Update on the New PRad-II Experiment and Plans for the Deuteron Radius (DRad) Measurement at Jefferson Laboratory

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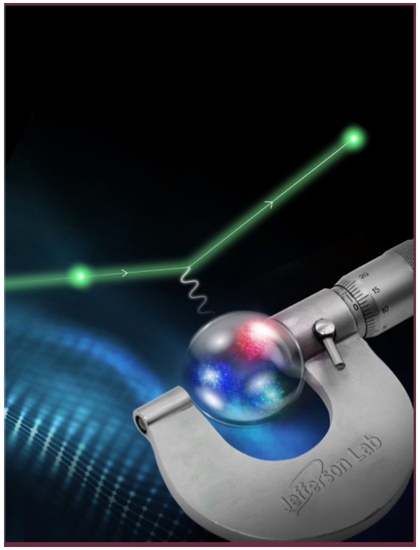
for the PRad collaboration

Outline

- the PRad approach for a new ep-scattering experiments
- first PRad experiment and the results
- status of the new PRad-II experiment (in preparation)
- status of the DRad proposal
- summary and outlook

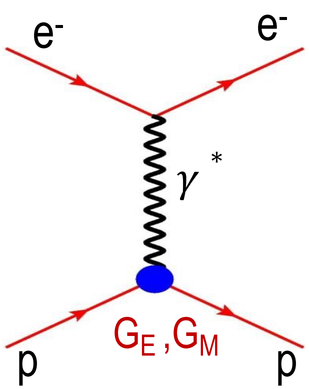


Proton Charge Radius from ep→ep Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

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

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

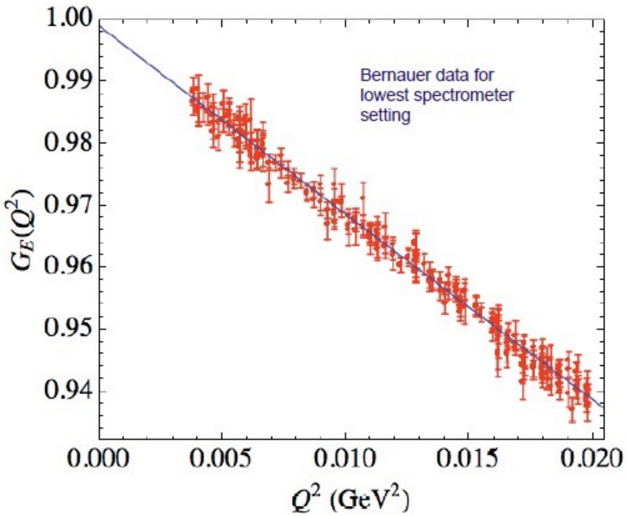


- Structureless proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2 \left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- G_E and G_M can be extracted using Rosenbluth separation
- for extremely low Q^2, the cross section is dominated by G_E
- 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 $Q^2 = 0$:

Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

definition of the proton rms charge radius →

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

First Measurement of the Proton Charge Radius

- Robert Hofstadter, experiments in 1955-1956
  - ✓ ep-elastic scattering
  - ✓ E_e = 188 MeV electron beam
  - ✓ at Stanford University

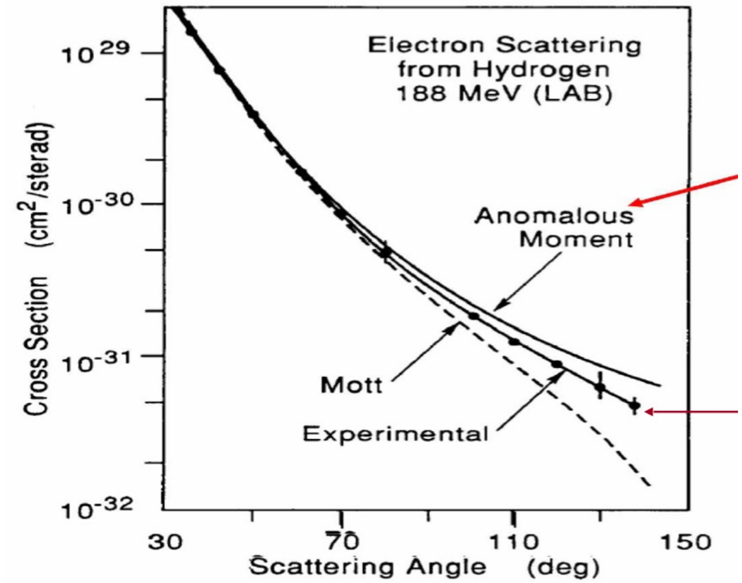
- Nobel prize in 1961:

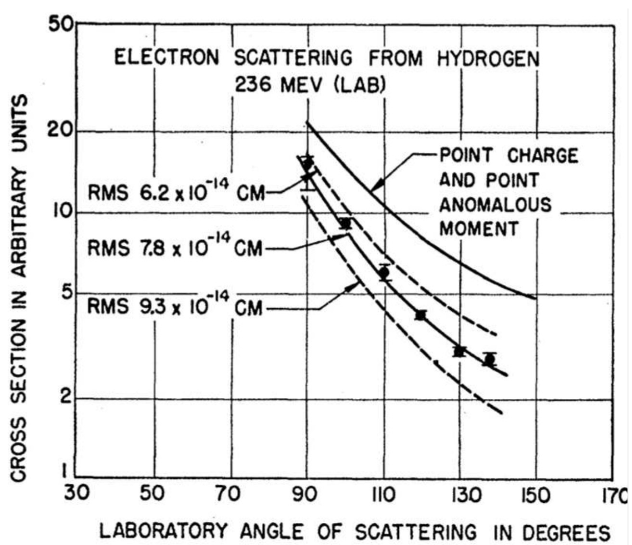
  "*for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the **structure of nucleons***"

"***proton has a diameter of $0.74 \mp 0.24 \times 10^{-13}$ cm***"

r_p = 0.74 fm   with a 32% uncertainty

Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956)





- Over 70 years of experimentation!
  - ✓ started from 0.74 fm
  - ✓ by 2010 it reached to 0.895 fm
  - ✓ it is 0.84 fm from 2018

Planning a New ep→ep Scattering Experiment (PRad at JLab)

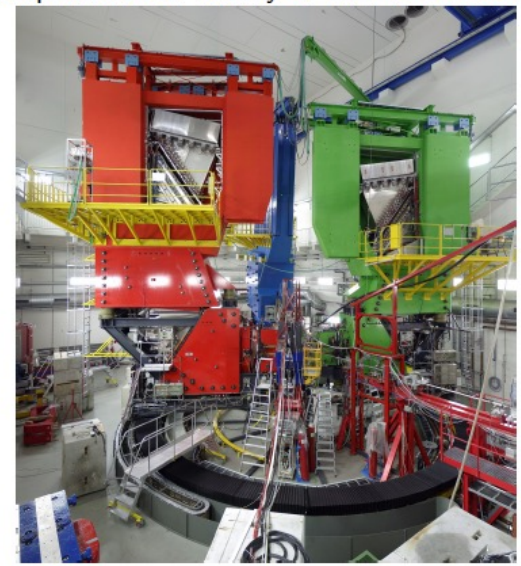
- Practically all ep-scattering experiments were performed with magnetic spectrometers and LH_2 targets!

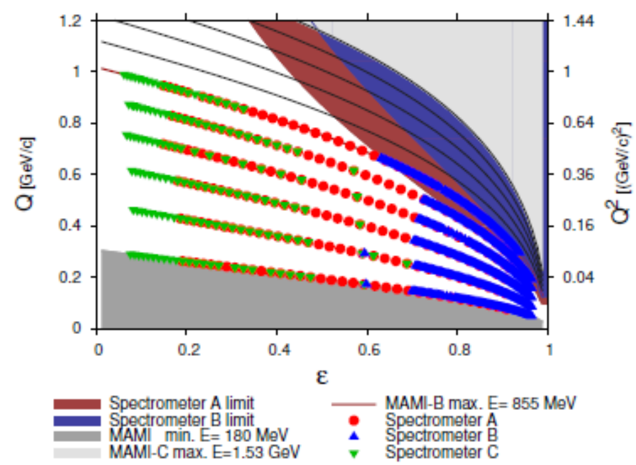
  - ✓ high resolutions but, very SMALL angular and momentum acceptances:
    - ➢ need many different settings of angle (Θ_e) , energies (E_e, E'_e) to cover a reasonable Q^2 fitting interval
    - ➢ normalization of each Q^2 bin
    - ➢ their systematic uncertainties

  - ✓ limitation on minimum Q^2: 10^{-3} GeV/C^2
    - ➢ min. scattering angle: $\theta_e \approx 5^0$
    - ➢ typical beam energies ($E_e \sim 1$ GeV)

  - ✓ limits on accuracy of cross sections: ~ 2 ÷ 3%
    - ➢ statistics is not a problem (< 0.2%)
    - ➢ control of systematic uncertainties???
      - ❖ beam flux, target thickness, windows,
      - ❖ acceptances, detection efficiencies,
      - ❖ ...

Three spectrometer facility of the A1 collaboration:





The PRad (and PRad-II) Experimental Approach

- PRad developed a novel experimental approach including:

1) Use large acceptance, high resolution electromagnetic calorimeter (HyCal) and two plains of large GEM coordinate detectors for tracking providing access to:

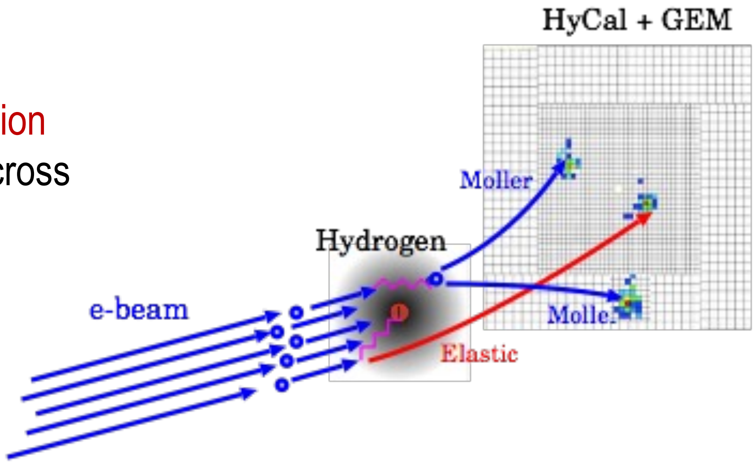
   ✓ measure all angles in one experimental setting ($\vartheta_e = 0.5^0 – 7.0^0$)
   ($Q^2 = 2x10^{-5} \div 6x10^{-2}$) GeV/c^2 ;

   ✓ access to smaller angles ($\vartheta_e \approx 0.5^0$)

