Proton Charge Radius from PRad Experiment at Jefferson Lab

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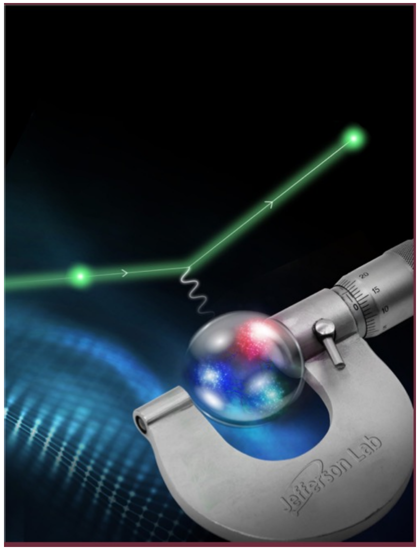
for the PRad collaboration

Outline

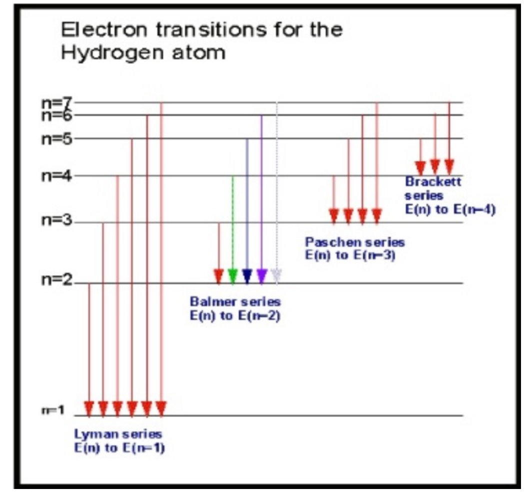
- the PRad approach for a new ep-experiment
- PRad experiment and the results
- new planned experiment, PRad-II
- summary



Proton Charge Radius

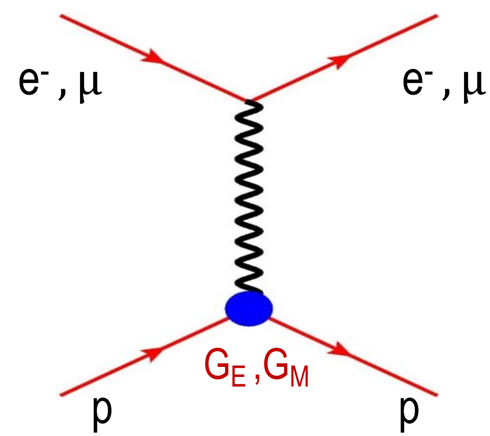
One of the most fundamental quantities in physics:

- atomic physics:
  - ✓ precision atomic spectroscopy (QED, Lamb shifts, Rydberg constant R_∞);
  - ✓ r_p is strongly correlated to R_∞
- nuclear physics:
  - ✓ QCD, test of nuclear/particle models
- connects atomic and subatomic physics.

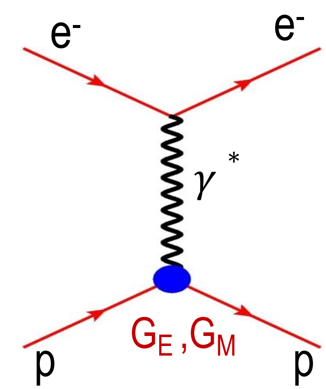


Methods to measure the Proton rms charge radius (r_p):

- Hydrogen spectroscopy (lepton-proton bound state, Atomic Physics):
  - ❖ regular hydrogen
  - ❖ muonic hydrogen
- Lepton-proton elastic scattering (Nuclear Physics):
  - ❖ ep- scattering (like PRad)
  - ❖ μp- scattering (like MUSE)



Proton 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:

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

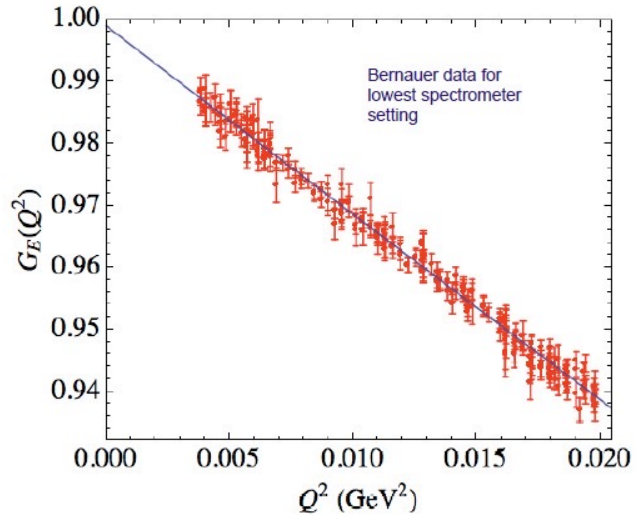
- G_E and G_M can be extracted using Rosenbluth separation
- for extremely low Q^2, the cross section is dominated by G_E
- Taylor expansion of G_E at low Q^2

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

derivative at $Q^2 = 0$:

definition of the proton rms charge radius →

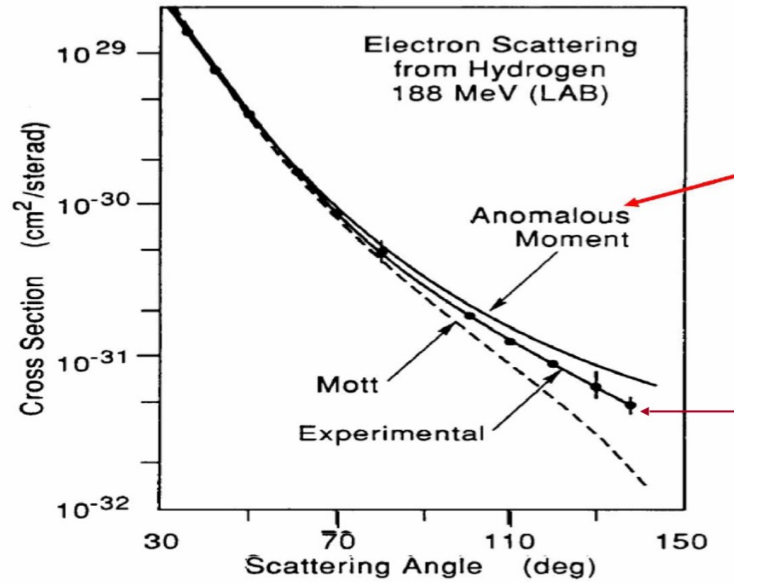
$$\langle r^2\rangle = -6 \left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$



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

First Measurement of the Proton Radius

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

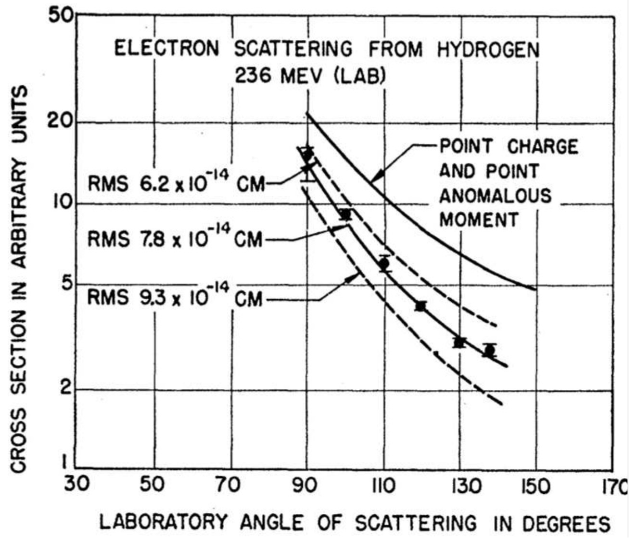


- Nobel prize in 1961:
  "*for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the* ***structure of nucleons***"

"***proton has a diameter of 0.74 ∓ 0.24 x 10^{-13} cm***"

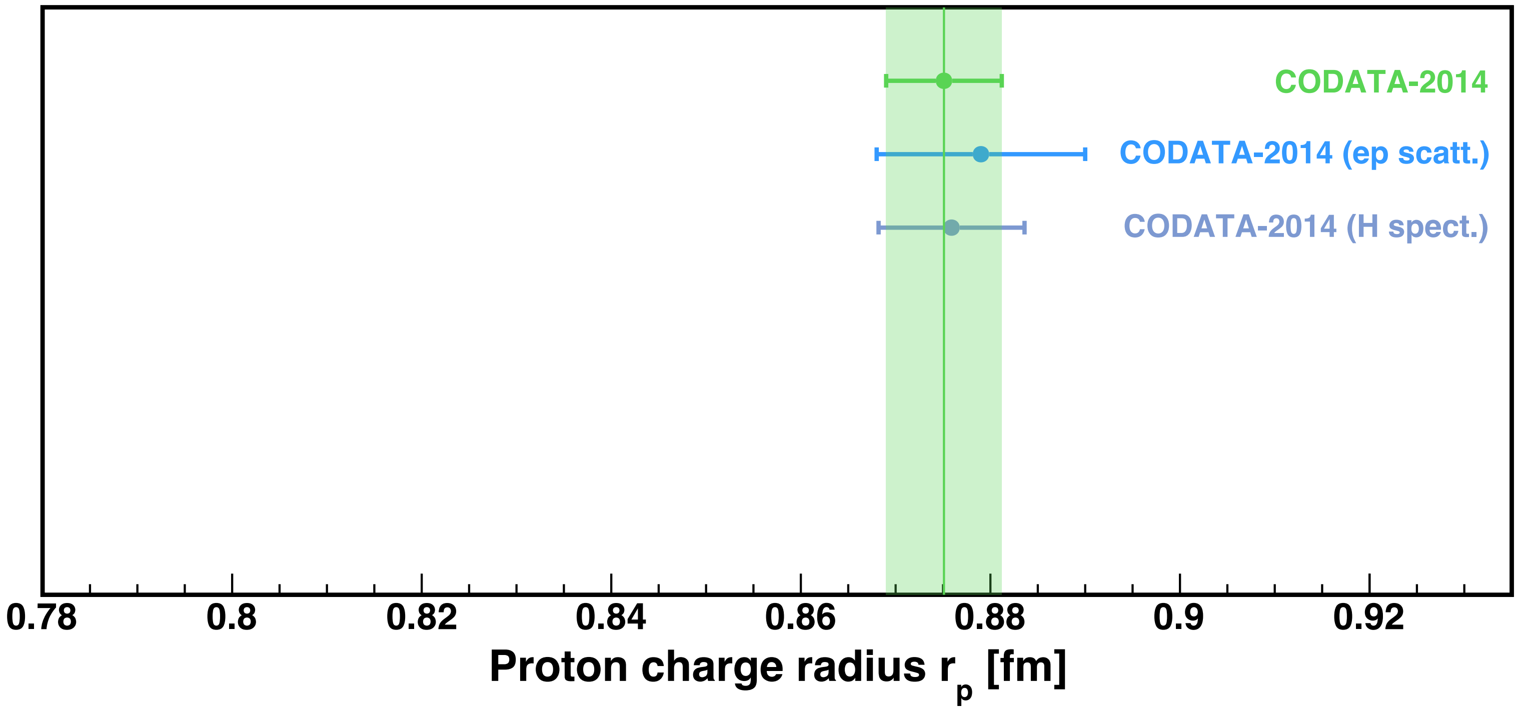
r_p = 0.74 fm   with a 32% uncertainty

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



- Over 50 years of experimentation!
  - ✓ started from 0.74 fm
  - ✓ ended to 0.895 fm by 2010.
  - ✓ where we are now ???

