Recent Results from the PRad Experiment

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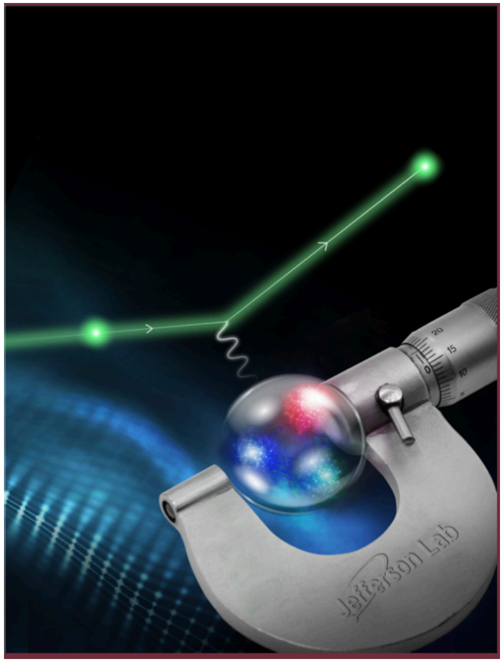
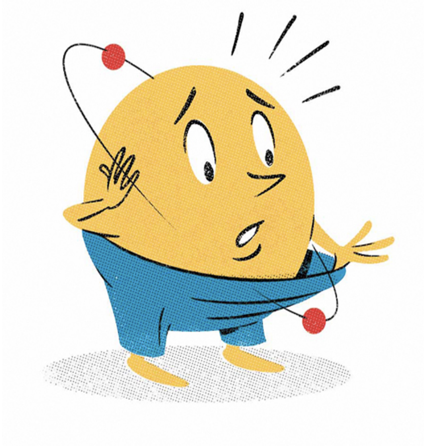
for the PRad collaboration



Outline

- the Proton Radius Puzzle, recent history
- our approach for a new ep-experiment
- the PRad experiment
- PRad results
- plans for new experiments
- summary and outlook

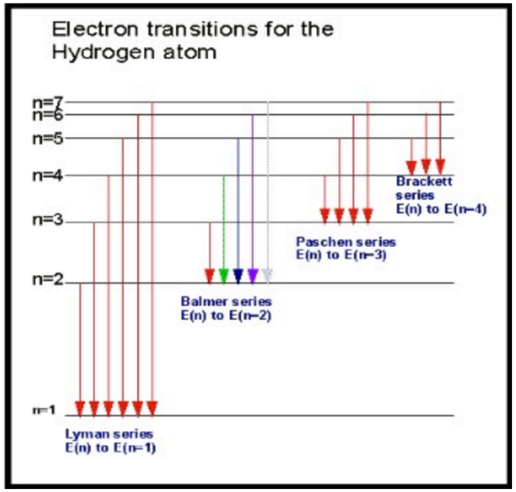


New York Times

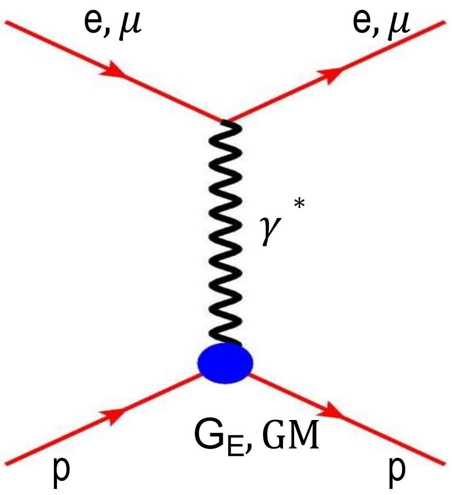
Methods to Measure the Proton Charge Radius

- Two different techniques:

✓ Hydrogen spectroscopy (lepton-proton bound states, Atomic Physics):
  - regular hydrogen
  - muonic hydrogen



✓ Lepton-proton elastic scattering (Nuclear Physics):
  - ep- scattering (like PRad)
  - μp- scattering (like MUSE)



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

With relativisticly correct definition of the Proton charge radius:

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

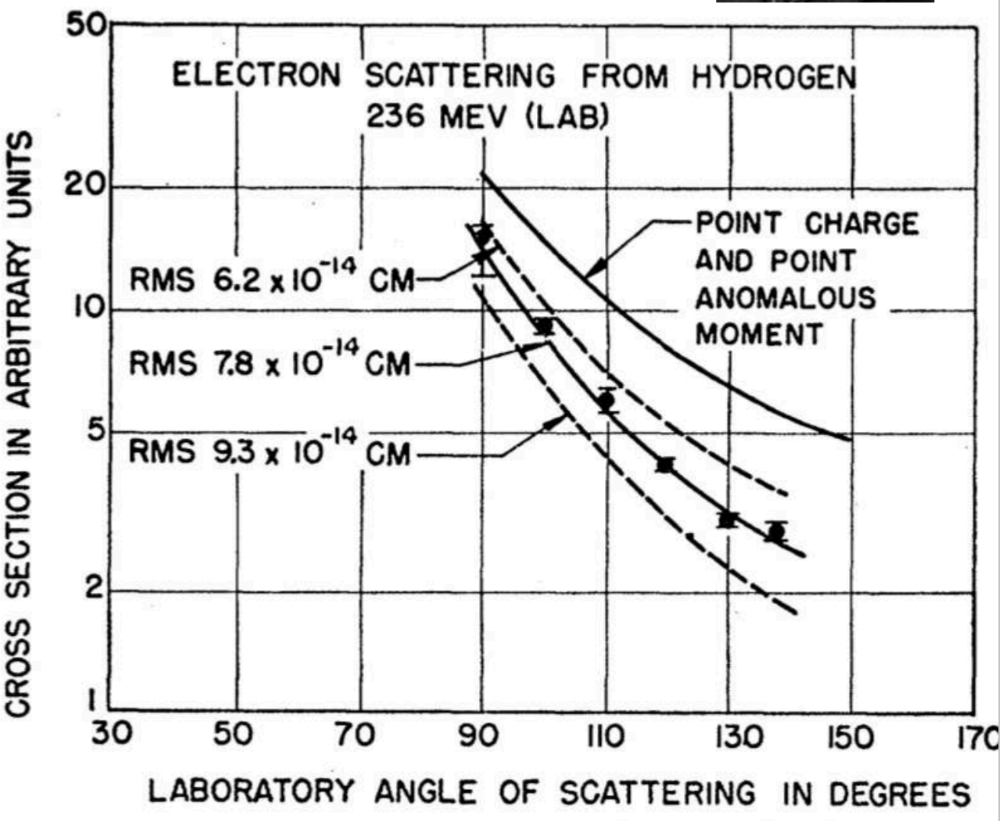
The First Measurement of the Proton Charge Radius (ep-scattering)

- started with Robert Hofstadter
  - ✓ Nobel prize in Physics (1961):
  - ✓ "… for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons …"

- The Proton rms charge radius in 1956 was measured to be:
  - ✓ 7.8 10^{-14} cm (0.78 fm)

    Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

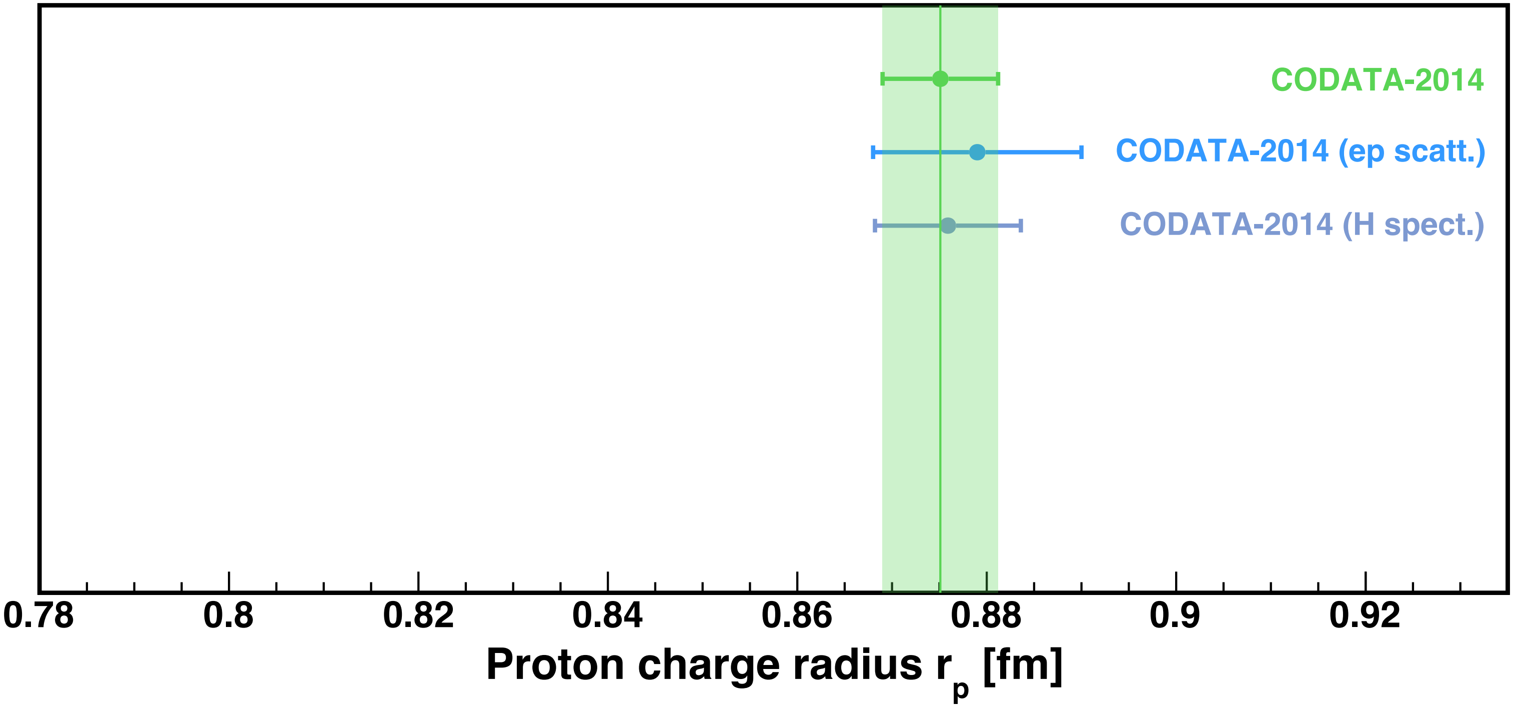
- Over 60 years of experimentation!
  - ✓ started from 0.78 fm
  - ✓ ended to 0.895 fm by 2010.
  - ✓ where we are now ???



Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).

Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

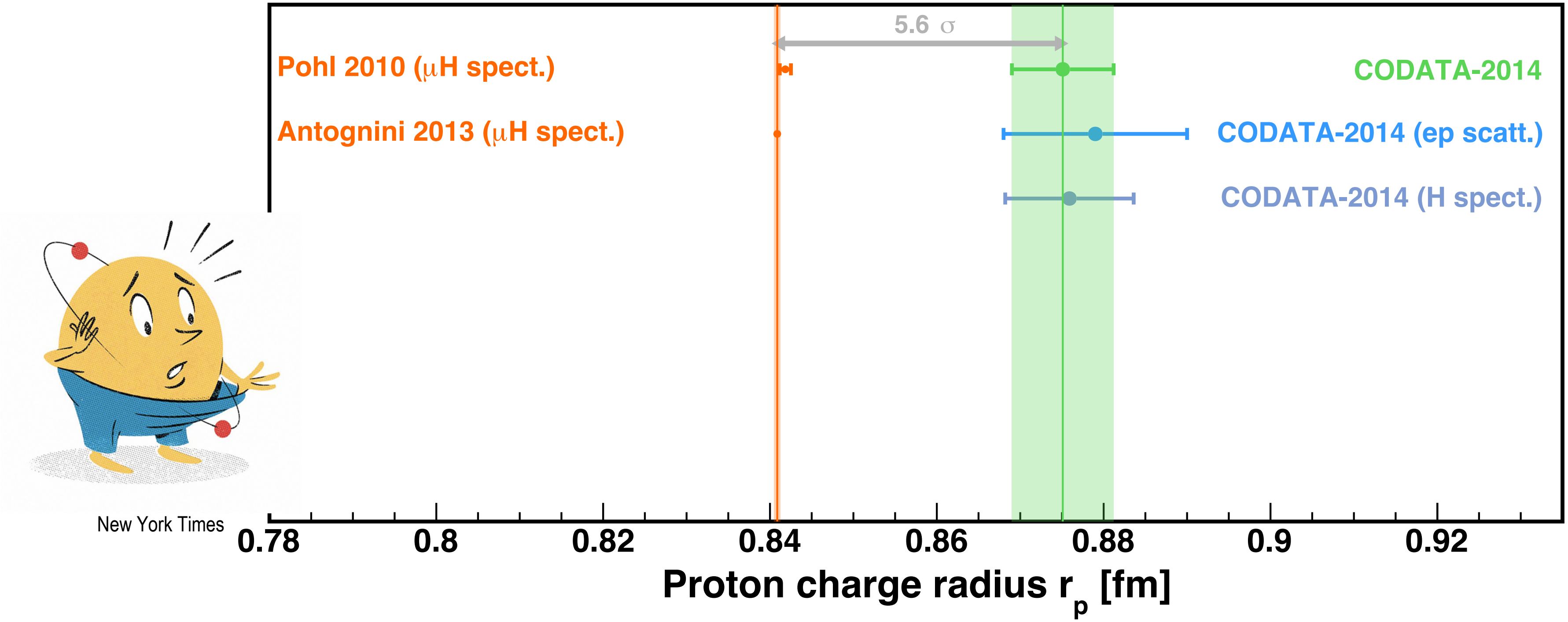
The Puzzle: Proton Radius before 2010



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 !