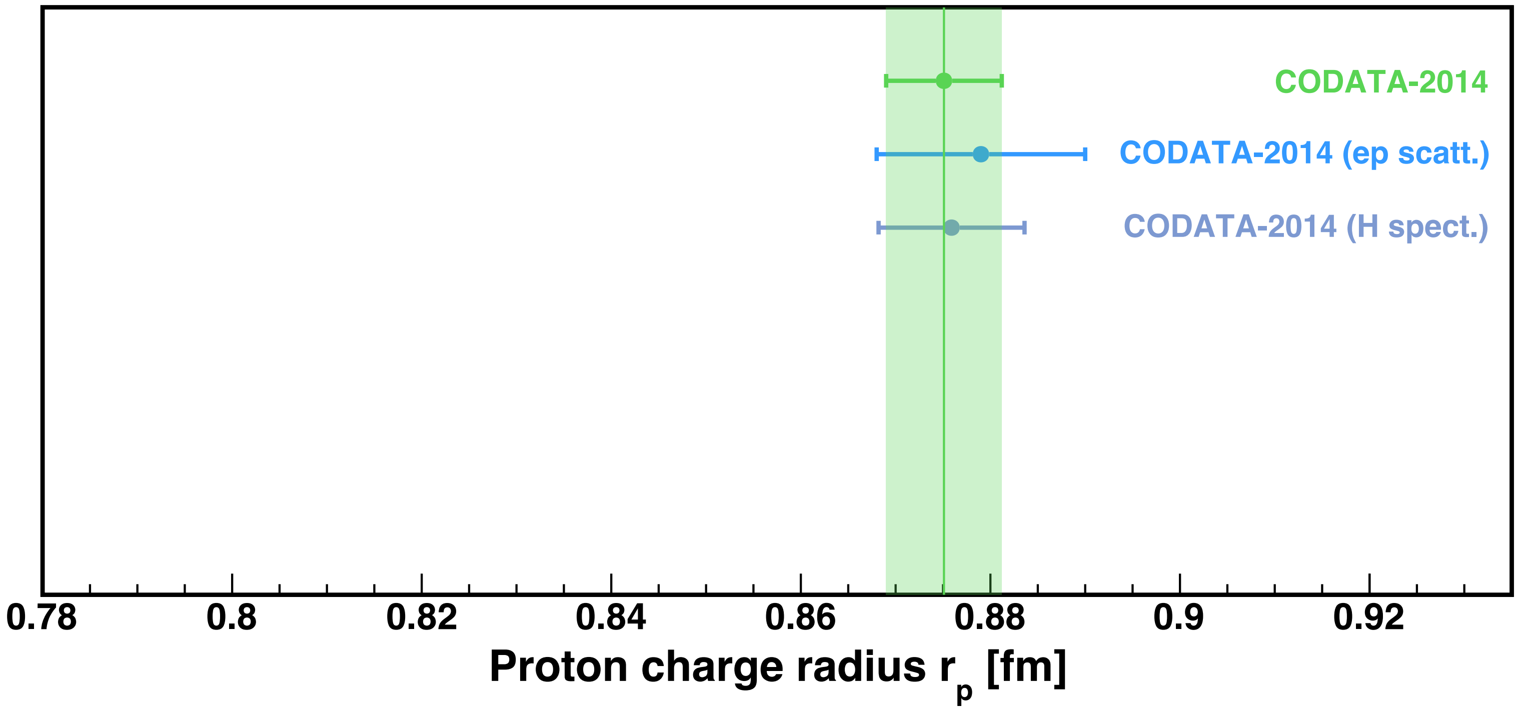
2) Azimuthal symmetry of the setup provides simultaneous detection of $ee \rightarrow ee$ Moller events, providing a robust calibration of ep-cross sections with a well-known QED process (best known control of systematics).

3) Use windowless H_2 gas flow target:

   ✓ minimize experimental background.



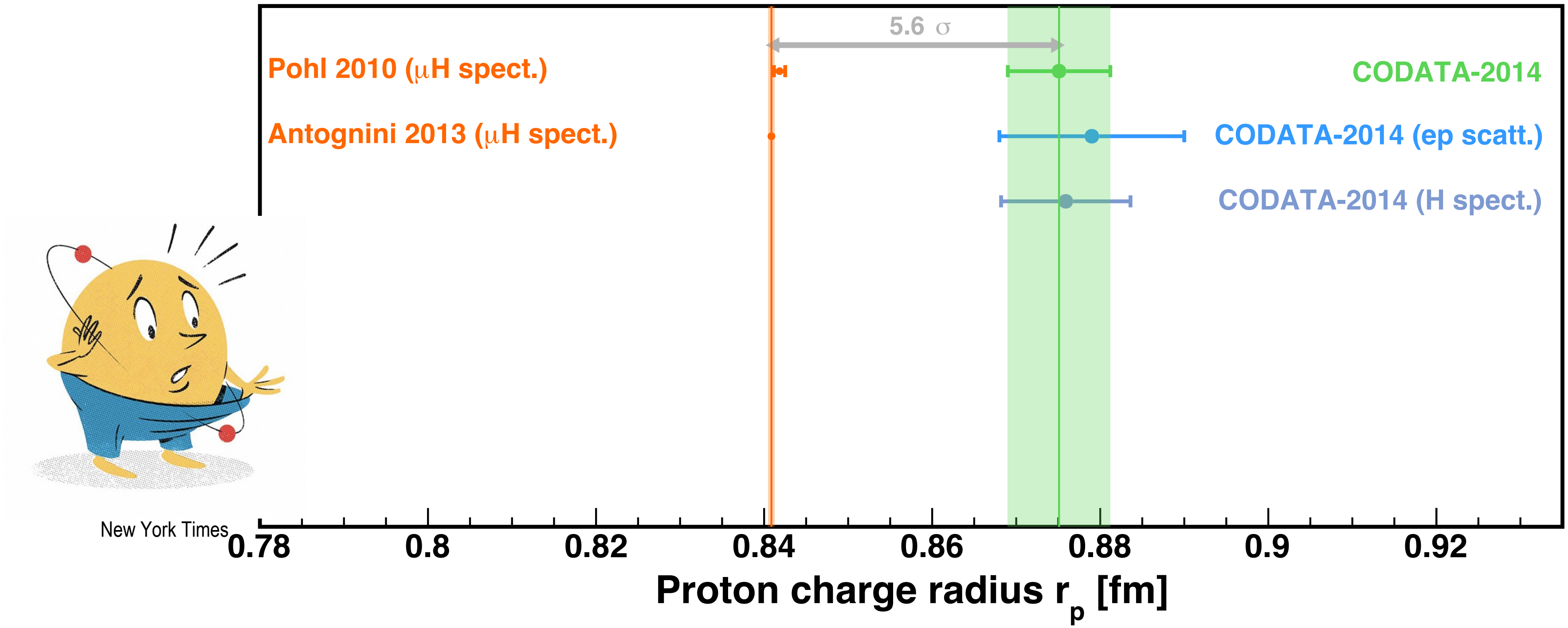
Proton Radius before the Puzzle (2010)



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

Very good agreement between ep-scattering and H-spectroscopy results !

The Proton Radius Puzzle before the PRad Experiment (2014)

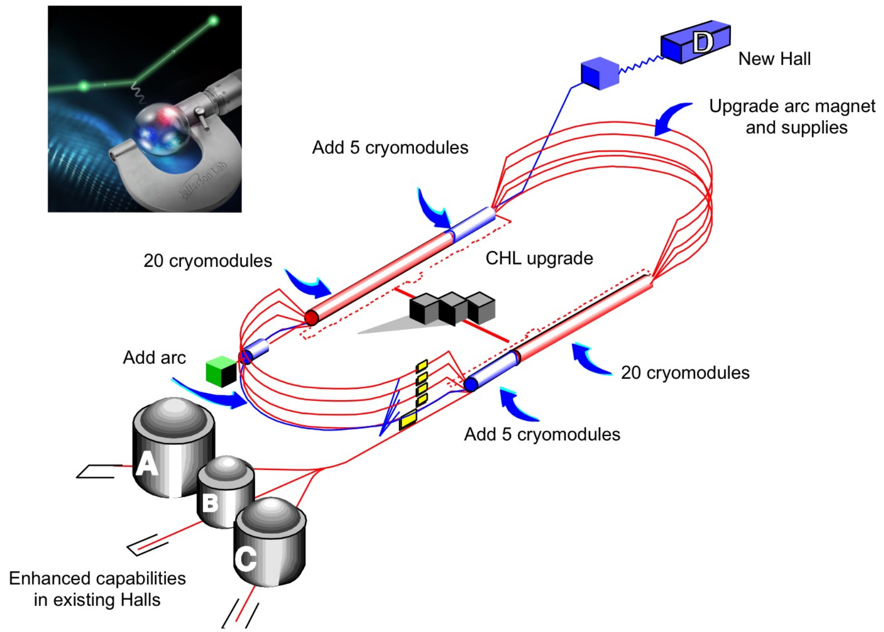


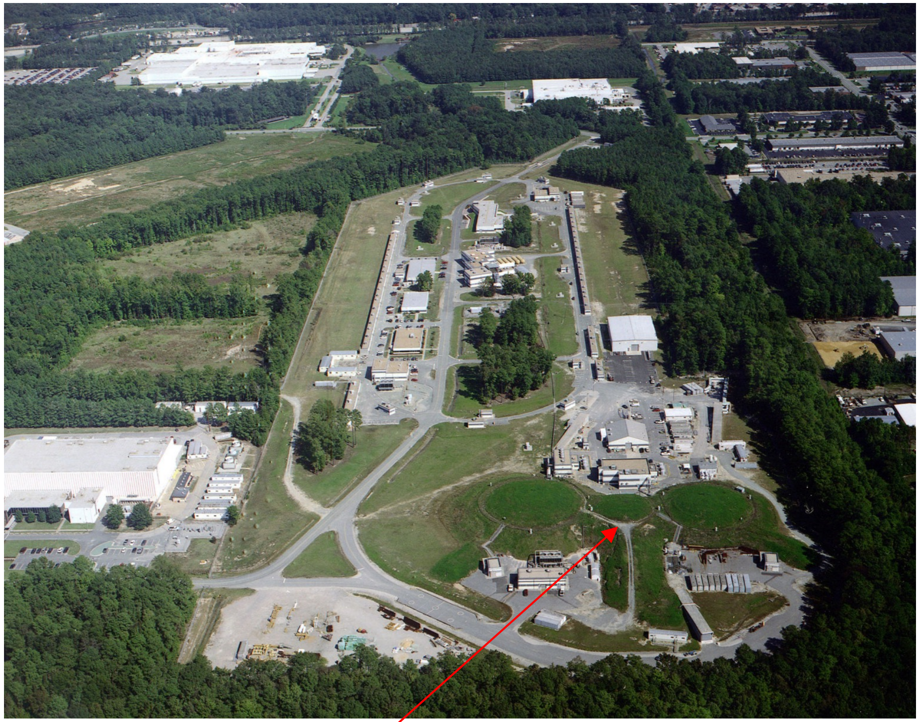
Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013):	0.8409 ± 0.0004 fm
Muonic hydrogen (CREMA coll. 2010):	0.84184 ± 0.00067 fm

PRad Experiment Timeline

✓ Initial proposal development:	2011-12
✓ Approved by JLab PAC39 (with an "A" rating):	2012
✓ Funding proposal for windowless H_2 gas flow target (NSF MRI #PHY-1229153)	2012
✓ Development, construction of the target:	2012 – 15
✓ Funding proposals for the GEM detectors: (DOE awards)	2013
✓ Development, construction of the GEM detectors:	2013-15
✓ Beam line installation, commissioning, data taking in Hall B at JLab:	January /June 2016
✓ Data analysis	2016 – 2019
✓ Publication in Nature journal	November, 2019

