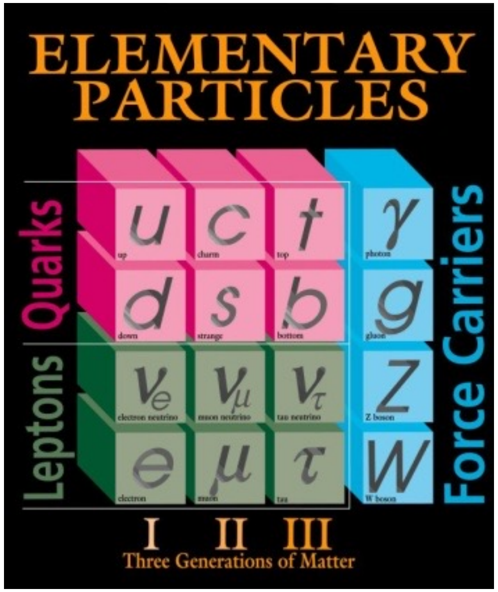
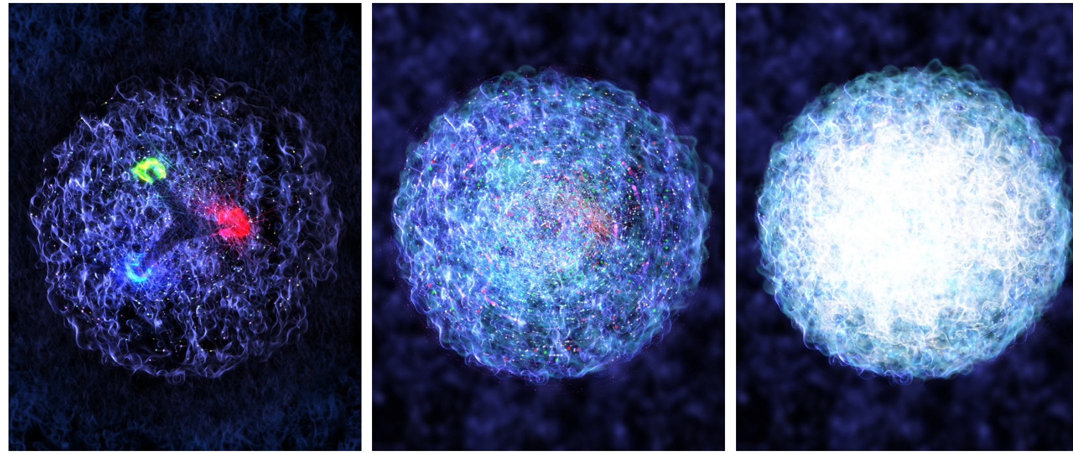
The Proton Charge Radius and PRad

Haiyan Gao
Nuclear and Particle Physics, BNL &
Duke University

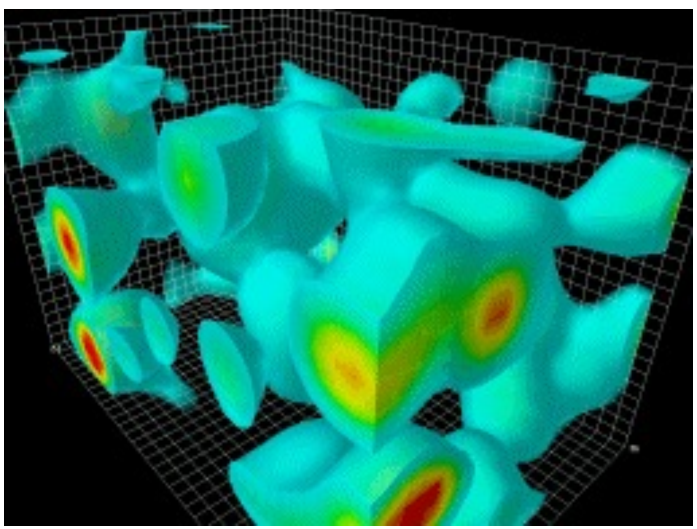
PAW-24 International Workshop March 18-20, 2024

Structure of visible matter





Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.



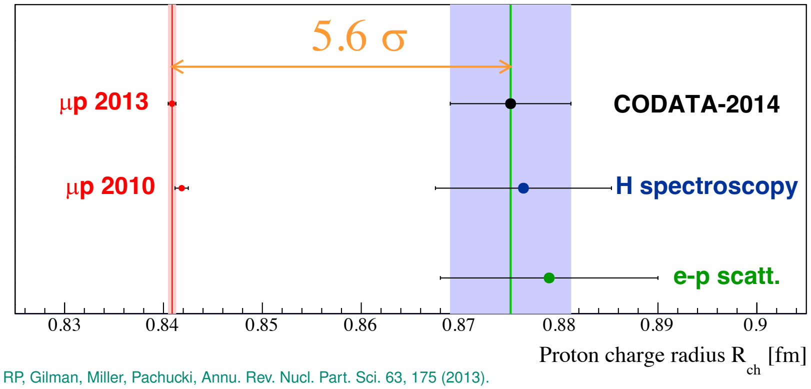
Credit: D. Leinweber

- ***Charge and magnetism (current) distribution***
- ***Spin and mass decomposition***
- ***Quark momentum and flavor distribution***
- ***Polarizabilities***
- ***Strangeness, charm content***
- ***Three-dimensional tomography***
- ***more***

Brookhaven National Laboratory

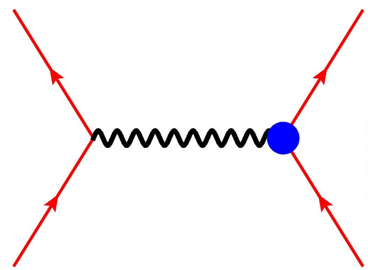
Proton Charge Radius and the Puzzle

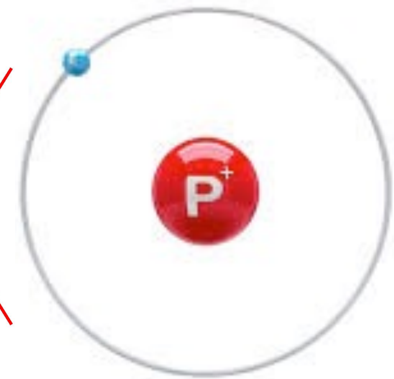
- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} – 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - ➢ Ordinary hydrogen
     - ➢ Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics)
     - ➢ *ep* elastic scattering (like PRad)
     - ➢ *μp* elastic scattering (like MUSE, AMBER)





➢ Important point: the proton radius measured in lepton scattering is defined in the same way as in atomic spectroscopy (G.A. Miller, 2019)

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

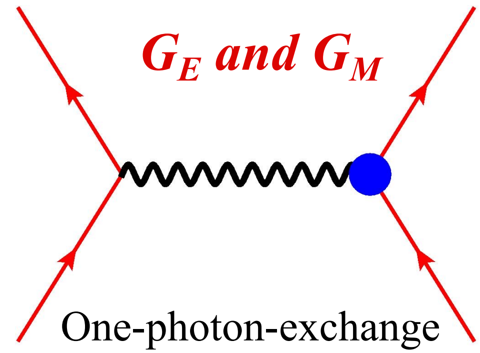
Brookhaven National Laboratory

Electron-proton elastic scattering

- **Unpolarized elastic e-p cross section** ***(Rosenbluth separation)***

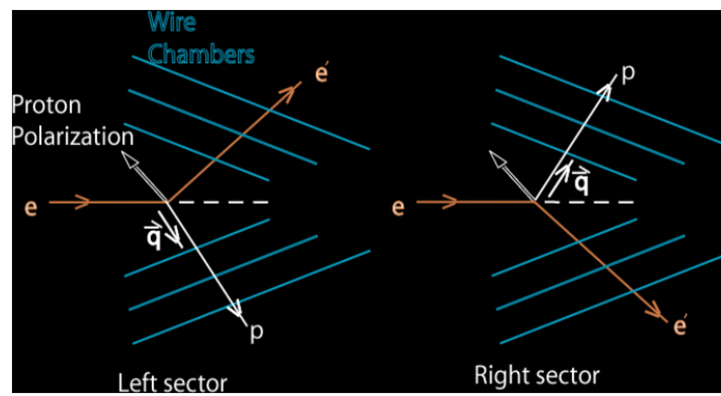
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E} \left(\frac{{G_E^p}^2 + \tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2\frac{\theta}{2} \right)$$

$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2\frac{\theta}{2} \right) \qquad \tau = \frac{Q^2}{4M^2}$$



- **Recoil proton polarization measurement** ***(pol beam only)***

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



- **Asymmetry (super-ratio) measurement**

(pol beam and pol target)

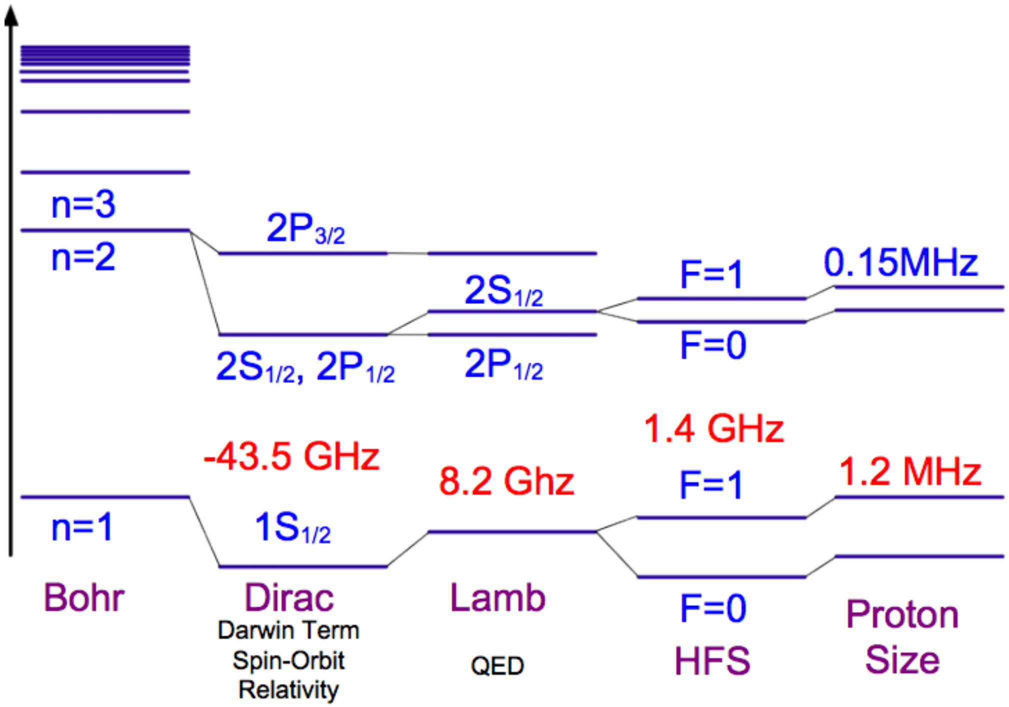
$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p/G_M^p}{a_2 - b_2 \cdot G_E^p/G_M^p}$$

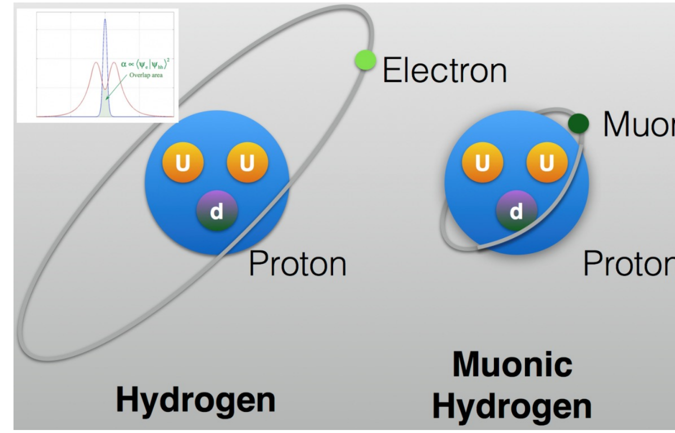
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$

Brookhaven National Laboratory

C. Crawford et al. PRL98, 052301 (2007)

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 Rydberg constant R_∞ (one of the most precisely known constants)