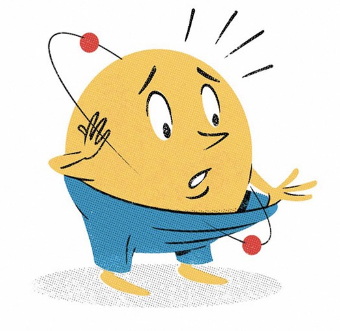
Proton Radius before the Puzzle (2010)

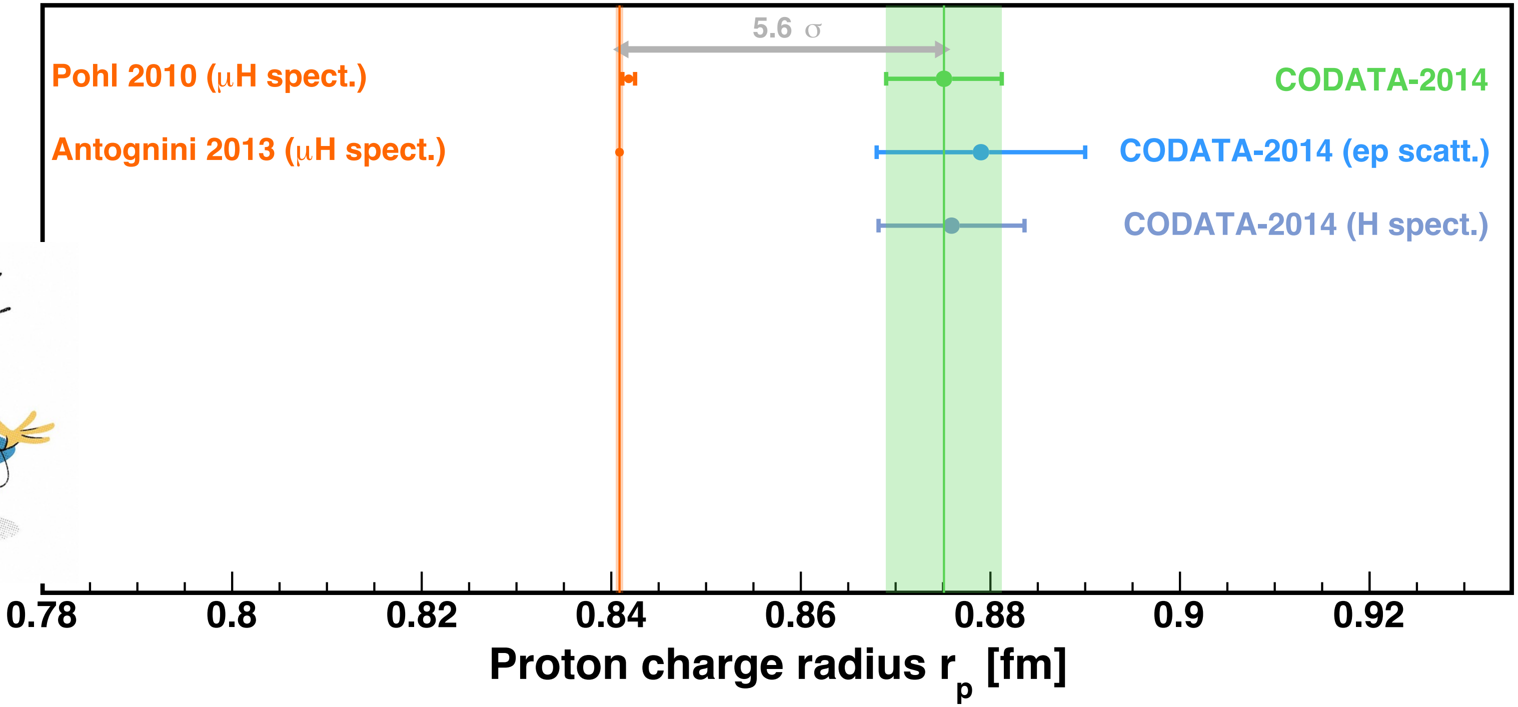


CODATA average:	0.8751 ± 0.0061 fm
ep-scattering average (CODATA):	0.879 ± 0.011 fm
Regular H-spectroscopy average (CODATA):	0.859 ± 0.0077 fm

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

The Proton Radius Puzzle before the PRad Experiment (2016)





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

Possible Resolutions to the *Proton Radius Puzzle*

- Some initial open questions about QED calculations:
  - additional corrections to muonic-hydrogen. — Not found
  - missing contributions to electronic-hydrogen. — Not found
  - higher moments in electric form factor; — Not significant
  - …
- Is the ep-interaction the same as μp-interaction (the lepton universality principle)?
- New Physics (forces) beyond the Standard Model? — Not found yet
  - ✓ many models, discussions, suggestions …
- Potential solutions:
  - need new high precision, high accuracy experiments:
    - ✓ ep-scattering experiments:
      - reaching extremely low Q^2 range (10^{-4} Gev/c^2)
      - possibly with new independent methods — PRad at JLab
      - measure absolute cross sections in ONE experimental setting!
      - MUSE at PSI, ISR at Mainz, ULQ^2 in Japan, AMBER at CERN …
    - ✓ ordinary hydrogen spectroscopy experiments:
      - York University in Canada, LKB in Paris, France, CREMA in Germany …

Planning a New ep→ep Scattering Experiment

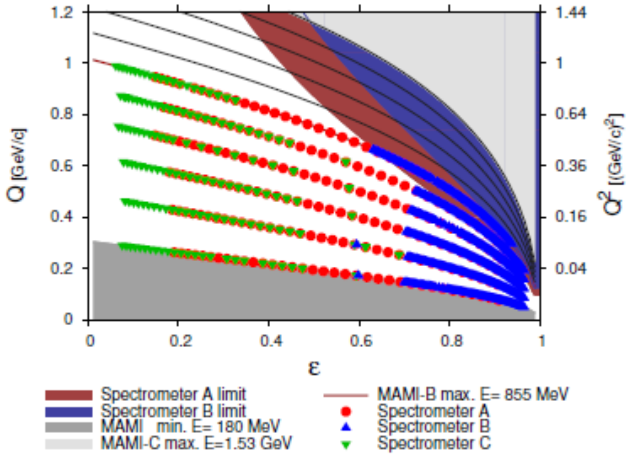
- Practically all ep-scattering experiments were performed with magnetic spectrometers and LH_2 targets!

  - ✓ 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 ($d\sigma/d\Omega$): ~ 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:



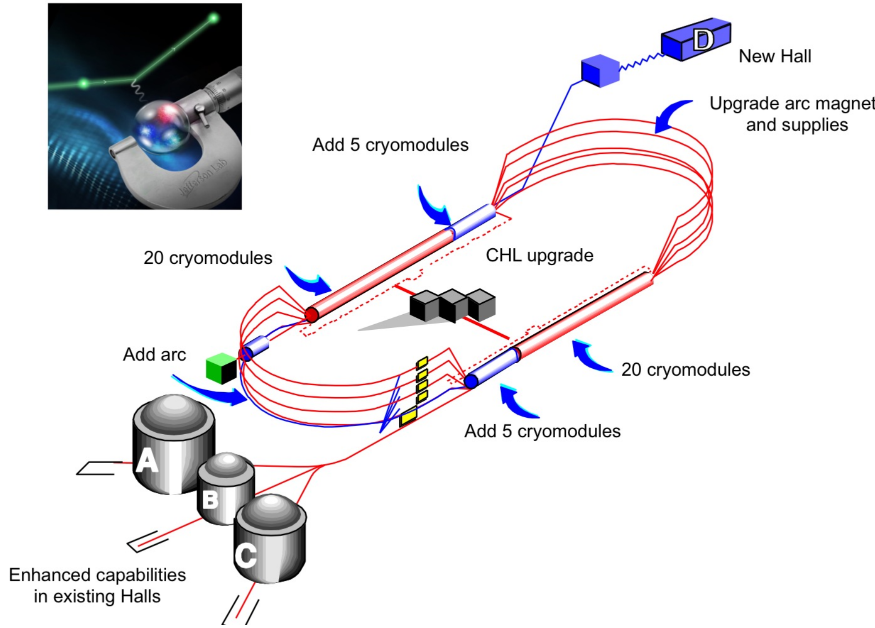
A Possible Solution: the PRad Experimental Approach

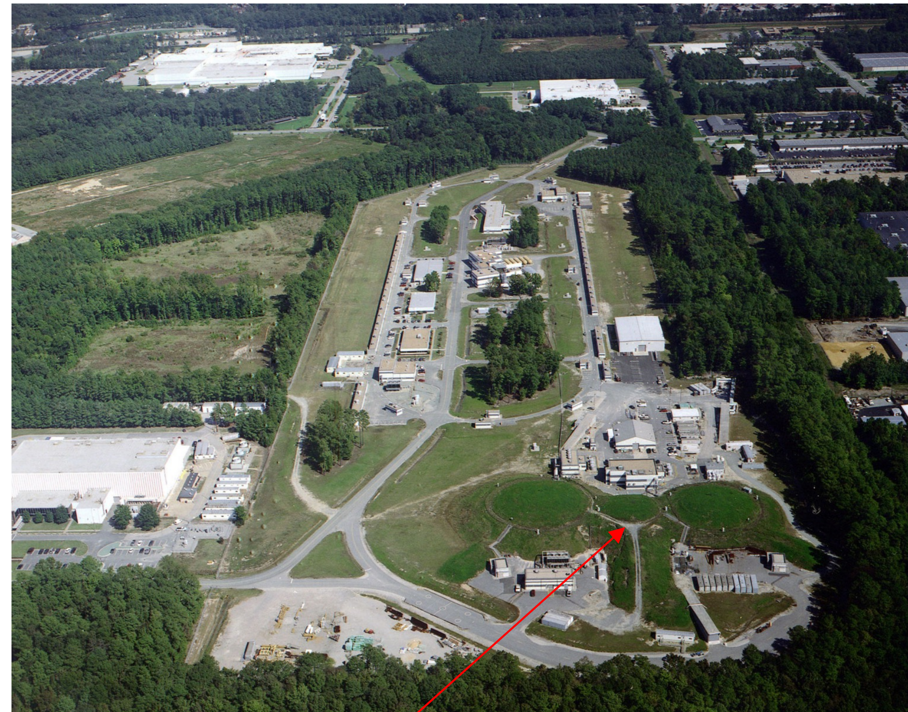
- Use large acceptance, high resolution electromagnetic calorimeter (together with a GEM coordinate detector):
  - ✓ measure all angles in one experimental setting ($\vartheta_e = 0.6^0 - 7.0^0$)
    ($Q^2 = 2x10^{-4} \div 6x10^{-2}$) GeV/$c^2$;
  - ✓ access to smaller angles ($\vartheta_e \approx 0.6^0$)
  - ✓ calibrate with a well-known QED process: azimuthal symmetry of the calorimeter, simultaneous detection of ee → ee Moller scattering (best known control of systematics).
- Use windowless H_2 gas flow target:
  - ✓ minimize experimental background.
- Use two beam energies only: E_0 = 1.1 GeV and 2.2 GeV to check the consistency of experimental data.

PRad Experiment Timeline

✓ Initial proposal development:	2011-12
✓ Approved by JLab PAC39:	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



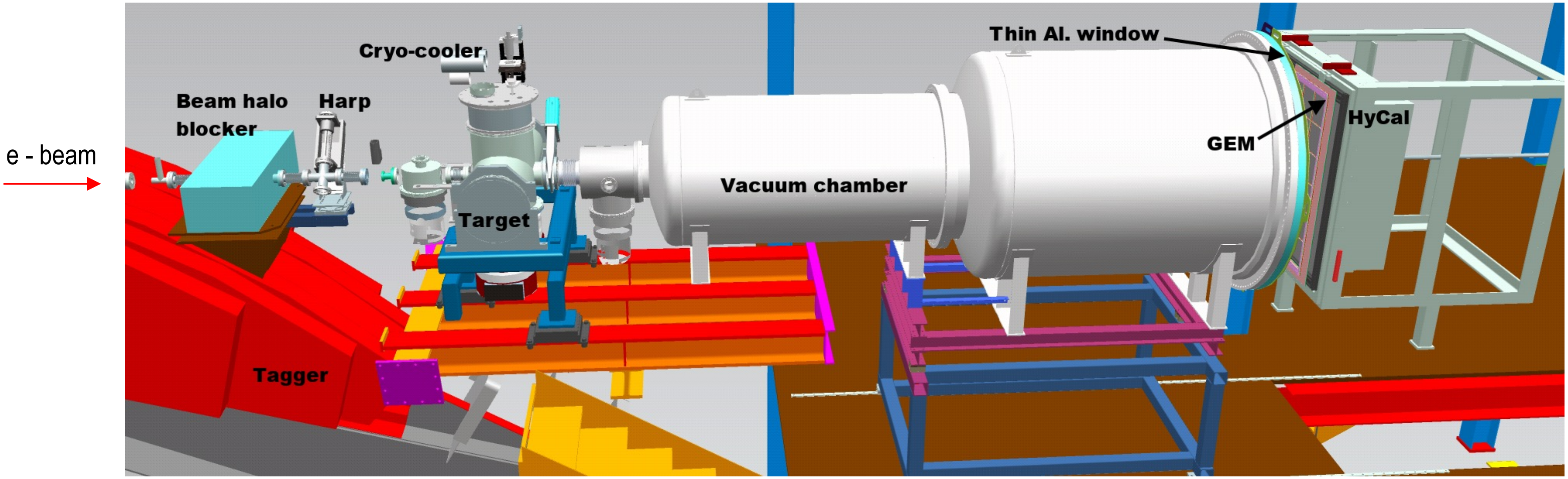


PRad was performed in Hall B at JLab
in January – June of 2016

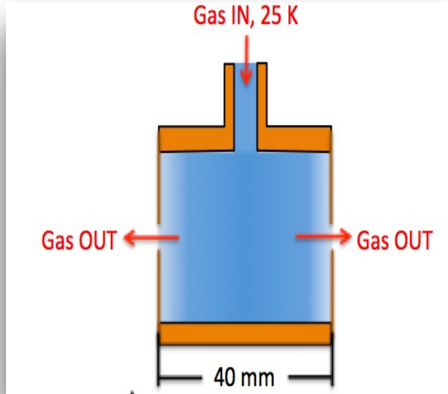
PRad Experimental Setup in Hall B at JLab (schematics)