PRad Experiment Performed in Hall B at Jefferson Lab in 2016



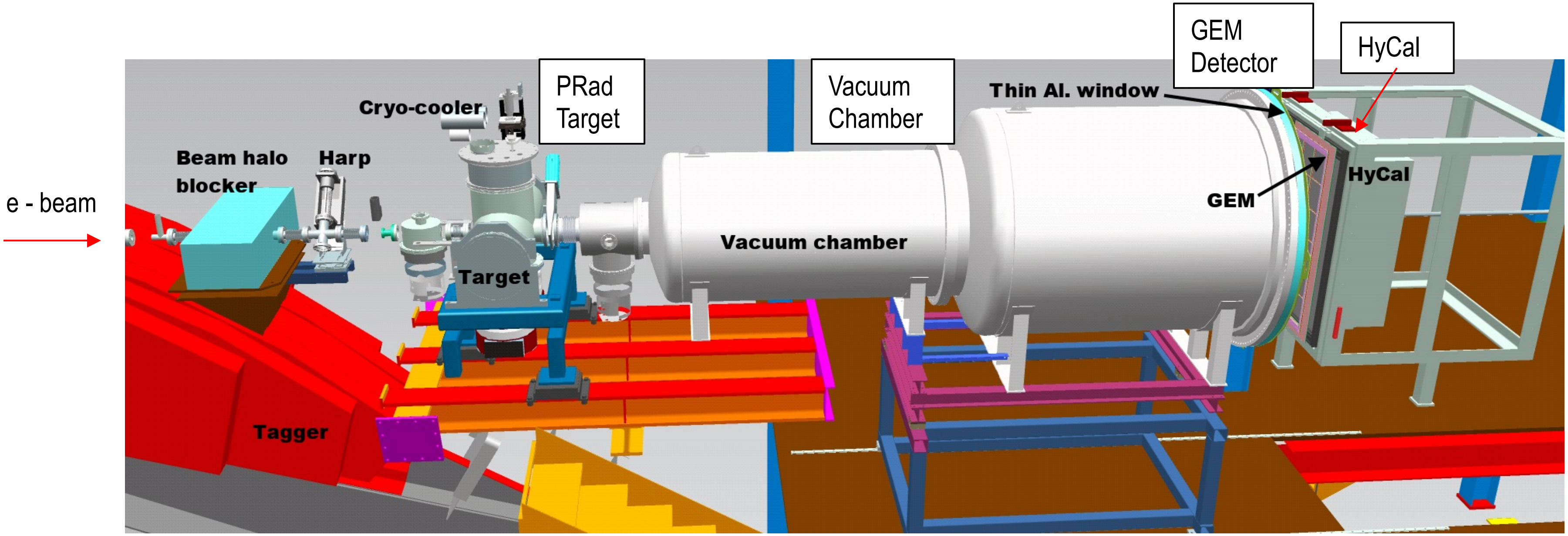


PRad was performed in Hall B at JLab
in January – June of 2016

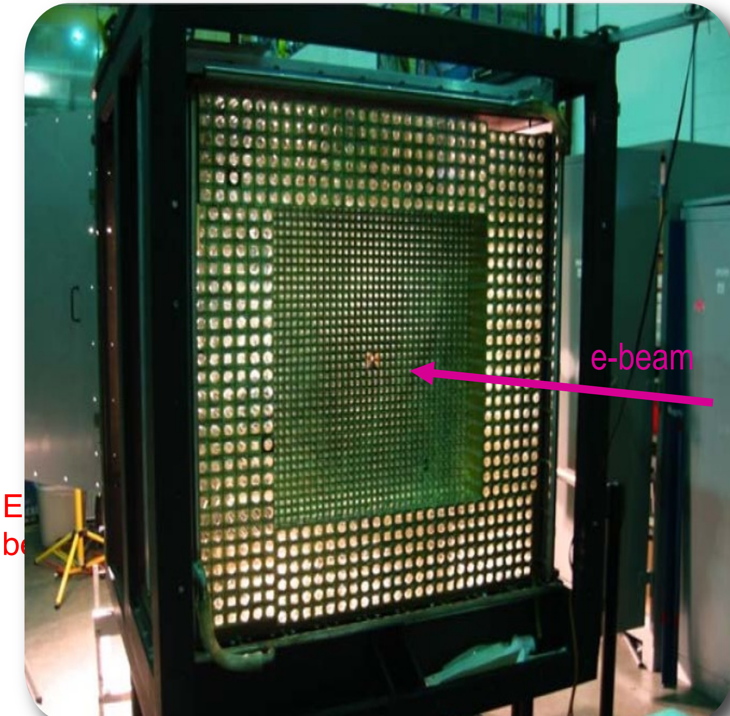
PRad Experimental Setup in Hall B at JLab (schematics)

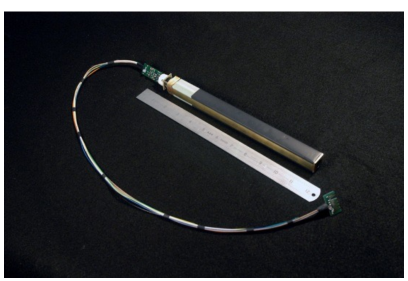
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo "cleanup")
  - Harp 2H00 I



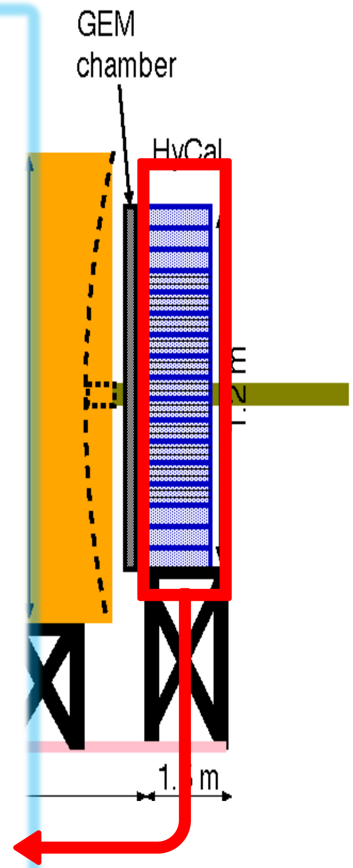
PRad Experimental Apparatus: HyCal El. Mag. Calorimeter



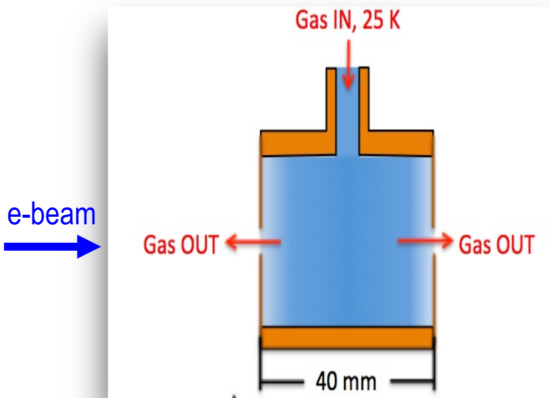


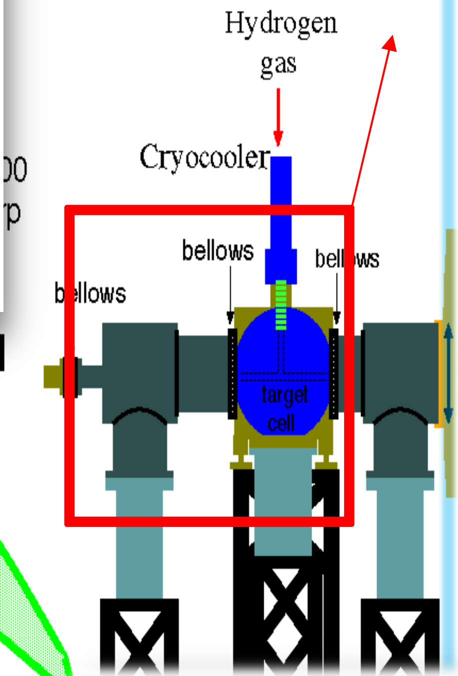
PRad Setup (Side View)

- hybrid EM calorimeter (HyCal)
  - ✓ inner 1156 $PbWO_4$ modules.
  - ✓ outer 576 lead glass modules.
- 5.8 m from the target.
- scattering angle coverage: ~ 0.6˚ to 7.5˚
- full azimuthal angle coverage
- high resolution and efficiency
  - ✓ 2.5% at 1 GeV for crystal part
  - ✓ 6.1% at 1 GeV for lead glass part
- energy calibration done with tagged photons

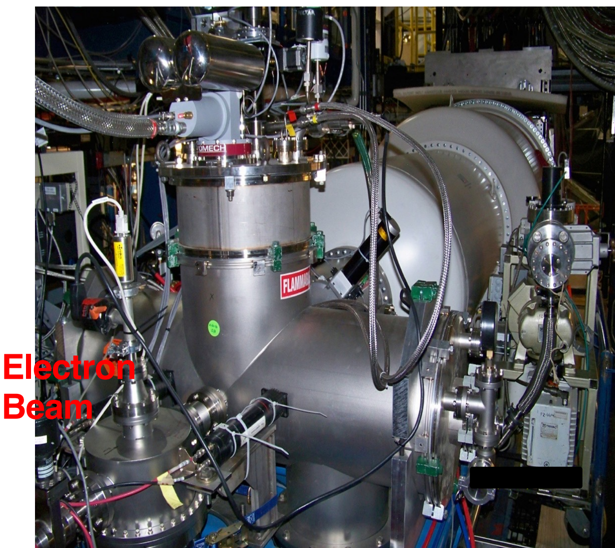


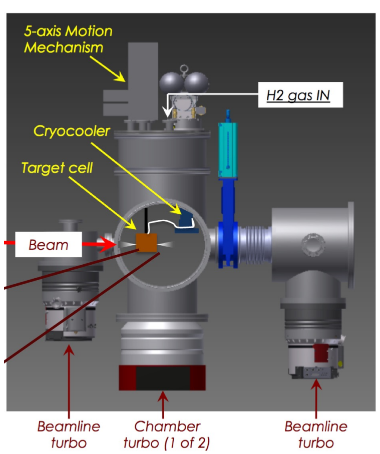
Windowless Hydrogen Gas Flow Target





PRad Setup (Side View)

