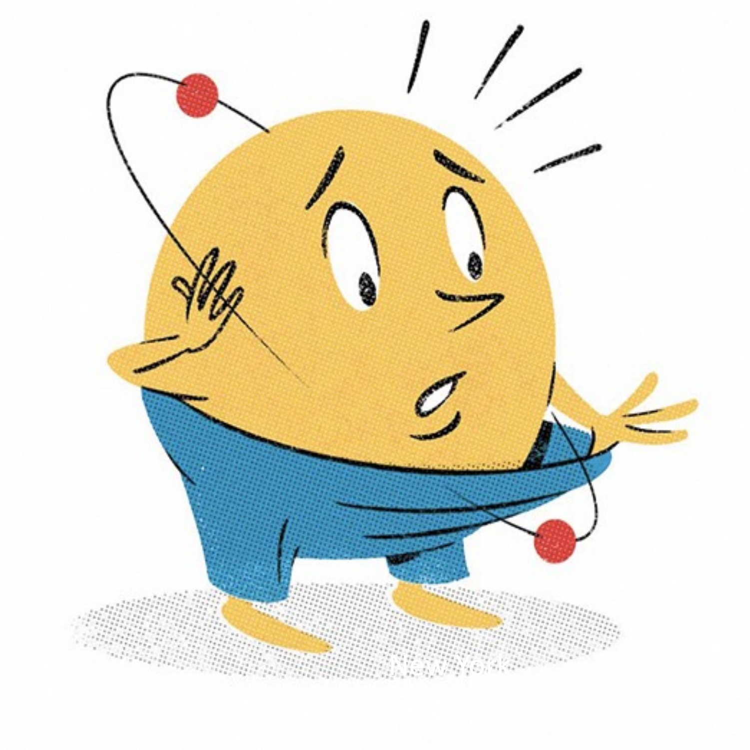


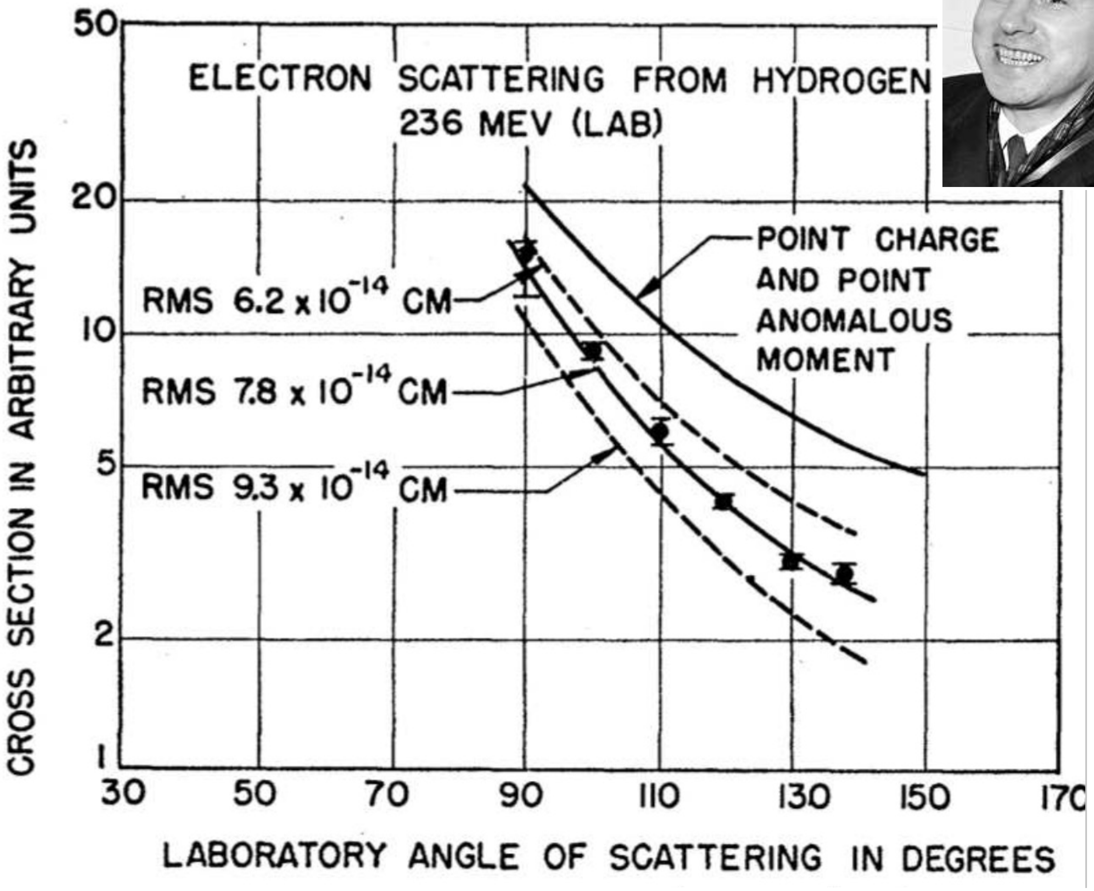
Proton Charge Radius Experiment at Jefferson Lab

- Weizhi Xiong (熊伟志)
- Shandong University

- LEES 2024, Tohoku University Sendai, Japan
- Oct. 28th – Nov. 1st 2024

Outline

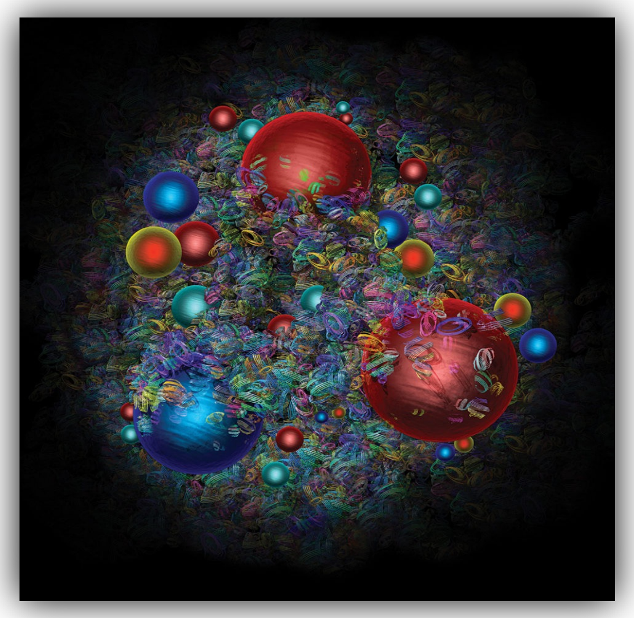
- ➢Introduction: proton charge radius and electromagnetic form factors
- ➢PRad experiment at JLab
- ➢Preparation of PRad-II
- ➢Summary



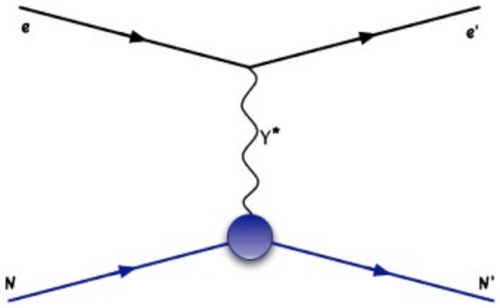
1956 Measurements @ Stanford

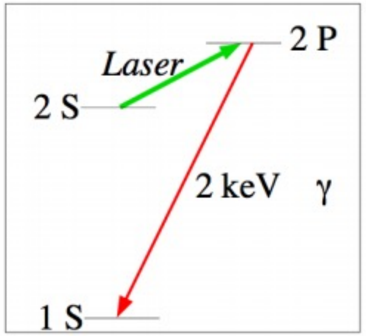
General Info on Proton Charge Radius

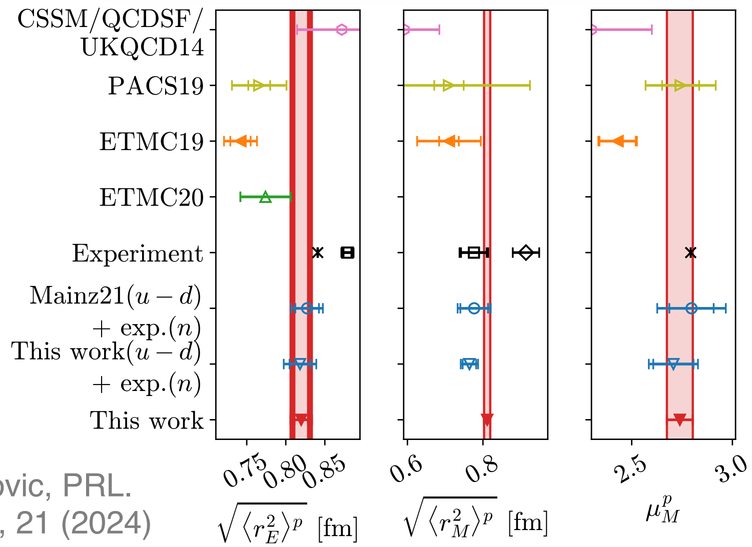
- Proton charge radius (r_p):
  1. Spacial distribution of proton's charge
  2. Important for understanding how QCD works
  3. Input to the bound state QED calculation for atomic hydrogen energy levels
  4. Critical in determining Rydberg constant (R_∞)



- Two well-established experimental methods:
  1. *e-p* elastic scattering (nuclear physics)
  2. Hydrogen spectroscopy (atomic physics)







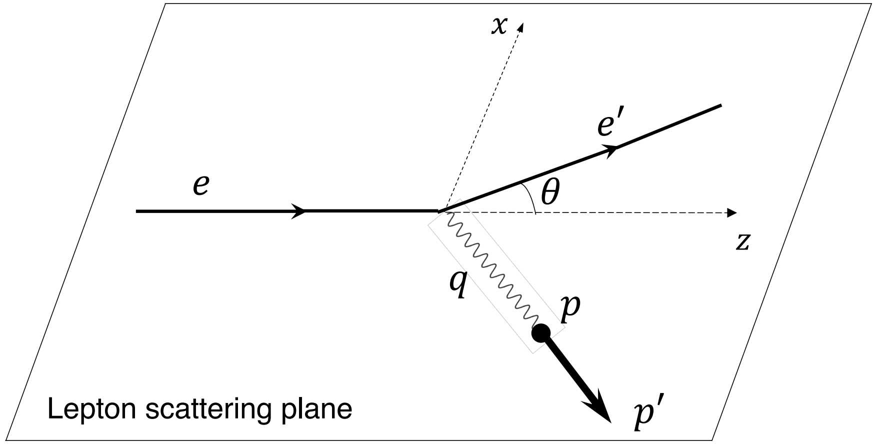
D. Djukanovic, PRL. 132, no.21, 21 (2024)

Unpolarized Lepton-Proton Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (neglecting lepton mass):

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

$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

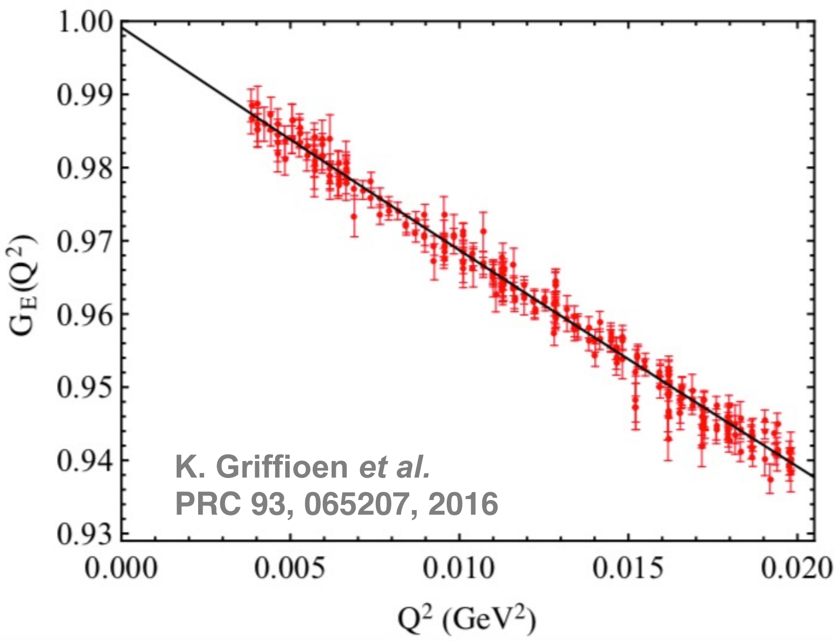


Taylor expansion of G_E at low Q^2

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

Derivative at low Q^2 limit

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



- Exploit ε dependency to separate G_E^p and G_M^p

Polarized ep Elastic Scattering

- Directly measure G_E^p/G_M^p at a given Q^2
- Combined with unpolarized cross section to separate G_E^p and G_M^p
- Ratio measurement, lots of cancellation for systematics
- Overcome several difficulties for unpolarized technique: G_E^p at high Q^2, radiative correction…