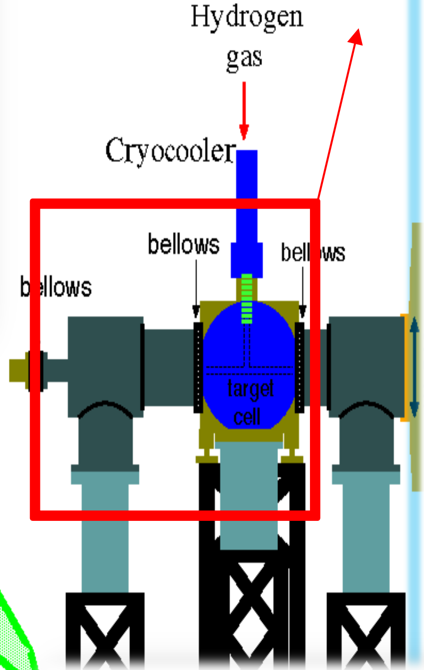
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- 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

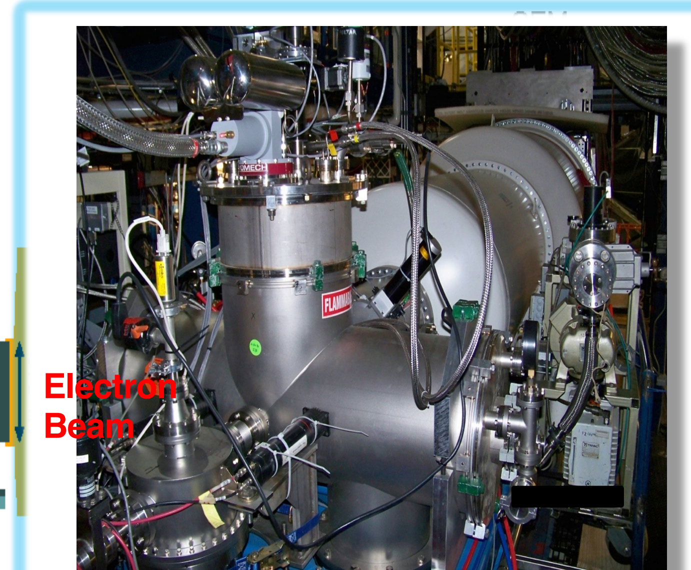


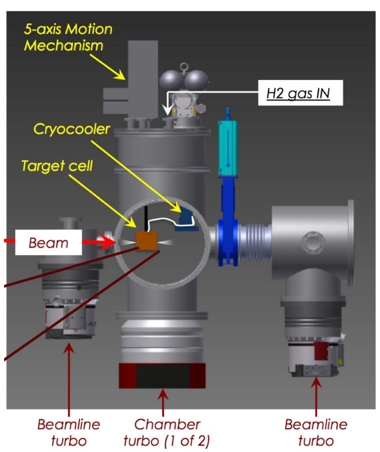
Windowless Hydrogen Gas Flow Target





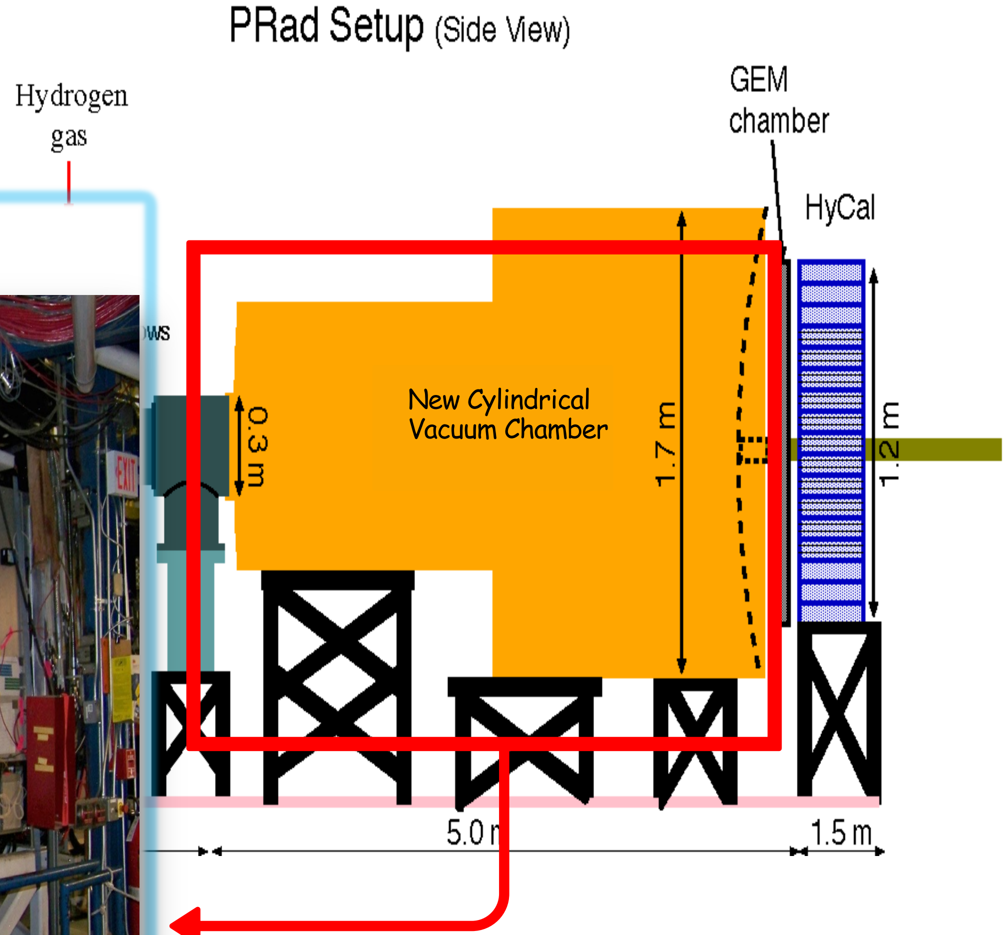
PRad Setup (Side View)





- 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: $1.8\times10^{+18}$ 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

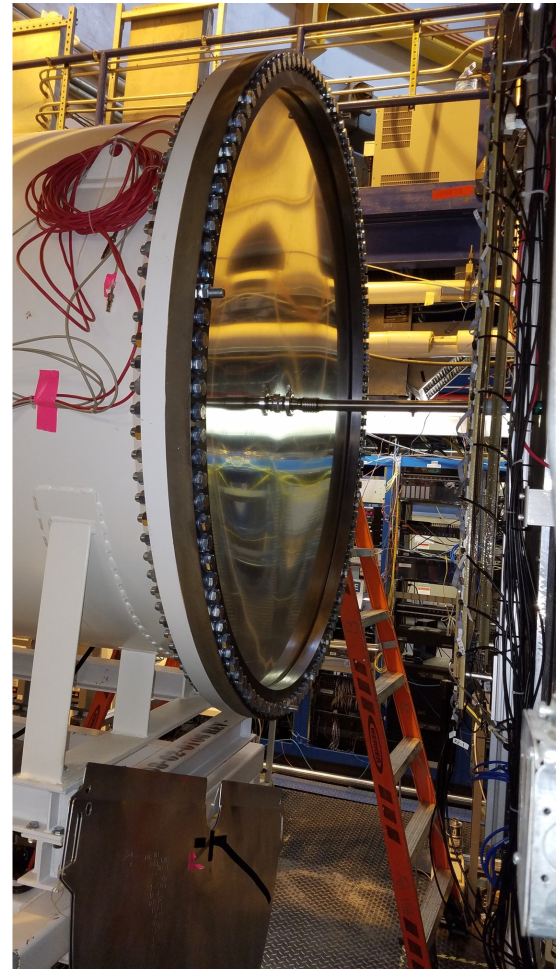
PRad Experimental Apparatus: Vacuum Chamber



- 5 m long two stages vacuum chamber, 1.7 m diameter, 2 mm Al vacuum window vacuum chamber pressure: 0.3 mTorr

PRad Experimental Apparatus: Vacuum Chamber and Window

2-stage vacuum box in Hall B beam line

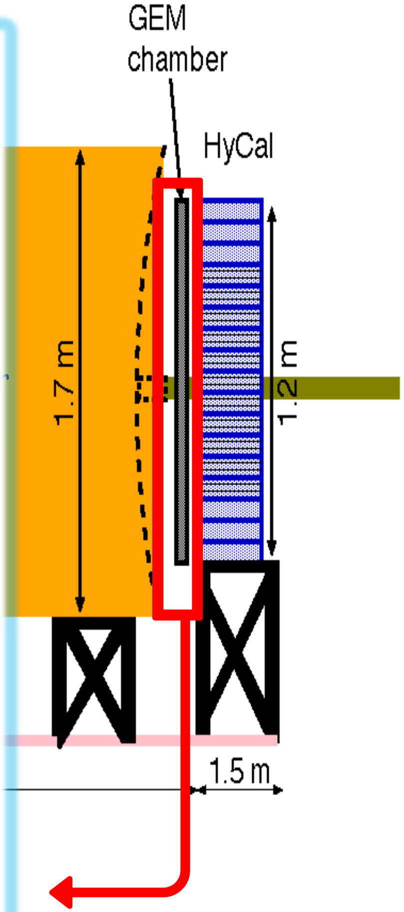


1.7 m diameter, 2 mm Al vacuum window

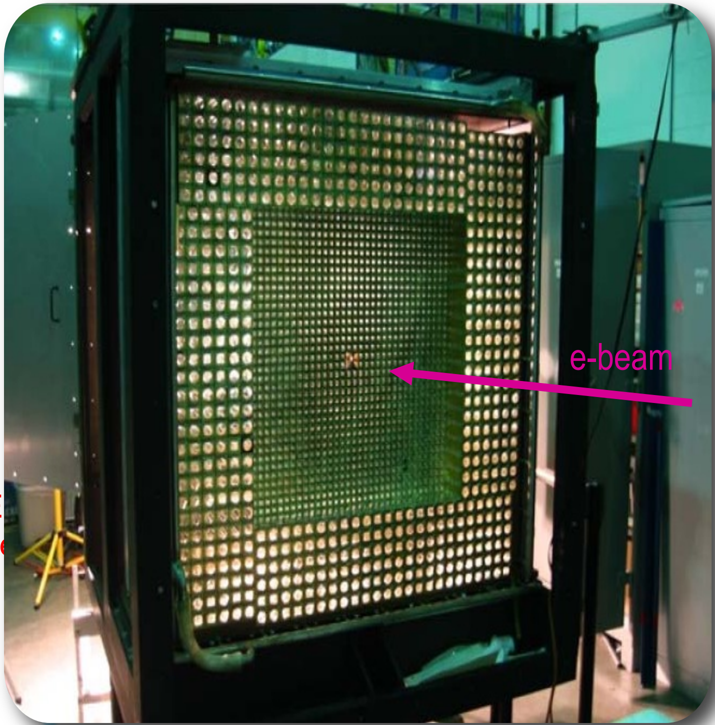
PRad Experimental Apparatus: GEM Coordinate Detectors

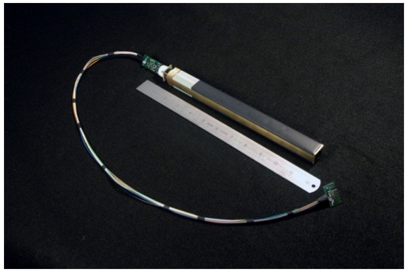
- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Large improvements in Q^2 determination

PRad Setup (Side View)



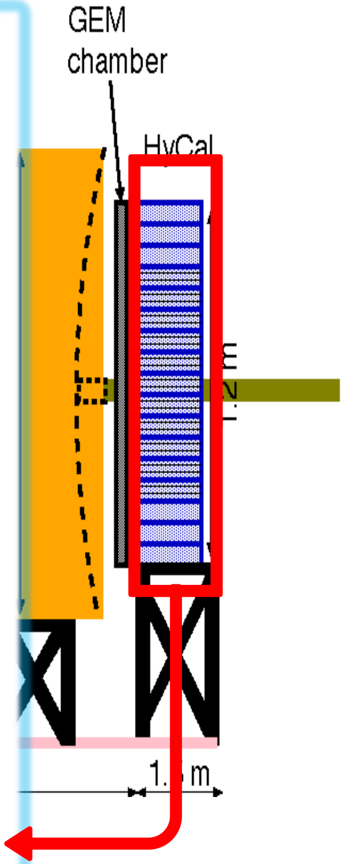
PRad Experimental Apparatus: HyCal El. Mag. Calorimeter