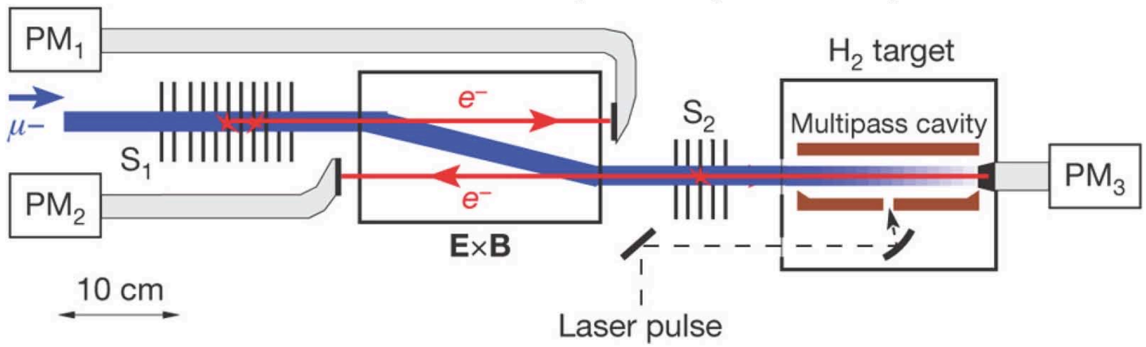
Comparing measurements to QED calculations that include corrections for the finite size of the proton can provide very precise value of the rms proton charge radius

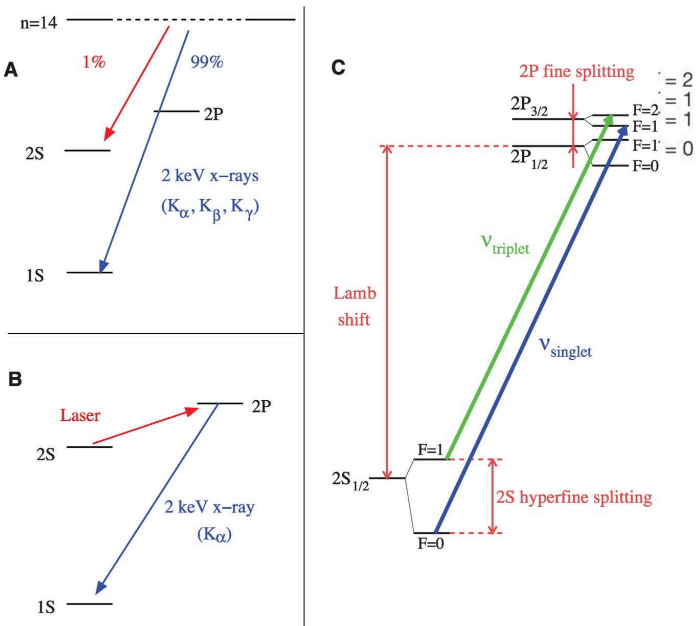
Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

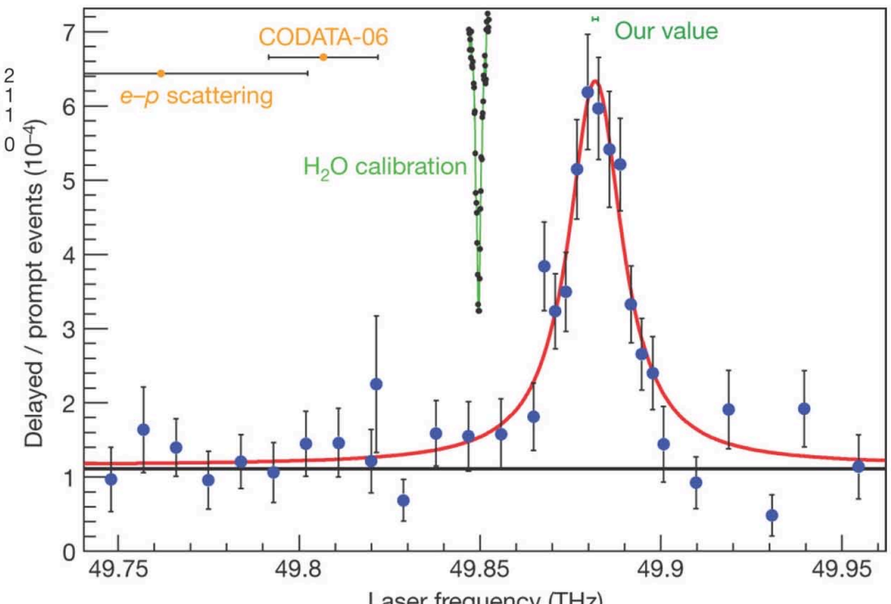
Brookhaven National Laboratory

Muonic hydrogen Lamb shift at PSI (2010, 2013)

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





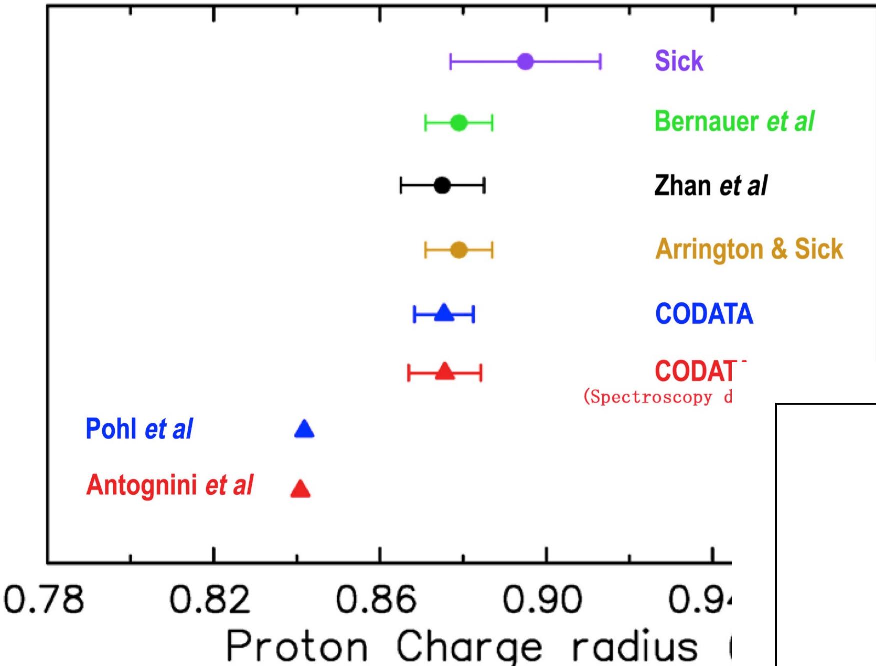


2010 value is r_p = 0.84184(67) fm

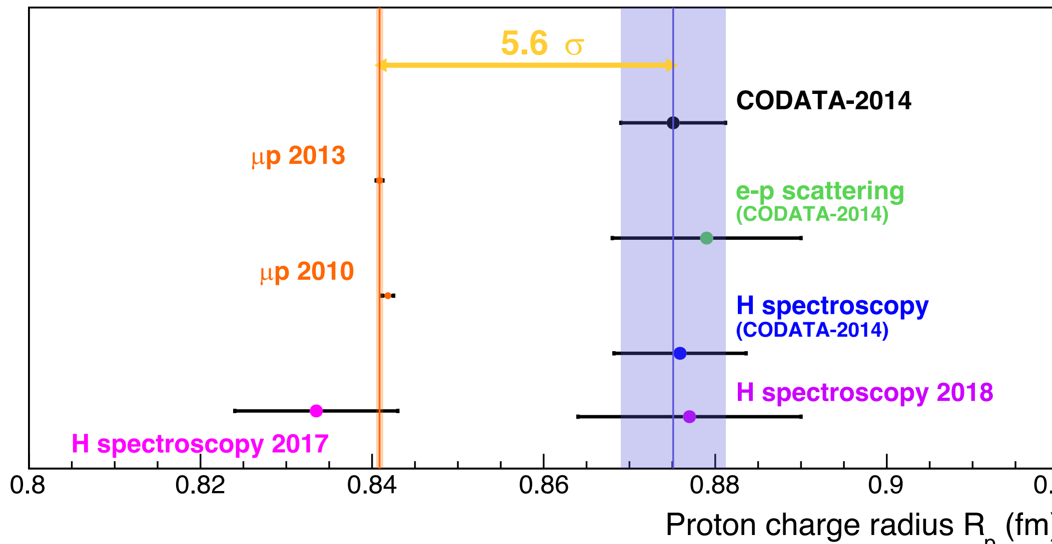
r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

Brookhaven National Laboratory

The situation on the Proton Charge Radius in 2013 and 2018



This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so

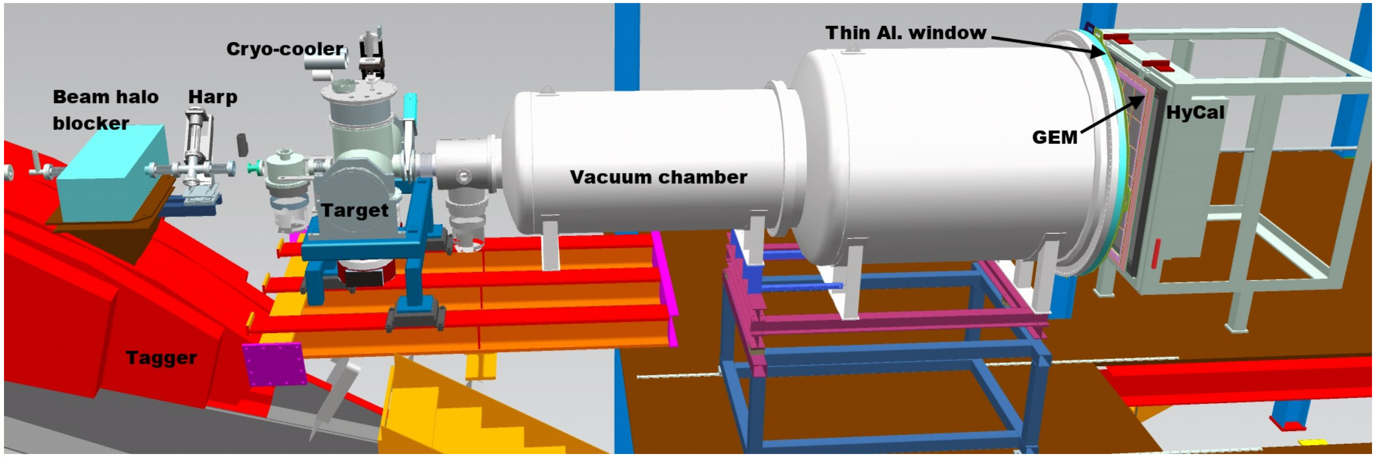


Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)
H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

ep scattering (ISR): $0.870 \pm 0.014_{stat.} \pm 0.024_{syst.} \pm 0.003_{mod.}$ (Mihovilovic 2019) (not shown)

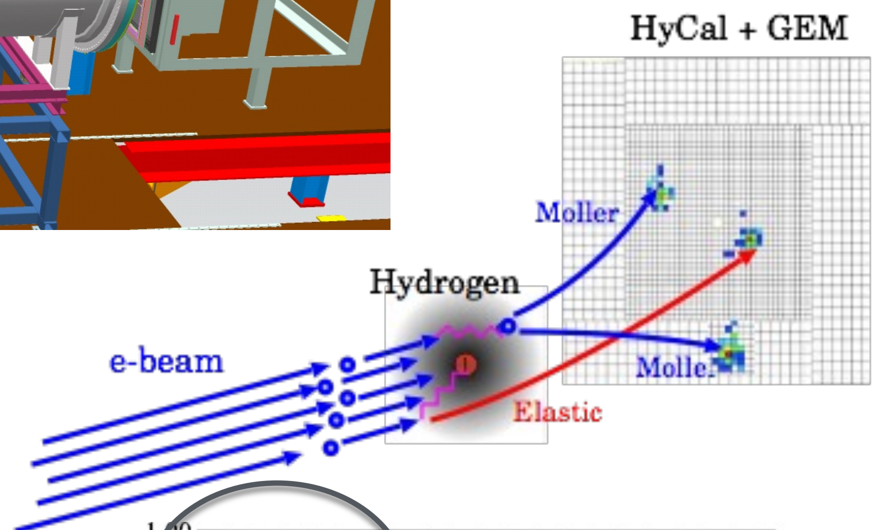
Brookhaven National Laboratory

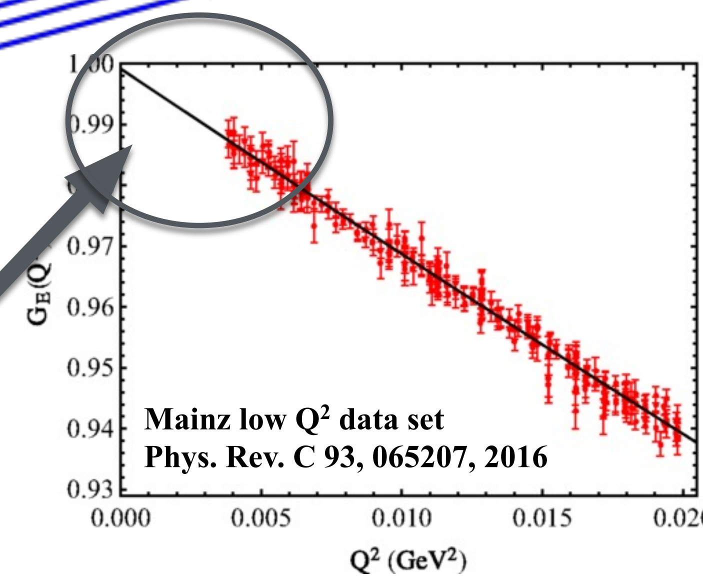
The *PRad Experiment in Hall B at JLab*



- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2×10^{-4} – 0.06 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum chamber**