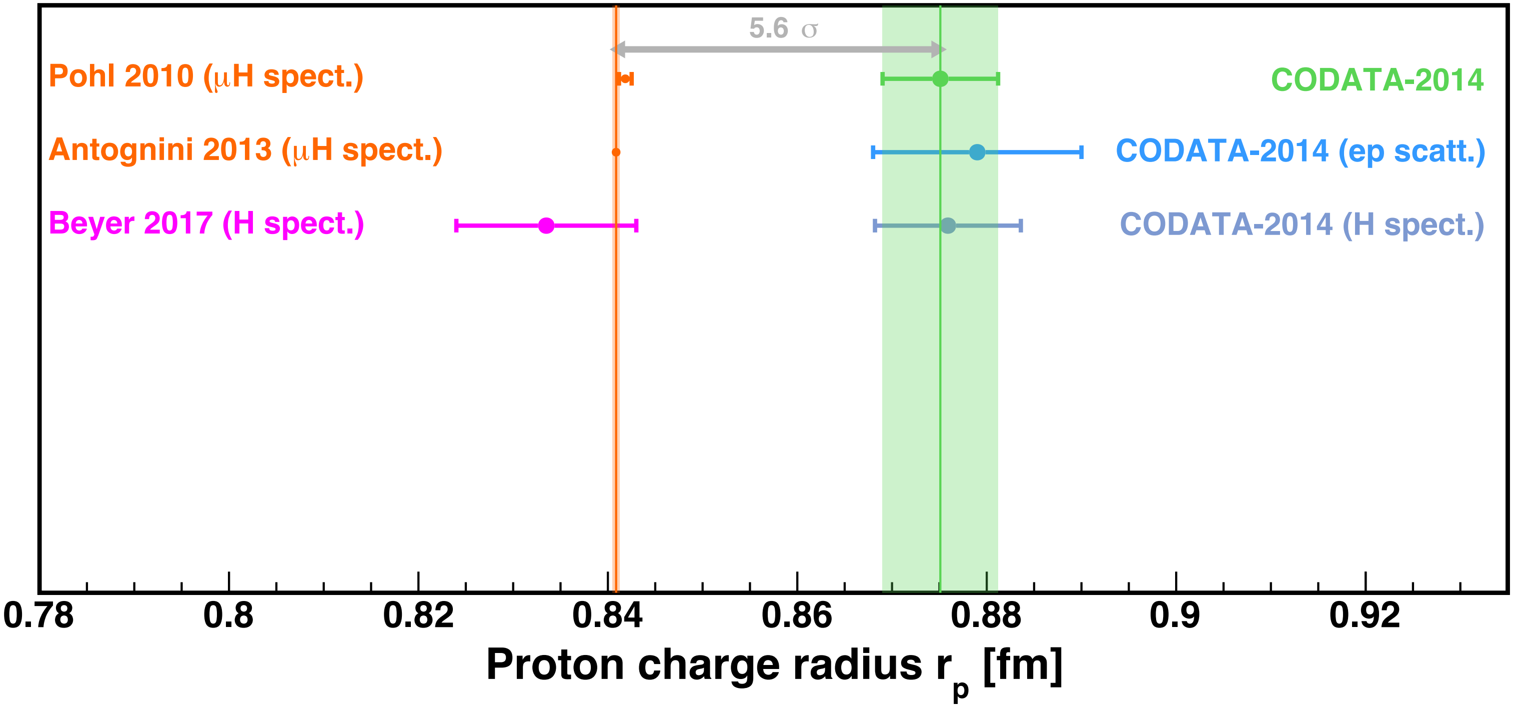
The Puzzle: Proton Radius in 2013



New York Times

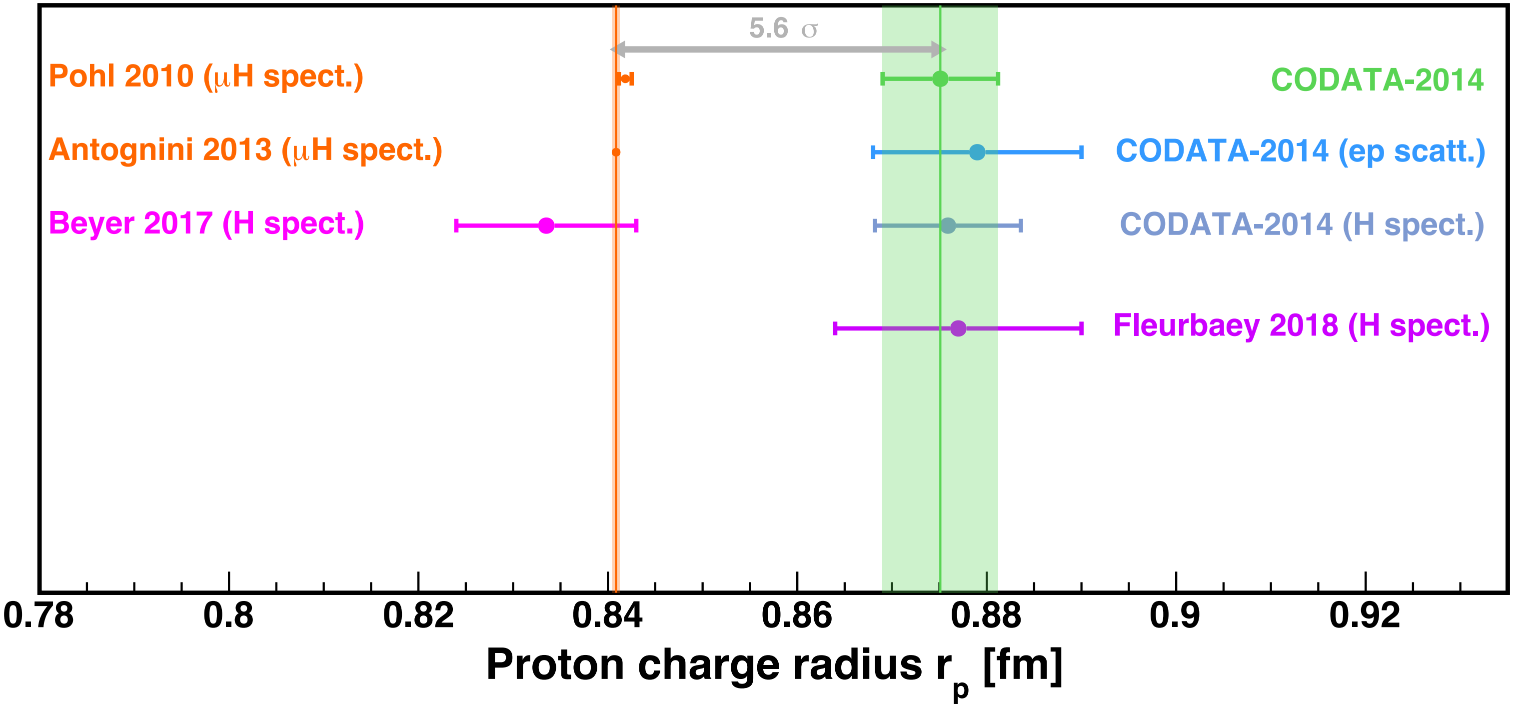
Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013):	0.8409 ± 0.0004 fm
Muonic hydrogen (CREMA coll. 2010):	0.84184 ± 0.00067 fm