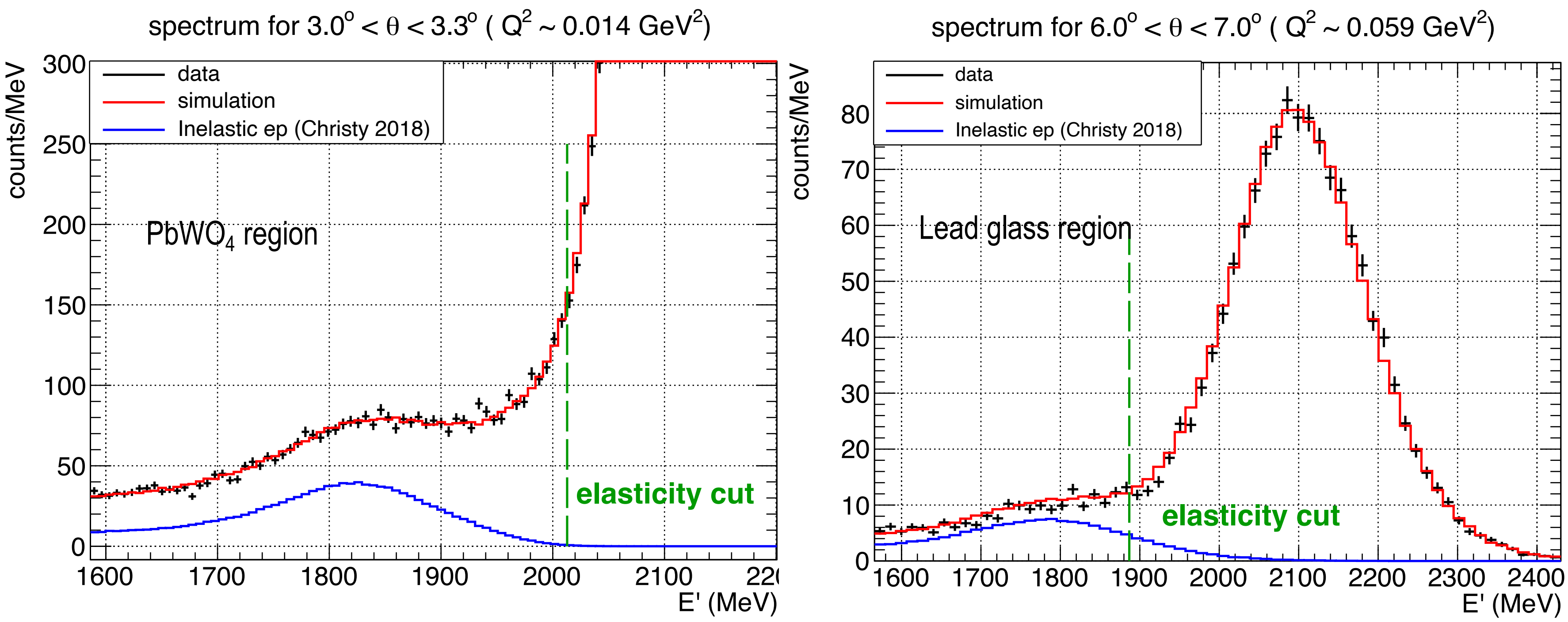




- 8 cm diam. X 4 cm long target cell
- 2 mm holes open at front and back of kapton foils for the beam passage
- areal density: $1.8\text{x}10^{+18}$ H atoms/cm^2
  - cell pressure: 471 mTorr
  - chamber pressure: 2.34 mTorr: cell vs. chamber pressures: 200:1
  - vacuum tank pressure 0.3 mTorr: cell vs. vacuum tank pressures: 1000:1
  - at temperature: 19.5 K

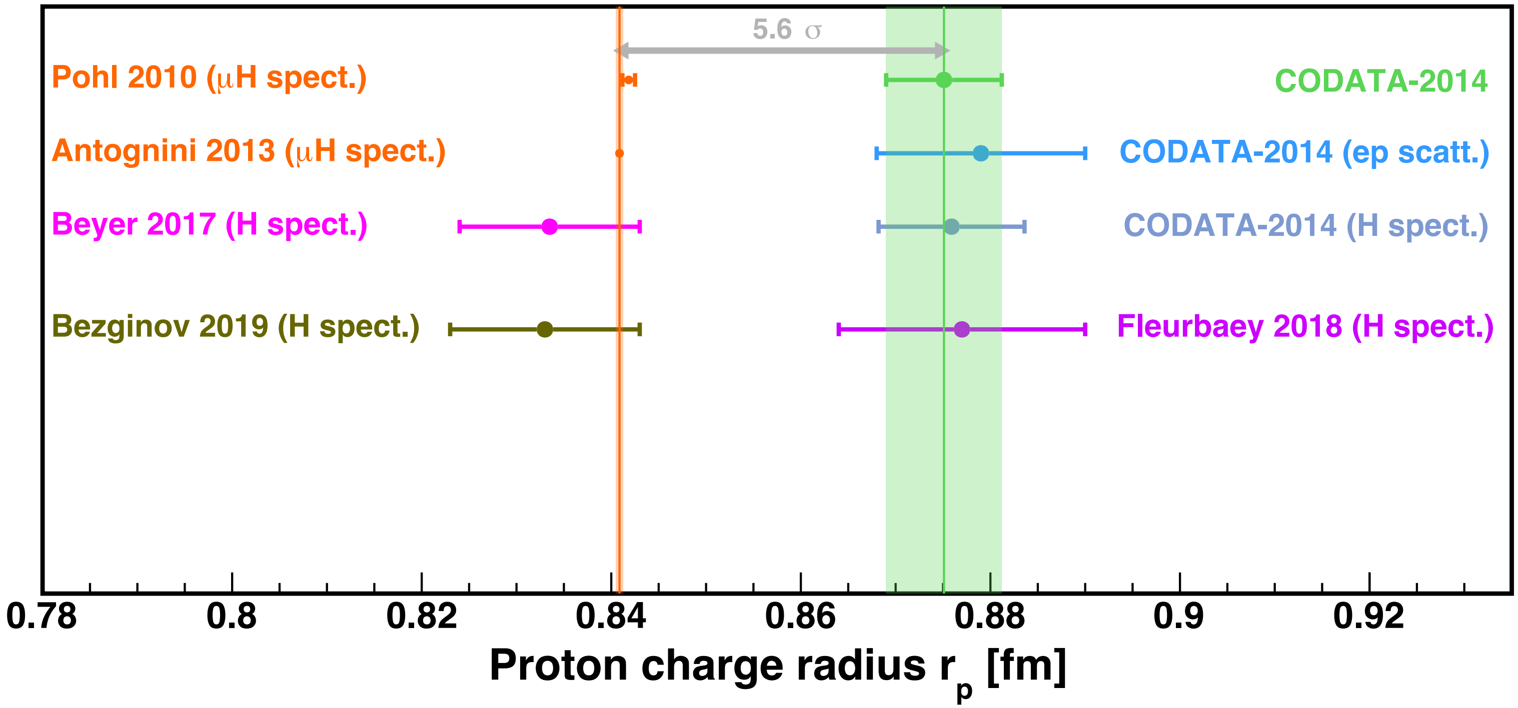
An Example of the Data Analysis Process: *ep-inelastic* Contributions

- 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



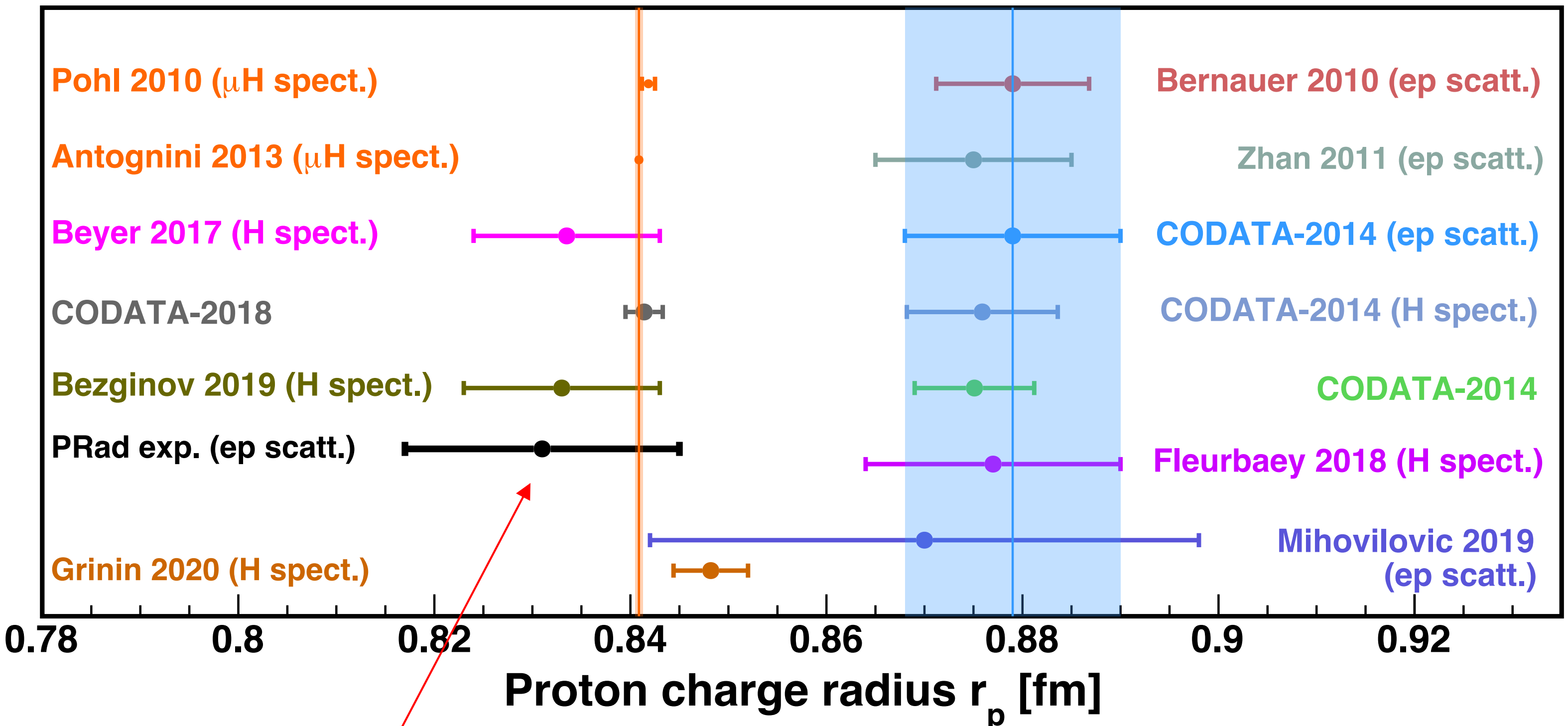
* M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)

The Proton Radius Puzzle before the PRad Publication



Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013, PSI):	0.8409 ± 0.0004 fm
Regular H-spectr. (2S ➔ 4P, Garching, PSI):	0.8335 ± 0.0095 fm
Regular H-spectr. (1S ➔ 3S, LKB, Paris):	0.877 ± 0.013 fm
Regular H-spectr. ($2S_{1/2}$ ➔ $2P_{1/2}$, York Un. Canada)	0.833 ± 0.010 fm

The PRad Final Result on the Radius



PRad final result: $R_p = 0.831 \pm 0.007 \text{ (stat.)} \pm 0.012 \text{ (syst.) fm}$

published in: Nature 575, 145–150 (2019)

PRad-I Results on the Form Factor (G_E^p) at Small Q^2 Range

- There is certain discrepancy between two very recent Form Factor precision measurements:
  PRad-I and A1 MAMI at Mainz.