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



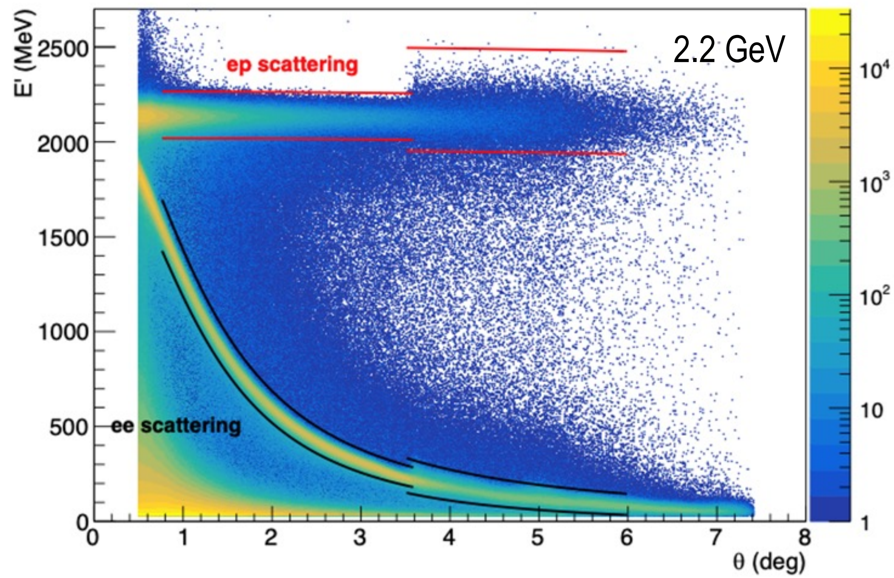
Data Analysis: Event Selection

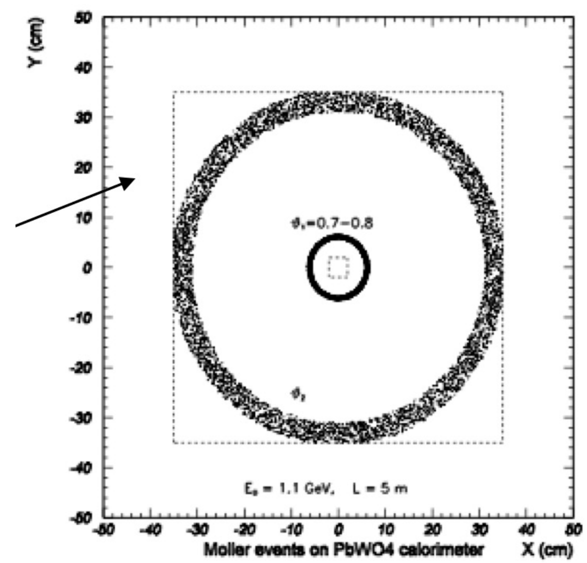
- Experimental data was taken with two beam energies:
  - ✓ 1.1 GeV (604 M events)
  - ✓ 2.2 GeV (756 M events)

- For all events, require hit matching between GEMs and HyCal

- For *ep* and *ee* events, apply angle dependent energy cut based on kinematics:
  - ➢ cut size depend on local detector resolution

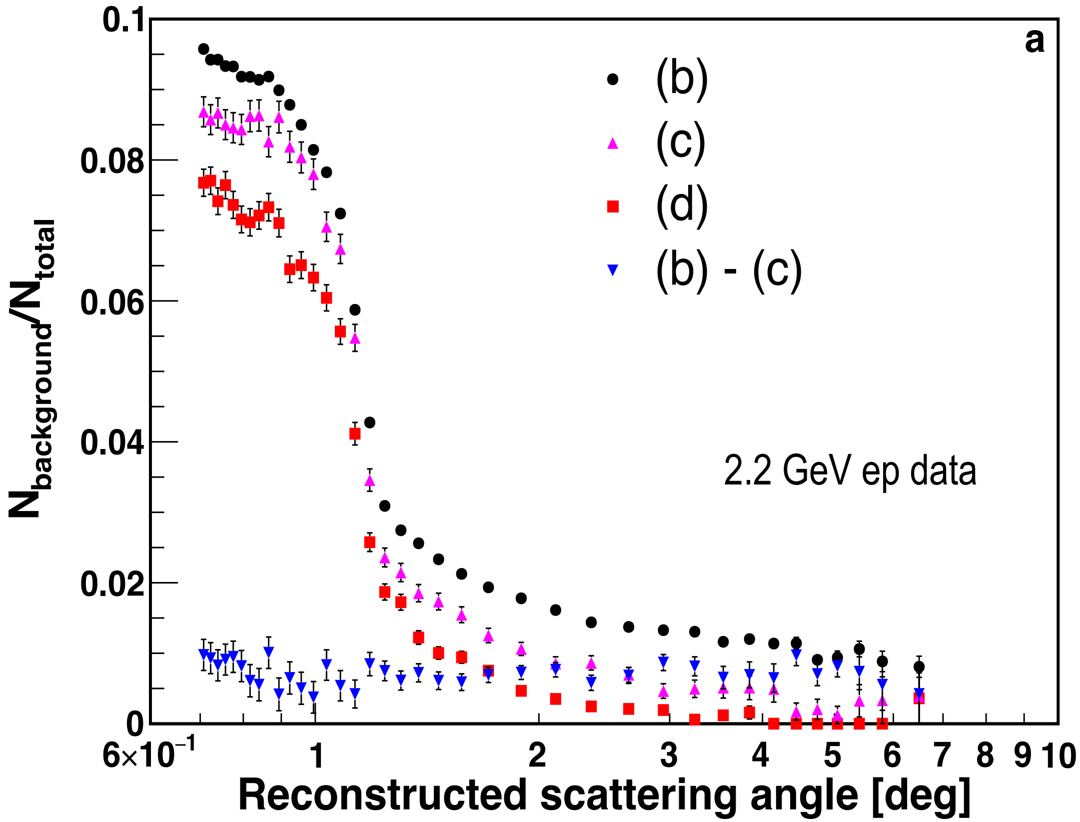
- For *ee*, if requiring double-arm events, apply additional cuts:
  - ✓ elasticity
  - ✓ co-planarity
  - ✓ vertex z (kinematics)

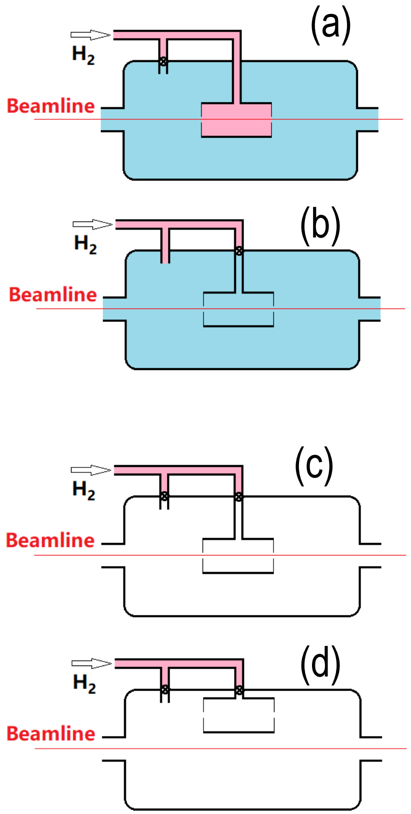




Data Analysis: Empty Target Runs for Background Subtraction

- ep background rate ~ 10% at forward angle (<1.1 deg, dominated by upstream beam halo blocker), less than 2% otherwise
- ee background rate ~ 0.8% at all angles

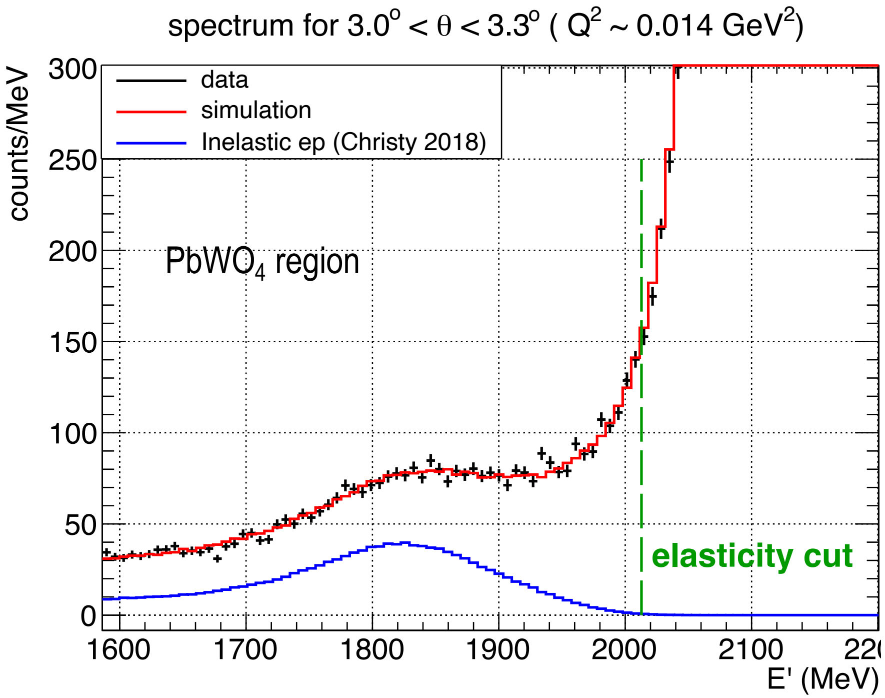


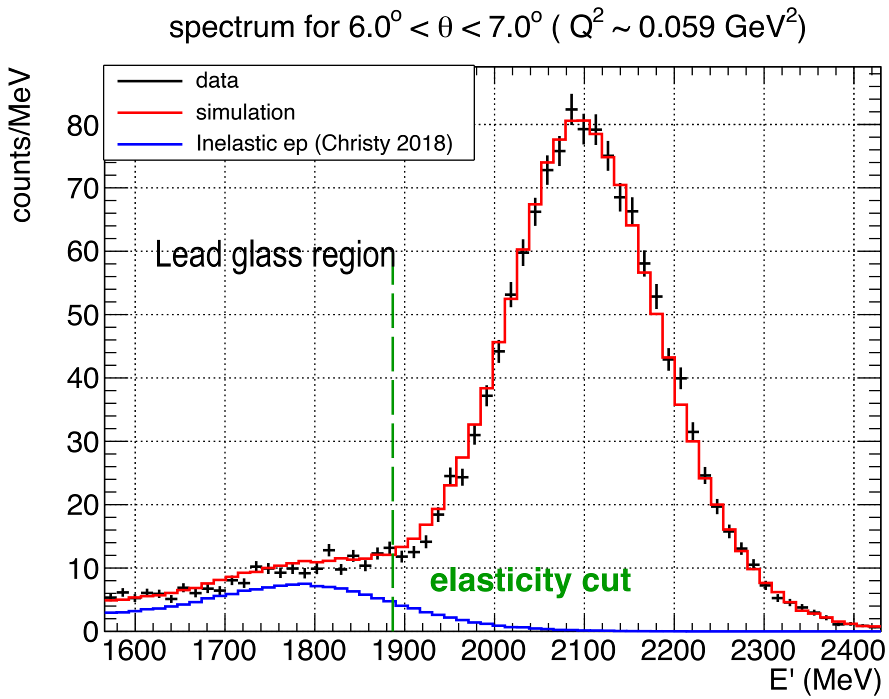


✓ Residual hydrogen gas: hydrogen gas filled during background runs

Data Analysis: *ep-inelastic* Contribution

- 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)

Extraction of the $ep \rightarrow ep$ Elastic Scattering Cross Section

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

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

  - method 1: bin by bin method – taking ep/ee counts from the same angle bin
  - method 2: integrated Moller method – integrate Møller in a fixed angle range and use it as common normalization for all angle bins

✓ Luminosity cancelled from both methods

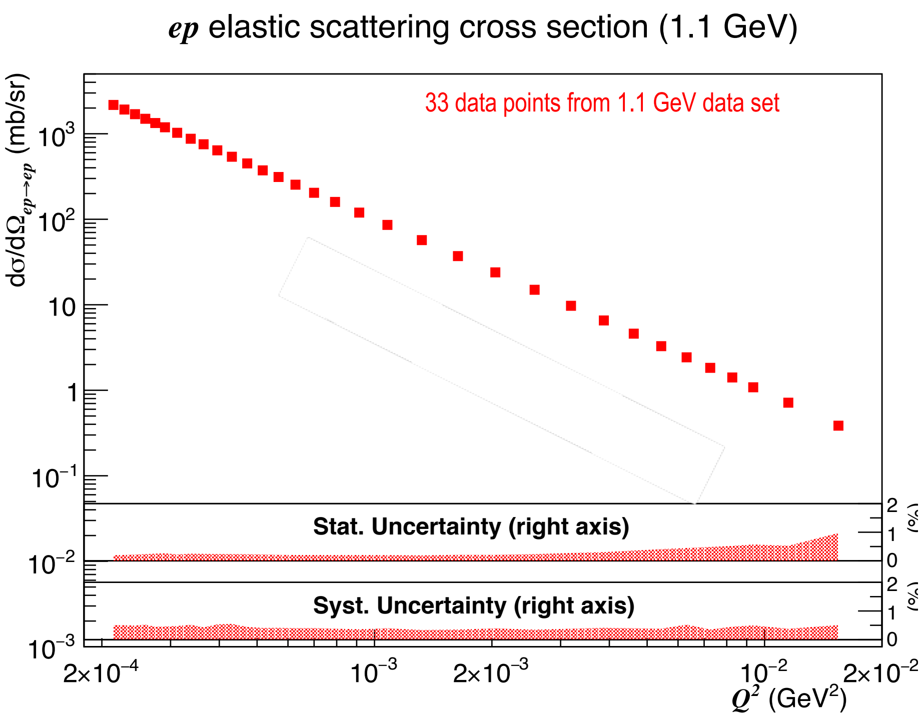
- Radiative effects corrected by Monte Carlo method:
  - ✓ GEANT4 based simulation package with full geometry setup
  - ✓ event generators with complete calculations of radiative corrections[1),2)]
  - ✓ iterative procedure applied for radiative corrections