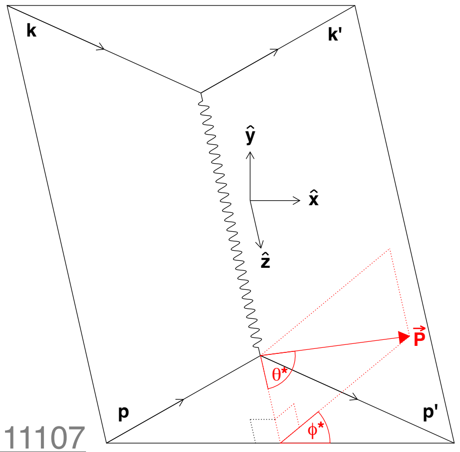
Double polarization, asymmetry measurements

$$A_{eN} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = P_{\text{beam}} P_{\text{targ}} \left[A_t \sin\theta^* \cos\phi^* + A_\ell \cos\theta^*\right]$$

$$A_t = -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}} \frac{r}{1+\frac{\epsilon}{\tau}r^2}$$

$$A_\ell = -\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2}$$

$$r \equiv G_E/G_M$$

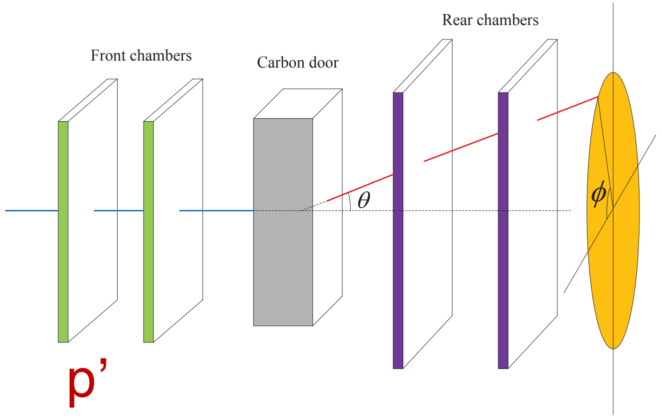


arXiv:2212.11107

Polarization transferred to final state proton

$$P_t = P_{\text{beam}} A_t$$
$$P_\ell = -P_{\text{beam}} A_\ell .$$

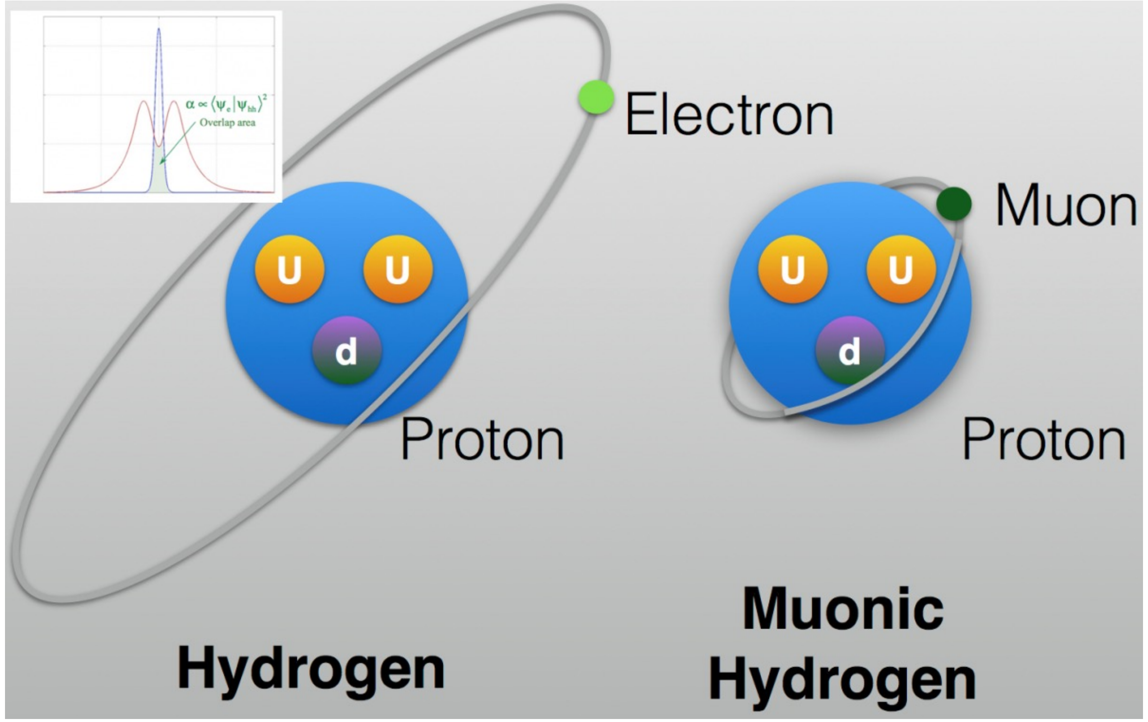
$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} = -\frac{P_t}{P_\ell}\frac{E_e + E_e'}{2M}\tan\left(\frac{\theta_e}{2}\right)$$



Ordinary Hydrogen v.s. Muonic Hydrogen

- One can do this with ordinary hydrogen or muonic hydrogen
- Muon is ~200 times heavier than electron
- Orbit much closer to proton, more sensitive to proton size

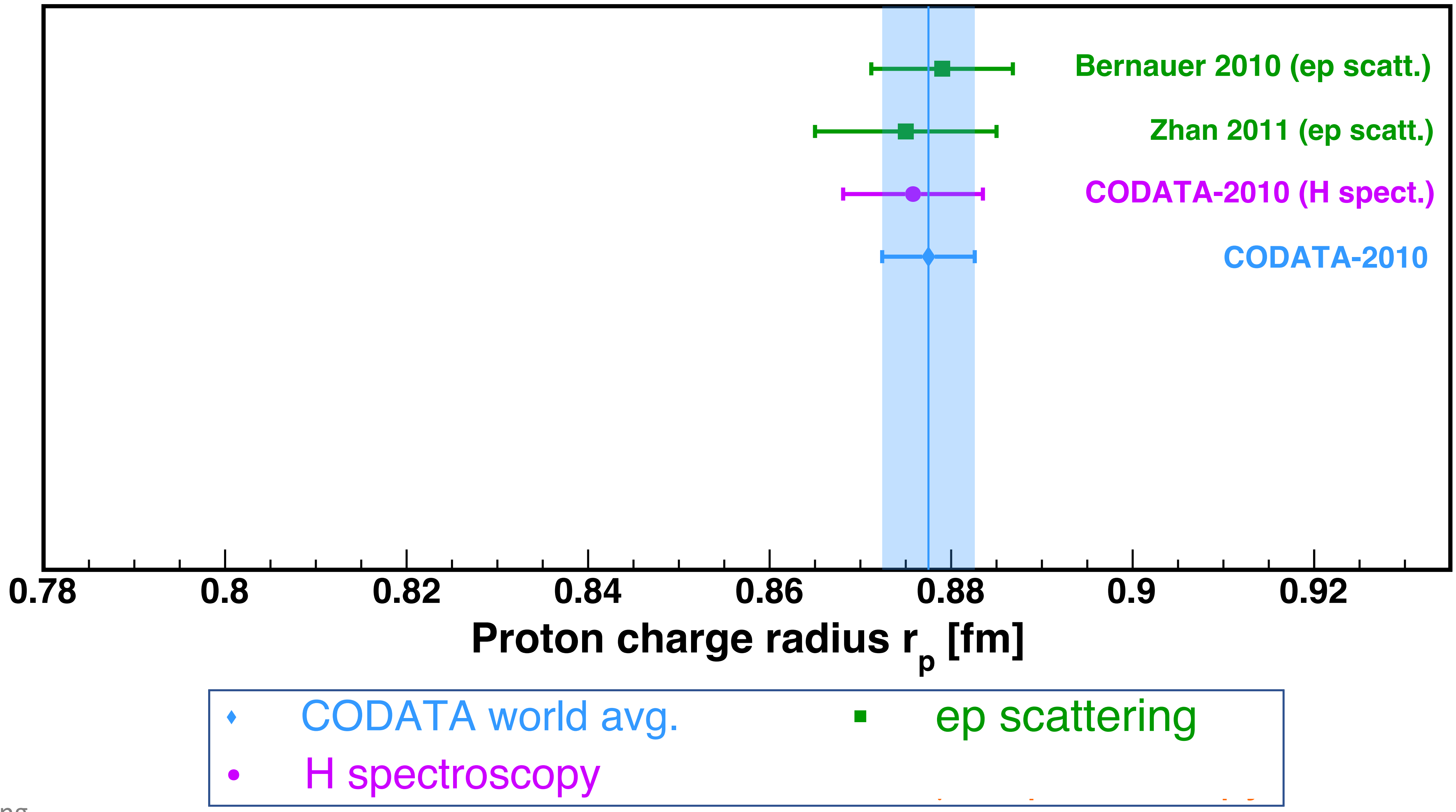
$$\langle r^{\mathrm{orbit}} \rangle \simeq \frac{\hbar}{Z\alpha\, m_r c} n^2$$



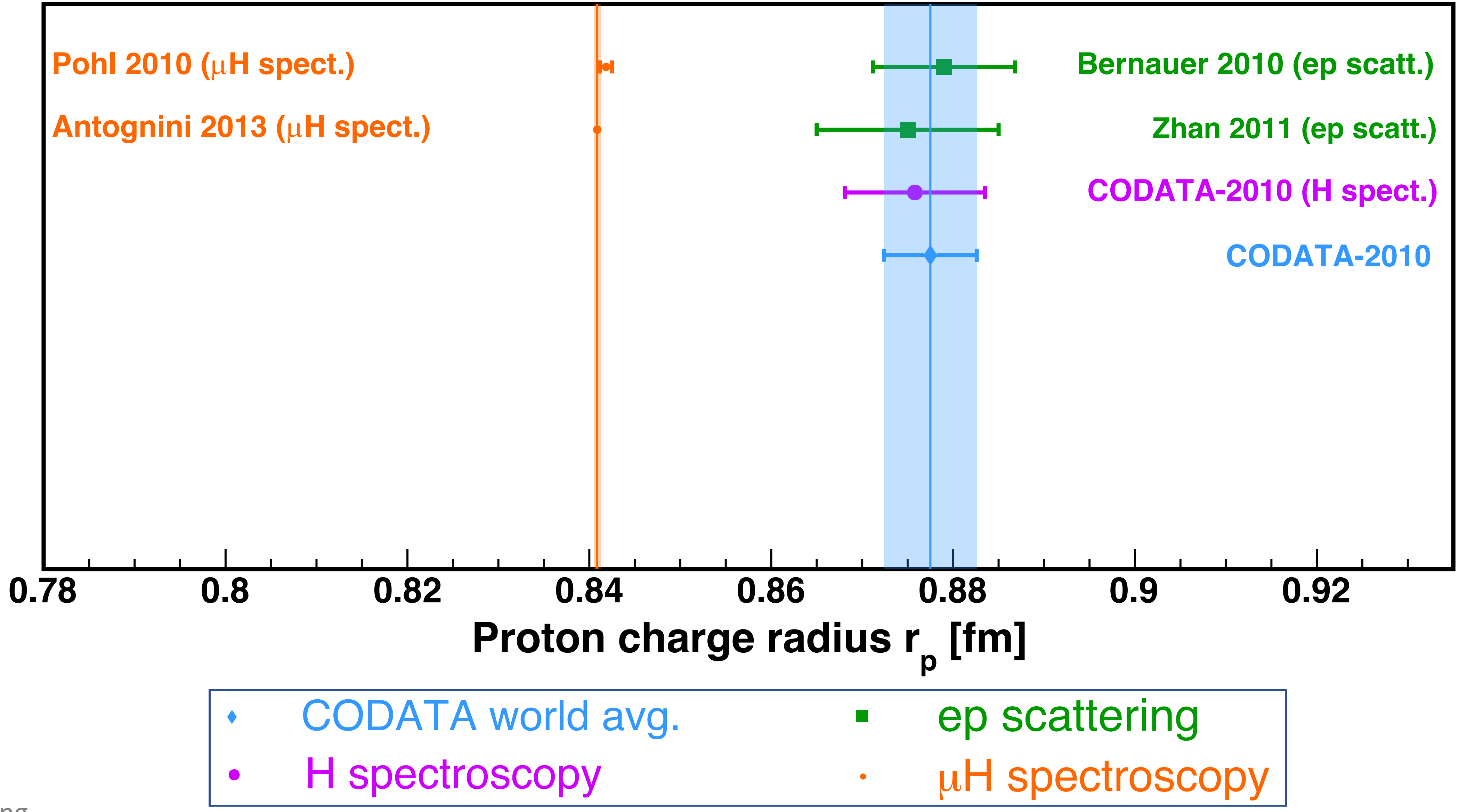
Proton finite size effect in 2S-2P: 2% in μH, 0.015% in H