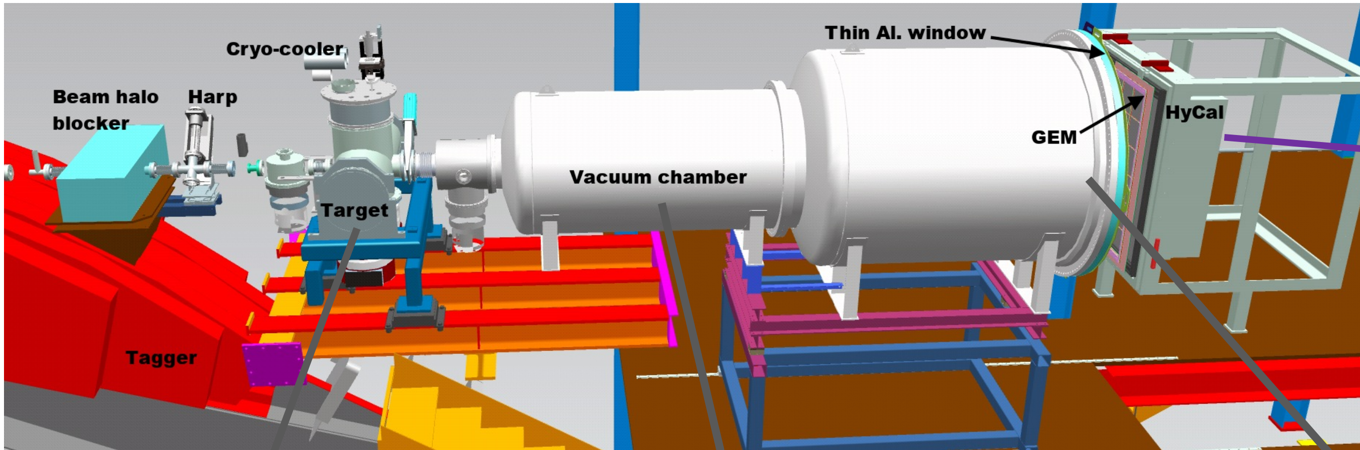
Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker

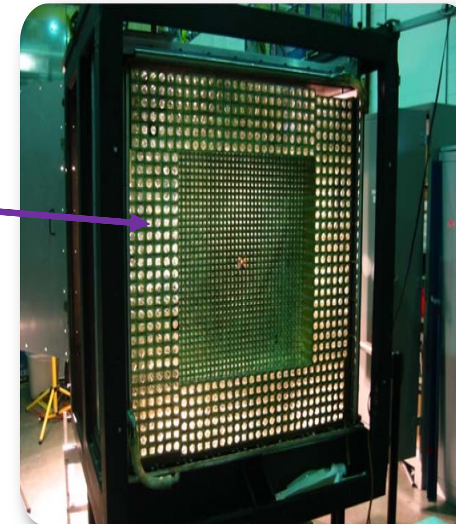




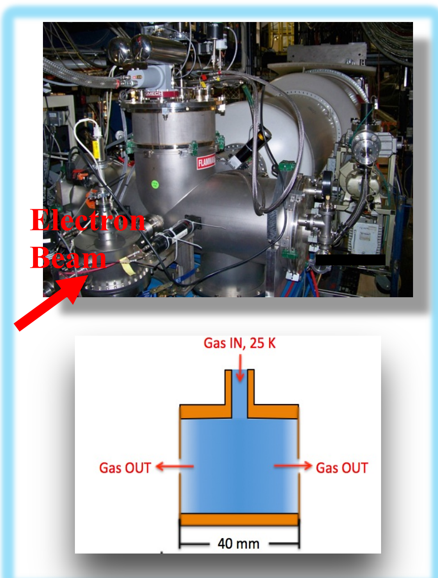
Brookhaven National Laboratory

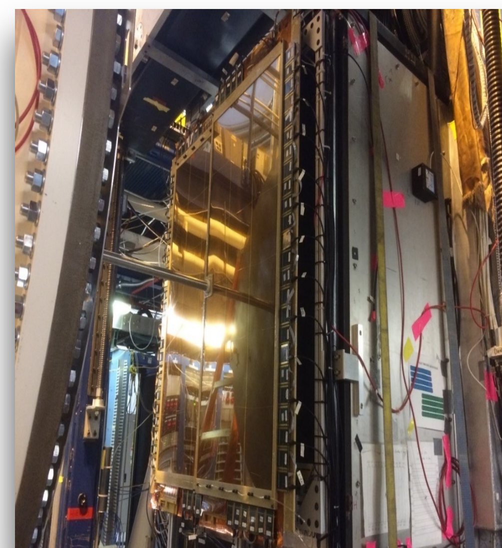
The *PRad Experimental* setup





I Larin, Y Y. Zhang, *et al.*, Science 6490, 506





Brookhaven National Laboratory

J. Pierce *et al.*, NIMA **1003**, 165300 (2021)

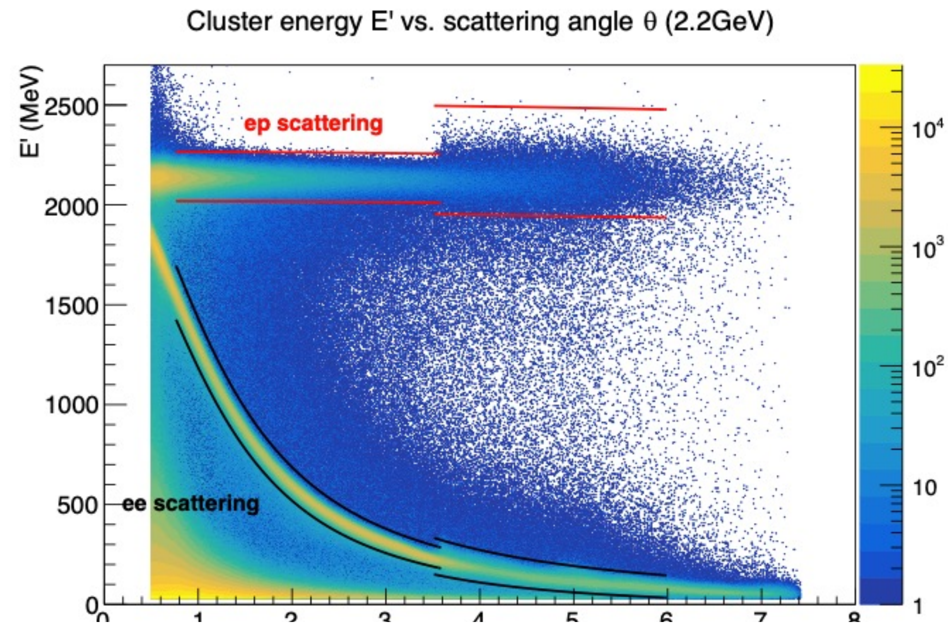
Analysis – Event Selection

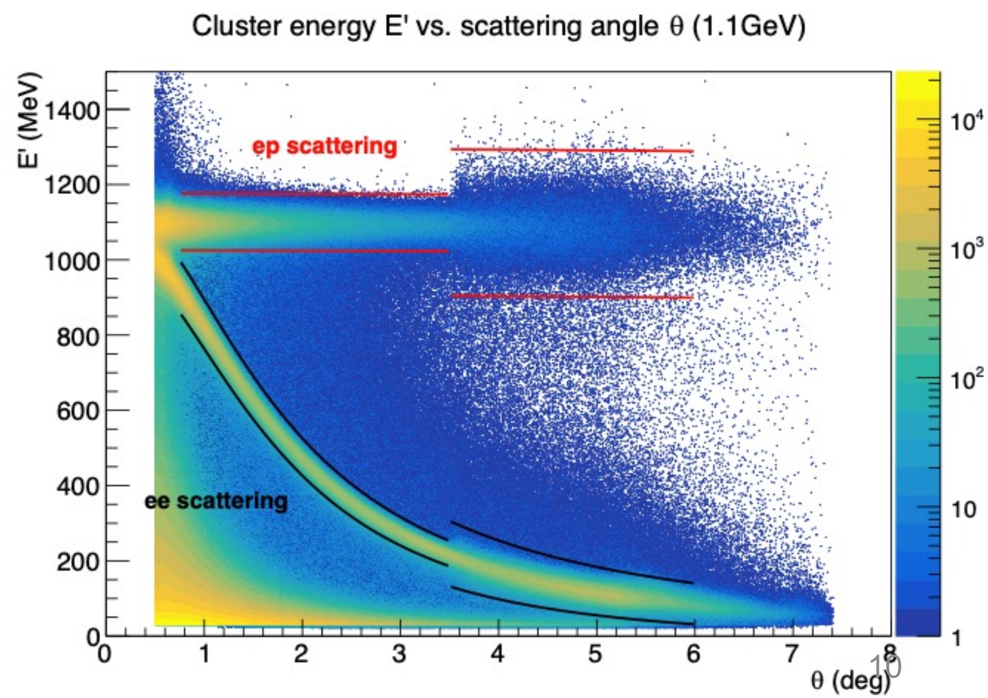
Event selection method

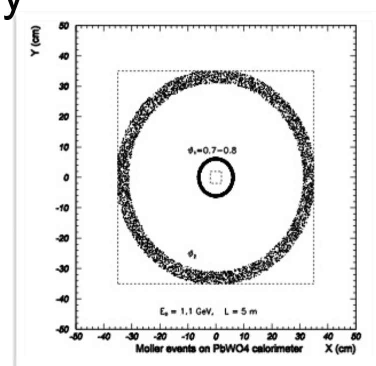
1. For all events, require hit matching between GEMs and HyCal

2. For *ep* and *ee* events, apply angle-dependent energy cut based on kinematics
    1. Cut size depend on local detector resolution

3. For *ee*, if requiring double-arm events, apply additional cuts
    1. Elasticity
    2. Co-planarity
    3. Vertex z







Brookhaven National Laboratory

Extraction of ep Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the ep cross section is normalized to the Møller cross section:

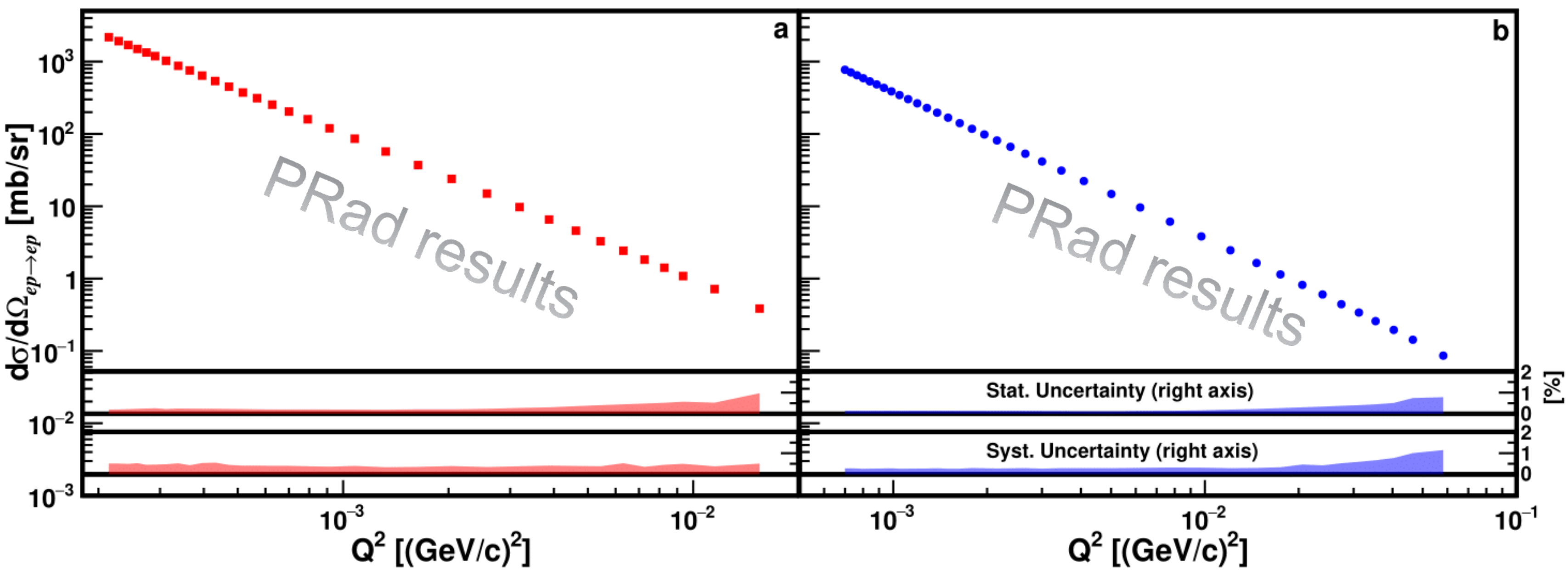
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \left[\frac{N_{\exp}(ep \to ep \text{ in } \theta_i \pm \Delta\theta_i)}{N_{\exp}(ee \to ee)} \cdot \frac{\varepsilon^{ee}_{\text{geom}}}{\varepsilon^{ep}_{\text{geom}}} \cdot \frac{\varepsilon^{ee}_{\text{det}}}{\varepsilon^{ep}_{\text{det}}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
  - Cancellation of energy independent part of the efficiency and acceptance
  - Limited coverage due to double-arm Møller acceptance
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angular bins
  - Needs to know the GEM efficiency well
- Luminosity cancelled from both methods
- PRad: Bin-by-bin range: 0.7^o to 1.6^o for 2.2 GeV, 0.75^o to 3.0^o for 1.1 GeV. Larger angles use integrated Møller method (3.0^o to 7.0^o for 1.1 GeV; 1.6^o to 7.0^o for 2.2 GeV)
- PRad-II: two planes of GEM/μRwell allow for ***integrated Møller method*** for the entire experiment
- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections – ***PRad-II with NNL for RC***
  1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  2. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (beyond ultra relativistic approximation)
- A Geant4 simulation package is used to study the radiative effects, and an iterative procedure applied

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

Elastic ep Cross Sections

- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data
- Statistical uncertainties: ~0.15% for 2.2 GeV, ~0.2% for 1.1 GeV per point
- Systematic uncertainties: 0.3%~1.1% for 2.2 GeV, 0.3%~0.5% for 1.1 GeV (shown as shadow area)



Systematic uncertainties shown as bands

Xiong et al., Nature 575, 147–150 (2019)

Proton Electric Form Factor G'_E (Normalized)

- n_1 and n_2 obtained by fitting PRad G_E t $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

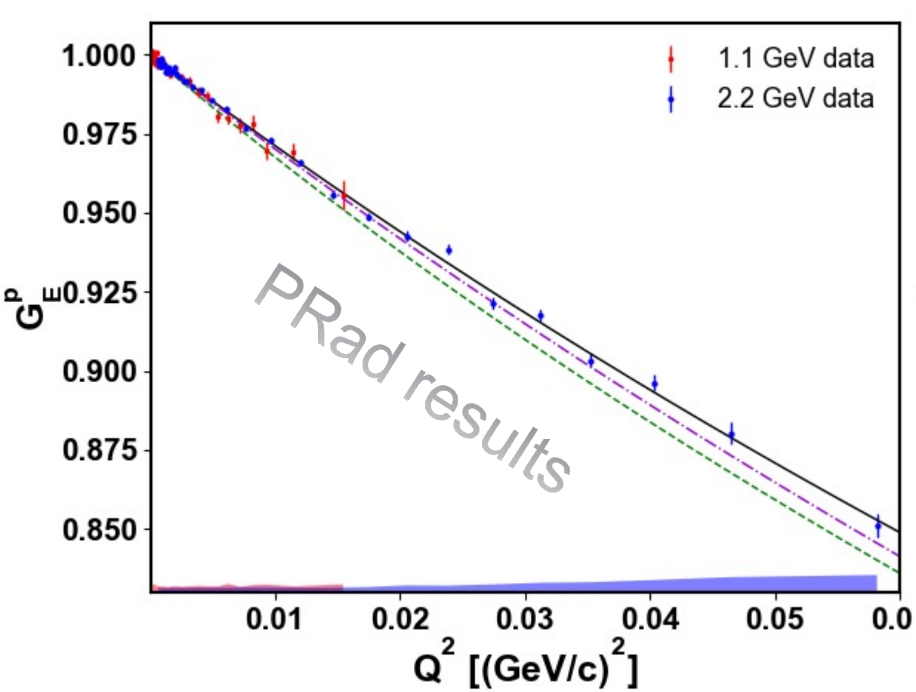
Using rational (1,1)

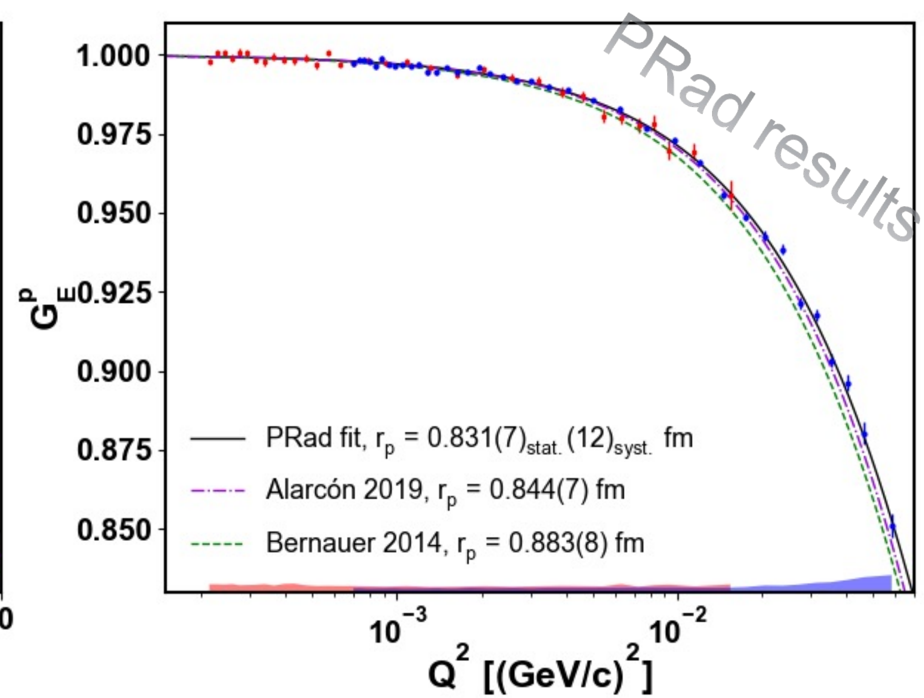
$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

- G'_E as normalized electric Form factor $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

Yan *et al*. PRC98,025204 (2018)

- PRad fit shown as $f(Q^2)$ r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



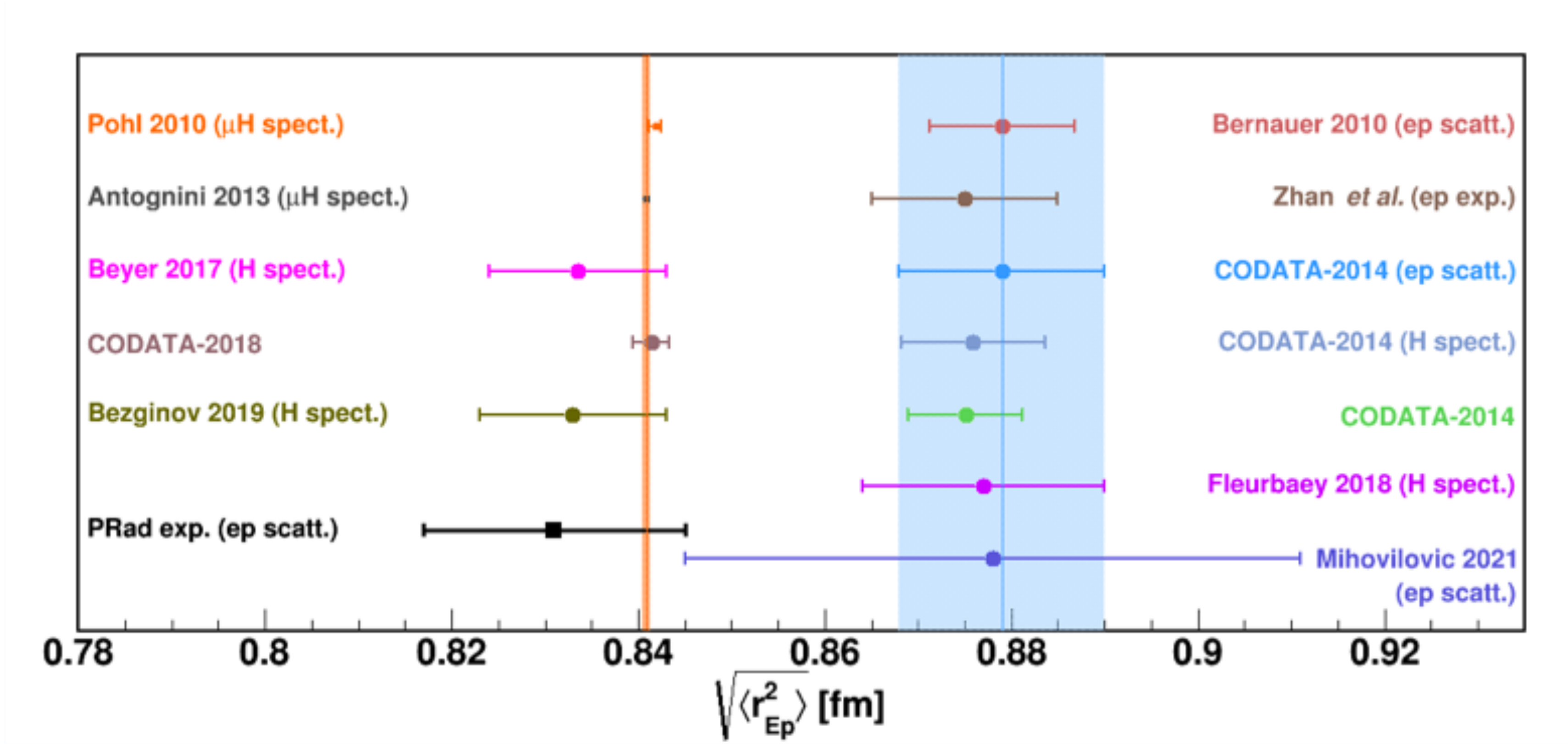


n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

Brookhaven National Laboratory

Proton radius at the time of PRad publication

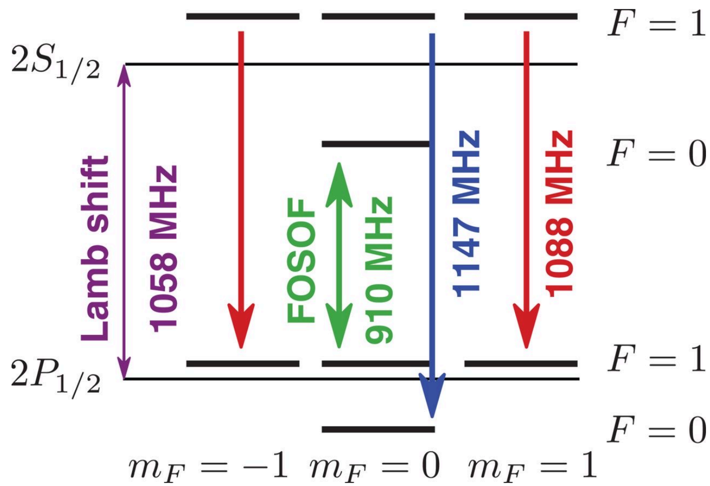
- PRad result r_p : 0.831 +/- 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*
- H Lamb Shift: 0.833 +/- 0.010 fm Bezginov *et al., Science* **365**, 1007-1012 (2019)
- CODATA 2018 value of r_p: 0.8414 +/- 0.0019 fm, *E. Tiesinga et al., RMP 93, 025010(2021)*