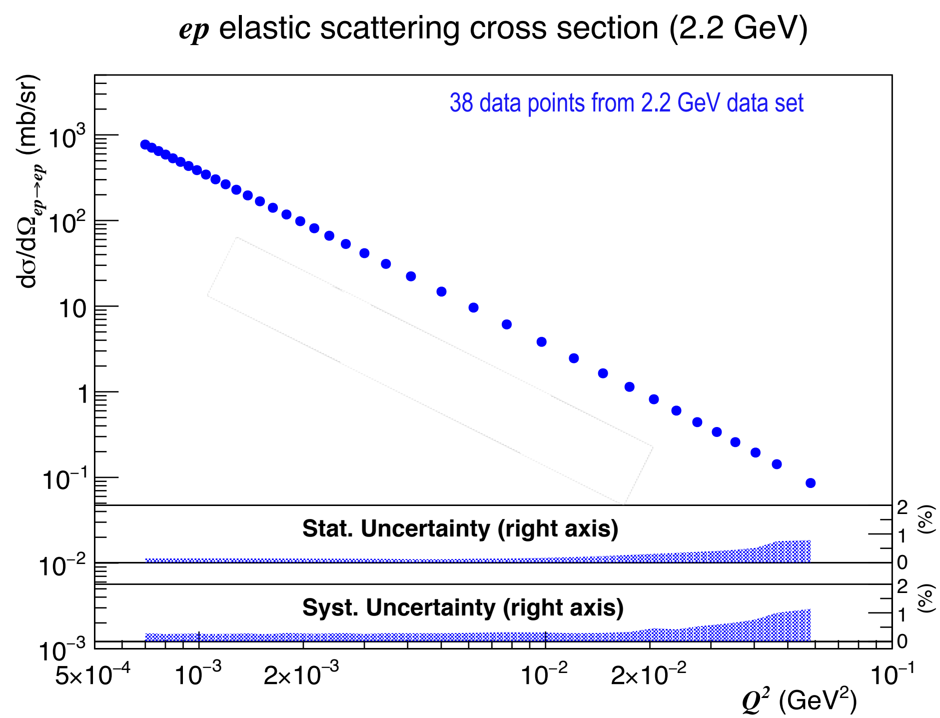
$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

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 (fully beyond ultra relativistic approximation).

Extracted ep→ep Elastic Differential Cross Sections

- Extracted differential cross sections vs. Q^2, with 1.1 and 2.2 GeV data.
- Statistical uncertainty: ~0.2% for 1.1 GeV and ~0.15% for 2.2 GeV per point.
- Systematic uncertainties: 0.3% - 0.5% for 1.1 GeV and 0.3 – 1.1% for 2.2 GeV per point.





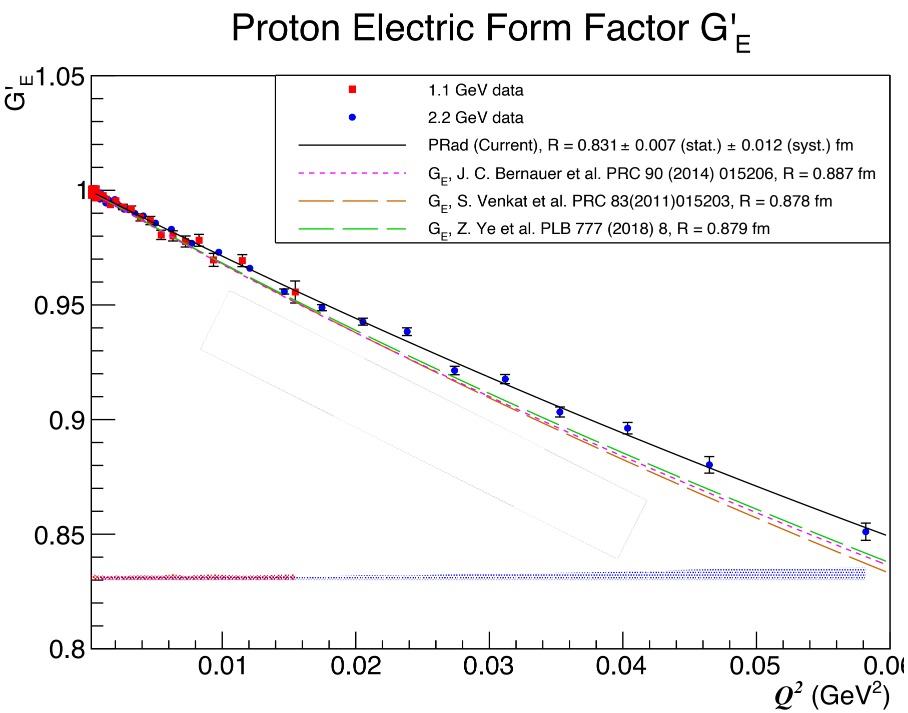
Fit to Extract the Proton Radius

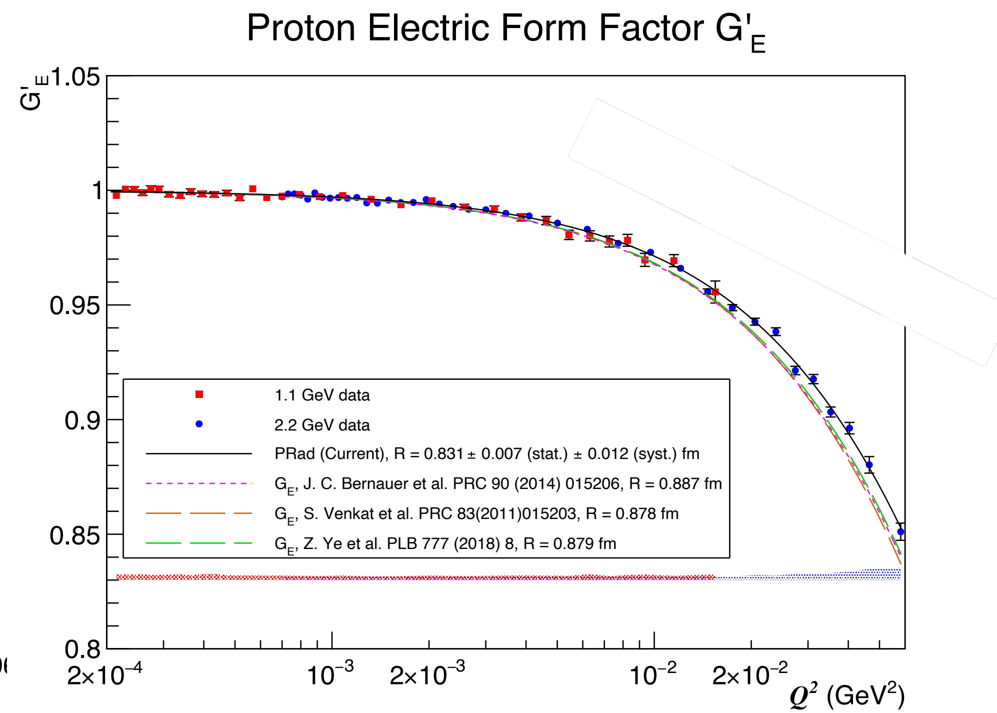
n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

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: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$

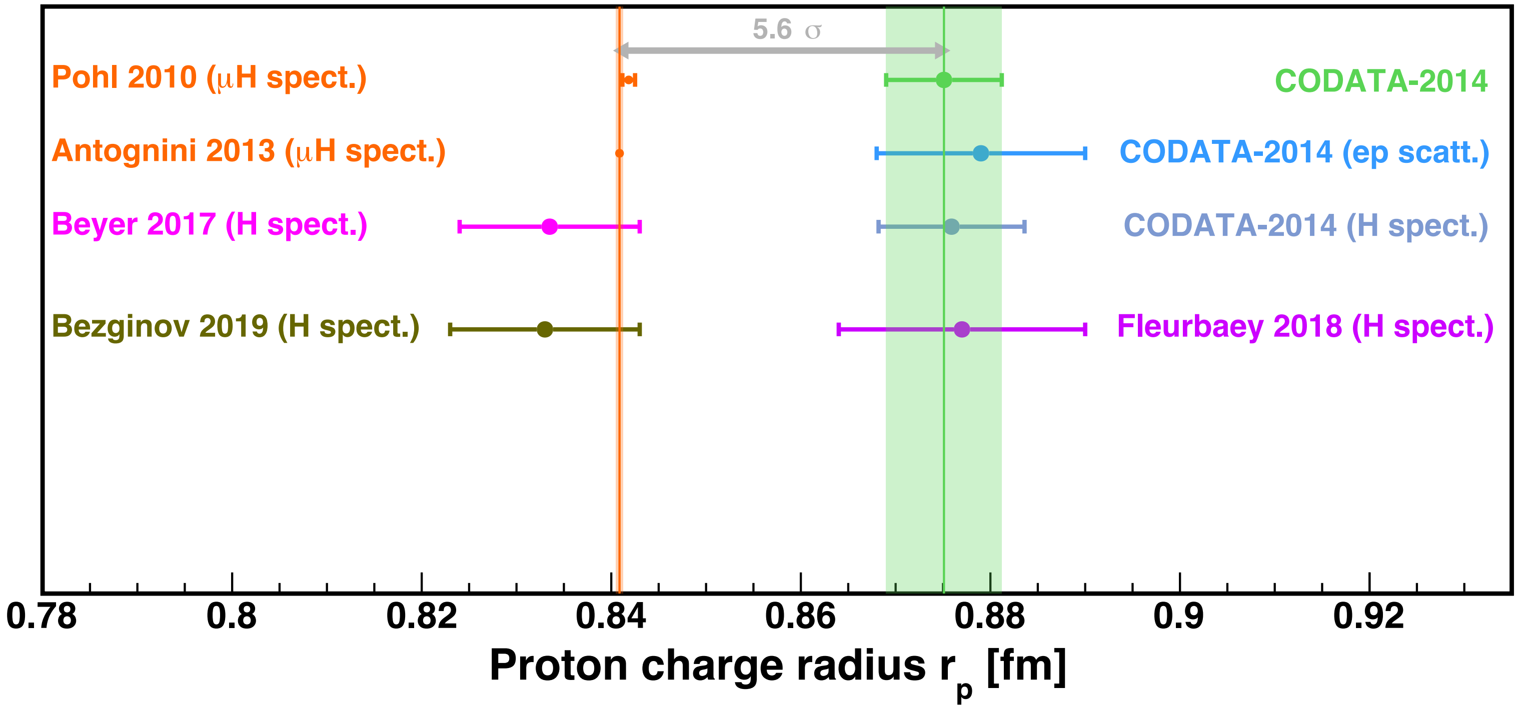
PRad fit shown as $f(Q^2)$ r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm





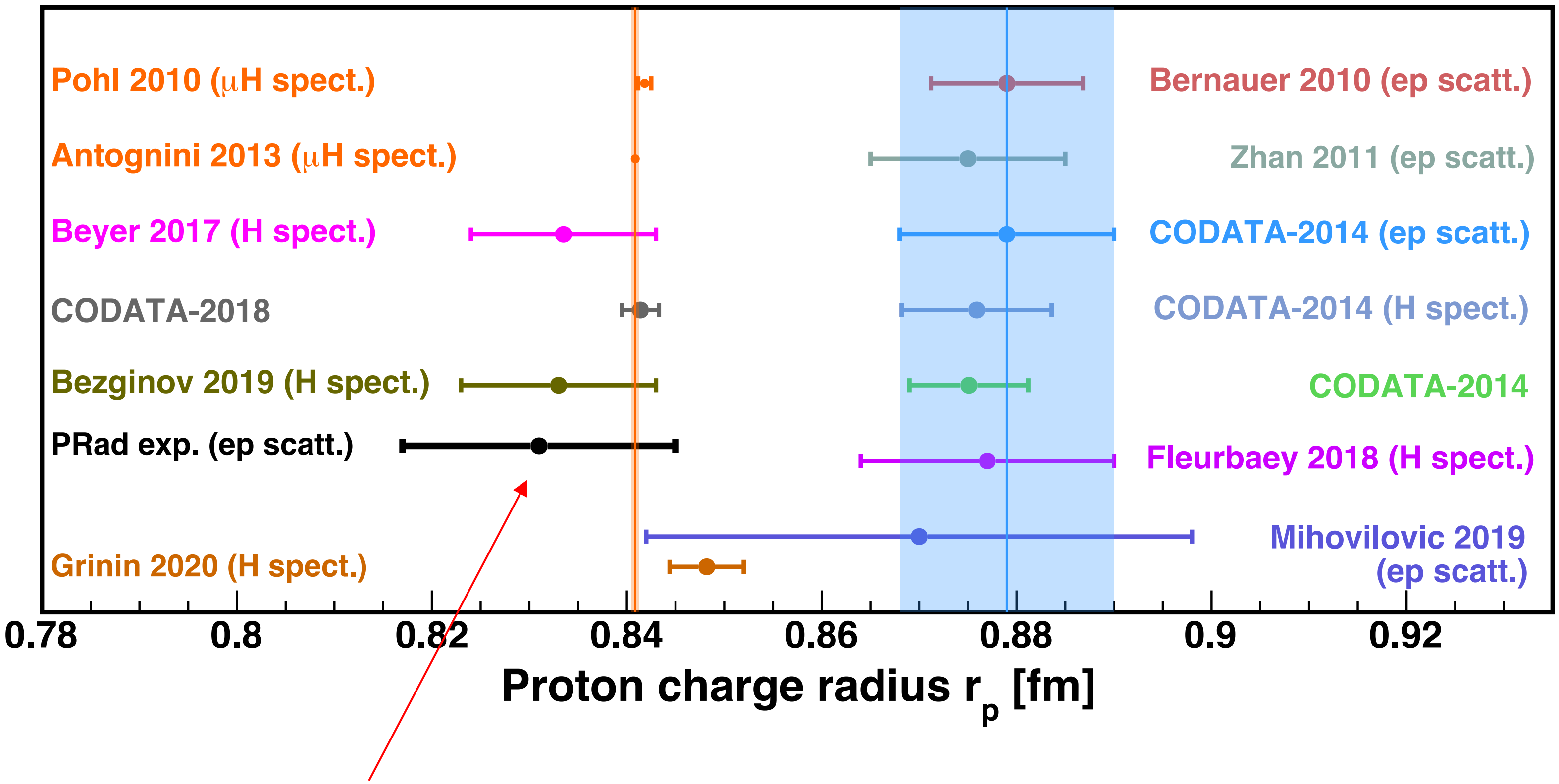
PRad final result: R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