Weizhi Xiong

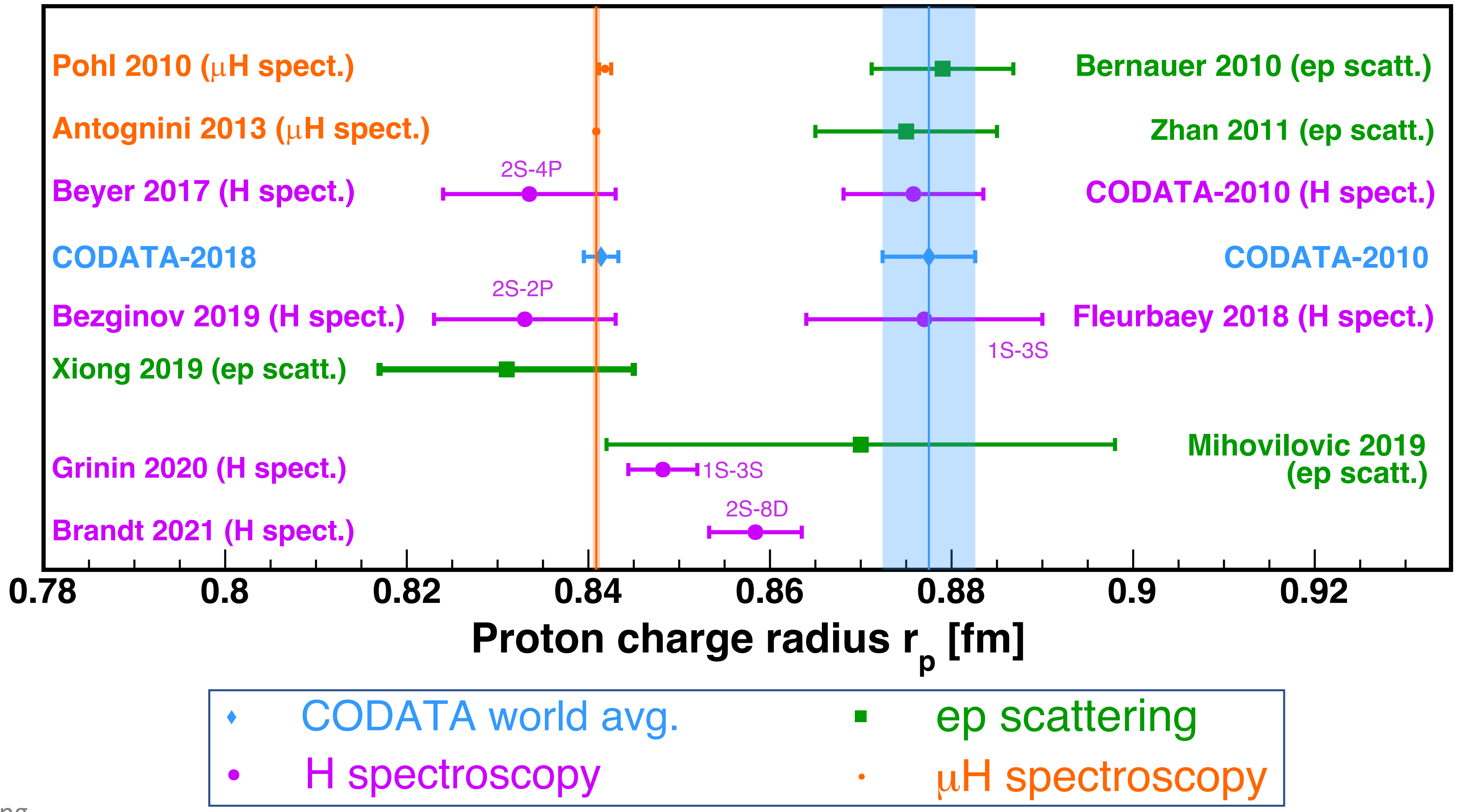
Proton Charge Radius



Proton Charge Radius Puzzle

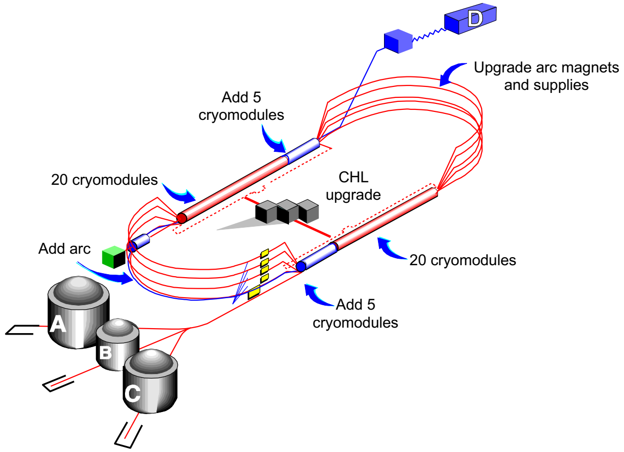


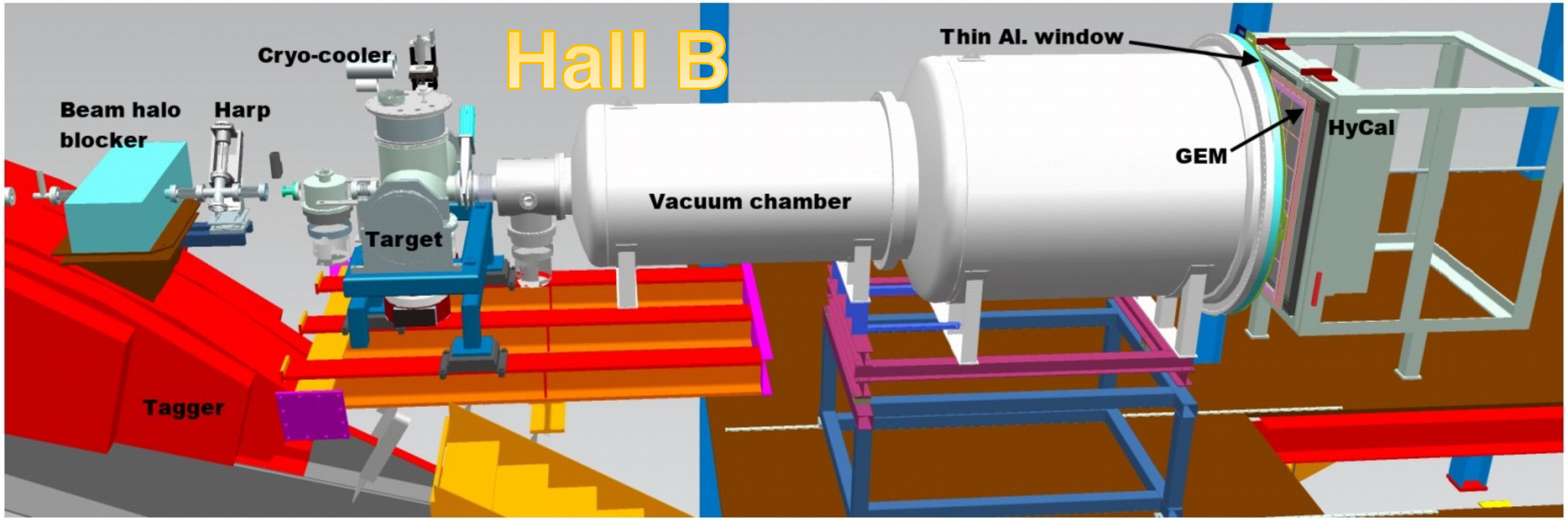
Proton Charge Radius Puzzle



PRad Experiment at Jefferson Lab

- Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA
- Data taking May/June 2016, 1.1 GeV and 2.2 GeV e beams





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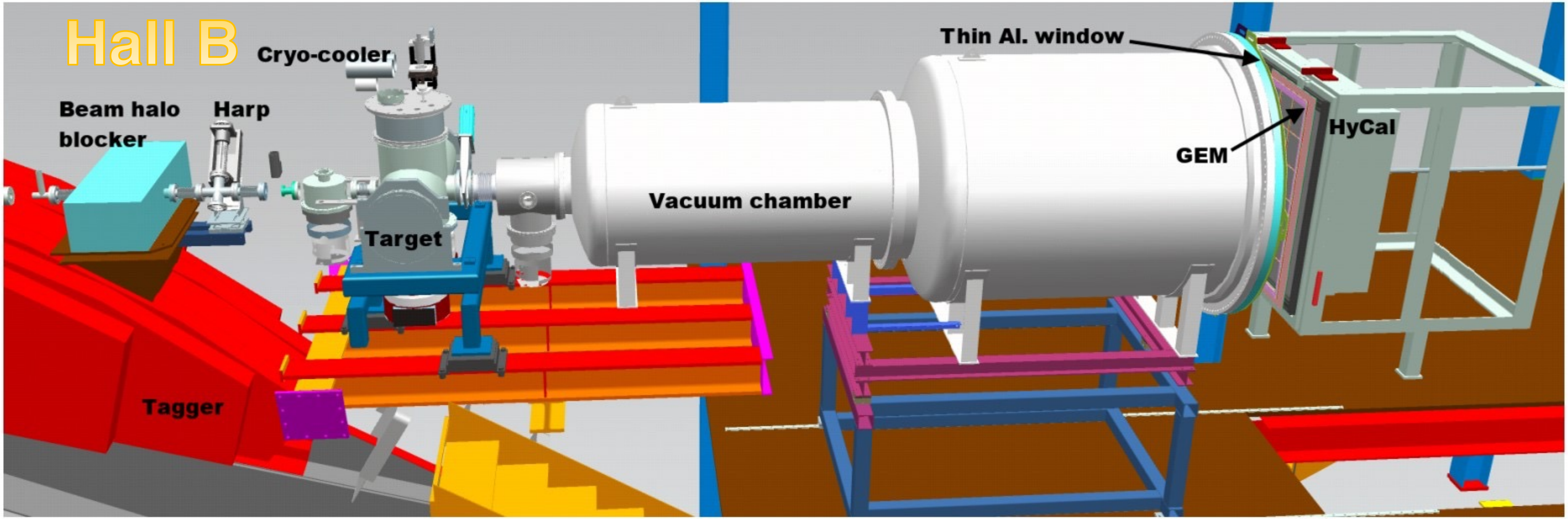
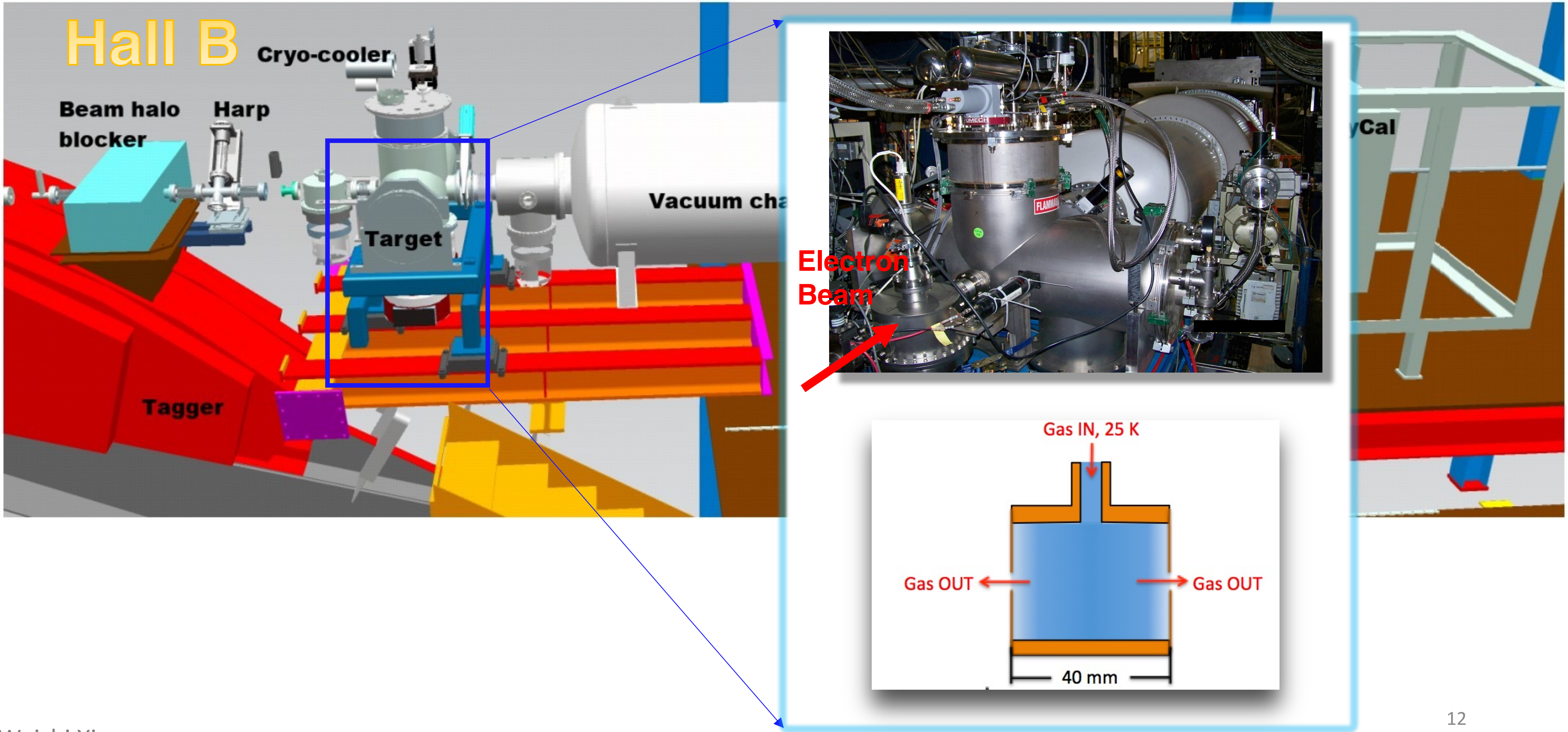
PRad Experimental Apparatus