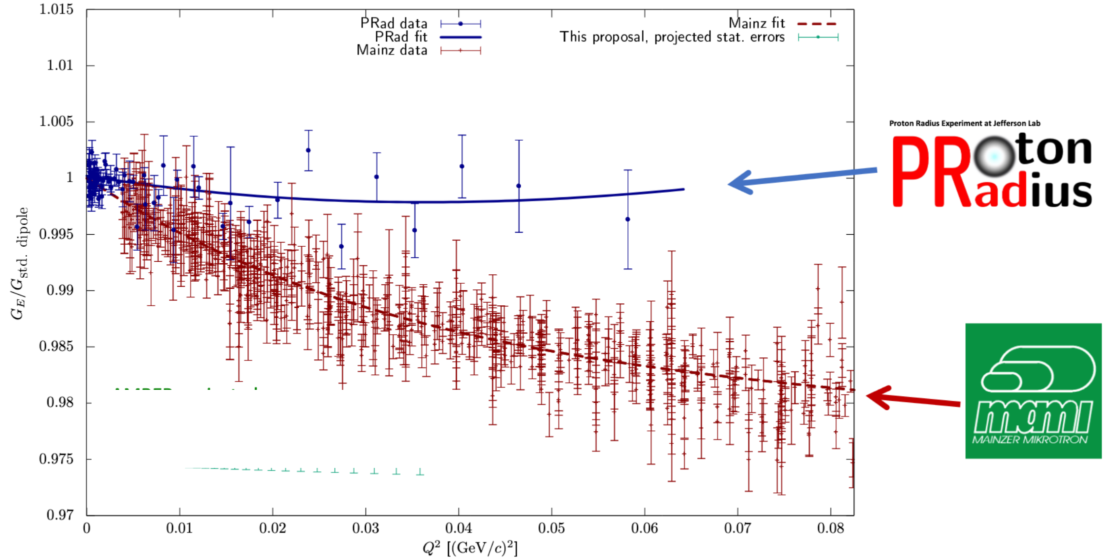


figure: J. Bernauer

- New high accuracy ep-scattering measurements are needed to address these differences.

PRad-II: Design Goals

1) Prad-II experiment (E12-20-004) was approved by PAC48 with an “A” rating to:

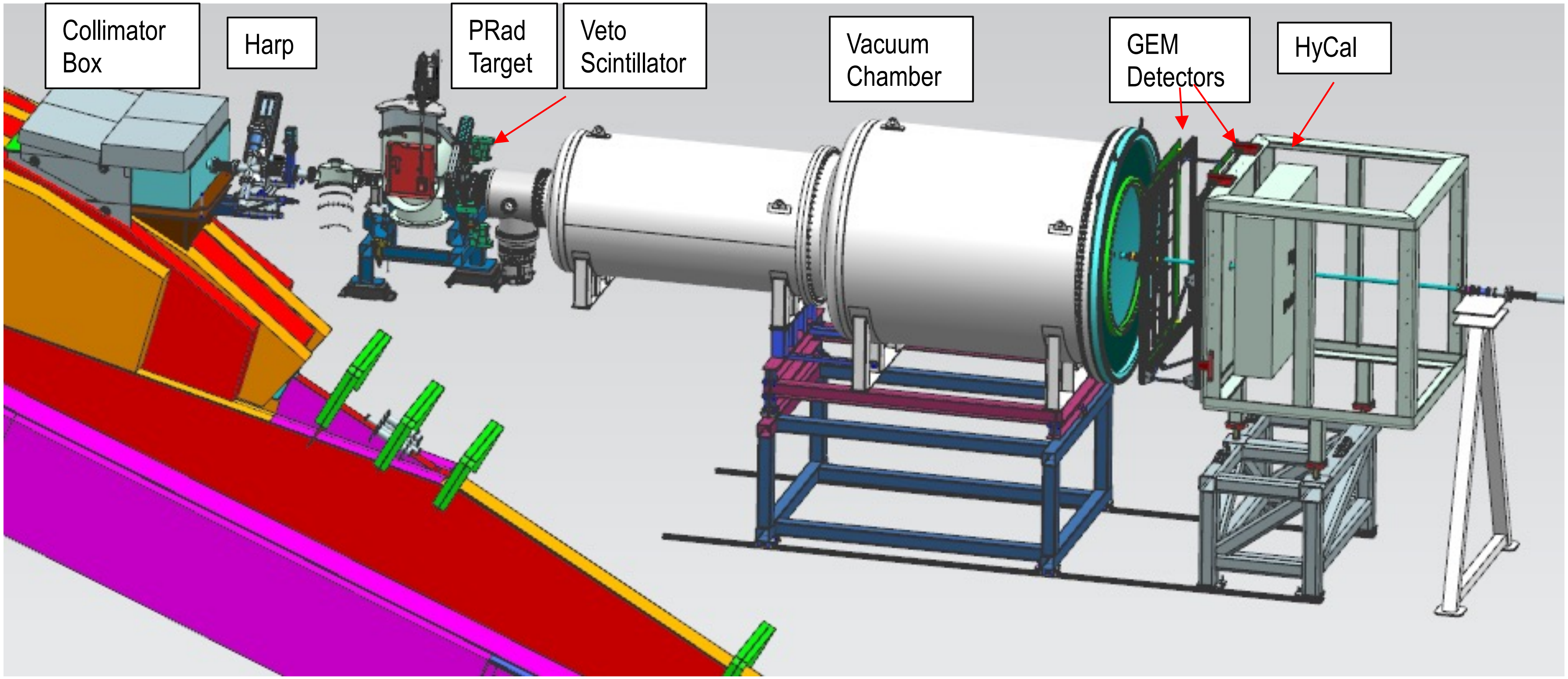
   a) remeasure the proton electric form factor with high accuracy at very low Q^2 range;
   b) address the existing differences between the PRad and all modern ep-experiments;
   c) extract the proton charge radius with a factor of 3 better than PRad;
   d) reach the $Q^2 \sim 10^{-5}$ Gev^2 range, for the first time in ep-experiments.

2) With an improved experimental setup:

   a) tracking capabilities (important for the background subtraction);
   b) new fADC based DAQ;
   c) veto counters to reach the smallest Q^2 range $Q^2 \sim 10^{-5}$ Gev^2;
   d) improved beamline (less beamline background);
   e) more statistics.

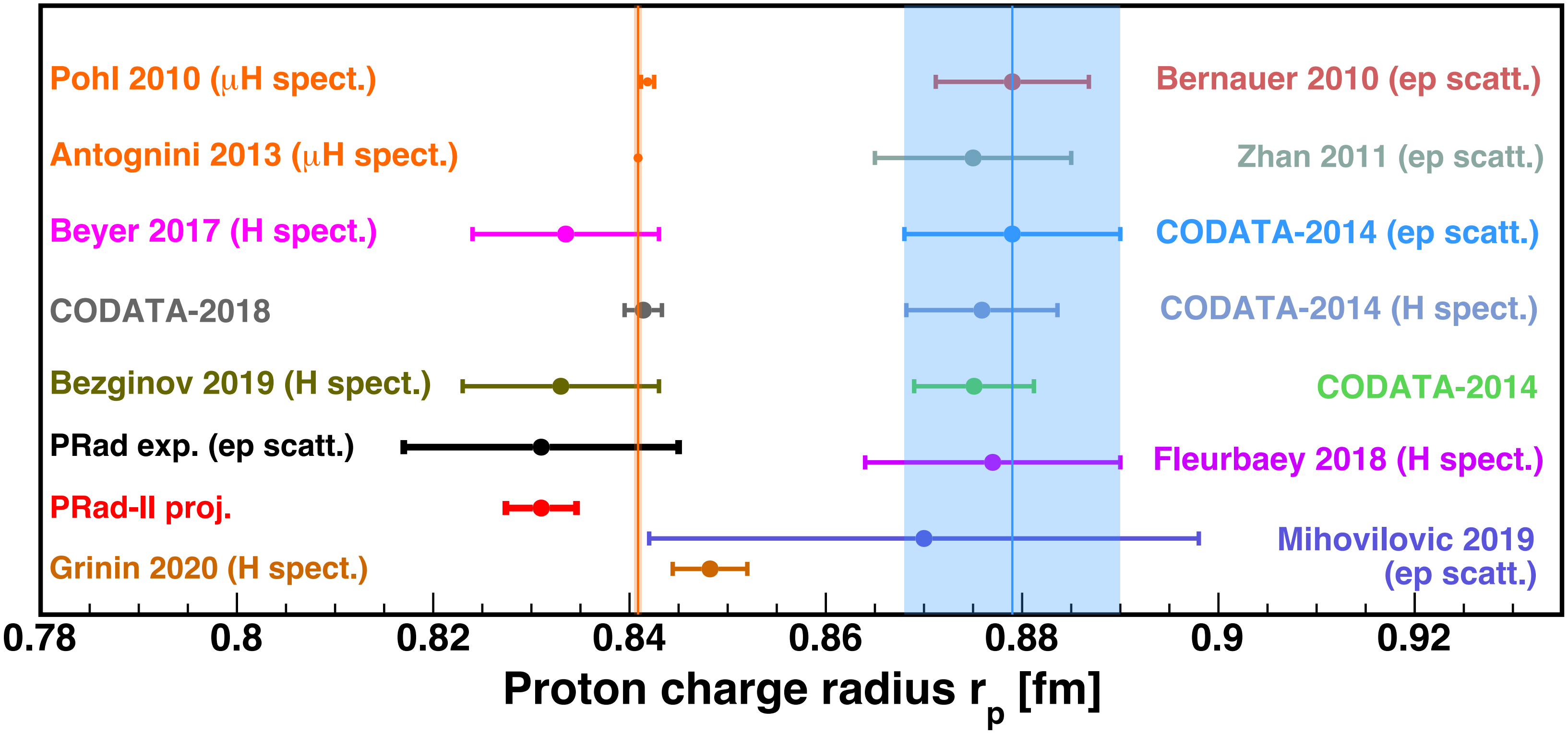
New PRad-II Experiment (E12-20-004)

- Significantly improved statistics (4 times less statistical uncertainties)
- Upgrade PRad experimental setup (improving the systematics):
  - adding full tracking capability (second plane of GEM detectors)
  - upgrade DAQ electronics to fADC based system (new trigger and fast readout)
  - small-size scintillator detectors downstream the target to veto Moller electrons to reach the 10^{-5} GeV^2 Q^2 range
  - adding new "beam halo blacker" just before the Tagger for less beam background
  - use the $PbWO_4$ crystal part only (high energy and position resolutions)



PRad-II: Projected Result on Radius

- Approved by JLab's PAC-48 in August, 2020
- Projected total uncertainty on radius: 0.43%



PRad-II: Improvements on the G^p_E Form Factor Measurement

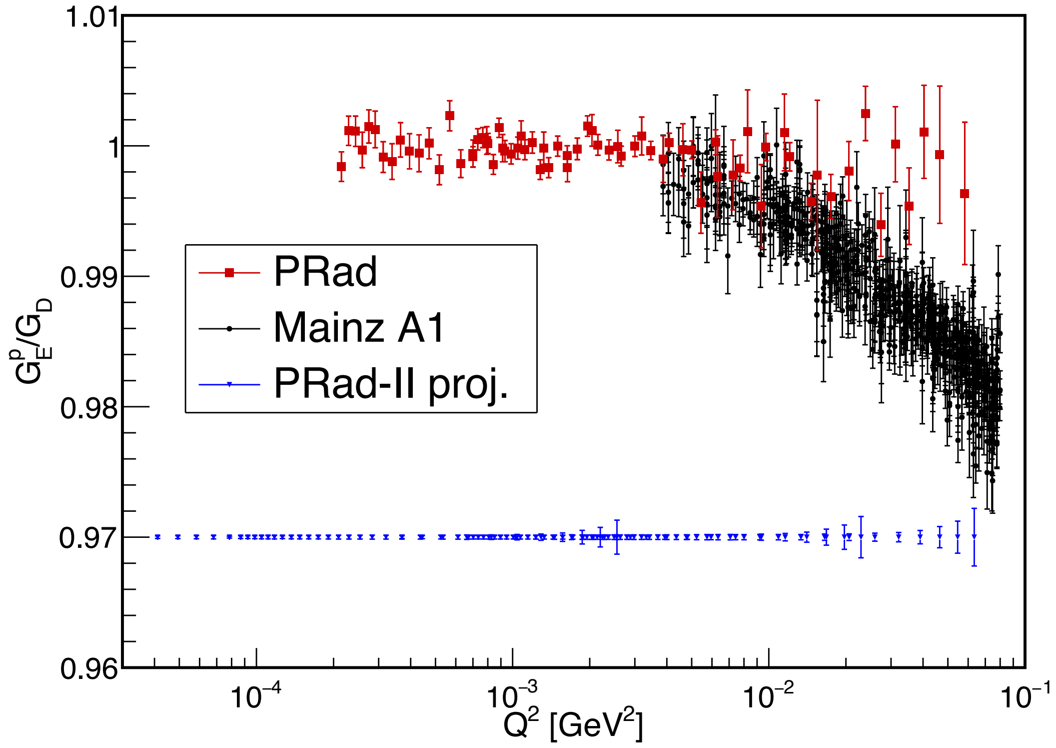
- To address the differences between A1 MAMI, Mainz (2010) and PRad, JLab (2019) results.