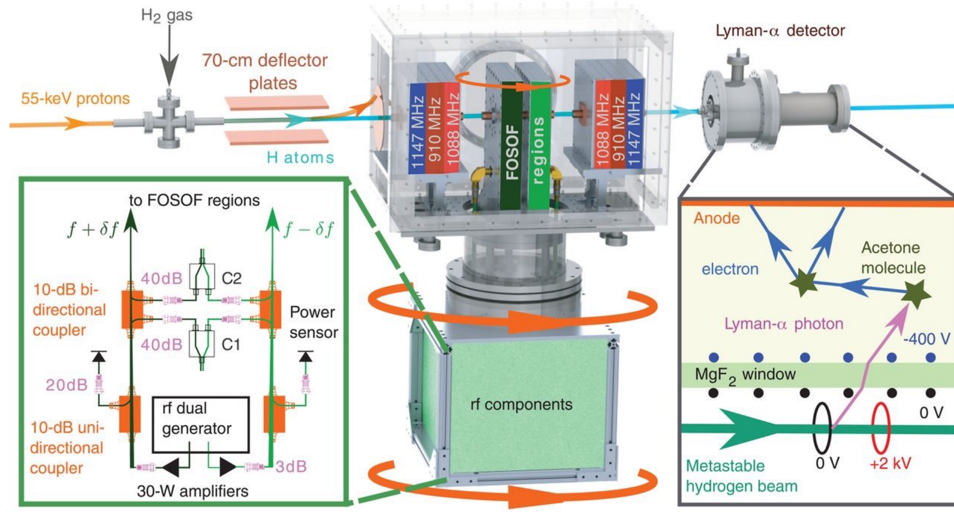


CODATA has also shifted the value of the Rydberg constant.

Brookhaven National Laboratory

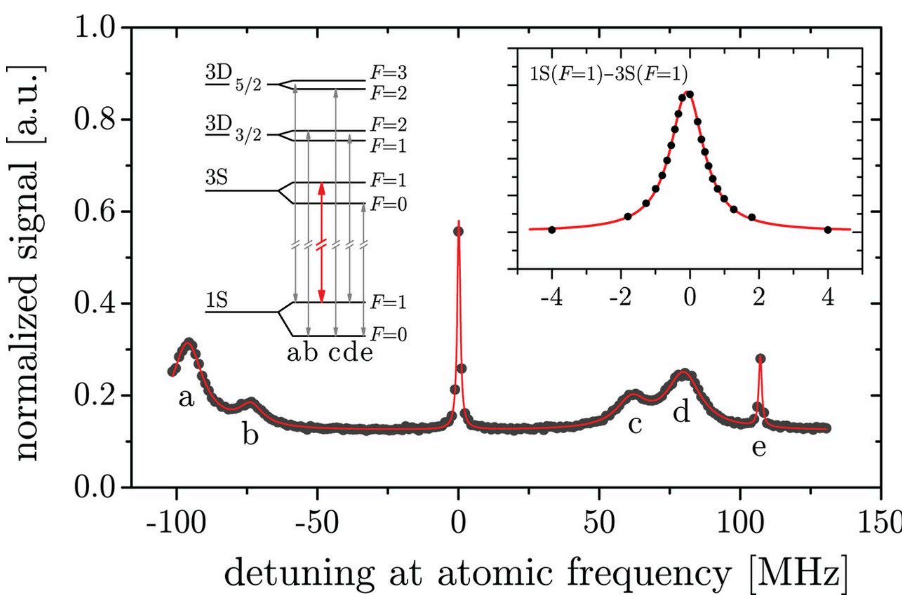
More from ordinary hydrogen spectroscopy

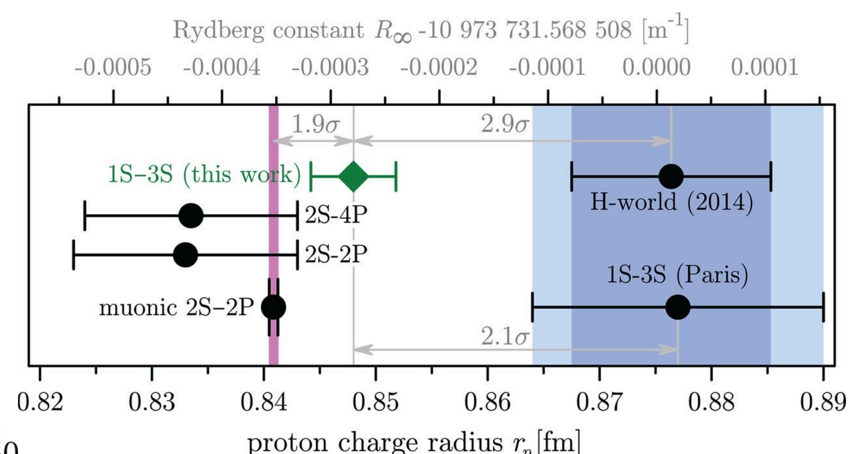




Bezginov *et al*., Science 365, 1007 (2019)

r_p = 0.833(10) fm





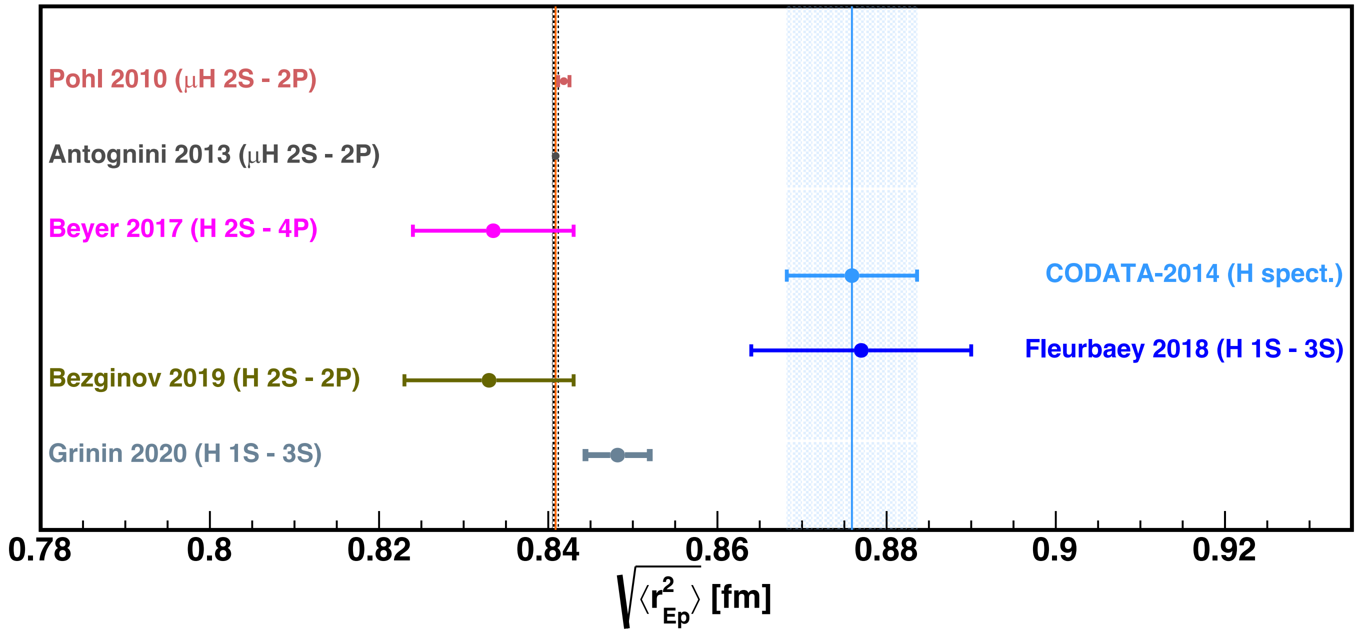
Grinin *et al*., Science 370, 1061 (2020)

r_p = 0.8482(38) fm

Brookhaven National Laboratory

Gao and Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)

Proton radius from ordinary and muonic H spectroscopy



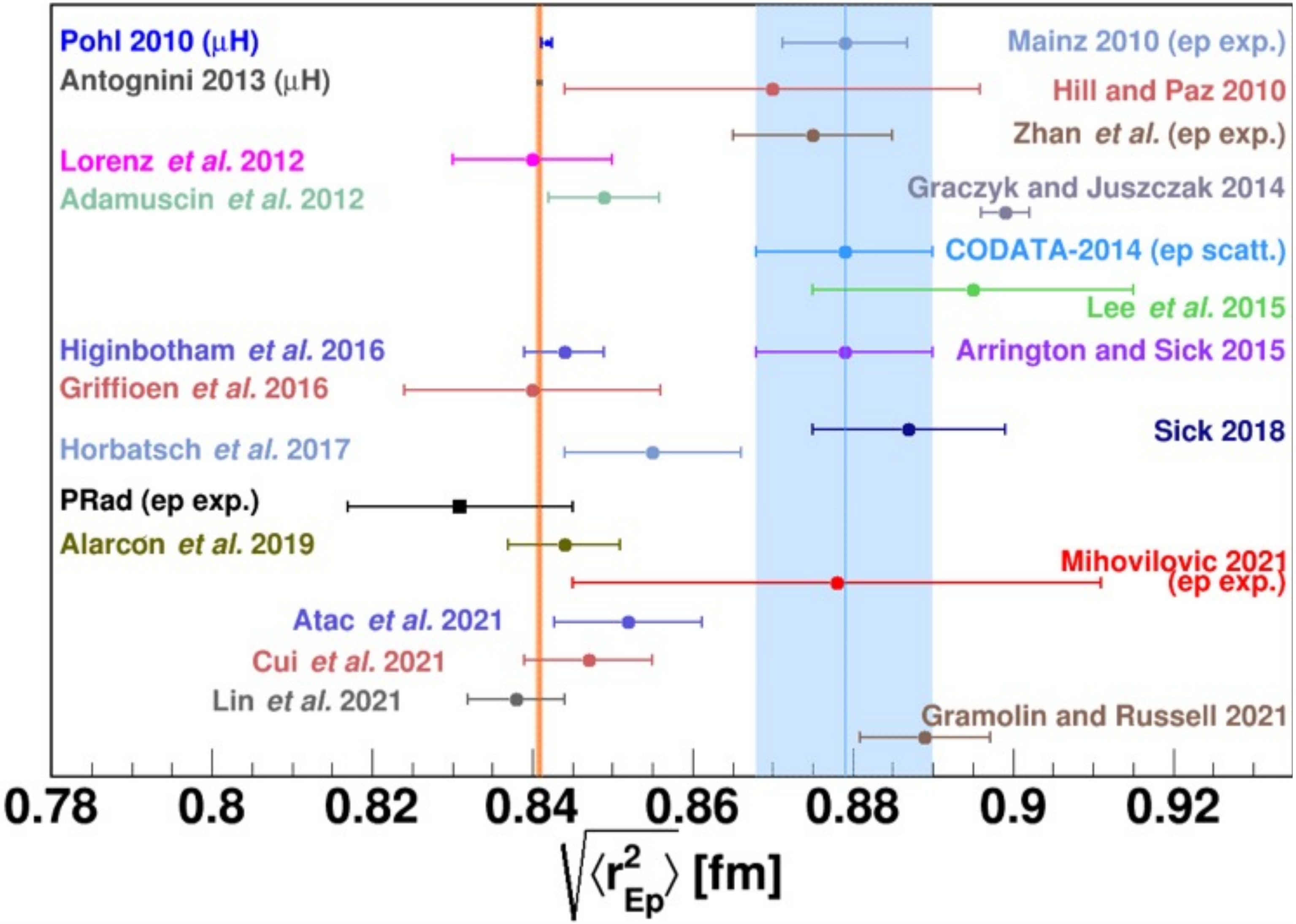
Experiment	Type	Transition(s)	$\sqrt{< r^2_{Ep} >}$ (fm)	r_∞ (m^{-1})
Pohl 2010	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$	0.84184(67)	
Antognini 2013	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$	0.84087(39)	
		$2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}$		
Beyer 2017	H	$2S - 4P$	0.8335(95)	10 973 731.568 076 (96)
		with $(1S - 2S)$		
Fleurbaey 2018	H	$1S - 3S$	0.877(13)	10 973 731.568 53(14)
		with $(1S - 2S)$		
Bezginov 2019	H	$2S_{1/2} - 2P_{1/2}$	0.833(10)	
Grinin 2020	H	$1S - 3S$	0.8482(38)	10 973 731.568 226(38)
		with $(1S - 2S)$		

Not included
Newest result:
Brandt PRL128, 023001 (2022):
measured $2S_{1/2}$ -$8D_{5/2}$ transition
& used 1S-2S

r_p=0.8584(51) fm
R_∞=10973731.568332(52) m^{-1}.