Large acceptance, small angle and non-spectrometer apparatus



PRad Experimental Apparatus

Large acceptance, small angle and non-spectrometer apparatus

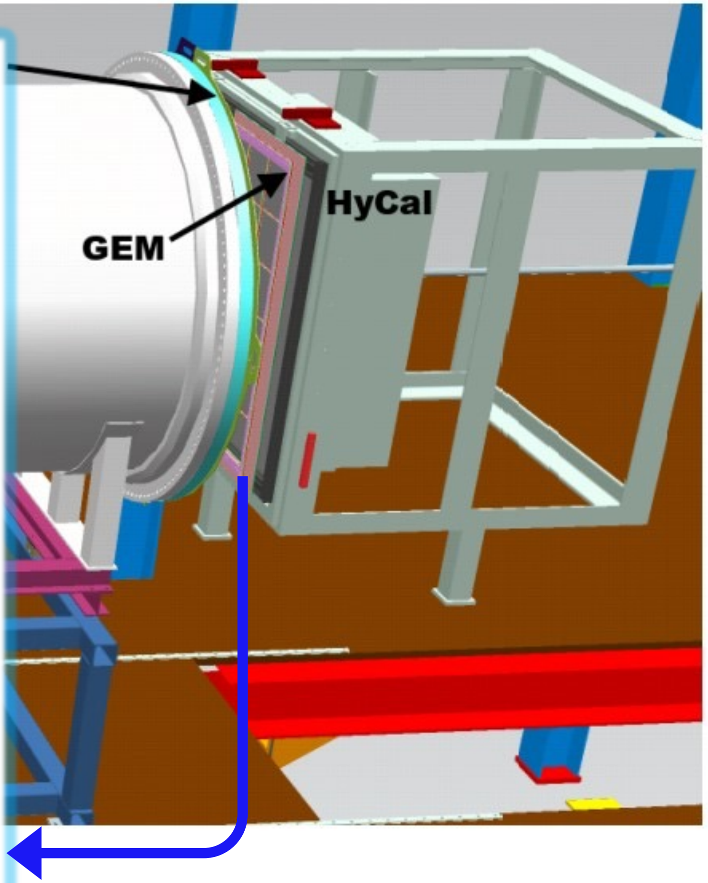


PRad Experimental Apparatus

Large acceptance, small angle and non-spectrometer apparatus

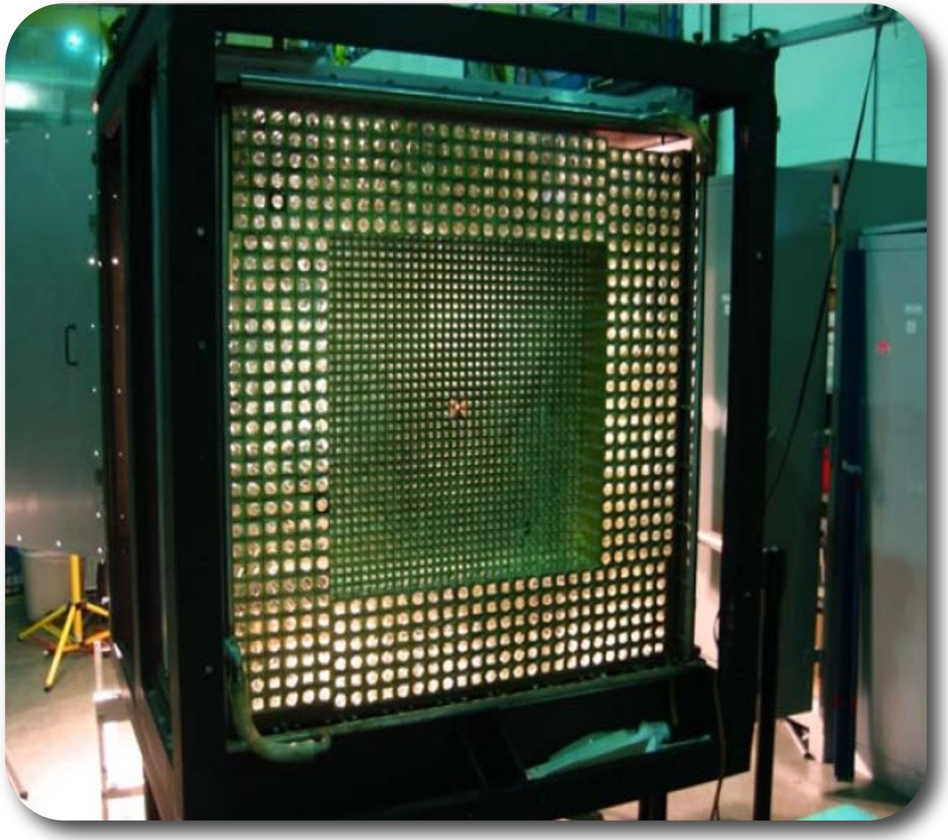
Hall B

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)

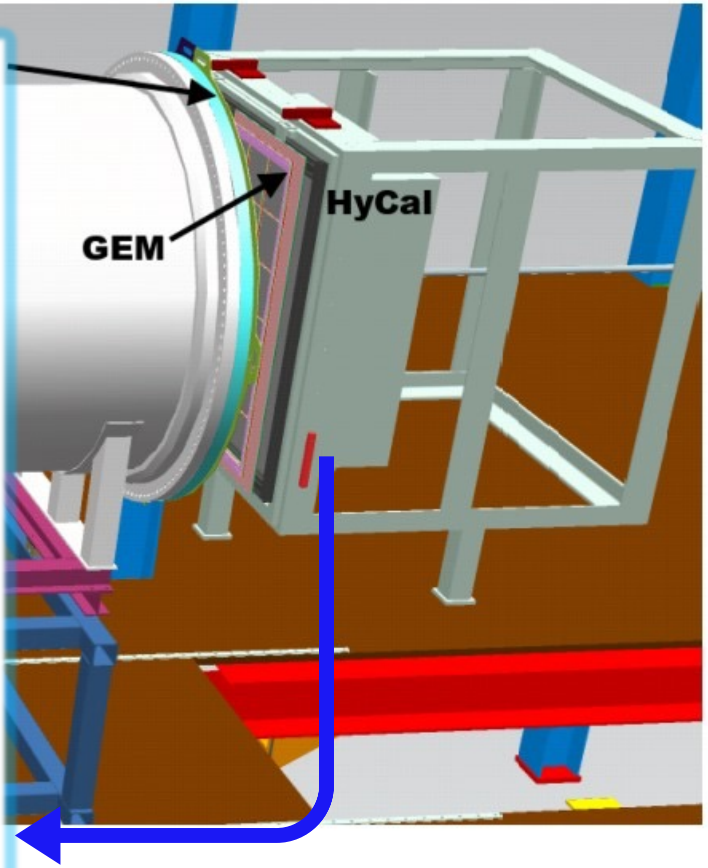


PRad Experimental Apparatus

Large acceptance, small angle and non-spectrometer apparatus



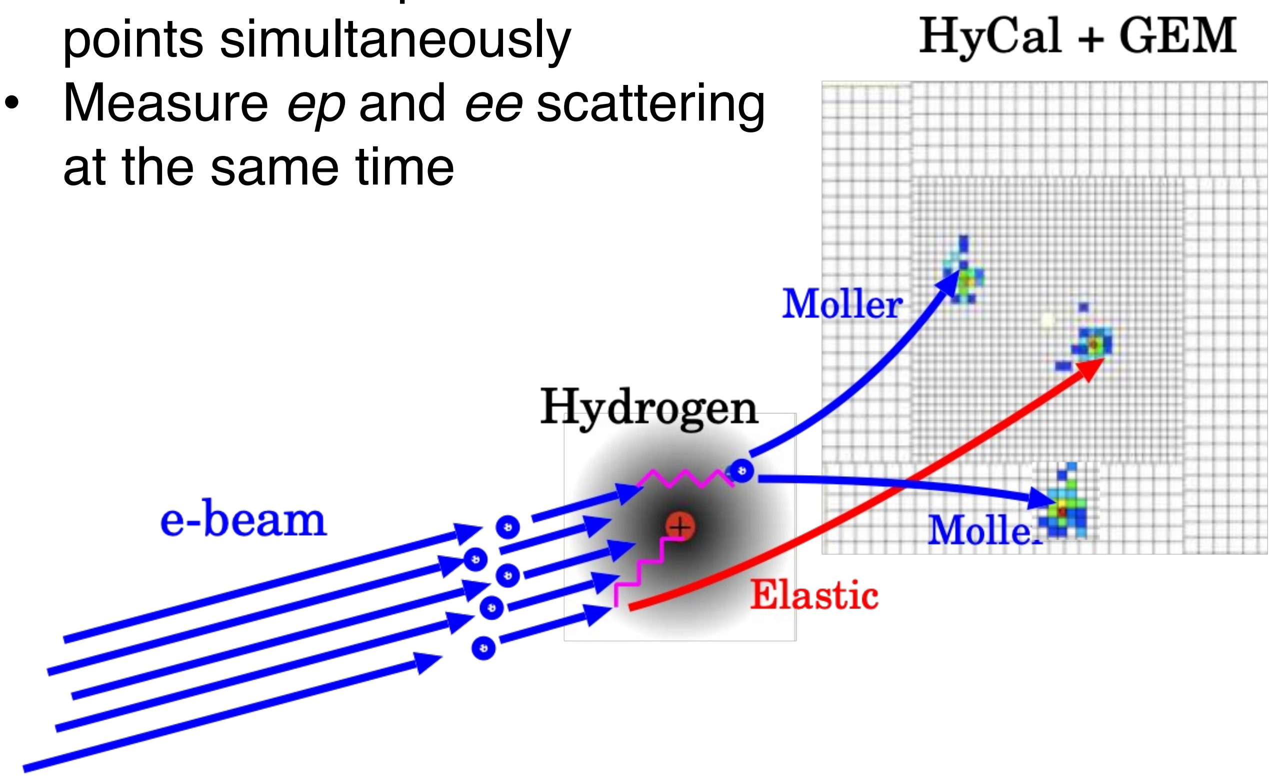
- Hybrid EM calorimeter (HyCal)
  - Inner 1156 $PbWO_4$ modules
  - Outer 576 lead glass modules
- Scattering angle coverage: ~ 0.7° to 7.0°
- Full azimuthal angle coverage
- High resolution and efficiency

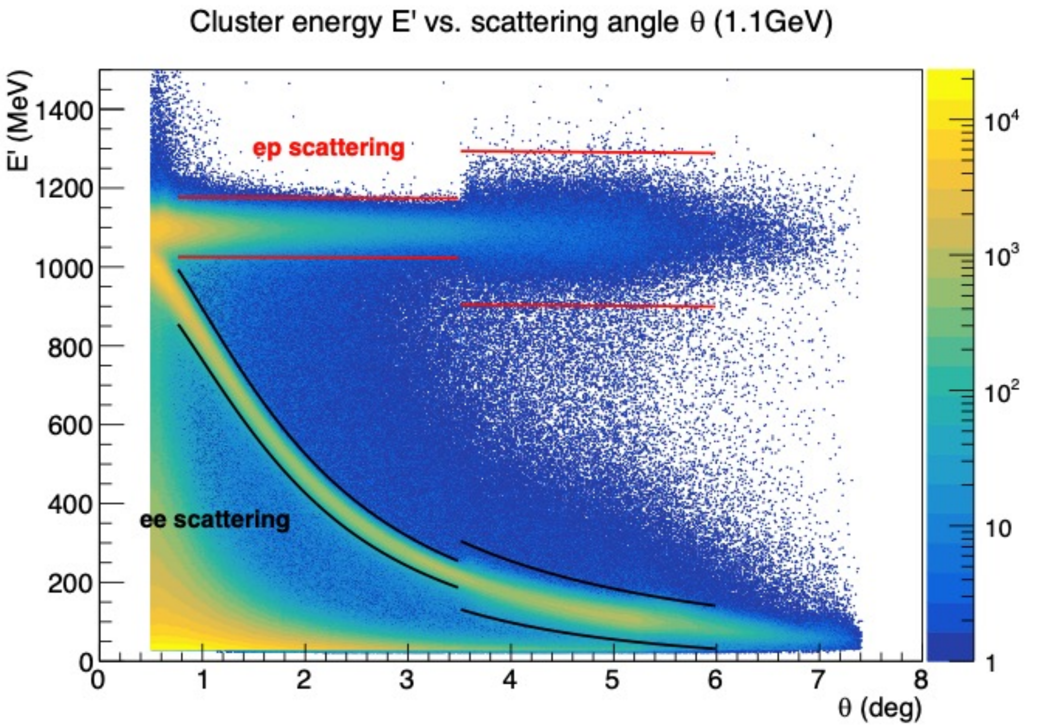


PRad Experiment at Jefferson Lab

Non-spectrometer apparatus

- Large acceptance:
  - Measure multiple Q^2 data points simultaneously
  - Measure *ep* and *ee* scattering at the same time