- statistical uncertainties only, with:

  - ✓ 6 days with 0.7 GeV, 20nA
  - ✓ 6 days with 2.1 GeV 150nA
  - ✓ 12 days with 3.5 GeV, 150nA

- Total beam time: 40 PAC days

- $PbWO_4$ part of HyCal will be used.



Current Status of the PRad-II Experiment in Hall B at JLab

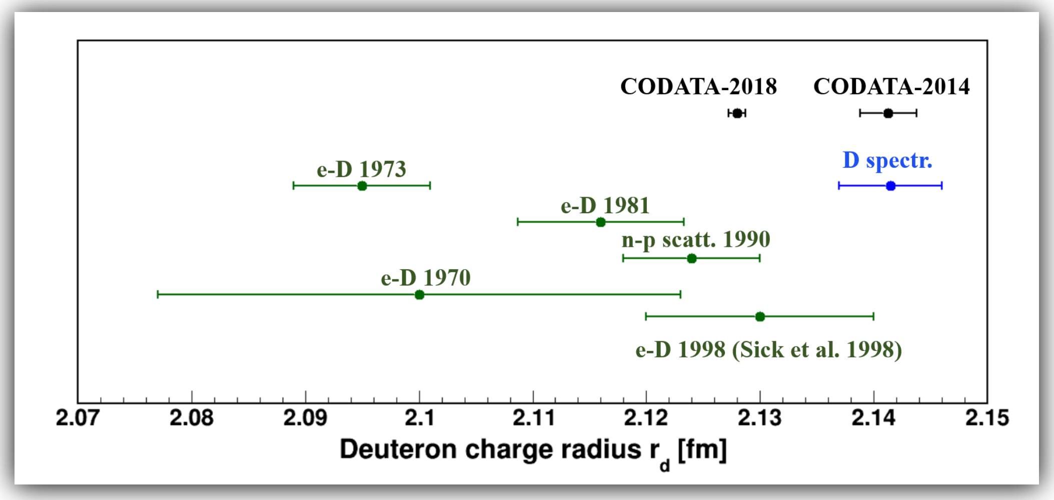
- ✓ All engineering design work (beam line elements, target and detector support systems) is completed.
- ✓ Most of mechanical parts are on site and ready for the beam line installation.
- ✓ Refurbishment and testing of $PbWO_4$ is completed, ready for the experiment.
- ✓ Construction of 4 GEM detectors is on track (UVa group), ready in September.
- ✓ New DAQ electronics (based on fADC-250) are onsite, ready for the experiment.
- ✓ The first Experimental Readiness Review (ERR) passed in May, working on recommendations.
- ✓ Beamline installation is planned to start from September.
- ✓ Experiment is scheduled to run from February to August 2026

Our Plans to Measure the Deuteron Charge Radius (DRad Proposal)

(current experimental data on eD-scattering experiments)

- Some data over 50 years old with: large uncertainties

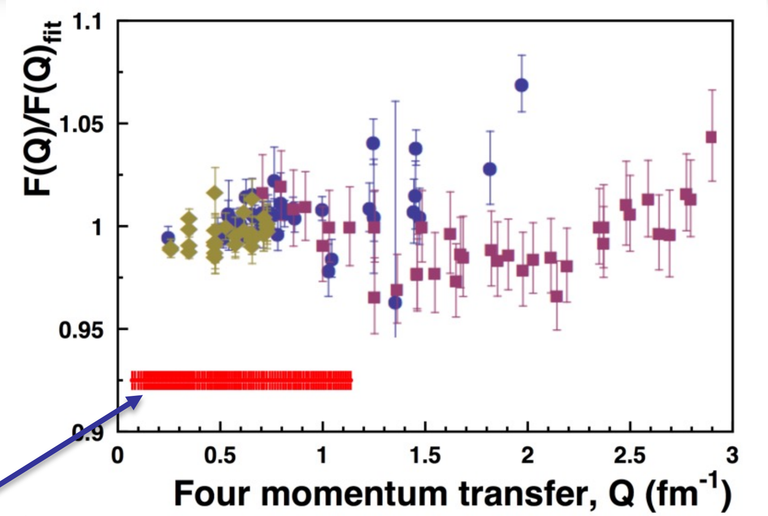
✓ all used magnetic spectrometer method
✓ normalized eD to ep-cross section
✓ large background from target windows
✓ Most recent result (I. Sick, 1998) is a reanalysis of old data.



R.W. Berard et al. PLB 47,355, (1973)
cooled H_2 and D_2 gas measured ratio of eD/ep cross section; Q = [0.2 – 0.7] fm^{-1}

G.G. Simon et al. NPA 364, 285 (1981)
gas and liquid targets; Q = [0.2 – 2.0] fm-1

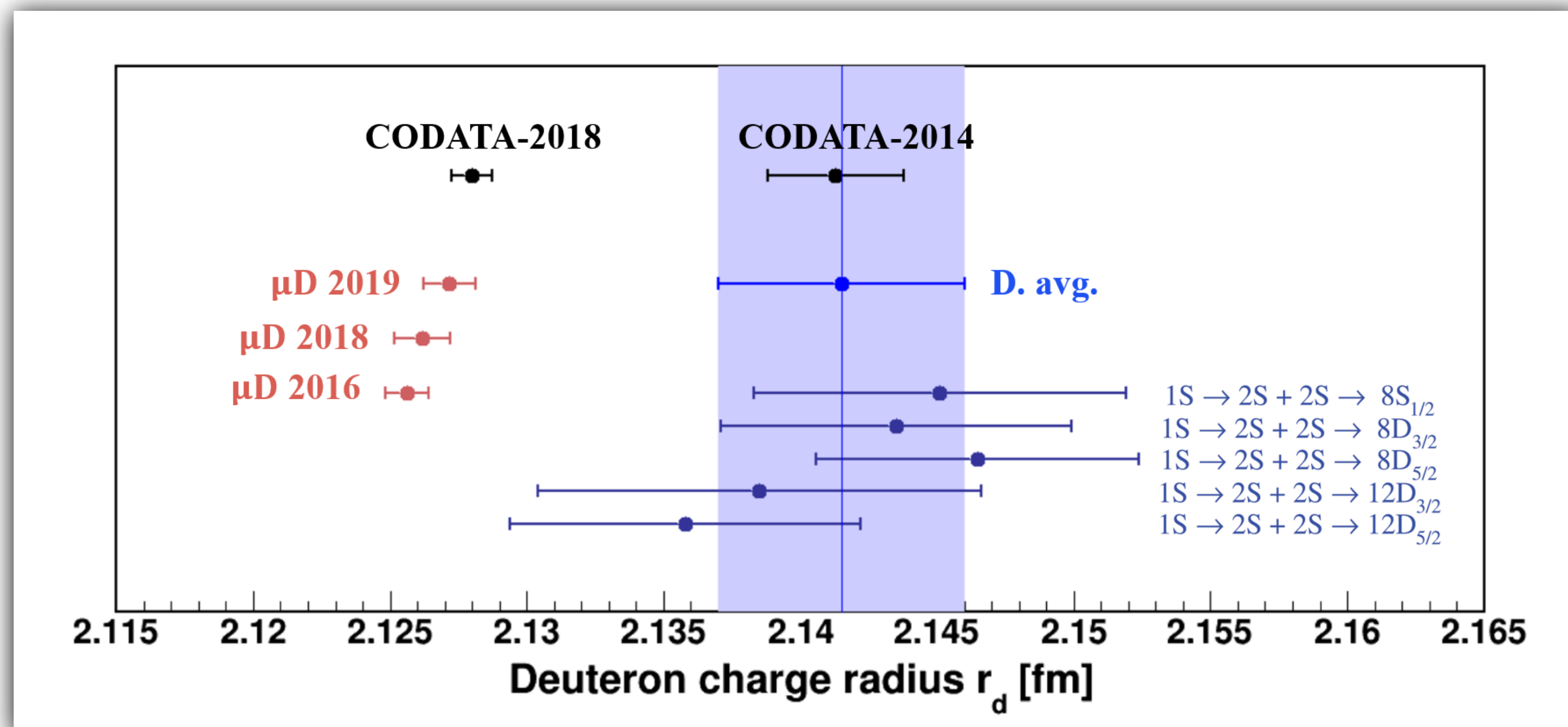
S. Platchkov, et al. NPA 510, 740 (1990)
LH2 and LD2 targets; Q = [0.7 – 4.5] fm^{-1}



Q^2 range of proposed experiment

The "Deuteron Charge Radius Puzzle" Started in 2016

- a $\sim 6\,\sigma$ discrepance between r_D from ordinary D and μD spectroscopy was observed a few years after the "proton radius puzzle" came to the fore.