The Puzzle: Proton Radius in 2017



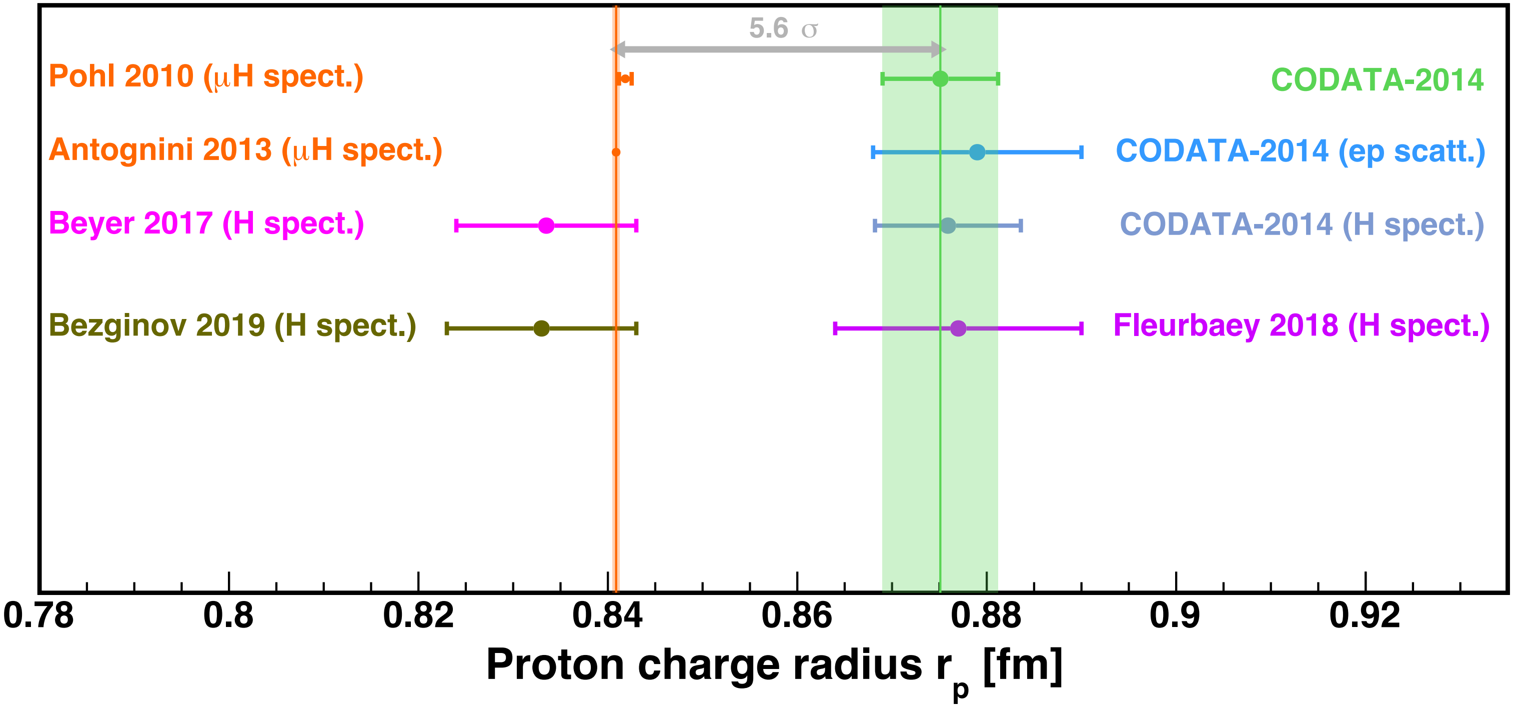
Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013):	0.8409 ± 0.0004 fm
Regular H-spectr. (2S ➔ 4P, Garching, PSI):	0.8335 ± 0.0095 fm

The Puzzle: Proton Radius in 2018



Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013):	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

The Puzzle: Proton Radius in 2019



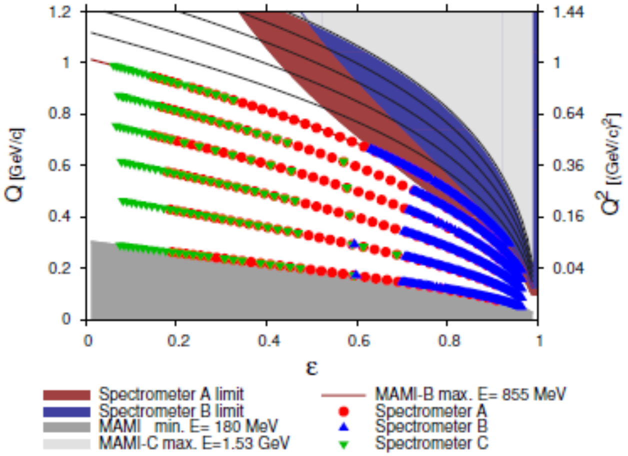
Regular hydrogen average (CODATA):	0.8751 ± 0.0061 fm
Muonic hydrogen (CREMA coll. 2013, PSI):	0.8409 ± 0.0004 fm
Regular H-spectr. (2S ➔ 4P, Garching, PSI):	0.8335 ± 0.0095 fm
Regular H-spectr. (1S ➔ 3S, LKB, Paris):	0.877 ± 0.013 fm
Regular H-spectr. ($2S_{1/2}$ ➔ $2P_{1/2}$, York Un. Canada)	0.833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

Planning a new ep⟶ep Experiment:

weaknesses of previous magnetic spectrometer experiments

- Practically all ep-scattering experiments are 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) to cover a reasonable Q^2 fitting interval
    - normalization of each Q^2 bins
    - thair 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:



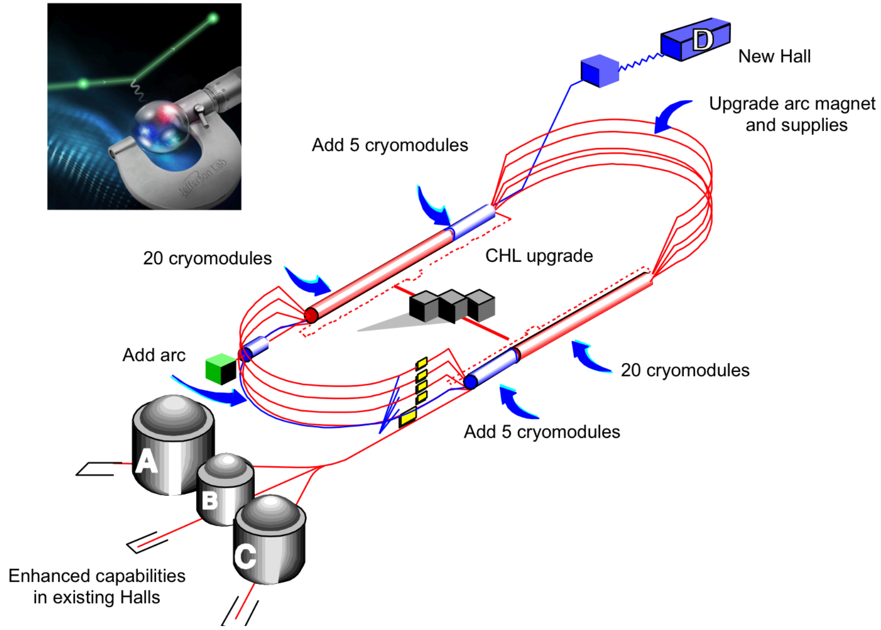
A Possible Solution: PRad Experimental Approach