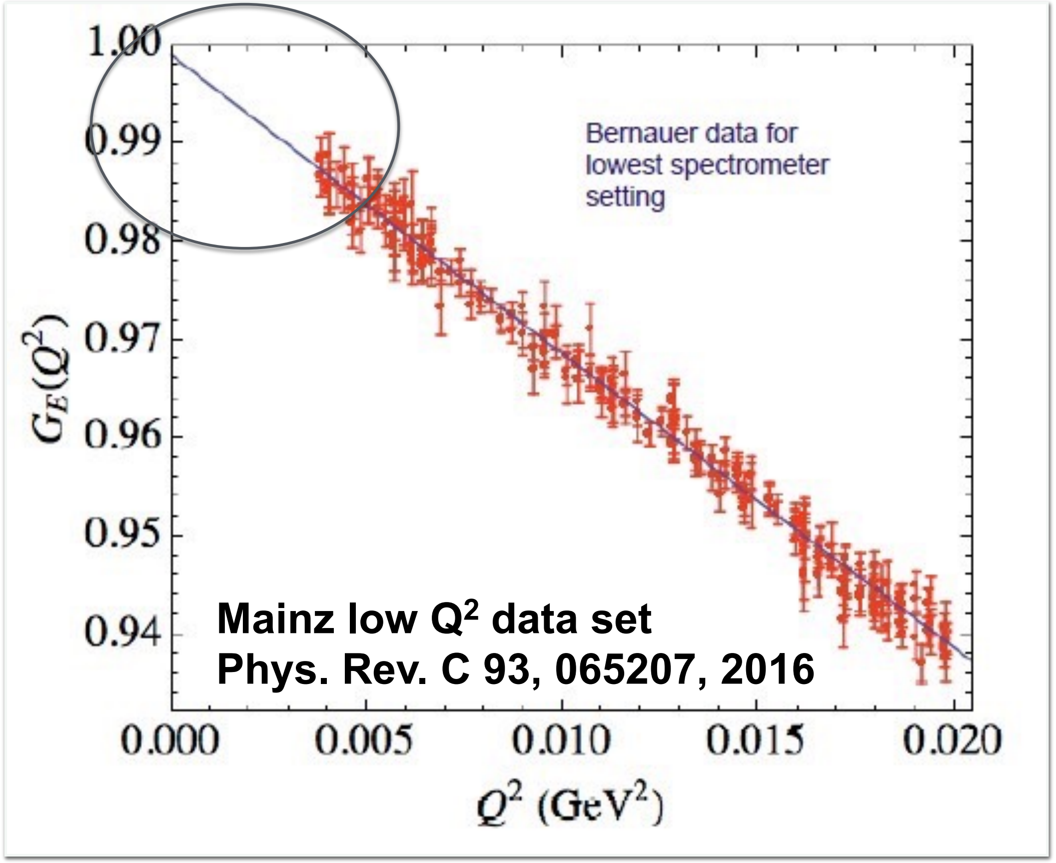


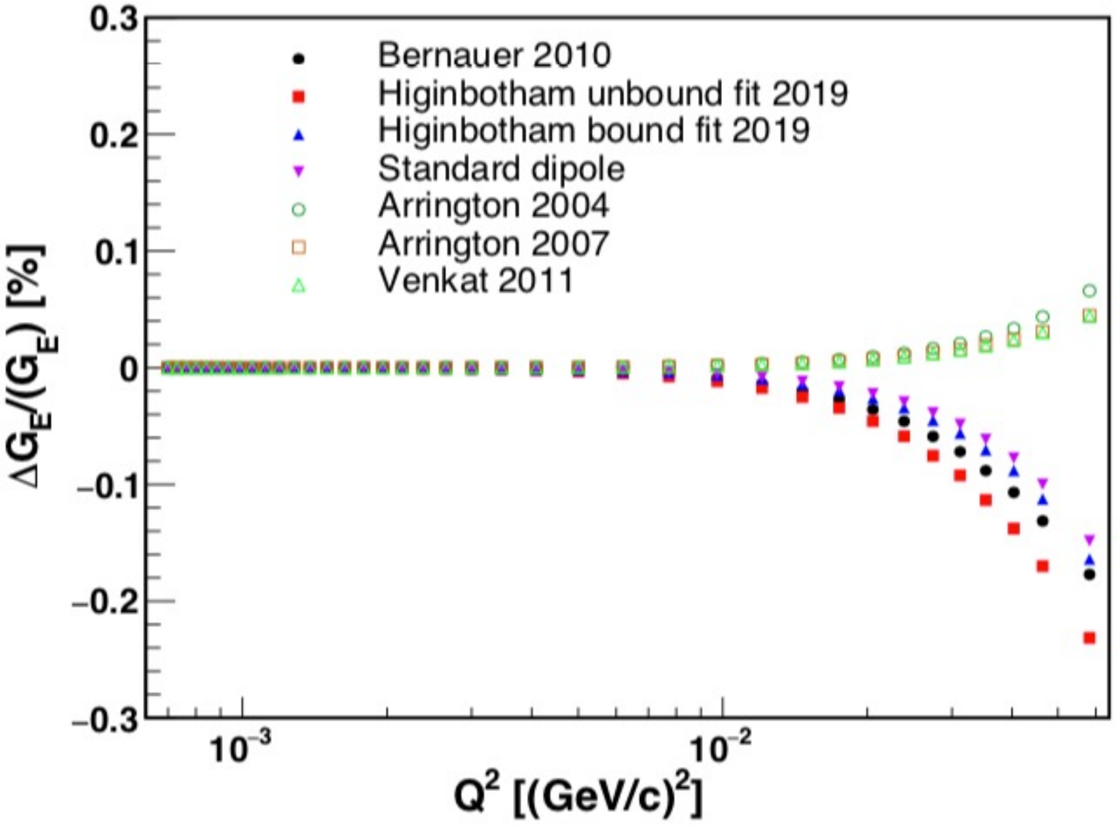
PRad Experiment at Jefferson Lab

Non-spectrometer apparatus

- Small scattering angle (0.5°-7.5°):
  - Unprecedented low Q^2 (~2x10^{-4} GeV^2)
  - Minimize G_M^p contribution

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





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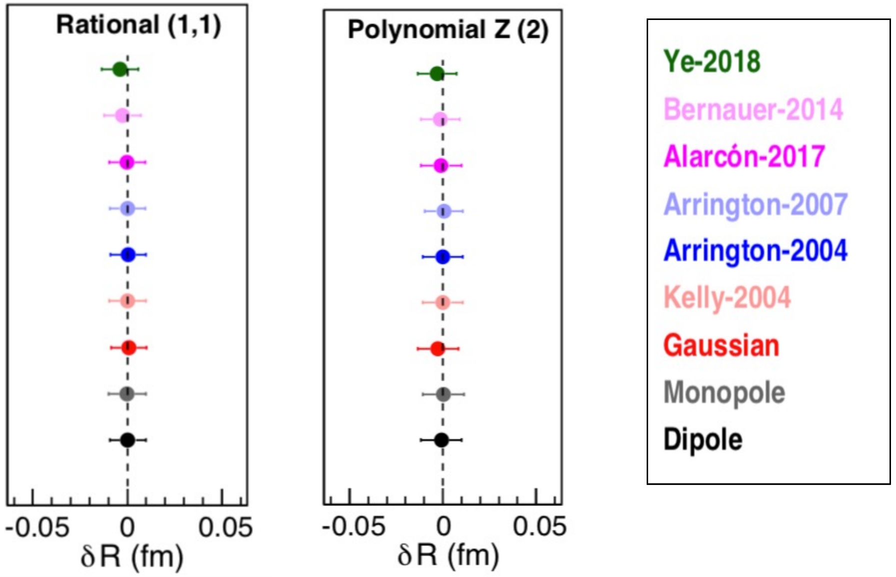
PRad Experiment at Jefferson Lab

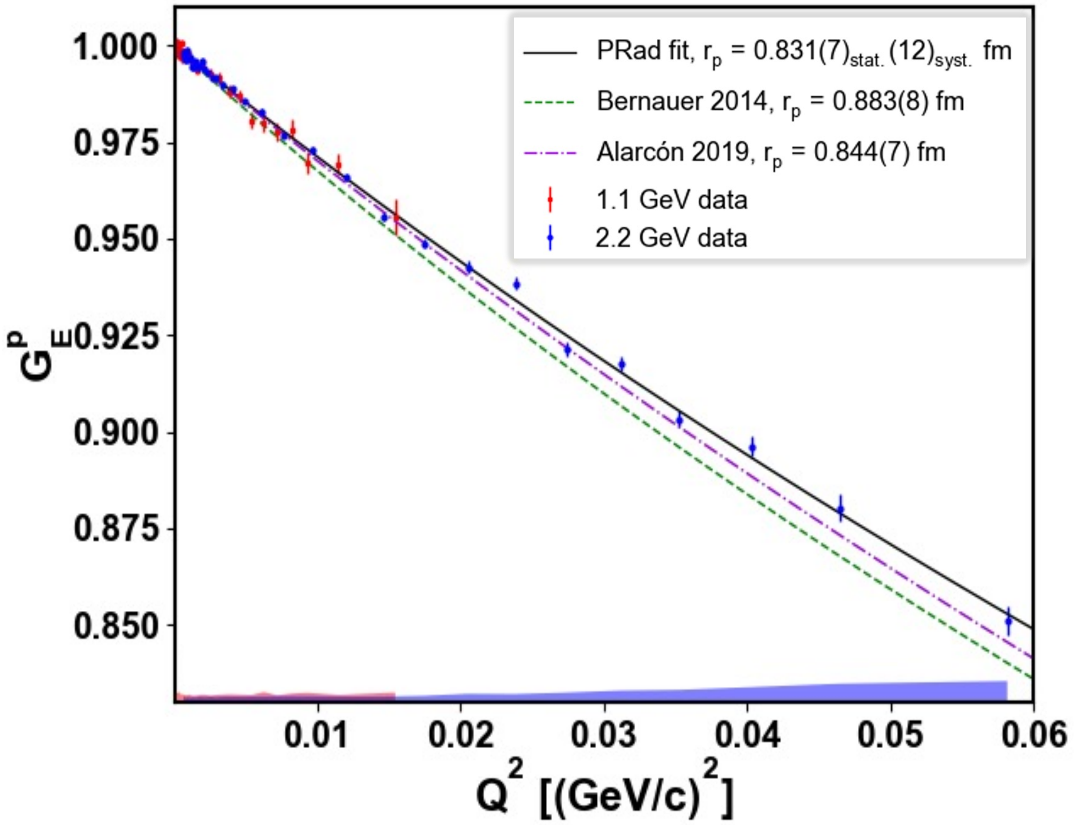
Non-spectrometer apparatus

- Numerous functional forms tested with 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 identified as robust fitters with reasonable uncertainties

r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm





Nature 575 (2019) 7781

Rational (1,1): $$\frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

Highlights of Future Lepton Scattering Experiments

Muon scattering

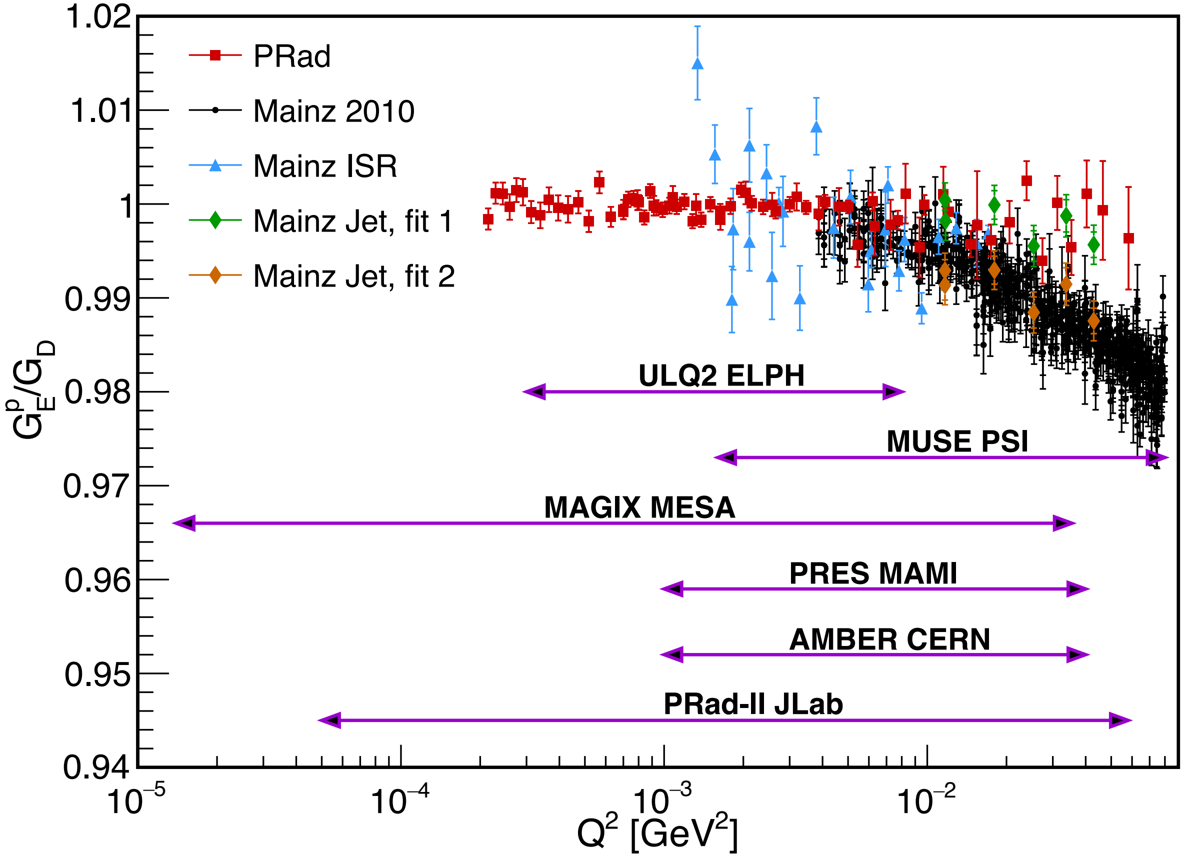
- MUSE exp. at PSI
  - ➢ First r_p measurement using muon
  - ➢ 4 types of incident leptons: $e^{\pm}$ and $\mu^{\pm}$
- AMBER exp. at CERN
  - ➢ 100 GeV muon beam, detecting scattered muon and recoiled proton
  - ➢ Ultra-small scattering angle, minimize G_M
  - ➢ Smaller RC for muon

Electron scattering

- Prad-II exp. at JLab
  - ➢ ultra-precise rp measurement (~4 times smaller uncertainty than PRad)
- PRES exp. at Mainz
  - ➢ detecting both scattered electron and recoiled proton
- MAGIX exp. at Mainz
  - ➢ Using jet target
- ULQ2 exp. at Tohoku University, Japan
  - ➢ Normalize to the well-known e-^{12}C cross section