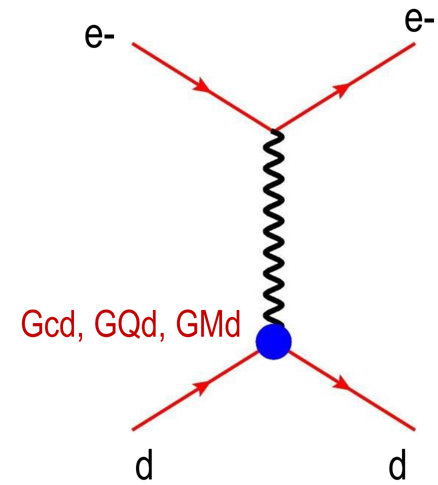
Deuteron Charge Radius from Elastic e-D Scattering at Low Q^2 Range

- In the limit of first Born approximation, elastic e-D scattering is expressed in terms of the $A(Q^2)$ and $B(Q^2)$ form factors:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{NS}[A(Q^2) + B(Q^2)\tan^2\theta/2]$$

- $A(Q^2)$ and $B(Q^2)$ are related to deuteron charge (G_{Cd}), electric quadrupole (G_{Qd}), and magnetic dipole (G_{Md}) form factors:

$$\begin{aligned} A(Q^2) &= G_{Cd}^2(Q^2) + \frac{2}{3}\eta G_{Md}^2(Q^2) + \frac{8}{9}\eta^2 G_{Qd}^2(Q^2) \\ B(Q^2) &= \frac{4}{3}\eta(1+\eta)G_{Md}^2(Q^2), \end{aligned}$$



with:

$$\eta = Q^2/4m_d^2$$

- At low Q^2 contribution from G_{Qd} and G_{Md} are small, and the deuteron rms charge radius is defined as:

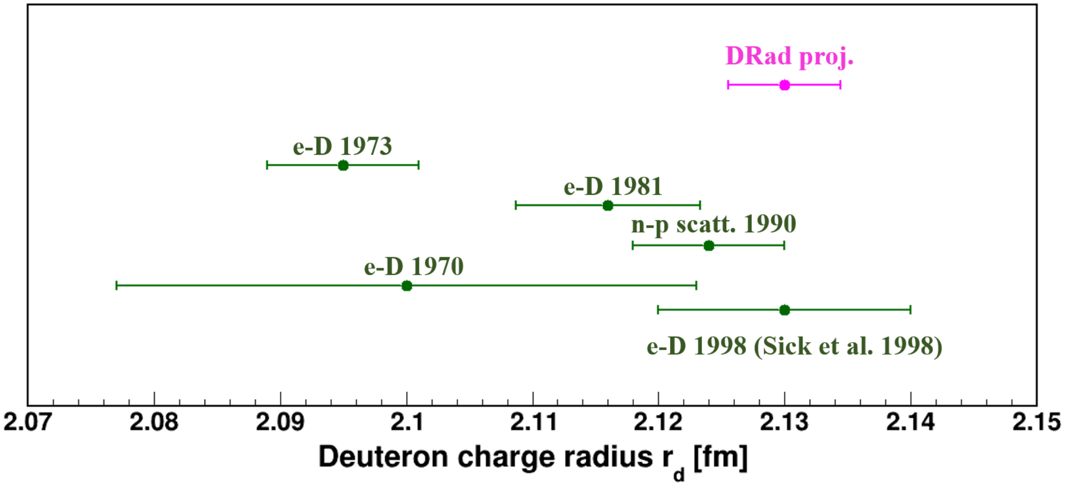
$$r_d^2 = -6\left[\frac{dA(Q^2)}{dQ^2}\right]_{Q^2=0}$$

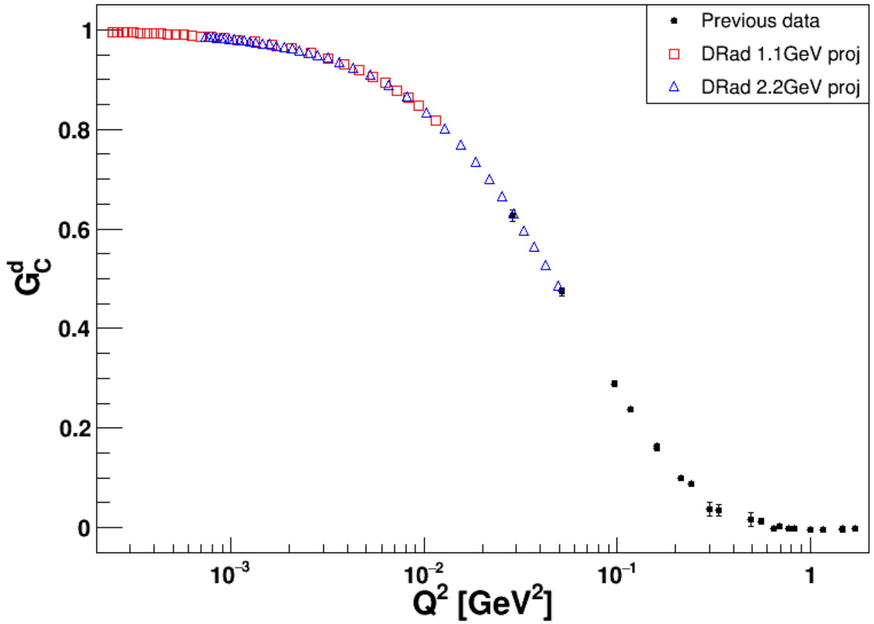
The Proposed DRad Experiment (JLab proposal PR12-23-011)

- The PRad calorimetric method will be used to measure the Deuteron charge radius (r_D) with a precision of 0.21%

- The Q^2 range of $2x10^{-4}$ to $5x10^{-2}$ GeV^2 will be covered, probing the lowest Q^2 range reached in e-D scattering experiments.

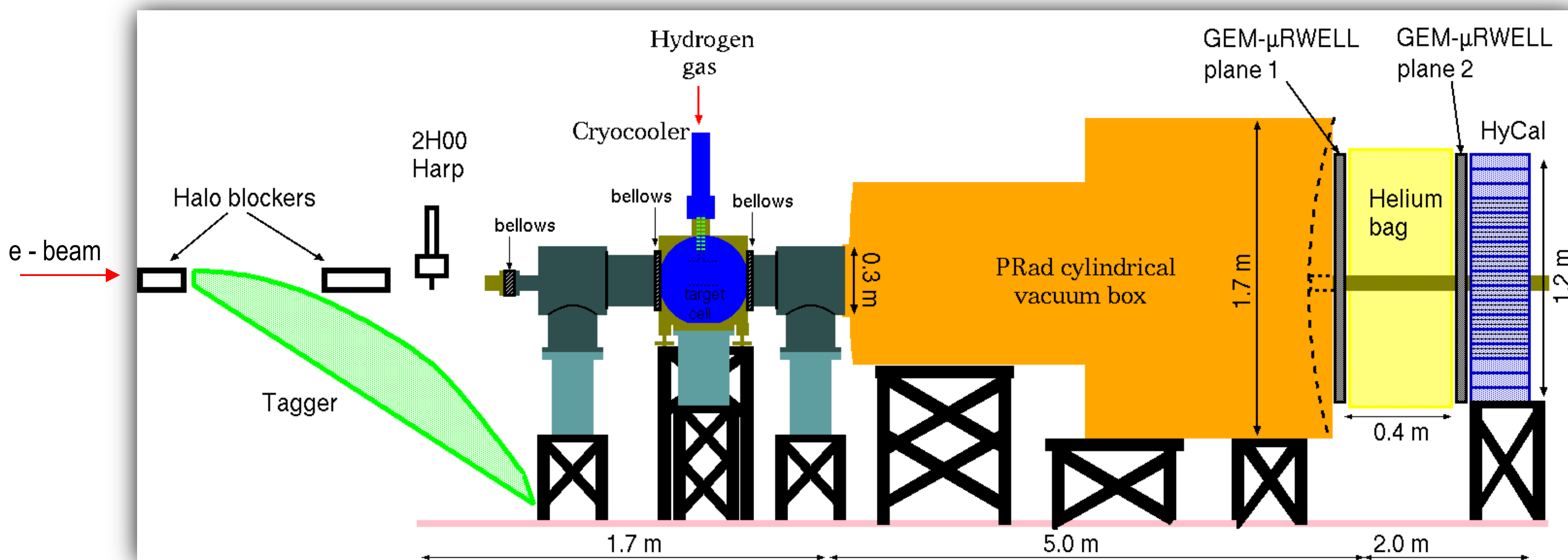
- The PRad-II experimental setup along with a new recoil detector will be used in this experiment.





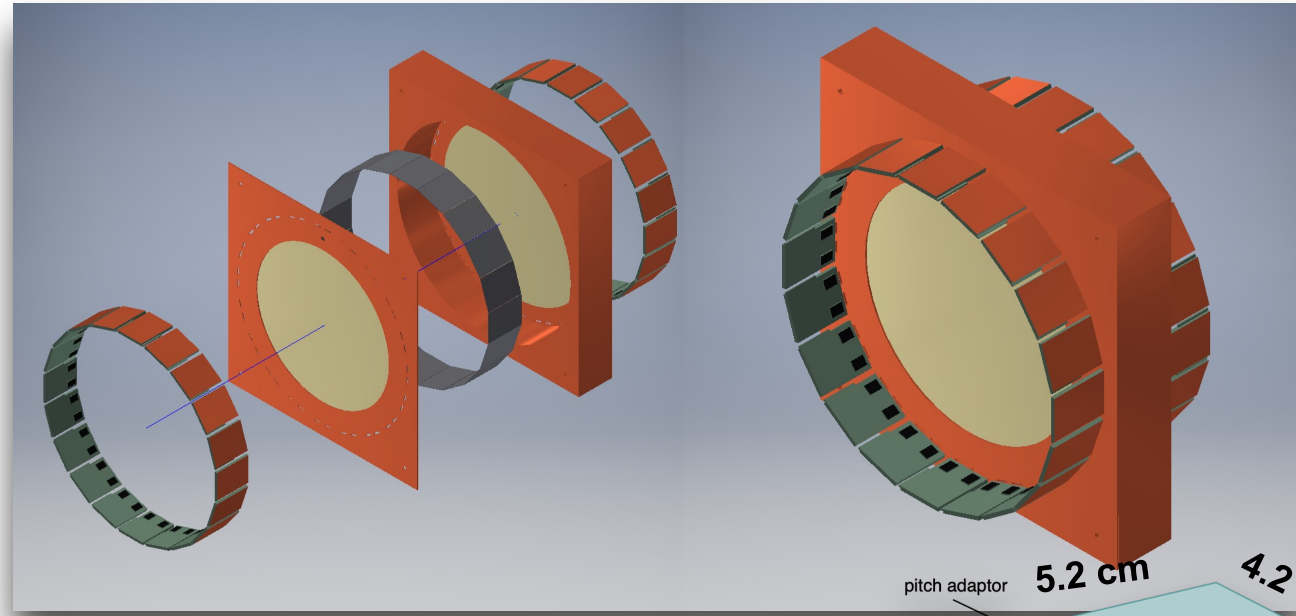
DRad: a Novel Electron-Deuteron Scattering Experiment

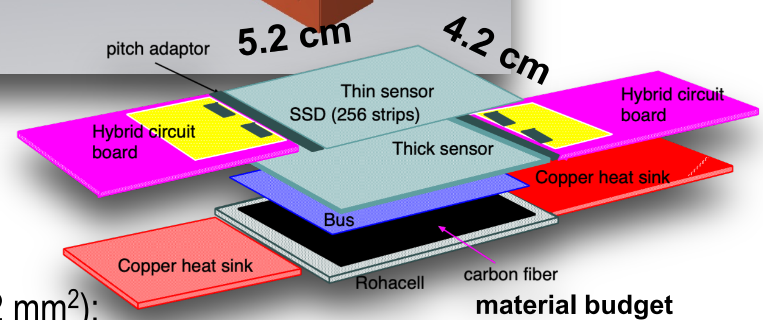
- Conceptual design of the DRad experiment:
  - ✓ PRad experimental approach with;
  - ✓ with the PRad-II experimental setup plus;
  - ✓ cylindrical recoil deuteron detector to ensure the elastic scattering.