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



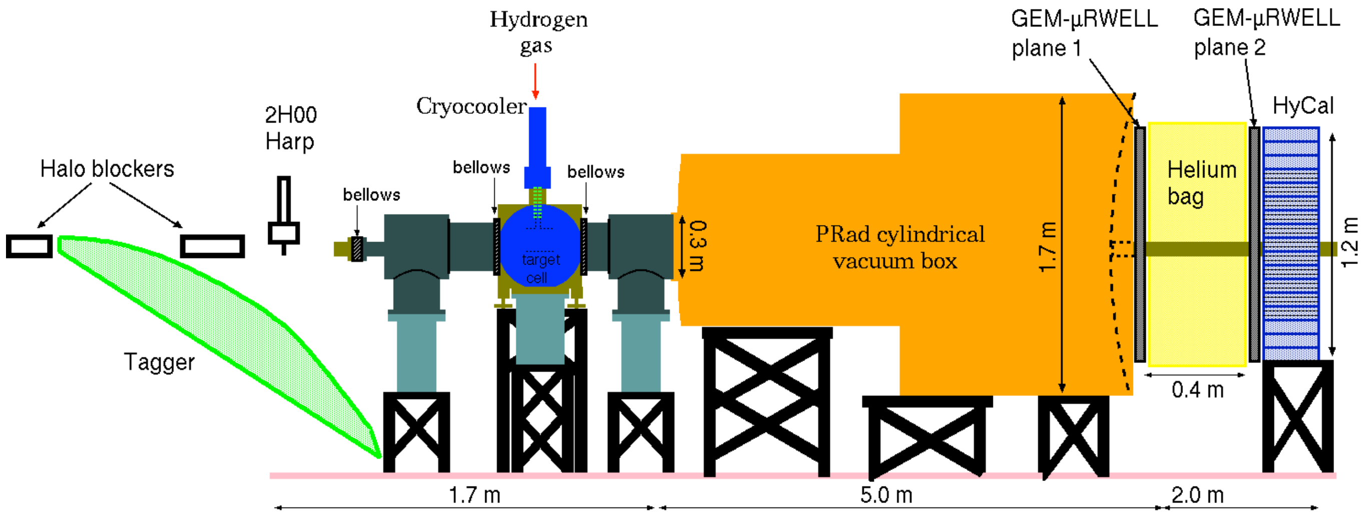
PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm

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

Planed New Experiment: PRad-II at JLab

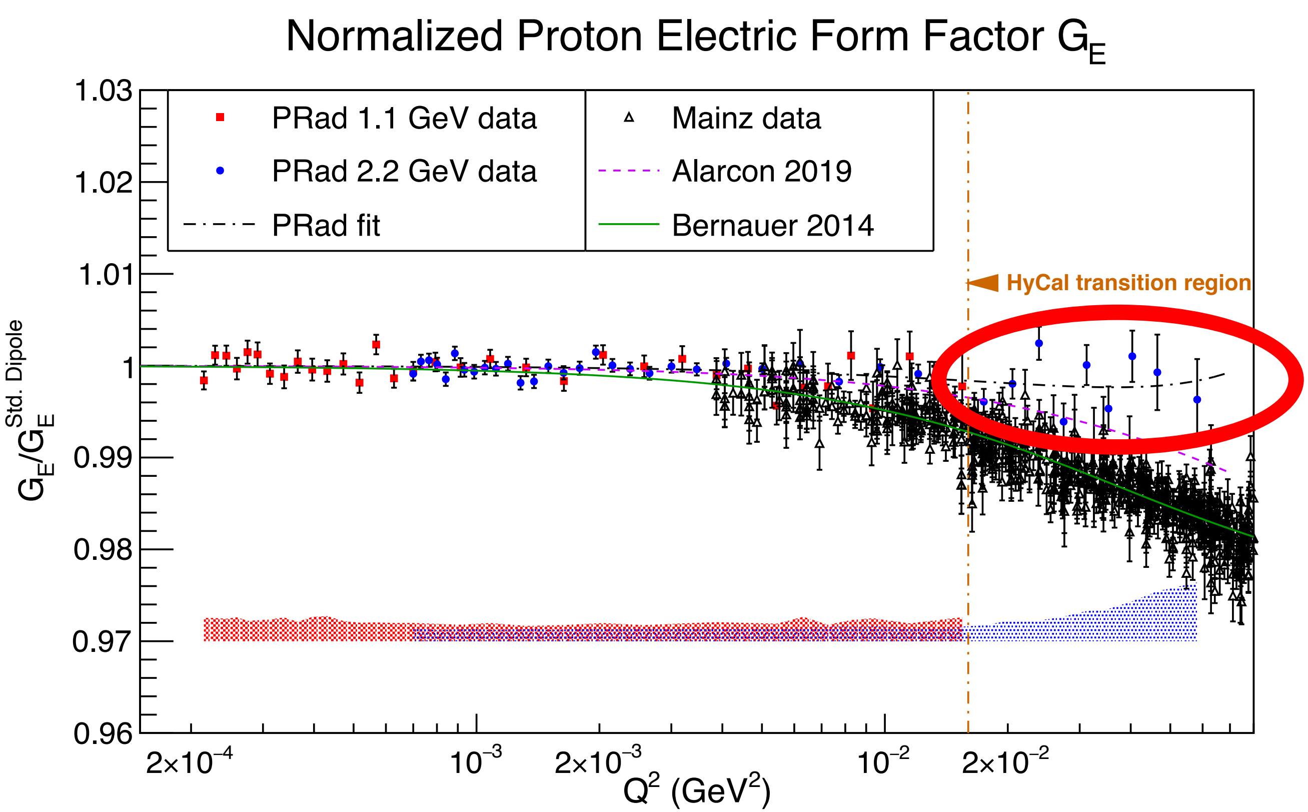
- PRad-II is planning to improve the PRad accuracy by a factor of 3.8 (to $\pm$ 0.43% on rp) by:
  - Significantly improved statistics (4 times less uncertainties);
  - Hardware upgrades:
    - adding full tracking capability (second plane of GEM/μRwell detectors).
    - small-size scintillator detectors just 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.
    - upgrade DAQ/electronics to fADC based electronics:
    - possible HyCal upgrade to all $PbWO_4$ crystals, essential for the ep-inelastic background suppression at relatively higher Q^2 range ($\approx 10^{-2}$ GeV^2) and uniformity over full acceptance.

PRad-II Experimental Setup (Side View)



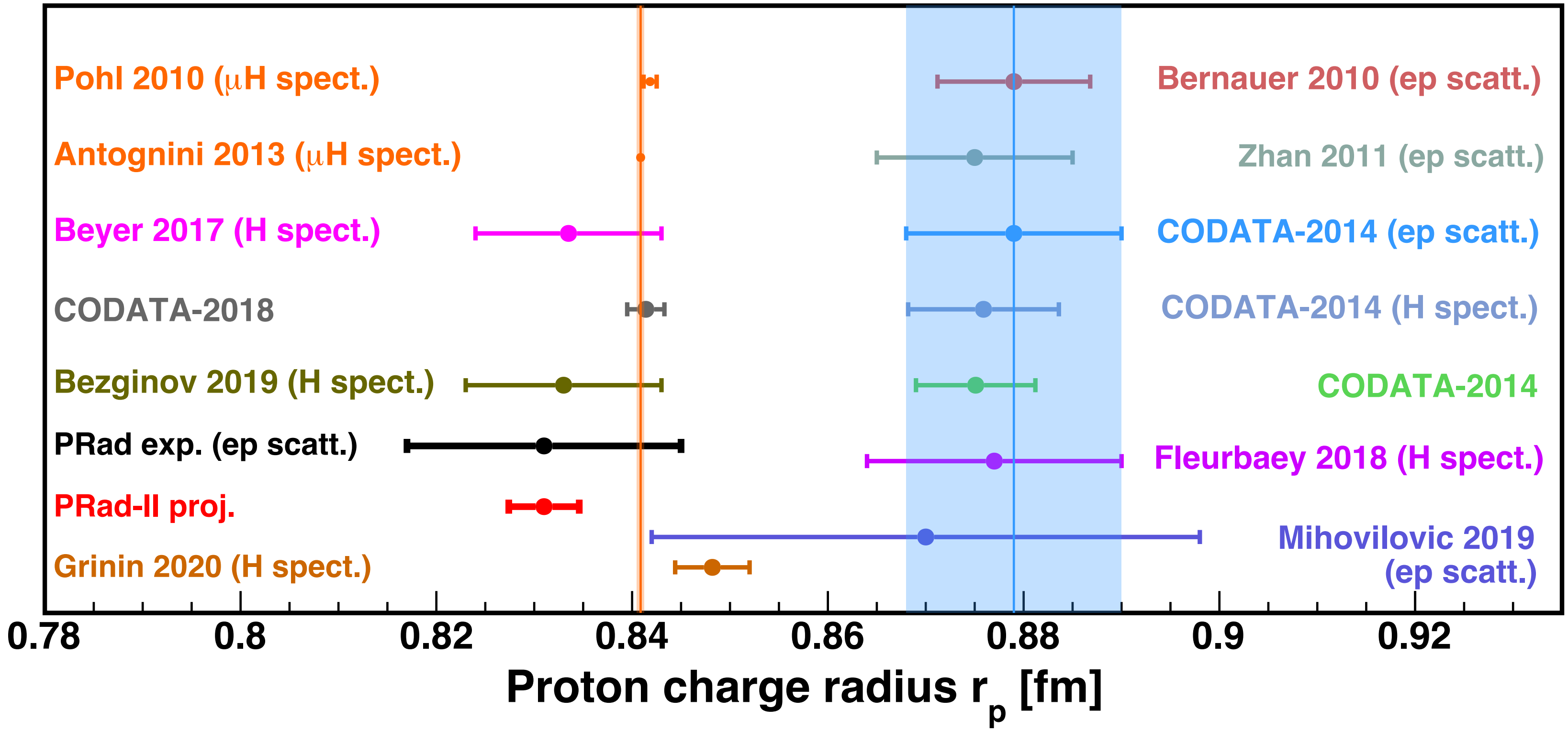
PRad-II Experiment

- The new PRad-III includes:
  1. Adding tracking capacity (second GEM plane)
  2. Upgraded HyCal with all high resolution $PbWO_4$ modules
  3. Convert to FADC based readout for HyCal
  4. Four times smaller stat. uncertainty
  5. Better RC calculating including NNLO diagrams



PRad-II: Projected Result

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



PRad-II: Current Status

- Approved by JLab's PAC-48 in August, 2020, (E12-004)

- NSF funding proposal was submitted in January 2022:

  - ✓ Major Research Instrumentation (MRI) Track-2 development type proposal, ~$4M total for:
    - HyCal partial upgrade to $PbWO_4$ crystals
    - second GEM detector
    - scintillator detectors to veto the Moller electrons at very small Q^2 range
  - ✓ Results are expected before July

- Also, for the calorimeter upgrade, we are looking for used crystal detectors from other experiments/institutions matching the $PbWO_4$ part of the HyCal

Summary

- PRad was uniquely designed and performed in 2016 to address the *"Puzzle":*
  - ✓ data in a large Q^2 range have been recorded with the same experimental setting, $[2\text{x}10^{-4} \div 6\text{x}10^{-2}]$ GeV/C^2.
  - ✓ lowest Q^2 data set (~10^{-4} GeV/C^2) has been collected for the first time in ep-scattering experiments;
  - ✓ simultaneous measurement of the Moller and Mott scattering processes has been demonstrated to control systematic uncertainties.