No μ-p scattering result yet

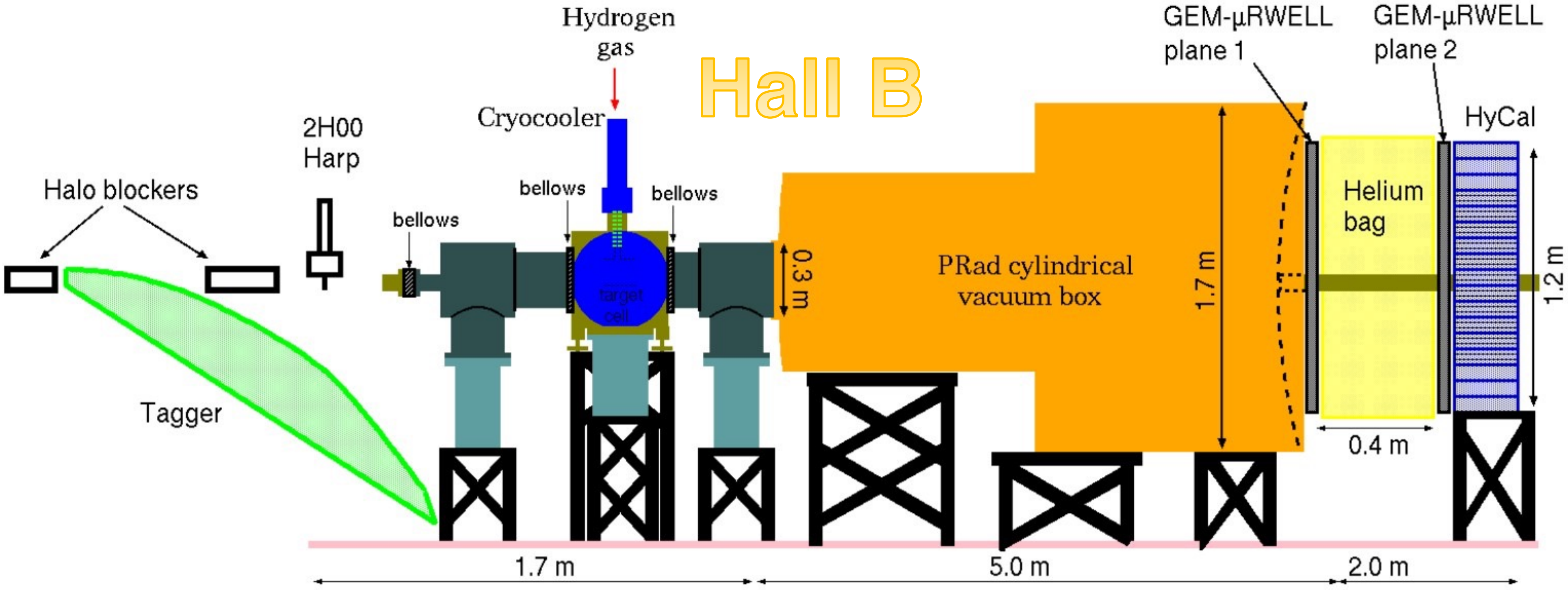
Projected Q^2 coverage



WX and Chao Peng (彭潮) *Universe* 9 (2023) 4, 182

PRad-II Experiment

- JLab PAC 48 approved PRad-II (PR12-20-004) with the highest scientific rating "A"
- Goal: reach ultra-high precision (~4 times smaller total uncertainty), resolve tension between modern *e-p* scattering results
  - ➢ Additional new GEM plane
  - ➢ Full DAQ and readout system upgrade
  - ➢ New scintillating detector, help reaching $Q^2 \sim 10^{-5}$ GeV^2



PRad-II Experiment

- Adding tracking capacity (second GEM plane)
  - ➢ Improve GEM efficiency measurement

Bin-by-bin method: taking the ep/ee ratio within the same angular bin

Good: Detector acc. and eff. cancal at leading order

Bad: Easily introduce Q2-dependent syst. from Moller

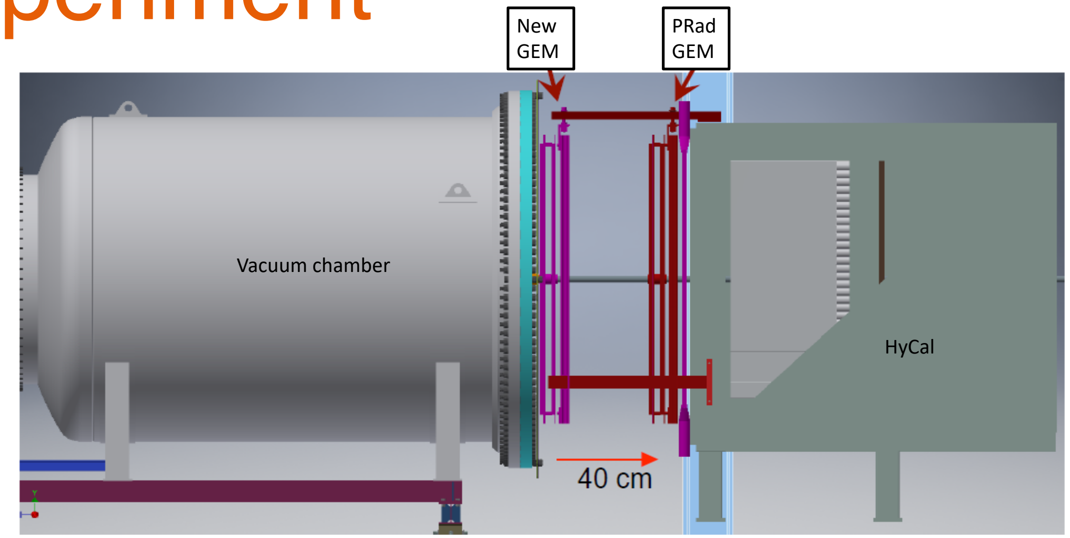
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ep \to ep \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ep}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm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

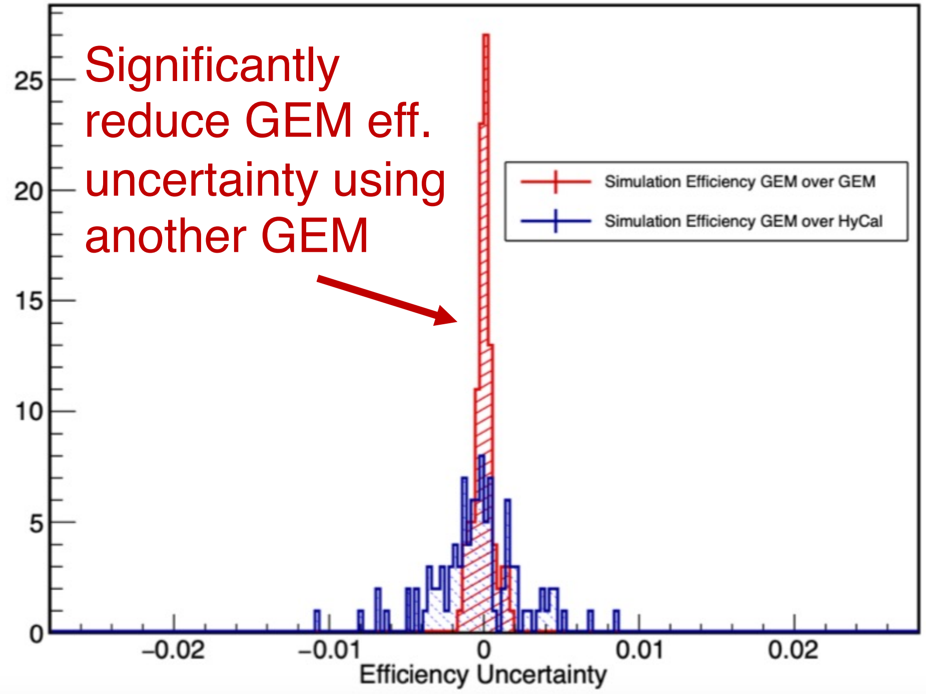
Integrated Moller method: select ee in an angular range, and use it to normalize all ep

Good: Not limited by Moller acceptance, Moller uncertainty only affect normalization

Bad: Need accurate GEM efficiency measurement

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





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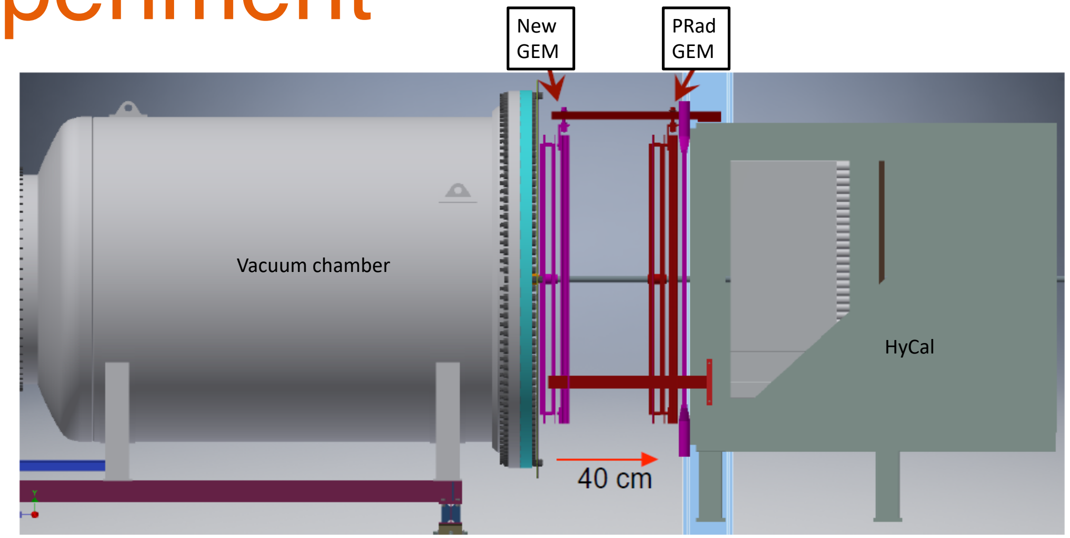
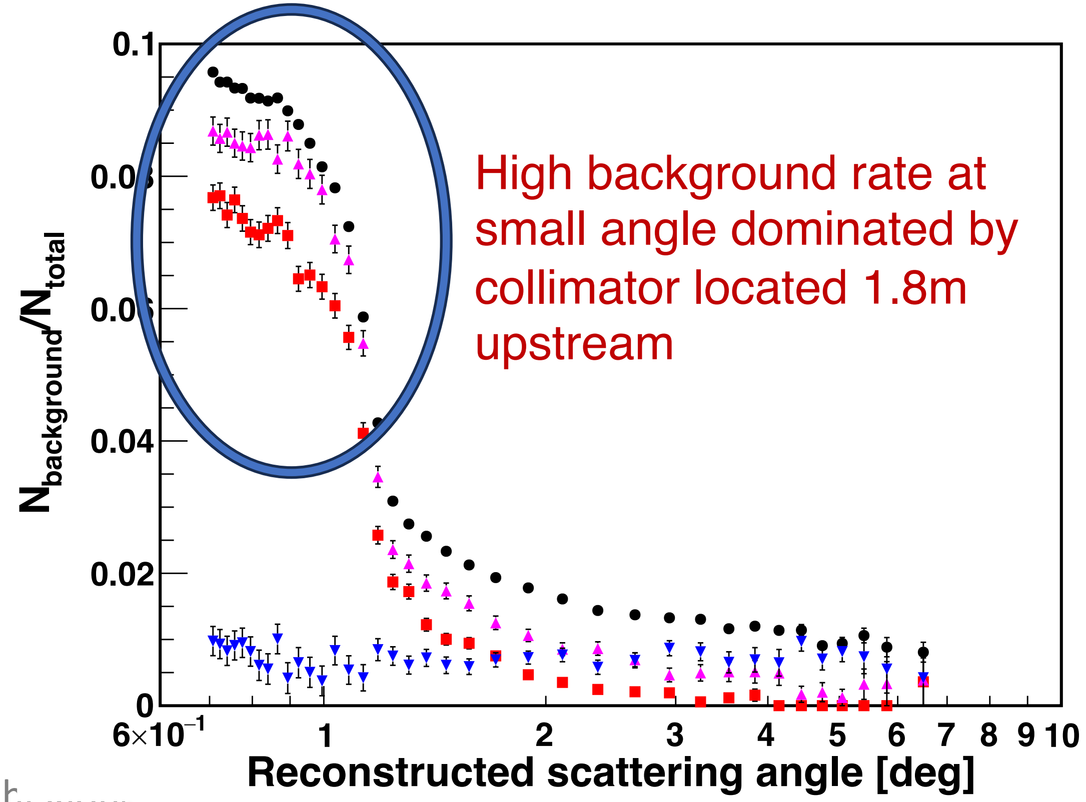
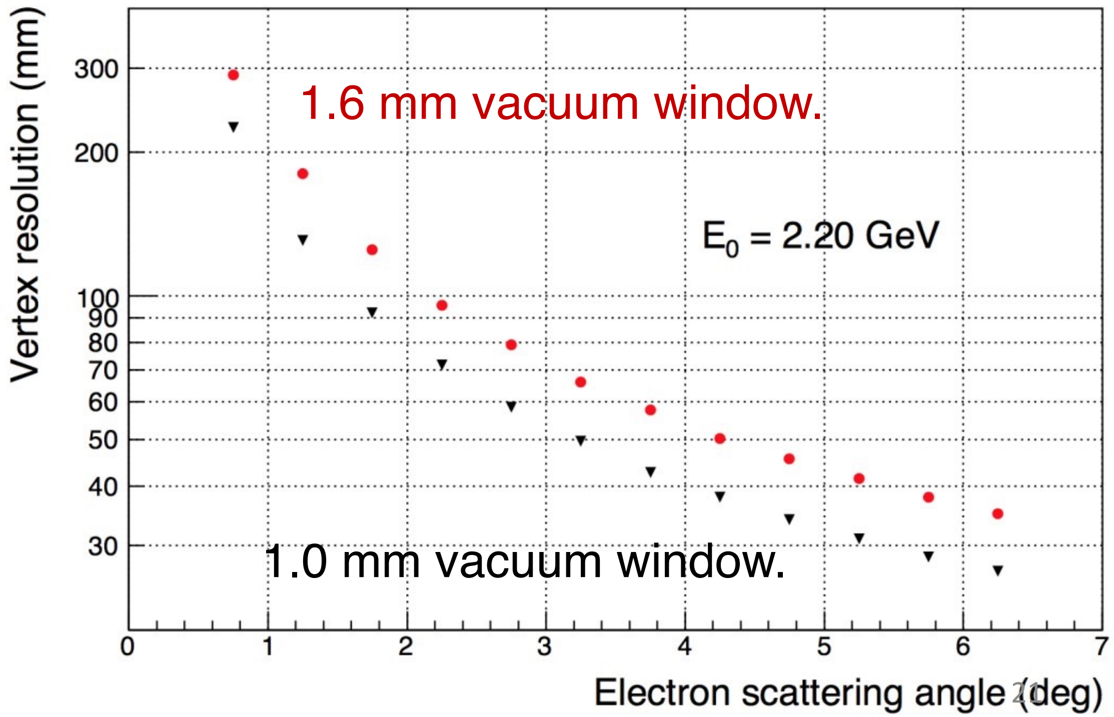
PRad-II Experiment

- Adding tracking capacity (second GEM plane)
  - Improve GEM efficiency measurement
  - Vertex-z reconstruction for *ep* to reject upstream background







