2019)