- PRad final result supports small proton charge radius (Nature 575, 145–150 (2019)):
  - ✓ **R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm (±1.67% total)**
  - ✓ significant input in changing the CODATA recommendation on radius.

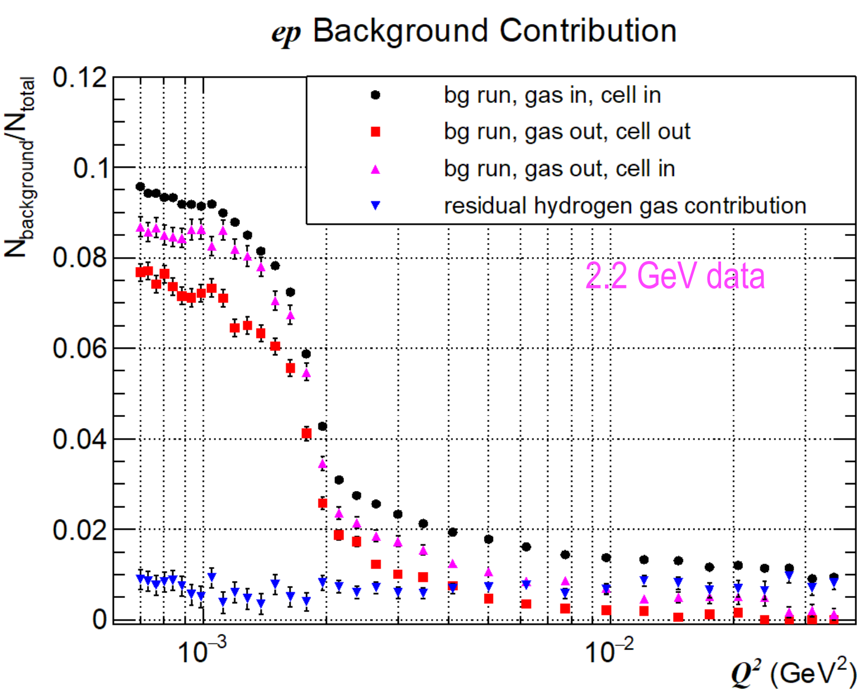
- PRad-II will improve the radius measurement by a factor of 3.8
  - ➢ will address the differences between PRad and all modern ep-experiments;
  - ➢ will reach the $Q^2 \sim 10^{-5}$ Gev^2 range, for the first time in ep-experiments
  - ➢ are there any possible systematic uncertainties in μH results?

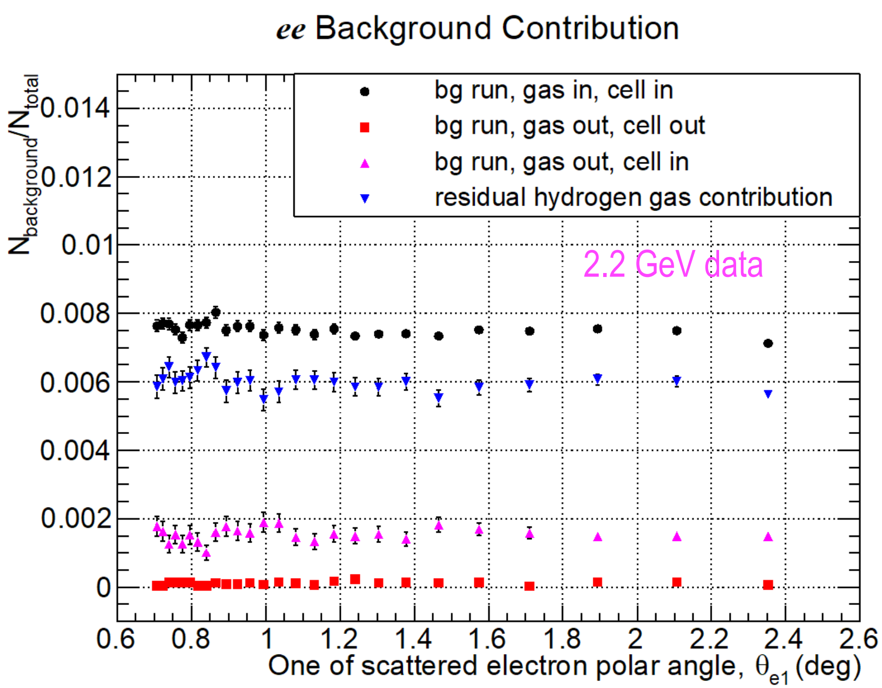
PRad was supported in part by NSF MRI #PHY-1229153 and DOE DE-FG02-03ER41231 awards.
my research work is supported in part by NSF award: PHY-1812421

Thank you!

Data Analysis: Beam Background Subtraction

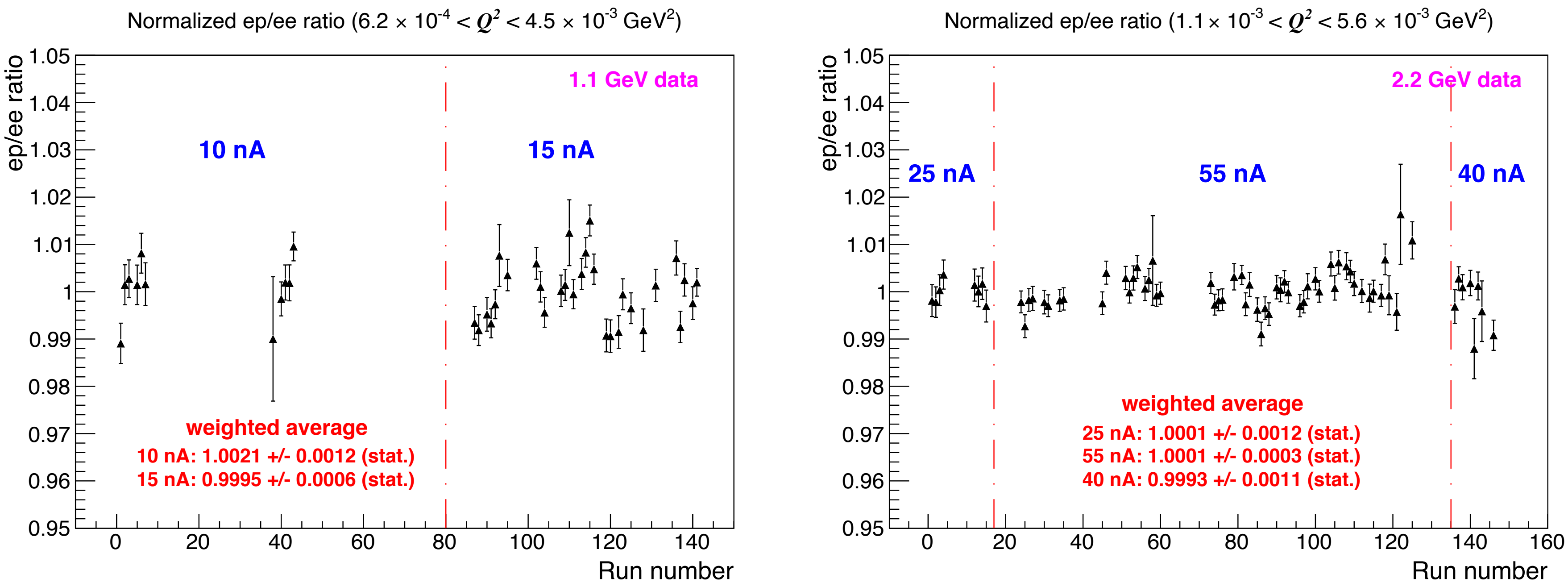
- *ep* background rate ~ 10% at forward angles (<1.3^0, dominated by upstream "collimator"), less than 2% otherwise.
- ee background rate ~ 0.8% at all angles .





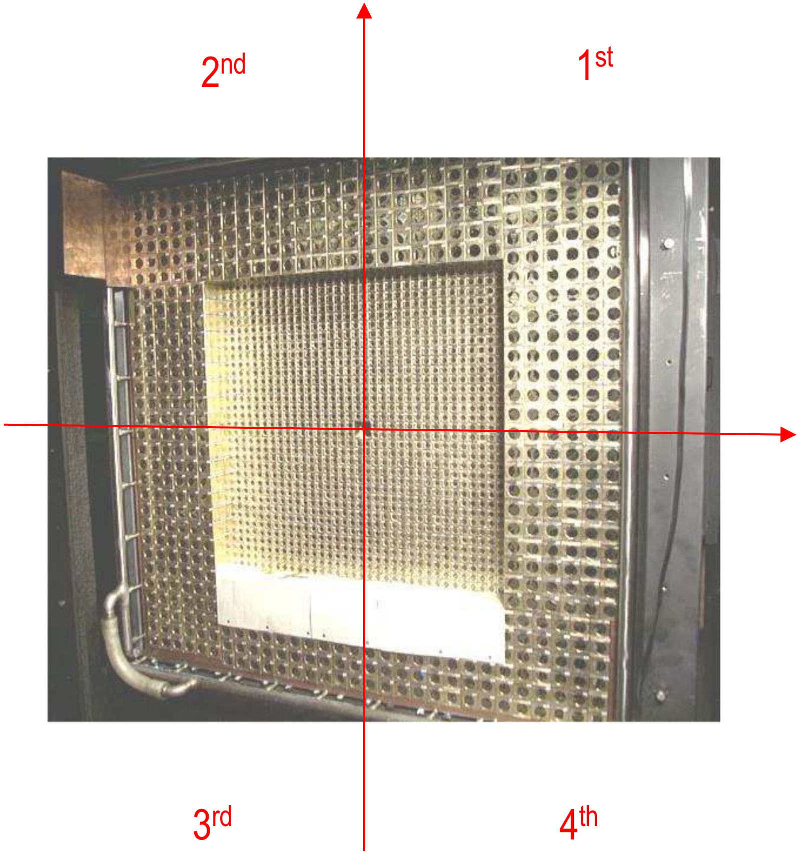
Data Analysis: Stability vs. Run Number

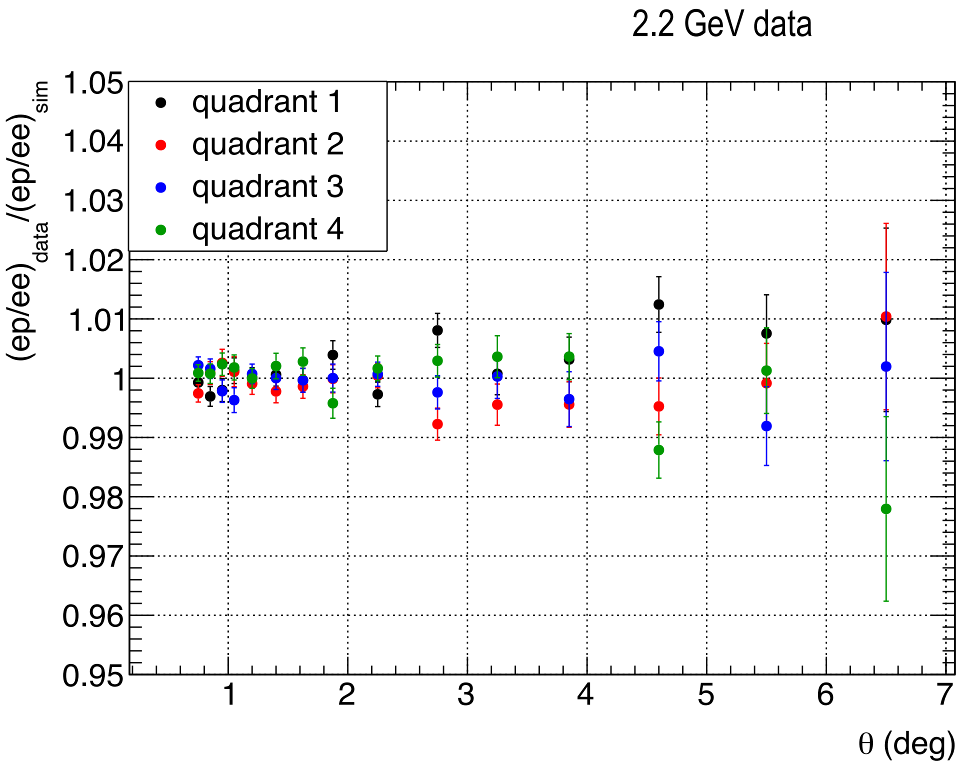
- Normalized *ep/ee ratio* vs. run number, (background subtracted with neighboring empty target runs).
- Sensitive to systematics like time variation of beam line background, …



Data Analysis: Azimuthal Uniformity

- Ratio $(ep/ee)_{dat} / (ep/ee)_{sim}$ vs. azimuthal quadrants
- Sensitive to detector efficiency, beam position, tilting angles, …