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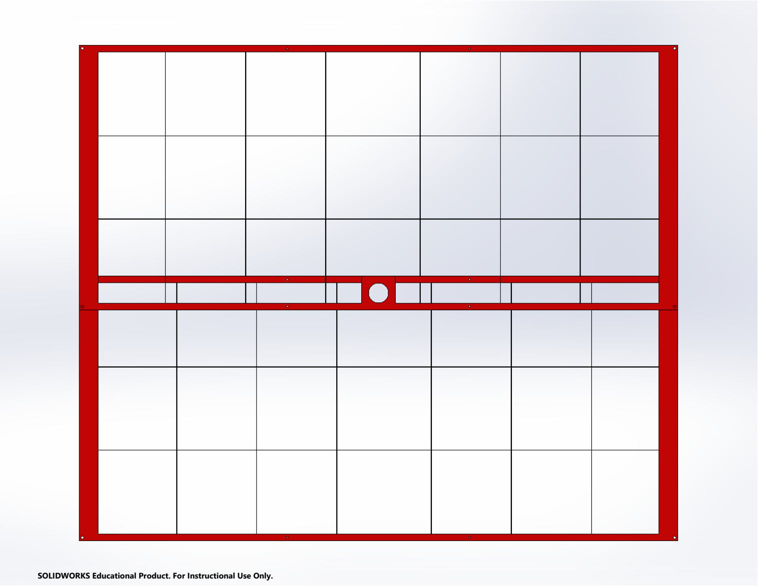
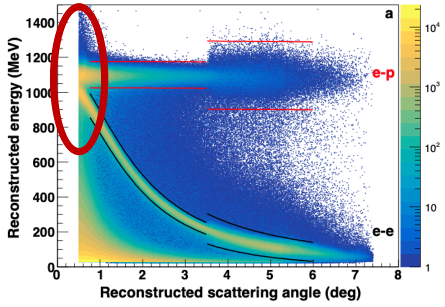
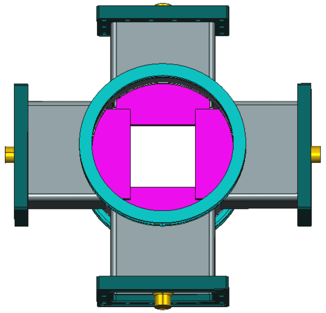
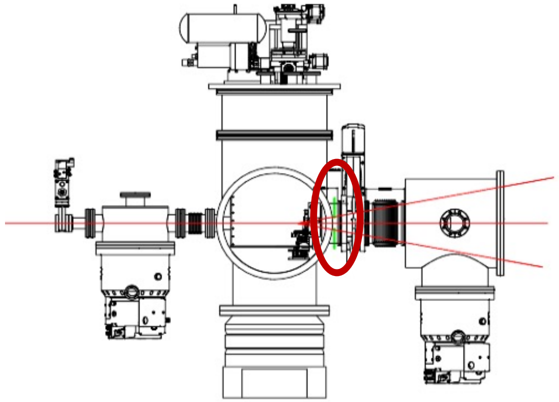
PRad-II Experiment

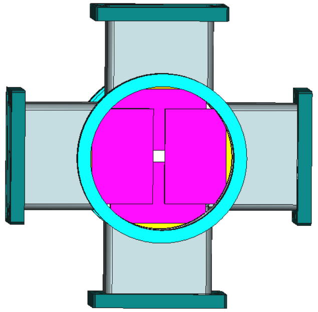
- 4 new GEM chambers to assemble 2 tracking layers.
  - ➢ Detector fabrication expected to be finished for all GEM parts, by March 2025.
  - ➢ All readout electronics ordered, expected by this November.
  - ➢ Will be ready for installation and testing by mid- spring, 2025.











- 4 movable scintillator detectors placed next to the H2 gas flow target chamber.
  - ➢ Conceptual design done, engineering design in progress
  - ➢ Manufacturing: by Spring, 2025
  - ➢ Estimated time for test in beamline: Summer, 2025.

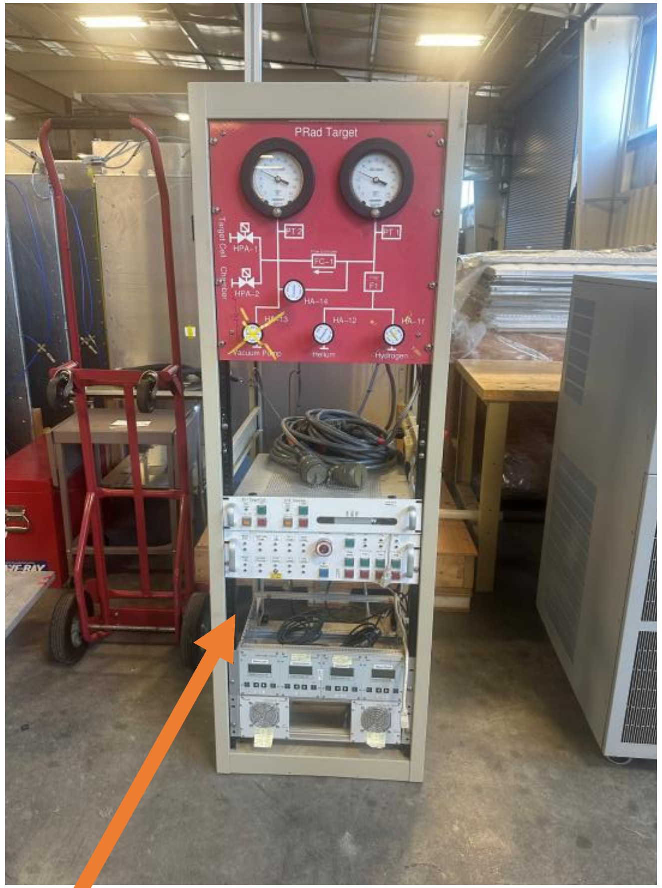
Preparation of PRad-II Experiment

- All FASTBUS crates with power supplies removed
- 5 new VXS crates is planned to install in next few weeks
- HyCal recently re-positioned and refurbishing on-going
- Planned to finish all tests by end of this year

Preparation of PRad-II Experiment

- PRad target system and contral rack moved to the experimental staging building
- Performing test and getting ready for the experiment

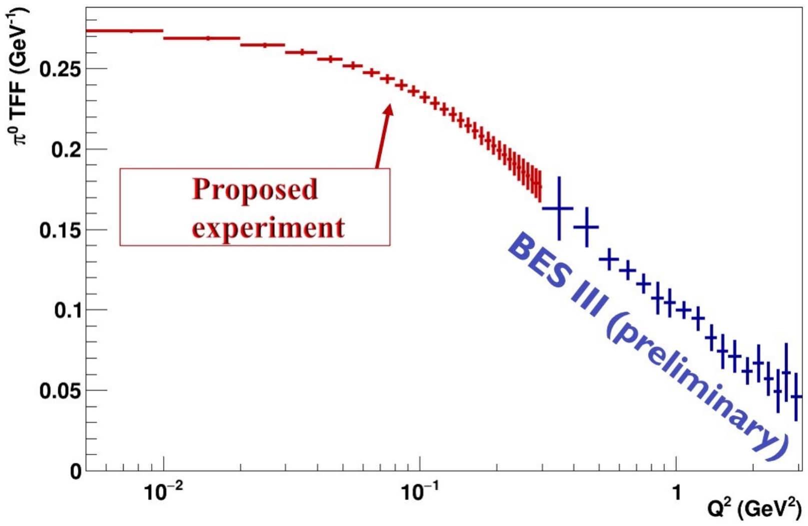
Main target vessel



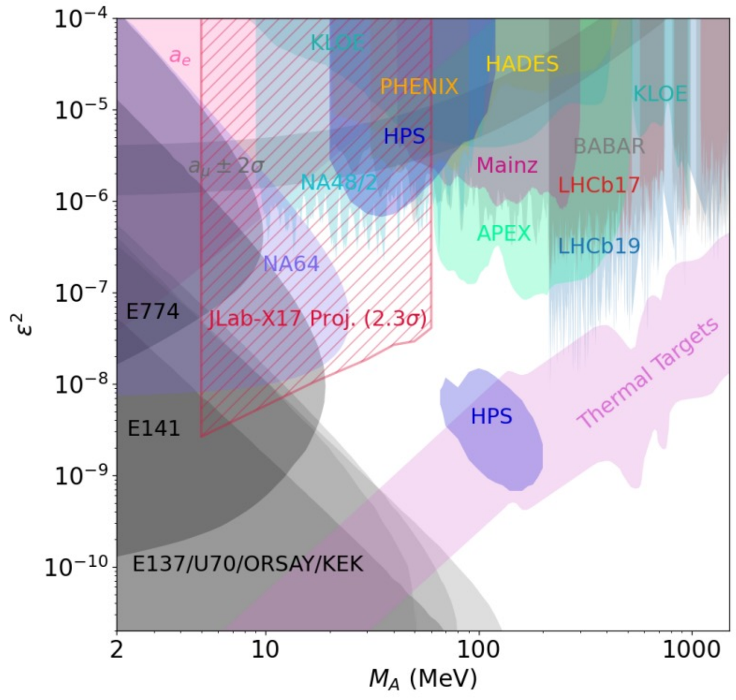
Contral rack

Other Experiments with PrimEx/PRad Setup

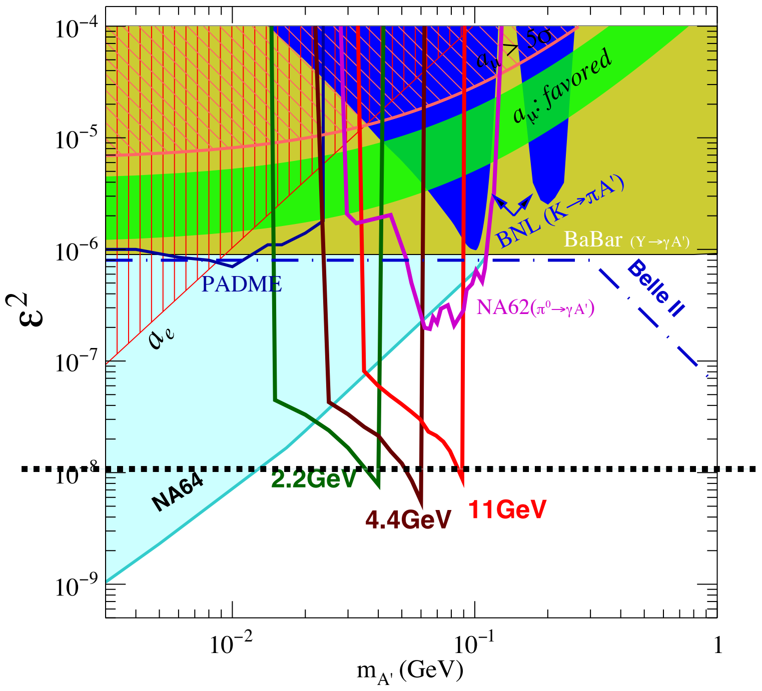
Precision Measurement of the Neutral Pion Transition Form Factor
Rate A-, 67 days



A Direct Detection Search for Hidden Sector New Particles in the 3-60 MeV Mass Range
Rate A, 60 days



A Dark Photon Search with a JLab Positron Beam
Rate A-, 55 days



Summary

- Puzzle considered partially resolved, but many problems remain
  - Tensions between some new H spec. results
  - Form factor difference between PRad and Mainz data
  - New physics may still be there

- Many future experiments on proton charge radius and form factors, and push precision frontier
  - New uH measurement for 1S HFS, 2S-2P transition…
  - First r_p measurement using muon scattering: MUSE and AMBER
  - PRad-II experiment with $\delta_r \sim 0.0036$ fm, aim to be most precise scattering result, new search for lepton-universality violation
    - Ready for ERR review in Spring 2025
    - Experiment ready to run from Fall 2025

PRad/PRad-II 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,
Kharkov Institute of Physics and Technology,
MIT, Old Dominion University, ITEP,
University of Massachusetts, Amherst
Hampton University, College of William & Mary,
Norfolk State University, Yerevan Physics Institute
Shandong University

PRad-II

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Buddhiman Tamang(MSU)
Yuan Li (SDU)

Post-docs:
Tyler Hague (NC A&T/LBNL)
Aruni Nadeeshani(MSU)

PRad

Graduate students (Thesis students):
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Li Ye (MSU)
Weizhi Xiong (Duke)
Xinzhan Bai (UVa)

Post-docs:
Chao Gu (Duke)
Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Latif-ul Kabir (MSU)

Backup

Extracting Form Factors

$$G_D = \frac{1}{(1+\frac{Q^2}{0.71\text{Gev}^2})^2}$$

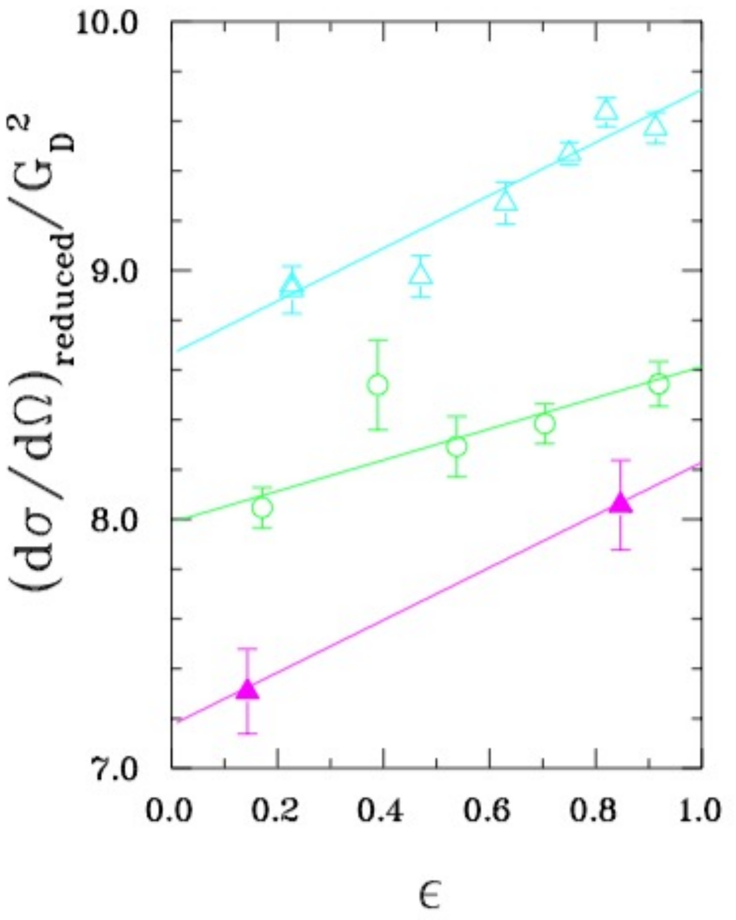
- One of the methods for form factor extraction is the well know Rosenbluth separation:

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

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{reduced}} = G_M^{p\,2}(Q^2) + \frac{\epsilon}{\tau} G_E^{p\,2}(Q^2)$$

$$\tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

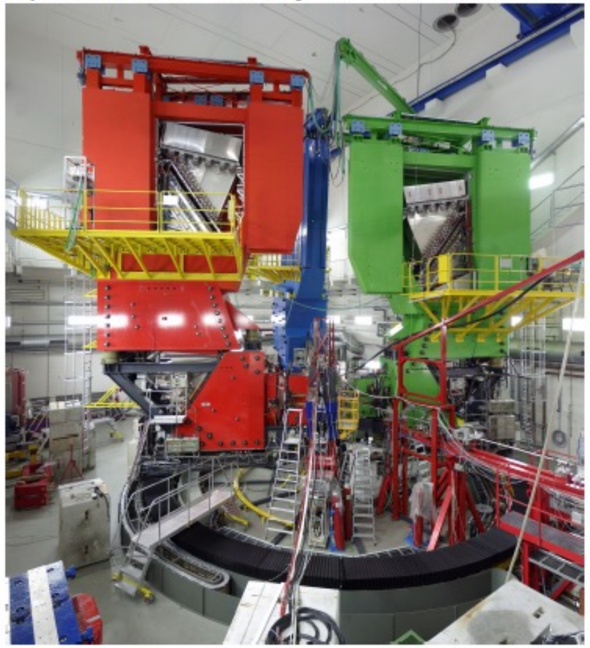
- Measure σ_{reduced} at same Q^2 but different values of ϵ
- G_E^p and G_M^p determined as slope and intersection from fits



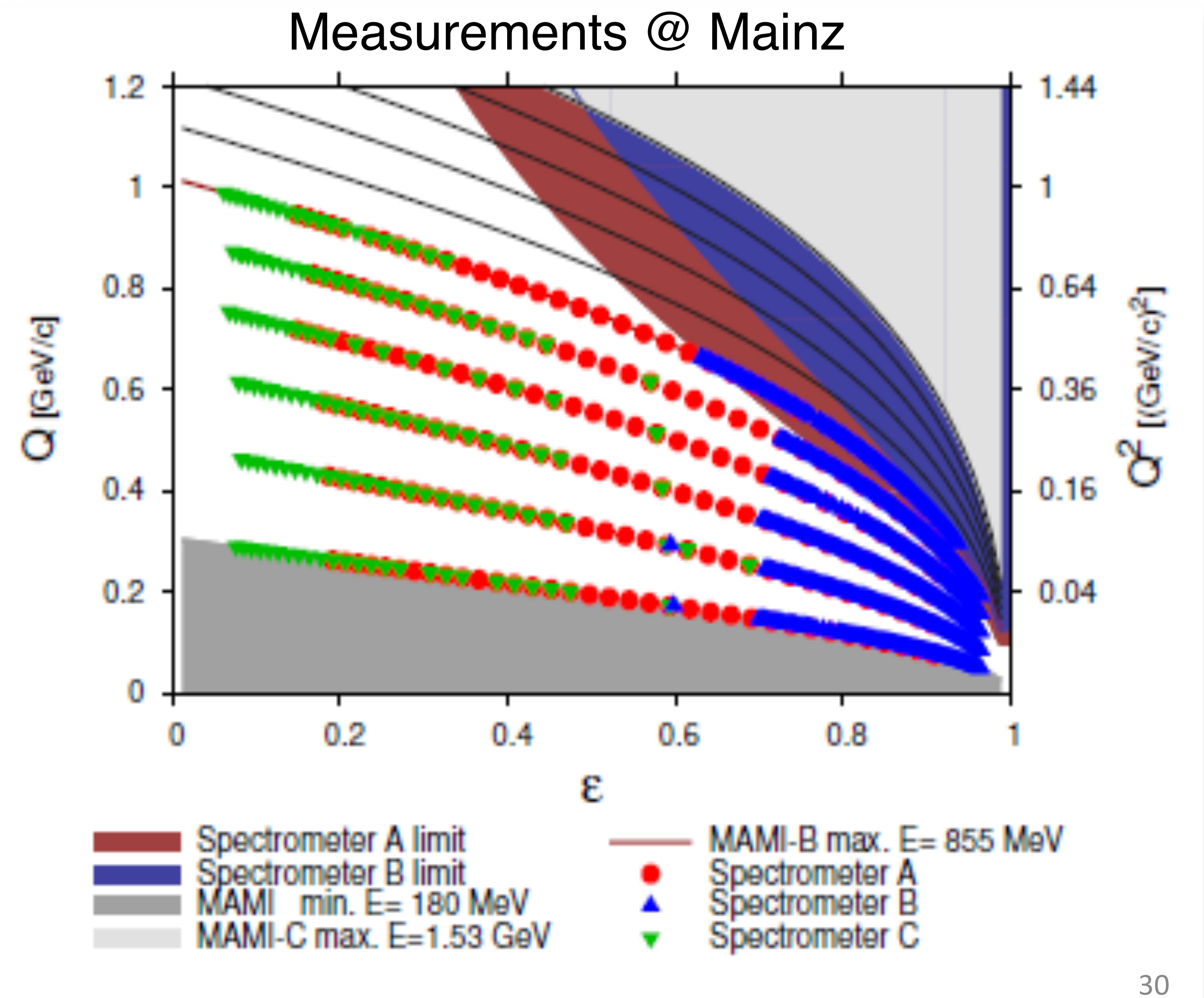
C. F. Perdrisat, V. Punjabi and M. Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694 (2007)

Unpolarized *ep* Elastic Scattering

Three spectrometer facility of the A1 collaboration:

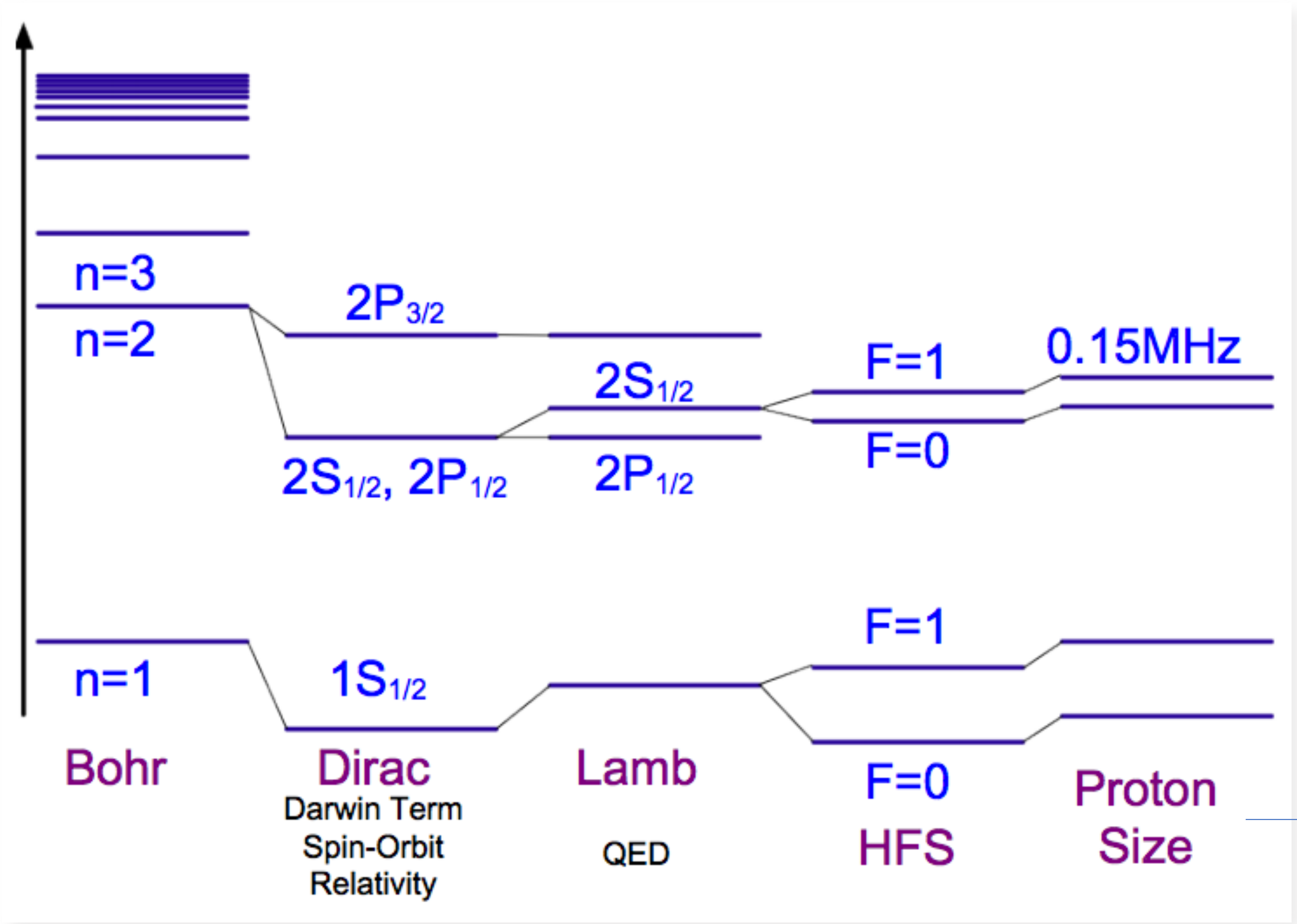


J.C. Bernauer *et al.* PRL. 105 (2010) 242001



- Large amount of overlapping data sets
- Statistical error $\leq 0.2\%$
- Luminosity monitoring with spectrometer
- $Q^2 = 0.004 - 1.0\ (\mathrm{GeV}/c)^2$
- result: $r_p = 0.8791(79)$ fm

Hydrogen Spectroscopy



- Physics origin of the proton finite size effect:
  - ➢ S-state wavefunction has overlap with the proton

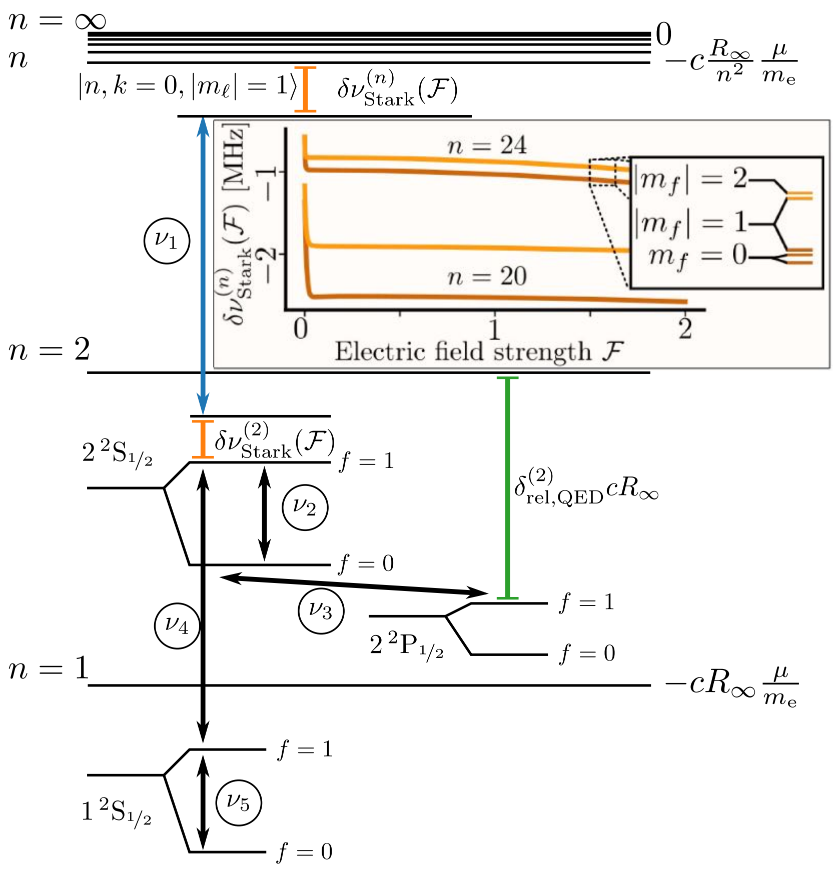
G. Miller PRC 99 035202 (2019)

$$\Delta E = -4\pi\alpha G'^{p}_{E}(0)|\psi_{n0}(0)|^2\delta_{l0}$$
$$= 4\pi\alpha\frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.$$

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

Recent High-n Rydberg State Measurement

$$cR_\infty\left[\left(\frac{1}{4}-\frac{1}{n^2}\right)\frac{\mu}{m_\mathrm{e}}+|\delta^{(2)}_{\mathrm{rel,QED}}|\right]$$
$$=\nu_1+\nu_2+\nu_3+|\delta\nu^{(n)}_{\mathrm{Stark}}(\mathcal{F})|+\delta\nu^{(2)}_{\mathrm{Stark}}(\mathcal{F}),$$



PRL 132, 113001 (2024)