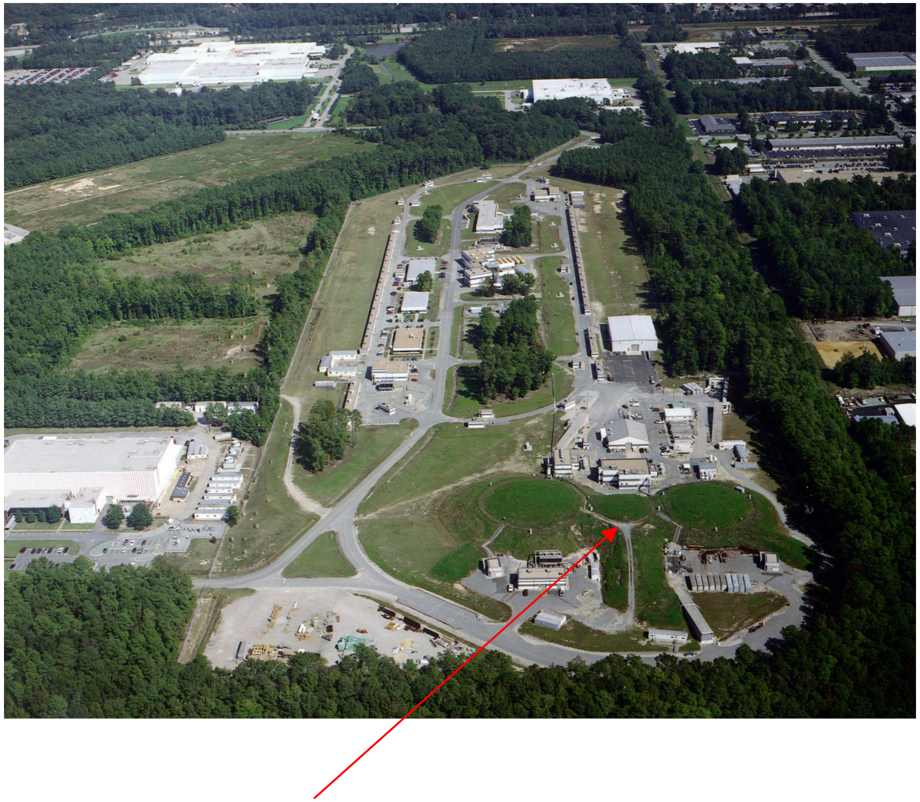
- Use large acceptance, high resolution electromagnetic calorimeter (together with a GEM coordinate detector):
  - ✓ measure a large interval of angles in one experimental setting ($\vartheta_e = 0.6^0 - 7.0^0$)
    ($Q^2 = 2\text{x}10^{-4} \div 6\text{x}10^{-2}$) GeV/c^2 ;
  - ✓ access to smaller angles ($\vartheta_e \approx 0.6^0$)
  - ✓ calibrate with a well-known QED processes: azimuthal symmetry of the calorimeter, simultaneous detection of $ee \rightarrow ee$ 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
✓	Date analysis	2016 – 2019
✓	Publication in Nature journal	November, 2019

PRad Experiment Performed in Hall B at Jefferson Lab



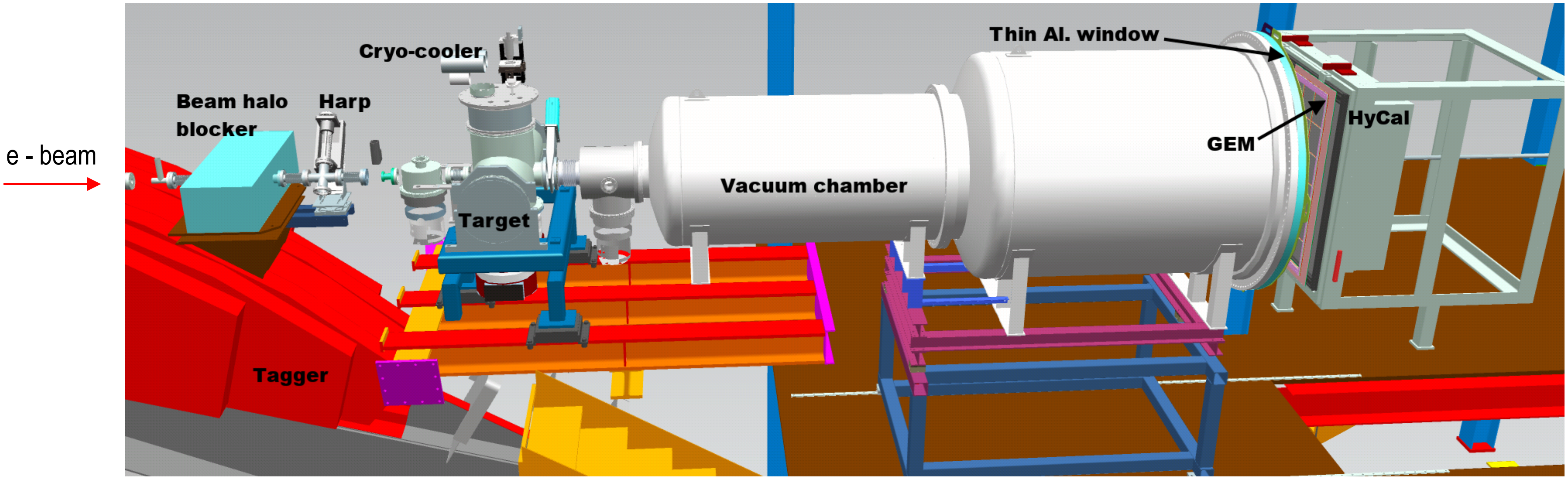


PRad was performed in Hall B at JLab

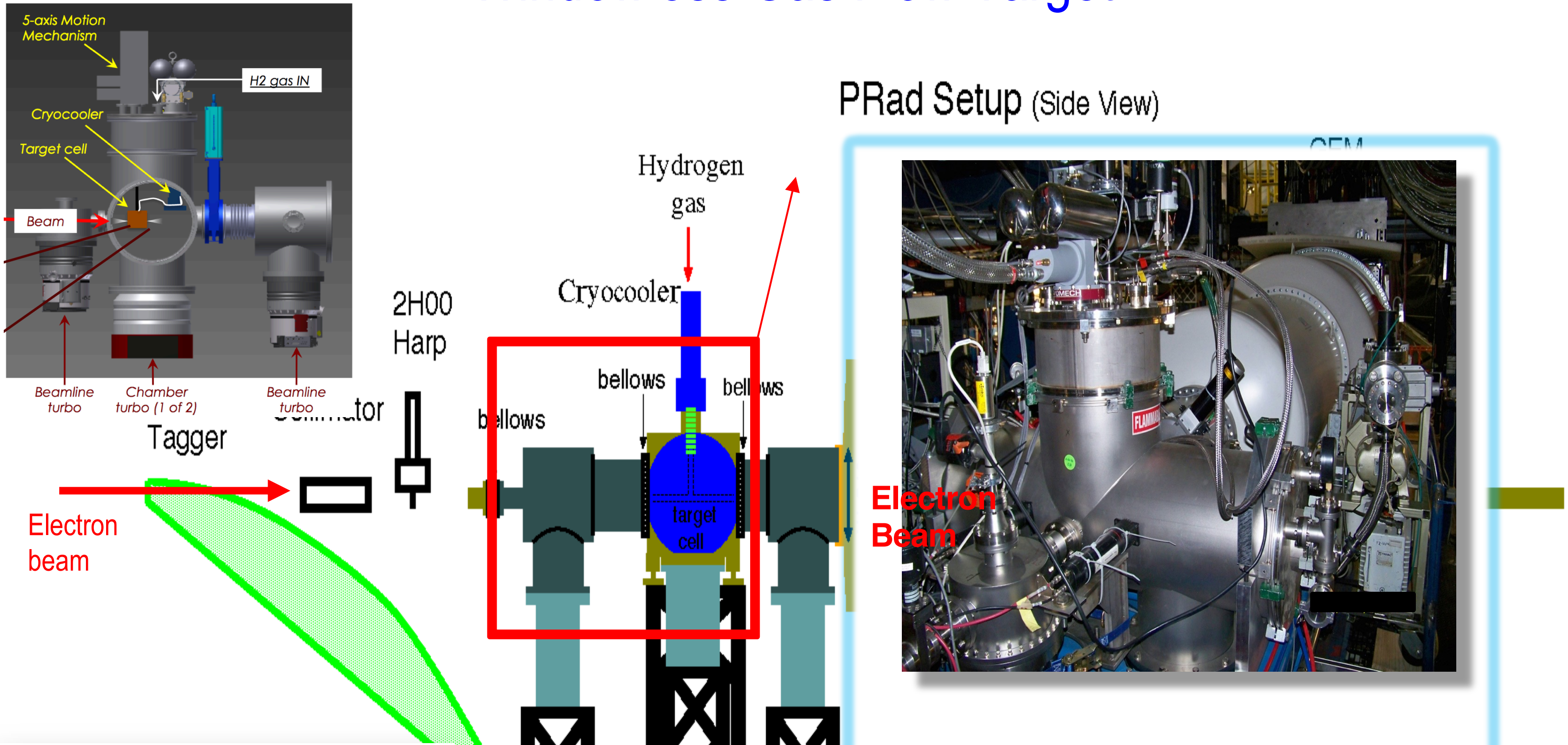
PRad Experimental Setup in Hall B at JLab (schematics)