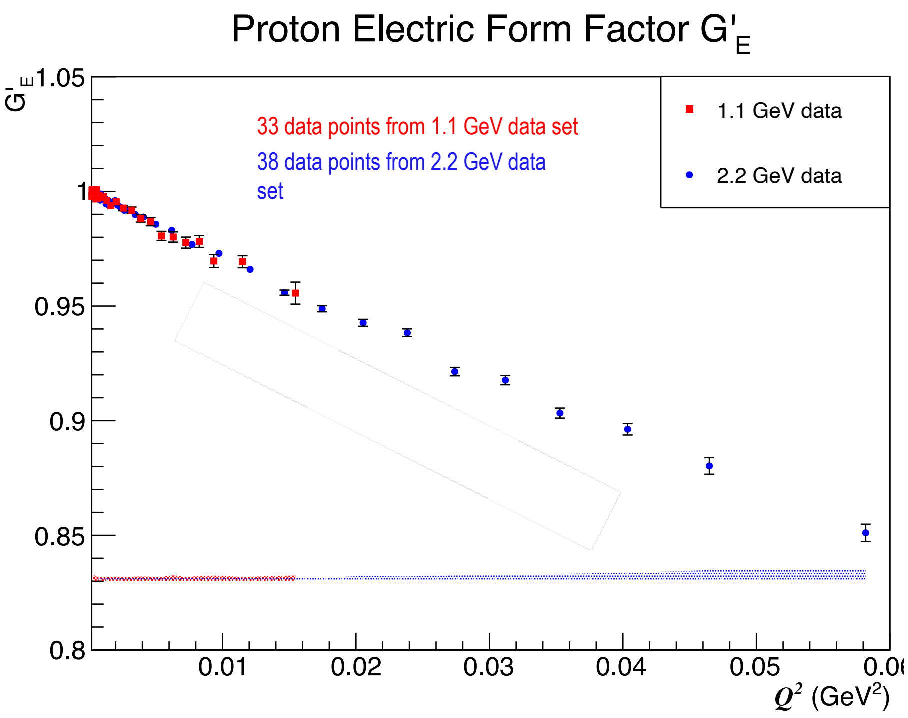
Extracted Proton Electric Form Factor, G_E vs. Q^2

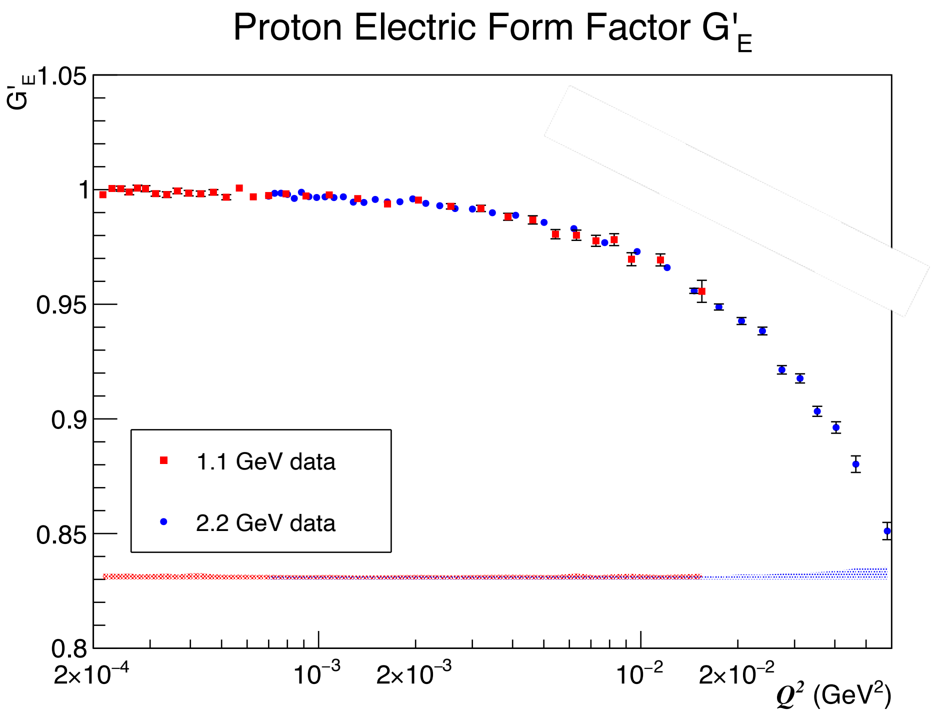
n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

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: $\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$





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

n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

PRad Systematic Uncertainties

Item	r_p uncertainty [fm]	n_1 uncertainty	n_2 uncertainty
Event selection	0.0070	0.0002	0.0006
Radiative correction	0.0069	0.0010	0.0011
Detector efficiency	0.0042	0.0000	0.0001
Beam background	0.0039	0.0017	0.0003
HyCal response	0.0029	0.0001	0.0001
Acceptance	0.0026	0.0001	0.0001
Beam energy	0.0022	0.0001	0.0002
Inelastic *ep*	0.0009	0.0000	0.0000
G_M^p parameterization	0.0006	0.0000	0.0000
Total	0.0115	0.0020	0.0013

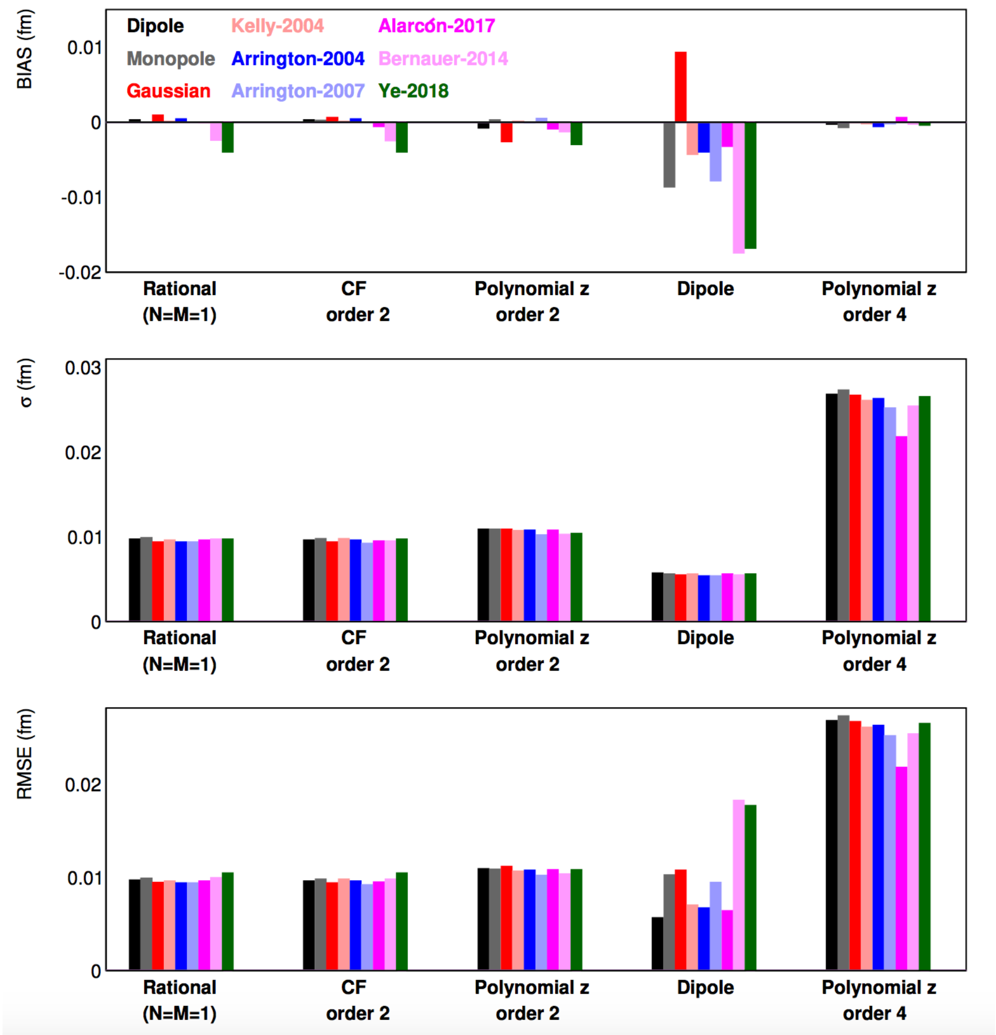
Recent Developments in Fitting Procedures

- The input form factors (with known r_p) are used to generate pseudo data using PRad kinematic range and uncertainties.
- All combinations of input functions and fit functions can then be tested repeatedly against regenerated pseudo data.
- Since the input radius is known, this allowed to find fitting functions that are robust for proton radius extractions in an objective fashion.

➢ The following fitters:

- ✓ two-parameter rational function
- ✓ two-parameter continued fraction
- ✓ second-order polynomial expansion of z

are identified as robust fitters with small uncertainties

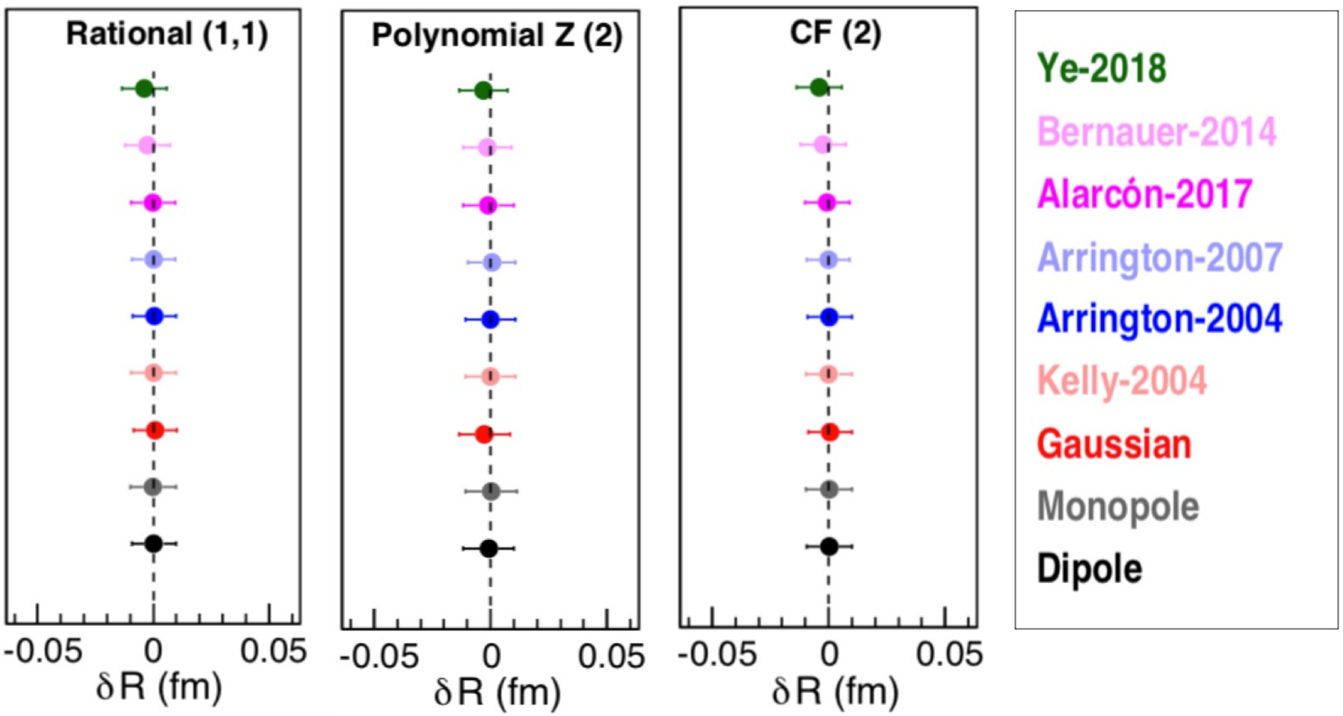


RMSE = $\text{sqrt}(\text{bias}^2 + \sigma^2)$

- X. Yan, et al.

"Robust extraction of the proton charge radius from electron-proton scattering data", PRC 98, 2, 025204, 2018

Recent Developments in Fitting Procedures



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)

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

PRad Collaboration

A part of the PRad collaboration
in December, 2019 at JLab

- Currently 14 collaborating universities and institutions:

Jefferson Laboratory, NC A&T State University,
Duke University, Idaho State University,
Mississippi State University, Norfolk State University,
University of Virginia, Argonne National Laboratory,
University of North Carolina at Wilmington, Hampton University,
College of William & Mary, Tsinghua University, China,
Old Dominion University, ITEP Moscow, Russia.

- **Graduate students:**

Chao Peng (Duke), Weizhi Xiong (Duke),
Xinzhan Bai (UVa), Li Ye (MSU)

- **Postdocs:**

Chao Gu (Duke), Xuefei Yan (Duke), Mehdi Meziane (Duke), Zhihong Ye (Duke), Tyler Hague (NC A&T SU), Maxime Lavilain (NC A&T), Krishna Adhikari (MSU), Latif-ul Kabir (MSU), Chandra Akondi (NC A&T)