Gao and Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)

(Re)analyses of e-p scattering data



Gao and Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)

Cui *et al*., arxiv:2204.05418, *Chinese Phys. C* **46** 122001 (2022)
Atoui *et al*., arxiv:2310.00412 (2023)

Brookhaven National Laboratory

PRad-II: goals and approaches

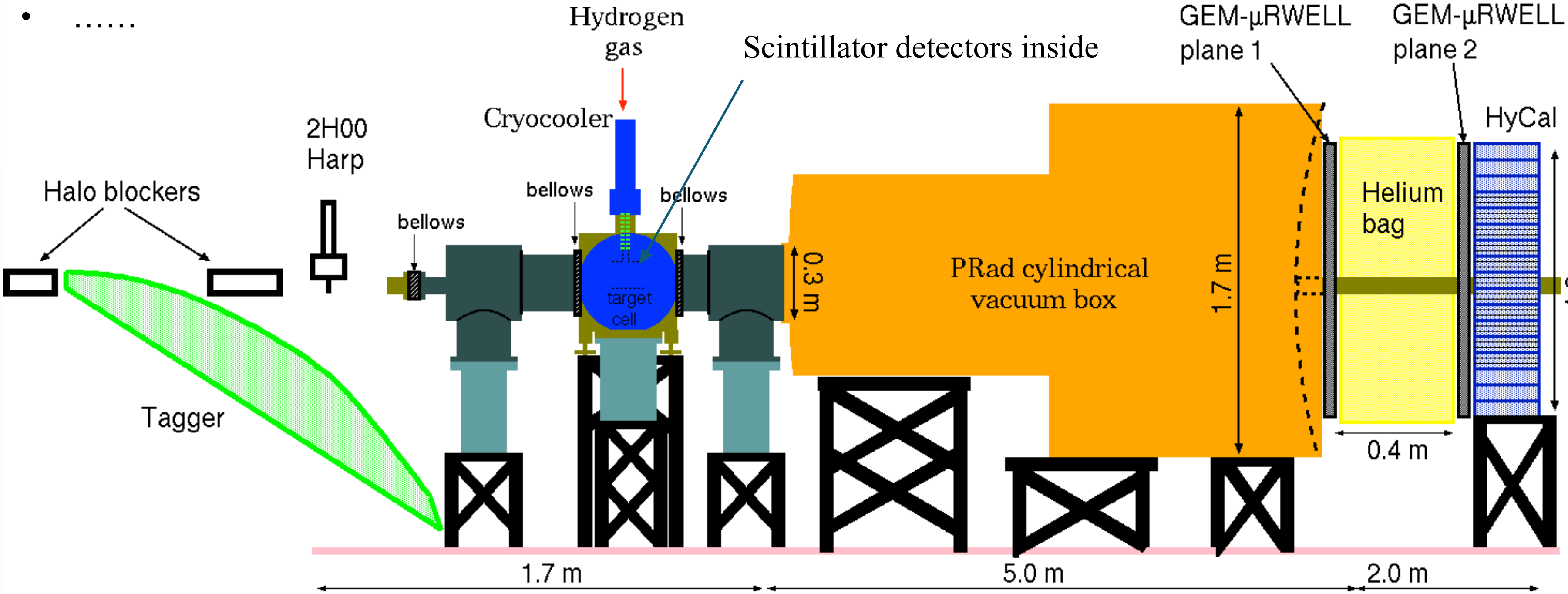
- Proposed to reduce the uncertainty of the r_p measurement by a factor of **3.8!**
- Reach an unprecedented low values of Q^2 : 4×10^{-5} $(GeV/c)^2$
- How?
  - Improving tracking capability by adding a second plane of tracking detector
  - Adding new rectangular cross shaped scintillator detectors to separate Moller from ep electrons in scattering angular range of 0.5^0- 0.8^0
  - Upgrading HyCal and electronics for readout
    - Replacing lead glass blocks by $PbWO_4$ modules (uniformity, resolutions, inelastic channel)
    - Converting to FADC based readout
  - Suppressing beamline background
    - Improving vacuum
    - Adding second beam halo blocker upstream of the tagger
  - Reducing statistical uncertainties by a factor of 4 compared with PRad
  - Three beam energies: 0.7, 1.4 and 2.1 GeV – ***0.7 GeV is critical to reach the lowest Q^2 (4×10^{-5} $(GeV/c)^2$)***
  - Improve radiative correction calculations by going to NNL order
  - Potential target improvement (***not used in projection***)

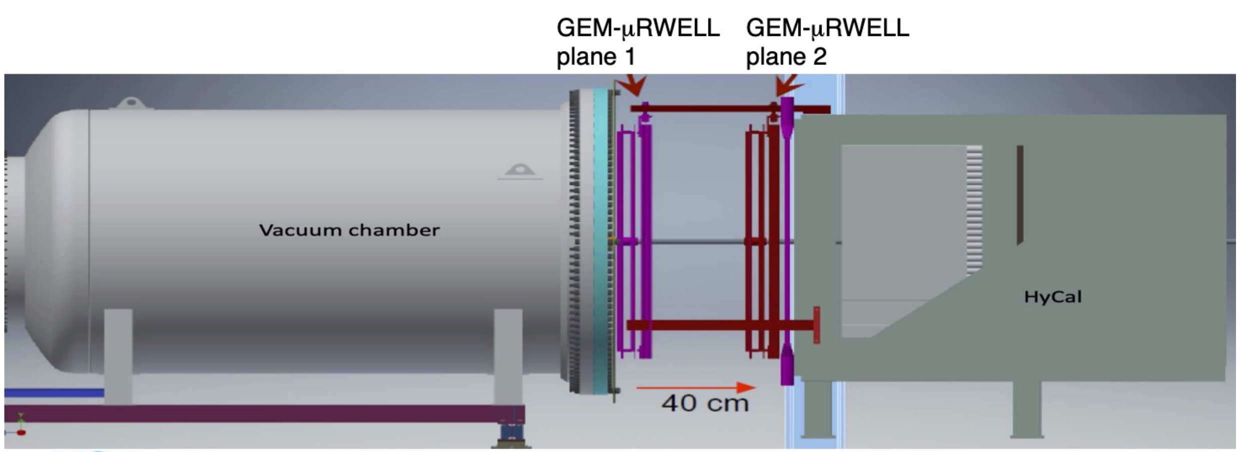
Approved with the highest rating by the JLab Program Advisory Committee in summer 2020

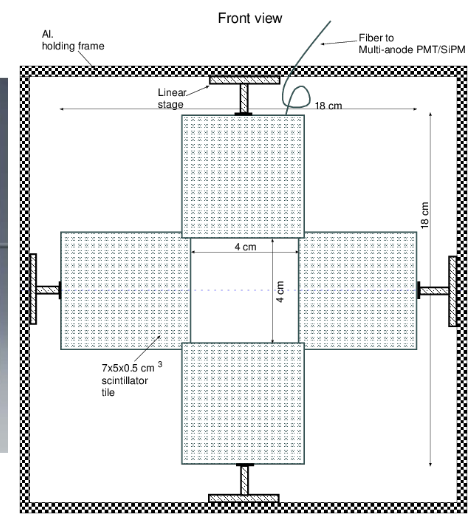
Brookhaven National Laboratory

PRad-II Experimental Setup (Side View)

- **Upgrade HyCal**
- **Adding 2nd tracker (GEM or μRWELL)**
- ……



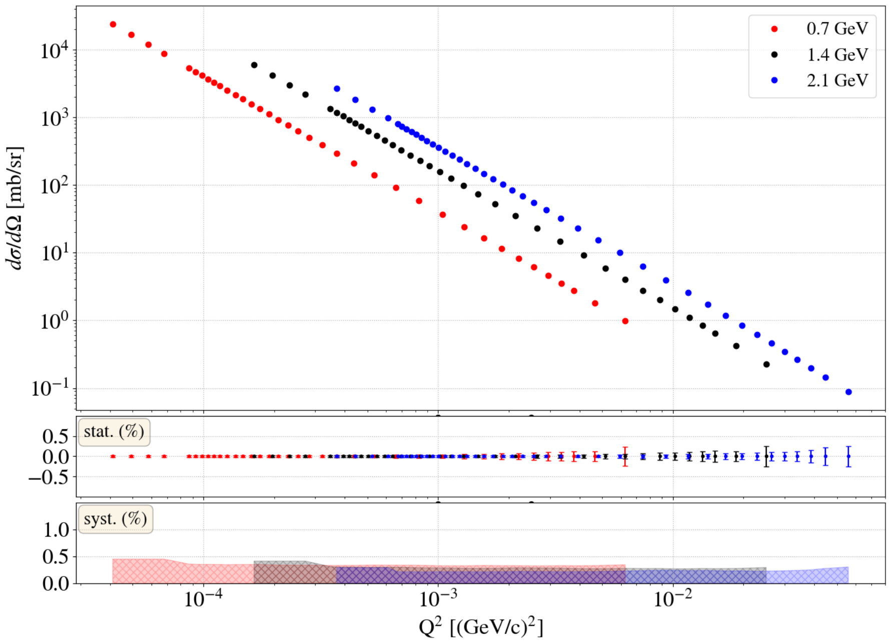




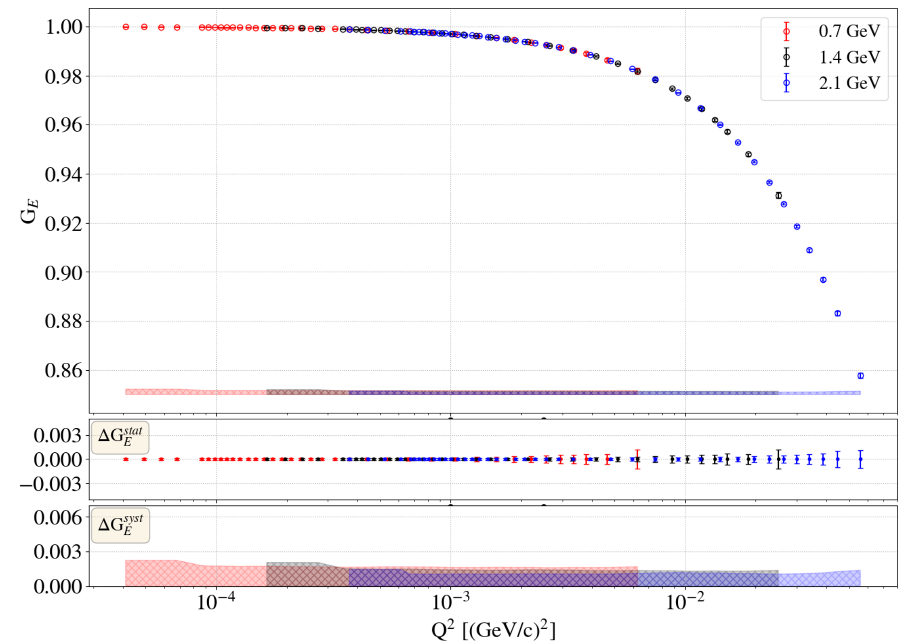
Brookhaven National Laboratory

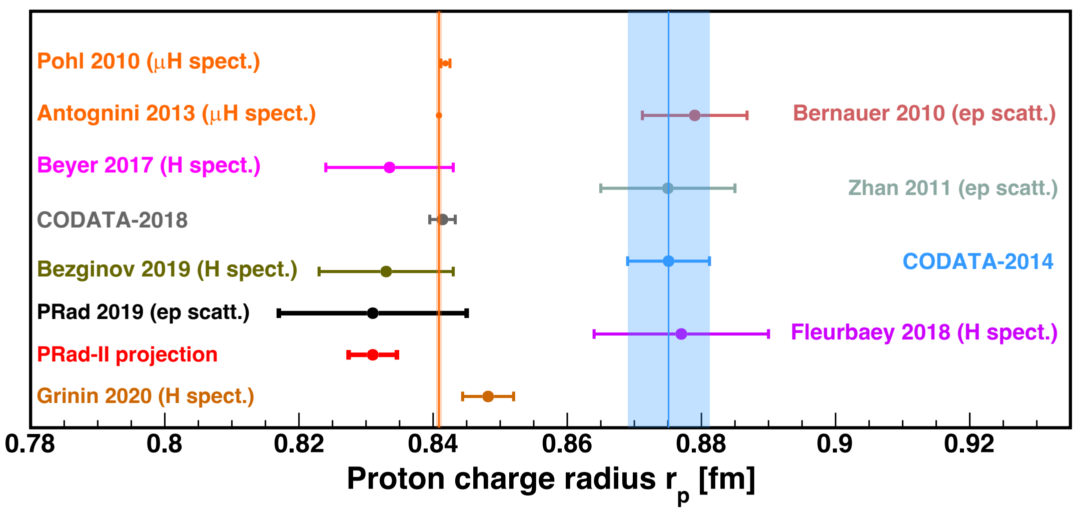
Projections for PRad-II

Differential Cross section



Electric form factor





- Nuclear deformation effects, Lin and Zou, arxiv:1910.13916
- New physics?