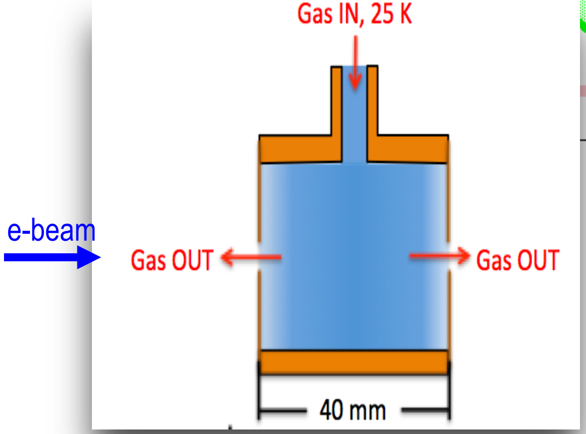
- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- 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



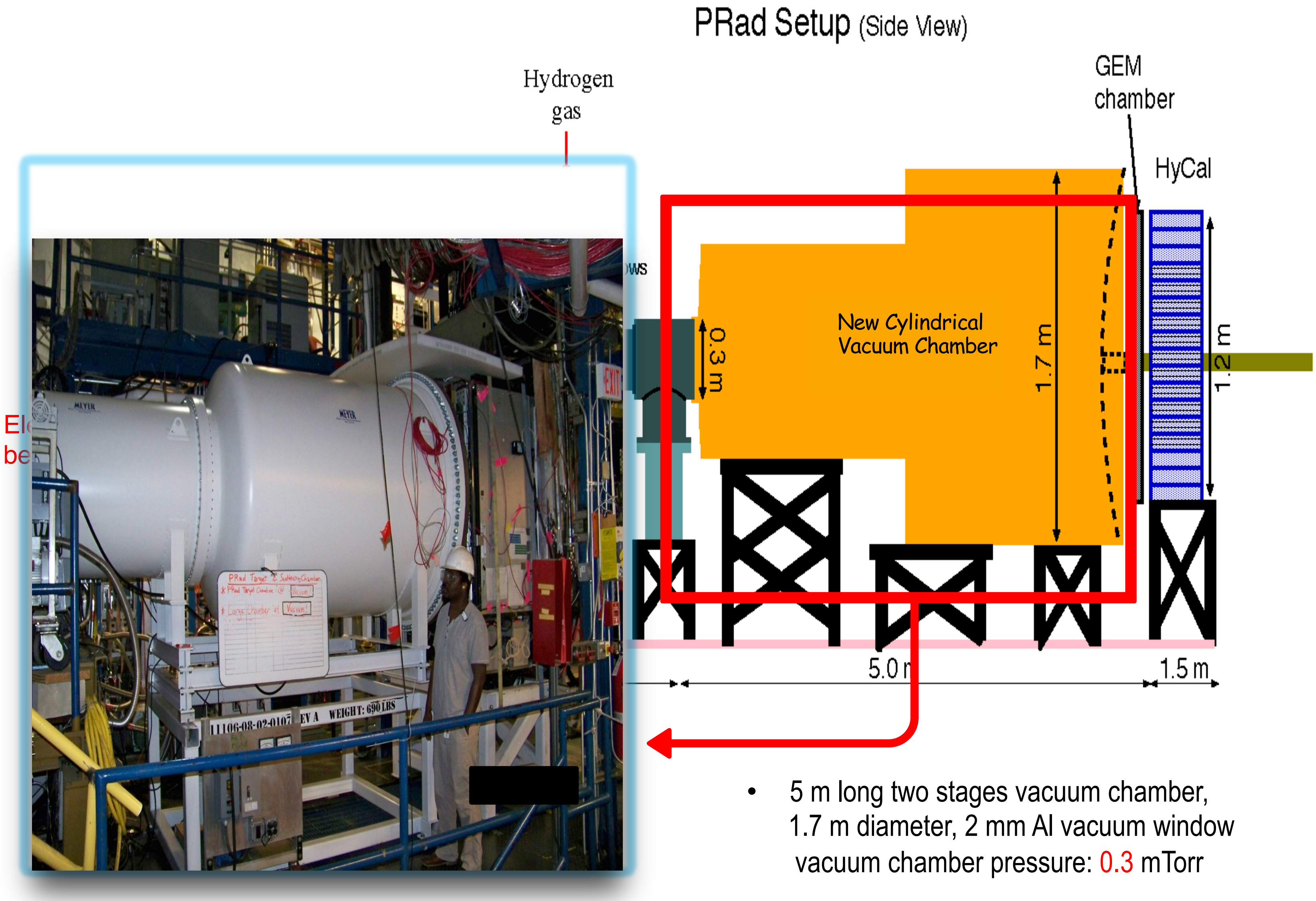
Windowless Gas Flow Target





- 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
    - Gas temperature: 19.5 K

PRad Experimental Apparatus: Vacuum Chamber



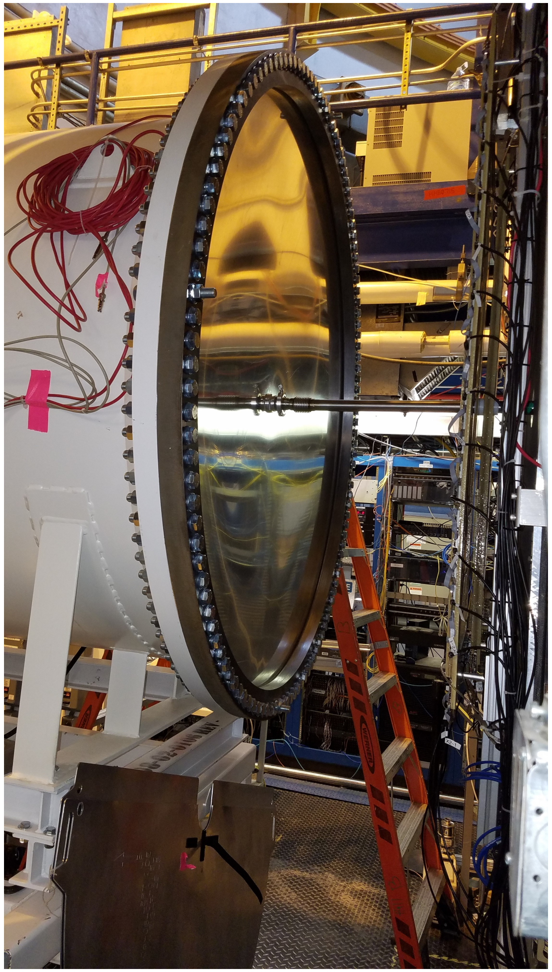
[redacted]