DRad: Si-strip Cylindrical Recoil Detector

- The elasticity of e-D scattering will be ensured with a cylindrical Si-strip-based recoil deuteron detector.

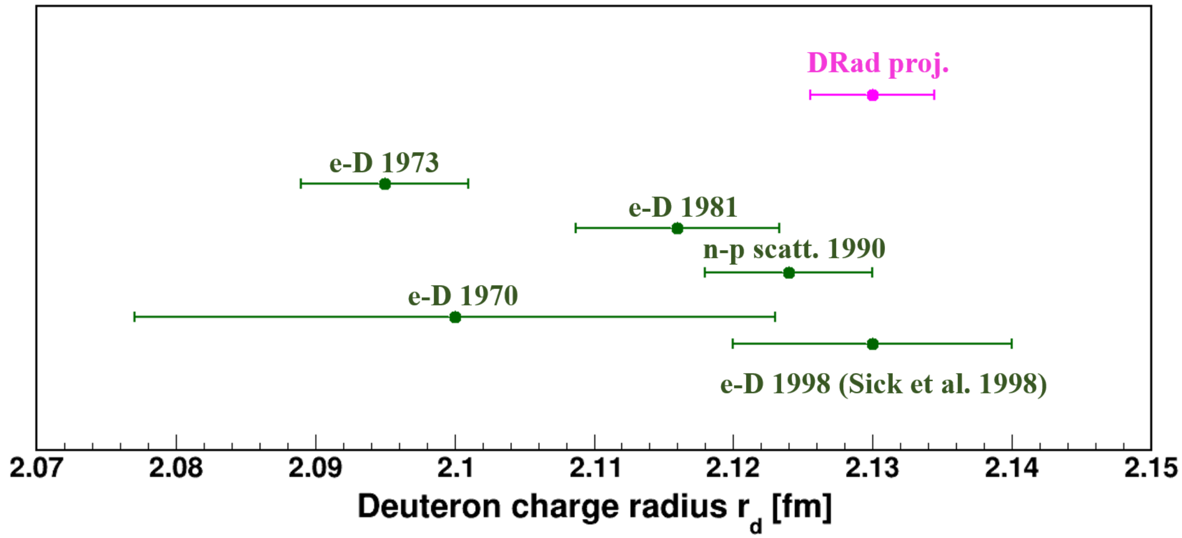


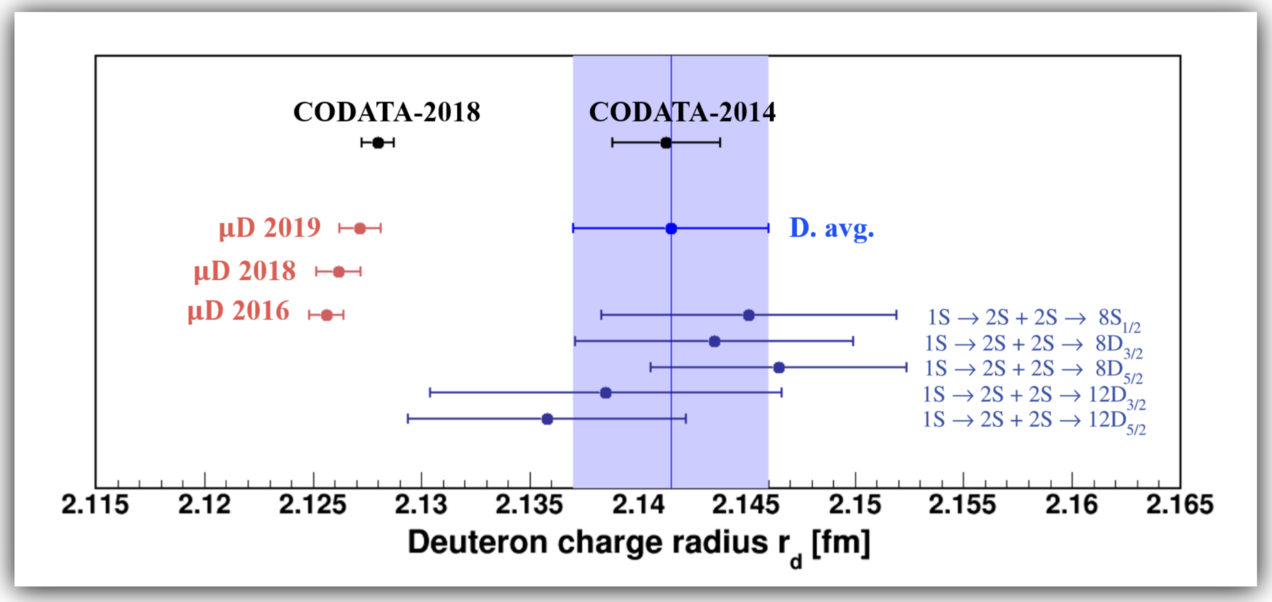


- consists of 20 panels of twin, single-sided Si-strip detectors (size; 42x52 mm^2);
- thickness: inner, ≈ 200 μm, outer ≈ 300 μm (to be optimized);
- dodecagon arrangement with R=13 cm radius;

The DRad Projected Result on r_D

- Beam energies:
  E_e = 1.1 and 2.2 GeV
- Q^2 range coverage:
  $2\times10^{-4} - 5\times10^{-2}$ GeV^2
- Requested beam time:
  40 PAC days
- Estimated total uncertainty on the extracted r_D is 0.21%
  (dominated by the efficiency of the recoil detector, 0.15%).





Summary and Outlook

1) The PRad-II experiment (E12-20-004) was approved by PAC48 with an “A” rating to:

   a) remeasure the proton electric form factor with high accuracy at very low Q^2 range;
   b) address the existing differences between the PRad and all modern ep-experiments;
   c) extract the proton charge radius with a factor of 3 better than PRad;
   d) reach the $Q^2 \sim 10^{-5}$ Gev^2 range, for the first time in ep-experiments.

PRad-II is scheduled to run from February 2026 in Hall B at JLab.
(beamline installation will start from this September).

2) We proposed a new high accuracy measurement of the deuteron charge radius (r_D) from elastic e-D scattering (DRad).

   a) will use the same PRad-II experimental setup, plus
   b) cylindrical Si-strip-based recoil detector, that will provide
   c) 0.21% precision in the extracted r_D

We plan to resubmit an updated proposal to Jlab’s PAC in the next 2 years
(after the PRad-II experiment.

my research work is supported in part by NSF award: PHY-1812421

Thank You

A part of the PRad collaboration in December 2019 at JLab

- Currently over 14 collaborating universities and institutions:

Backup Slides

Recent Lattice Calculation Results (2024)

PHYSICAL REVIEW LETTERS 132, 211901 (2024)

Precision Calculation of the Electromagnetic Radii of the Proton and Neutron from Lattice QCD

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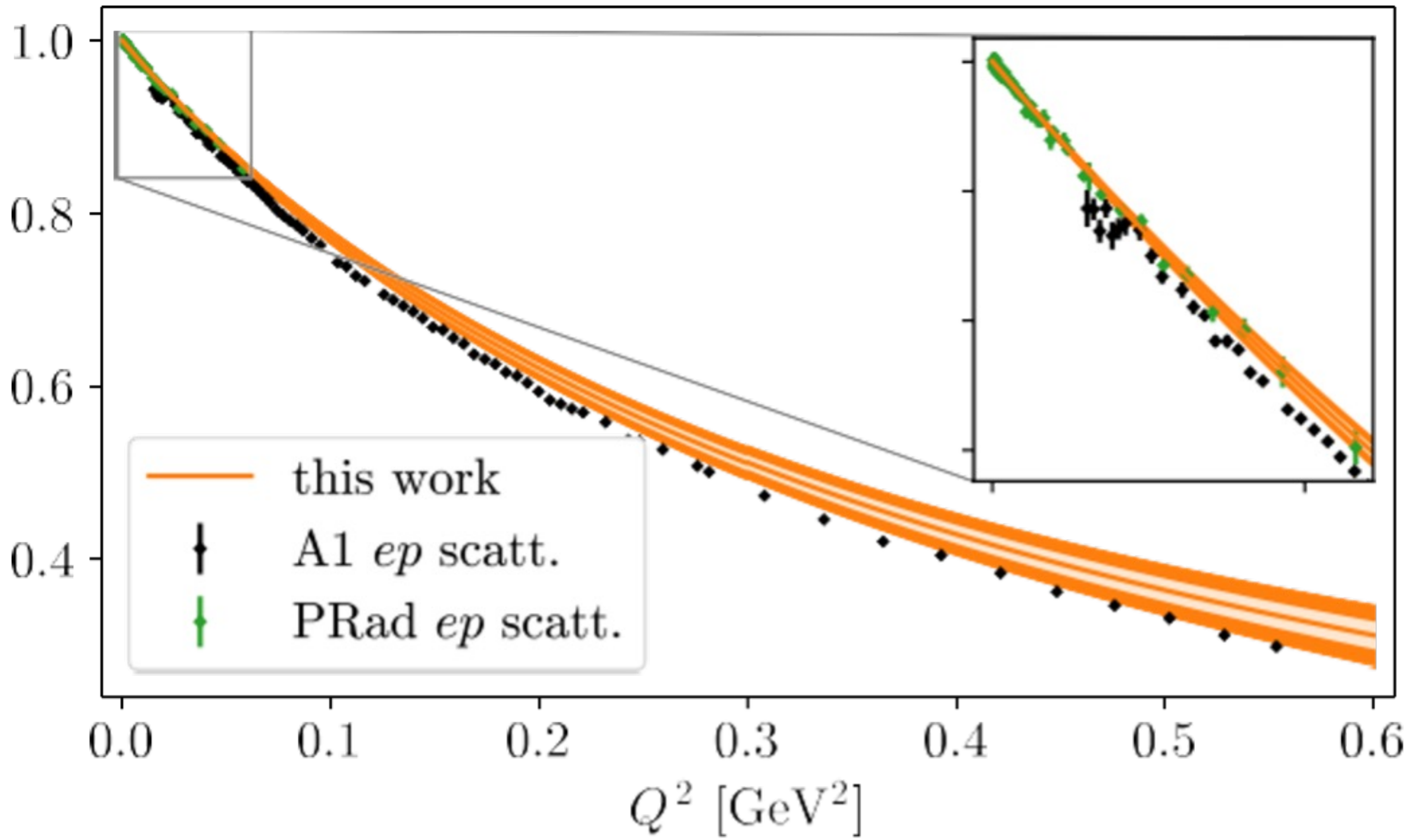
(Received 20 September 2023; accepted 17 April 2024; published 22 May 2024)

We present lattice-QCD results for the electromagnetic form factors of the proton and neutron including both quark-connected and -disconnected contributions. The parametrization of the Q^2 dependence of the form factors is combined with the extrapolation to the physical point. In this way, we determine the Electric and magnetic radii and the magnetic moments of the proton and neutron.

For the proton, we obtain at
the physical pion mass and in the continuum and infinite-volume limit 0.820.14. fm,

DOI: 10.1103/PhysRevLett.132.211901

Recent Lattice Results on Form Factor



PRad-II: Improvements on Proton Radius Extraction

Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0015
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0025
Beam background	0.0039	0.0014
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p parameterization	0.0006	0.0005
Total syst. uncertainty	0.0115	0.0043
Total uncertainty	0.0137	0.0046