Most precise ordinary hydrogen result:
$r_p = 0.8482 \pm 0.0038$ fm
Grinin *et al.*, Science **370**, 1061 (2020)

- PRad-II: total uncertainty 0.0036 fm (proposed)

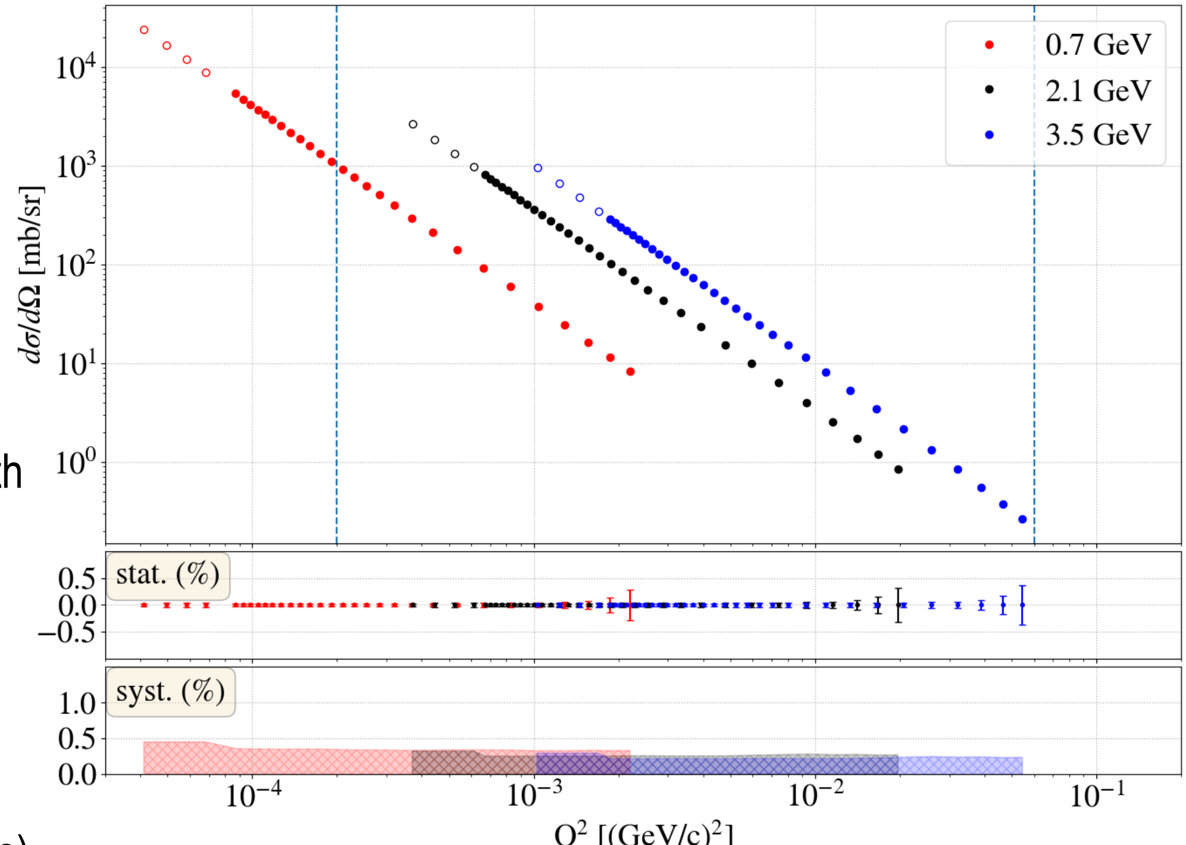
  Gasparian *et al.* arXiv:2009.10510

Brookhaven National Laboratory

Updated Suggestions to Run the PRad-II Experiment:

Since the planned HyCal upgrade to all $PbWO_4$ crystals are still uncertain we suggest the following new conditions to run the PRad-II experiment:

- ✓ Use the central $PbWO_4$ crystal part only
- ✓ Replace E_e=1.4 GeV run with a new E_e=3.5 GeV
- ✓ Keep the total run time the same: 40 days



Original proposal:

E (GeV)	Beam (nA)	Time (days)
0.7	20	4
1.4	70	5
2.1	70	15

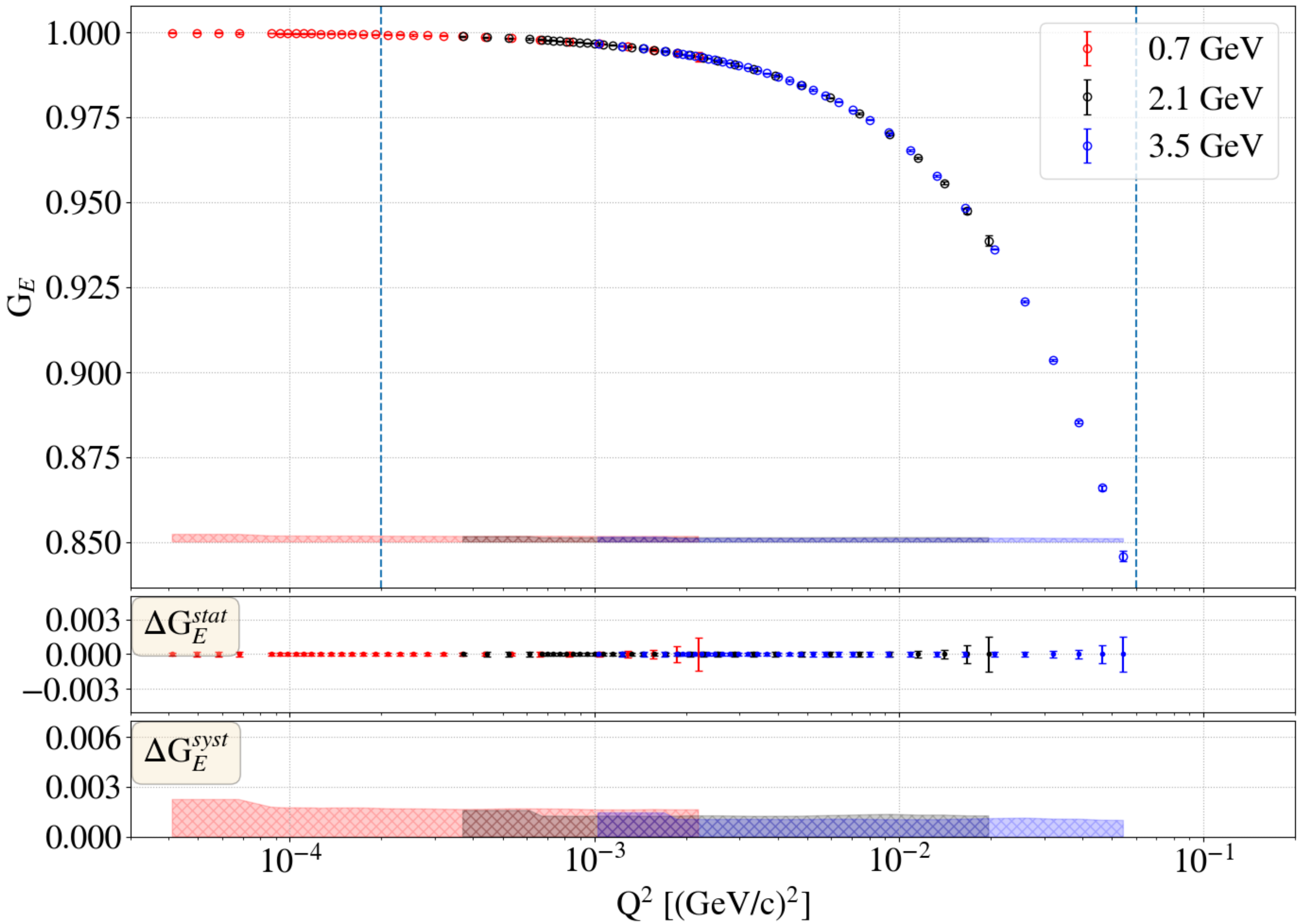
Beam current was limited by DAQ

Suggested Run:

E (GeV)	Beam (nA)	Time (days)
0.7	20	4
2.1	150	5
3.5	150	15

Brookhaven National Laboratory

Simulated Uncertainties on G_e for the Suggested New PRad-II Run Conditions



Simulated Uncertainties on R_p for the Suggested New PRad-II Run Conditions

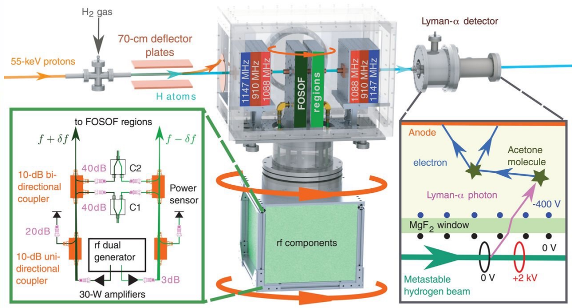
	PRad-II (proposal and PAC48)	PRad-II (current)
Stat. uncertainty	0.0017	0.0014
GEM efficiency	0.0027	0.0023
Acceptance	0.0002	0.0002
Beam energy related	0.0002	0.0002
Event selection	0.0027	0.0027
HyCal response	0.0001	0.0001
Beam background	0.0016	0.0014
Radiative correction	0.0004	0.0004
Inelastic ep	0.0001	0.0002
Magnetic form factor model	0.0005	0.0006
Total syst. uncertainty	0.0042	0.0041
Total uncertainty	0.0045	0.0043

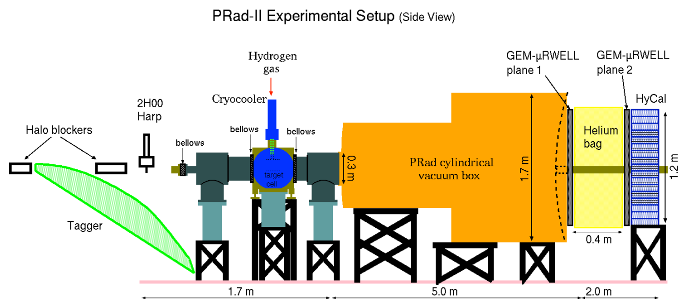
- Both cases assume regular GEMs with dead-area
- PRad-II (proposal) assumes HyCal upgrade to full $PbWO_4$
- Current PRad-II uses only $PbWO_4$ part of current HyCal

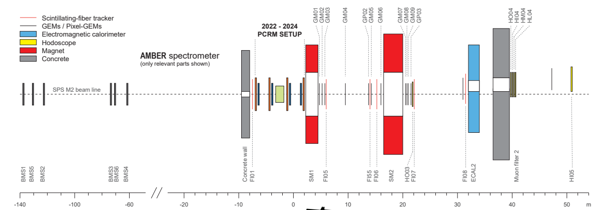
A factor of 3.2 improvement over PRad on R_p