- 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

[redacted]

2-stage vacuum box in Hall B beam line



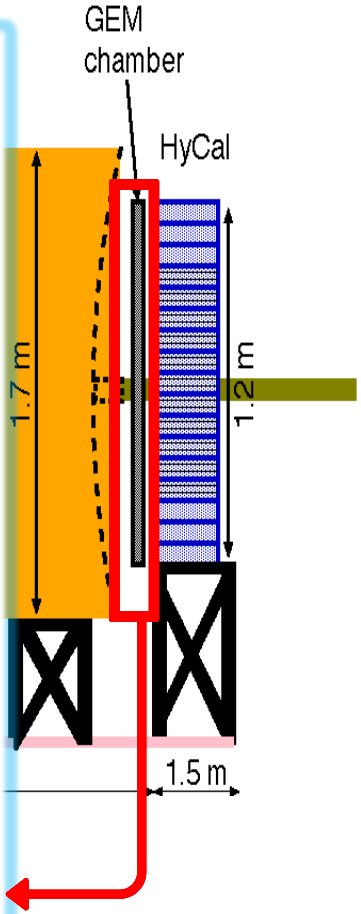
1.7 m diameter, 2 mm Al vacuum window

PRad Experimental Apparatus: GEM Coordinate Detectors

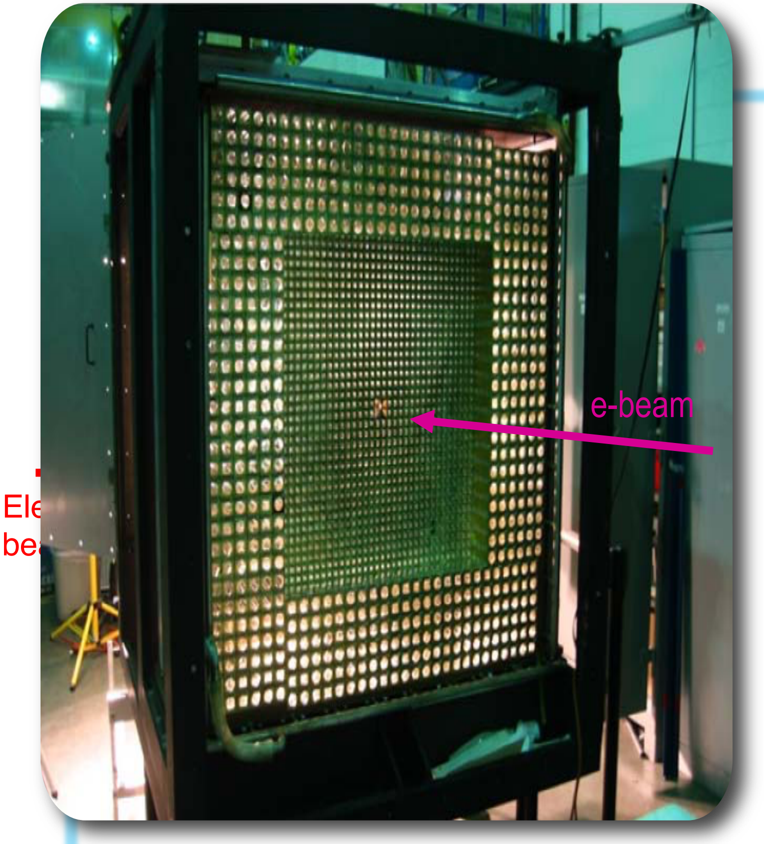
PRad Setup (Side View)

Ele
bea

- 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 Experimental Apparatus: HyCal El. Mag. Calorimeter



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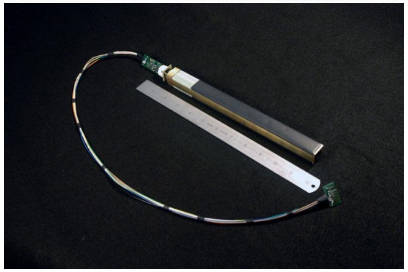
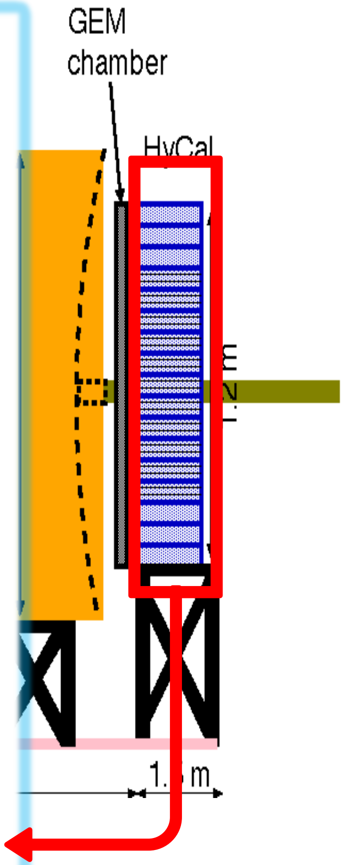


PRad Setup (Side View)