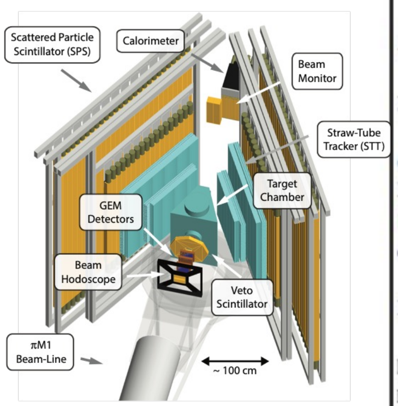
- Compared to PRad-II proposal:
  1. slightly better statistical uncertainty due to higher beam currents
  2. slightly better GEM efficiency due to more statistics and new GEM structure
  3. slightly better beam background due to higher beam energy used
- Total uncertainty comparable to the proposal and PAC48 version (with GEM detectors in both cases)

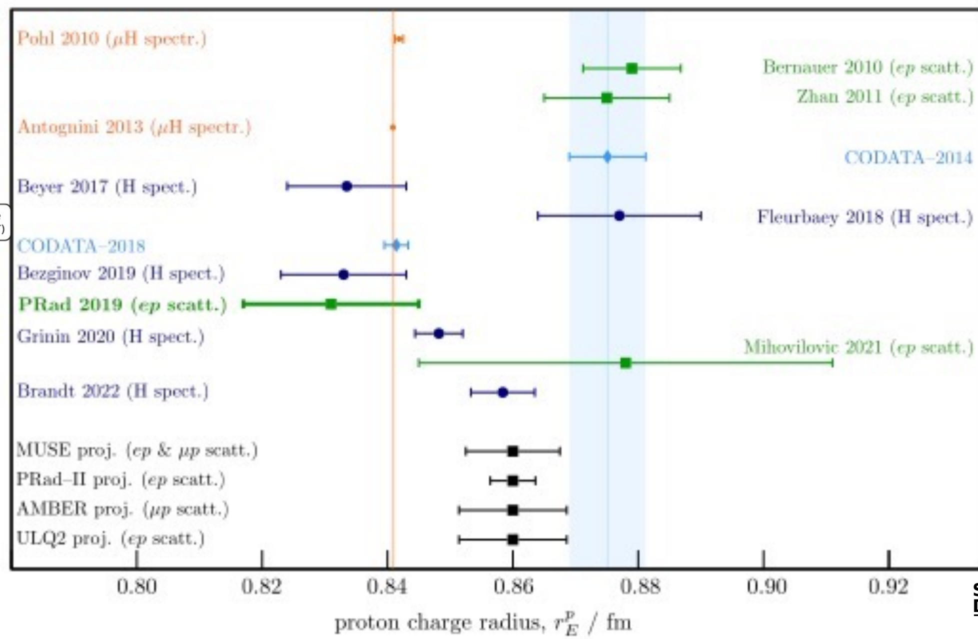
World-wide effort in Nuclear and Atomic Physics on Proton Charge Radius

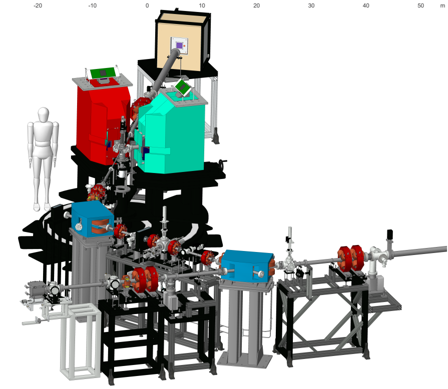


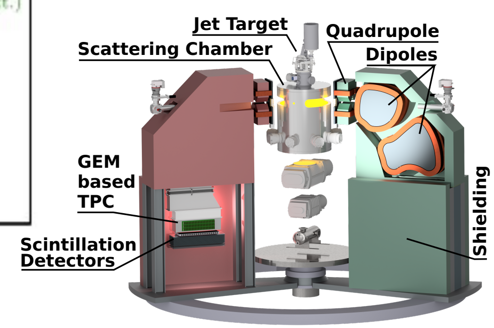






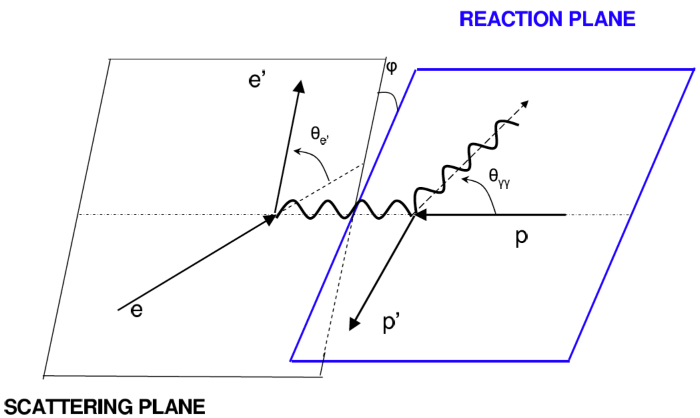


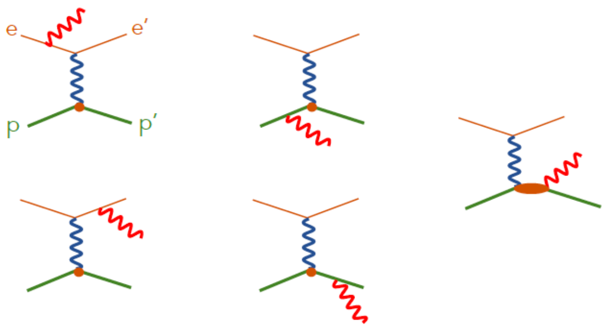




Gao & Vanderhaeghen Rev. Mod. Phys. 94, 015002 (2022)

Virtual Compton Scattering and Proton Polarizability Radii





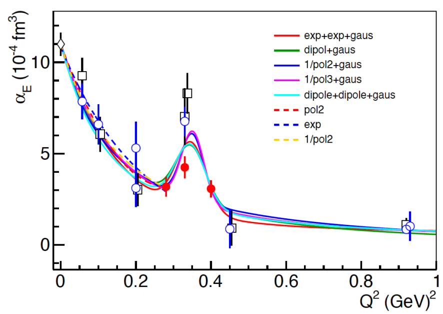
Bethe-Heitler Born VCS non-Born VCS

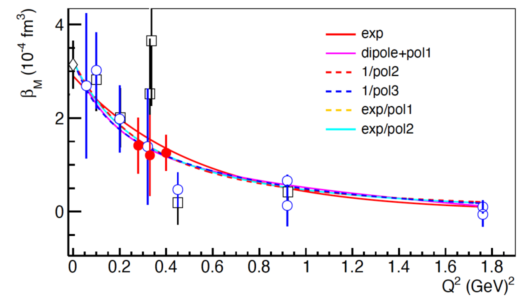
Elastic FFs **Generalized polarizabilities**

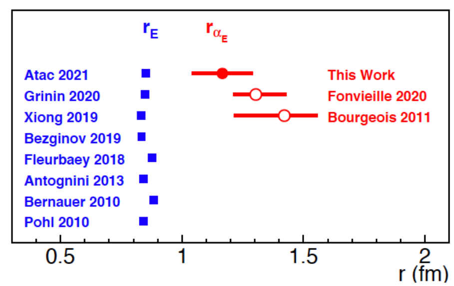
R. Li *et al*., Nature 611, 265 (2022)

$$\langle r^2_{\alpha_E}\rangle = \frac{-6}{\alpha_E(0)}\cdot\frac{d}{dQ^2}\alpha_E(Q^2)\Big|_{Q^2=0}$$

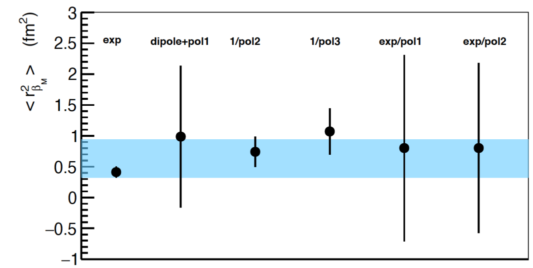
$$\langle r^2_{\beta_M}\rangle = \frac{-6}{\beta_M(0)}\cdot\frac{d}{dQ^2}\beta_M(Q^2)\Big|_{Q^2=0}$$







$$\langle r^2_{\alpha_E}\rangle = 1.36 \pm 0.29\ \mathrm{fm}^2$$



$$\langle r^2_{\beta_M}\rangle = 0.63 \pm 0.31\ \mathrm{fm}^2$$

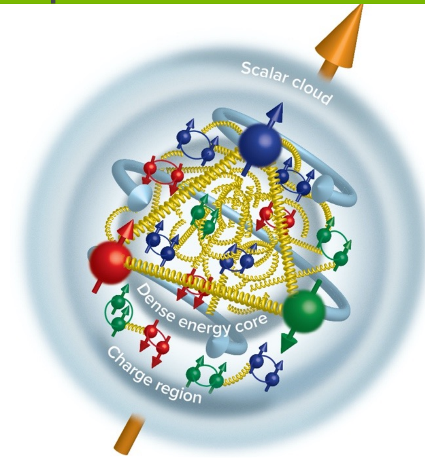
Real Compton Scattering experiments at Mainz and HIγS and nucleon EM and spin polarizabilities

Nikos Sparveris, Spin 2023 Symposium and EINN 2023

Brookhaven National Laboratory

FIRST EXTRACTION OF GLUONIC SCALAR/MASS RADIUS OF THE NUCLEON

A picture of three zones?



Definition of gluonic mass and scalar radius

B. Duran *et al.*, Nature 615, 813 (2023)

$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

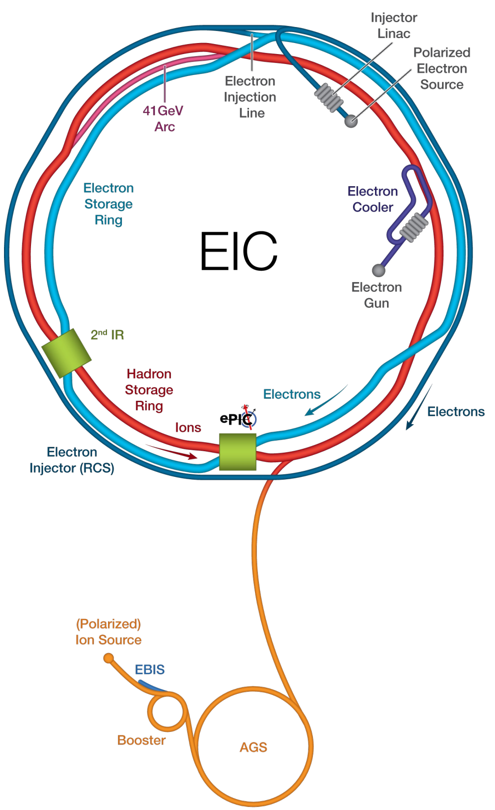
$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

Theoretical approach GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_g}$ (fm)
Holographic QCD Tripole-tripole	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.067	1.069±0.126
GPD Tripole-tripole	0.924	2.71±0.19	1.28± 0.50	-0.20 ± 0.11	0.472±0.085	0.695±0.162
Lattice Tripole-tripole		1.641± 0.043	1.07± 0.12	-0.483± 0.133	0.7464±0.055	1.073±0.114

Zein-Eddine Meziani, Spin 2023 Symposium; S. Joosten, D. Pefkou, EINN2023

The Electron-Ion Collider

2023 LRP Recommendation:
We recommend the expeditious completion of the EIC as the highest priority for facility construction.



Major discovery potential!

Polarized electrons colliding with polarized protons, polarized light ions, and heavy ions will allow us to study sea-quarks and gluons to understand:

- mass and spin of the proton.
- spatial and momentum distribution of low-x partons
- Possible gluon saturation
- modifications of parton distribution functions when a nucleon is embedded in a nucleus
- hadron formation

The EIC is a partnership between BNL and Jefferson Lab.

CD-1 June 2021, successful CD-3A review November 2023

Project is aiming for CD2/3 in 2025

ePIC detector design is advanced. Significant international support and participation (160+ institutions, 24 countries)

EIC Resource Review Board (RRB) formed and RRB met April, December 2023, next one May 2024, Rome

Argonne National Lab, Fermilab, Lawrence Berkeley National Lab, Oak Ridge National Lab and SLAC all contribute to its construction, together with US universities and numerous international partners.

Thank you for your time and attention!

Acknowledgement: PRad Collaboration

Duke work supported by Department of Energy under contract DE-FG02-03ER41231;

Brookhaven National Laboratory is supported by the U.S. Department of Energy's Office of Science.

Brookhaven National Laboratory