- 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



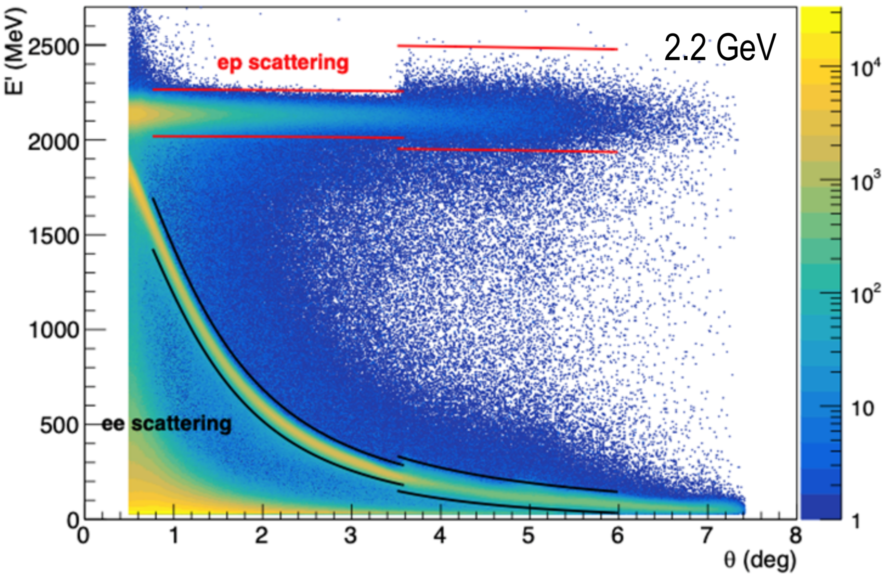
Experimental Data Set: Event Selection

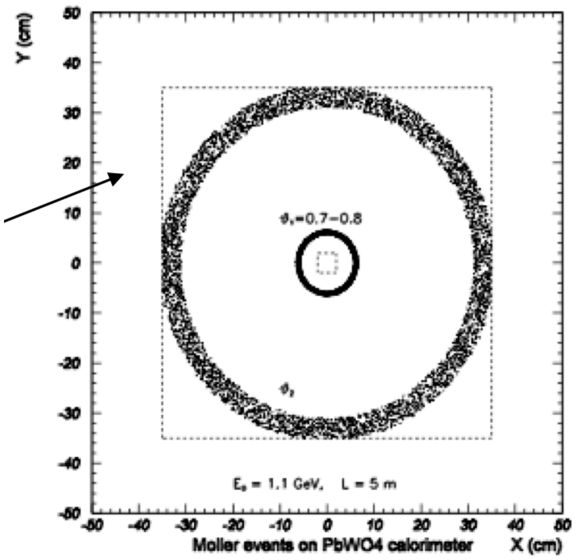
- Experiment performed in May/June, 2016 with two beam energy settings:
  - ✓ 1.1 GeV (604 M events)
  - ✓ 2.2 GeV (756 M events)

- 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

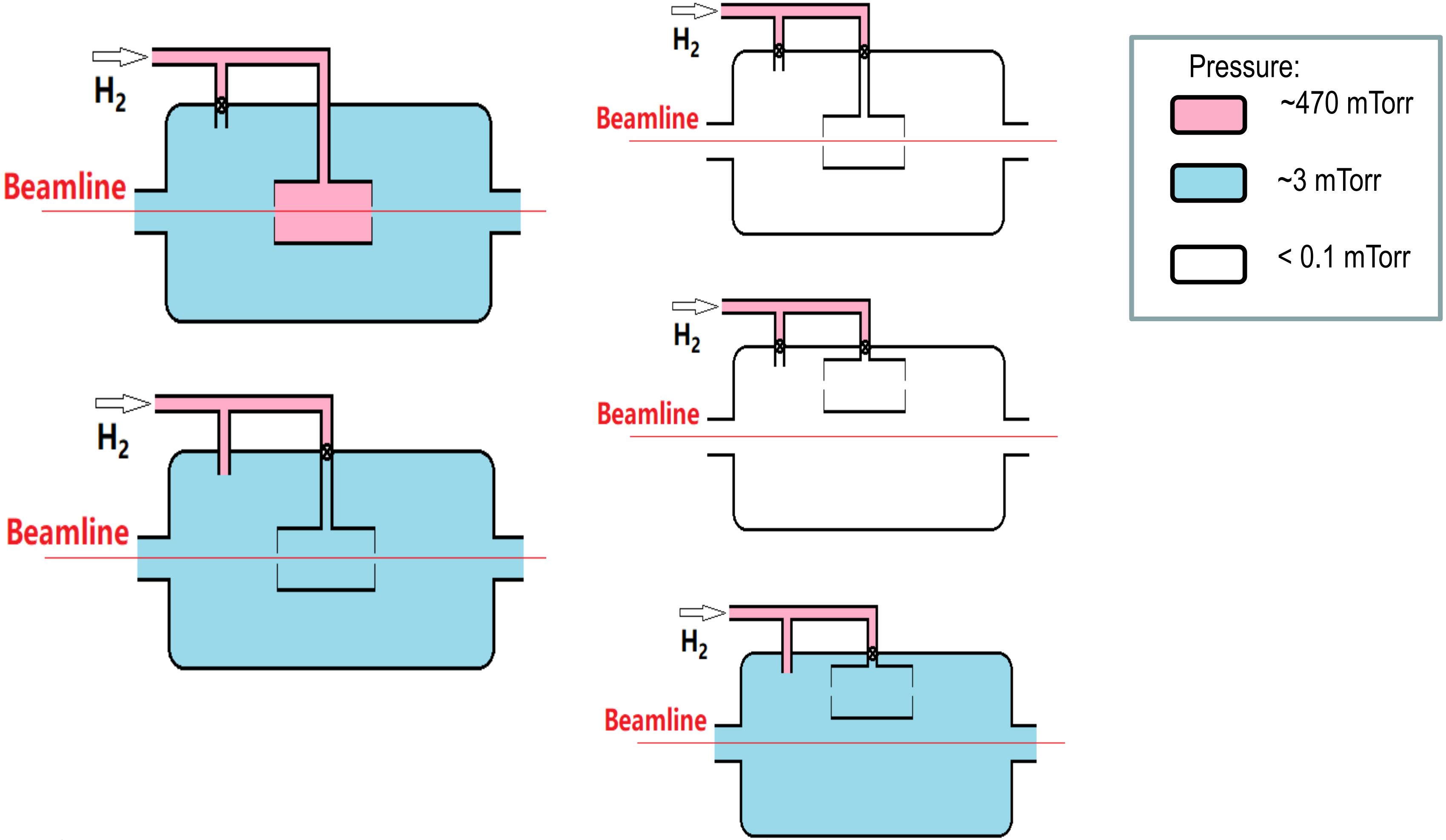
- For *ee*, if requiring double-arm events, apply additional cuts:
  - ✓ elasticity
  - ✓ co-planarity
  - ✓ vertex z (kinematics)





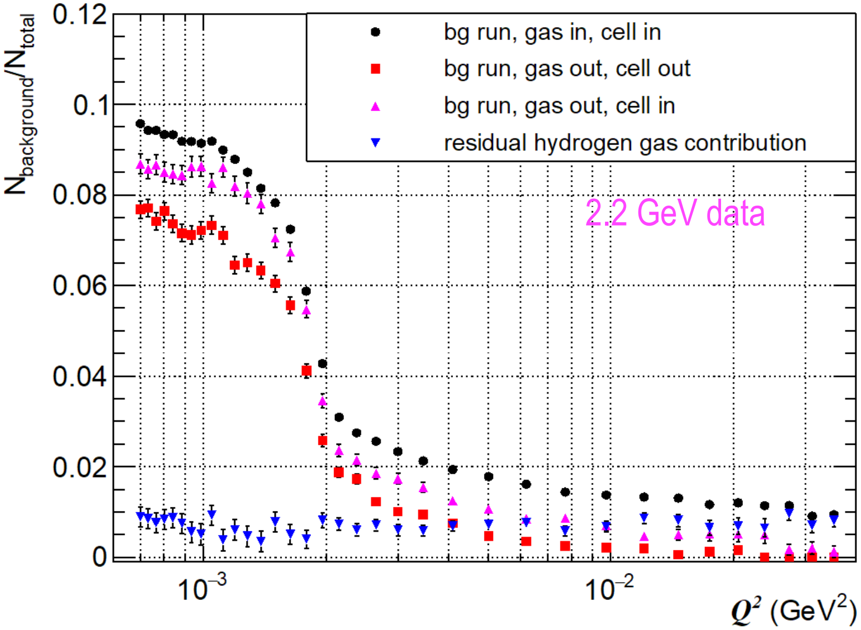
Data Analysis – Background Subtraction

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

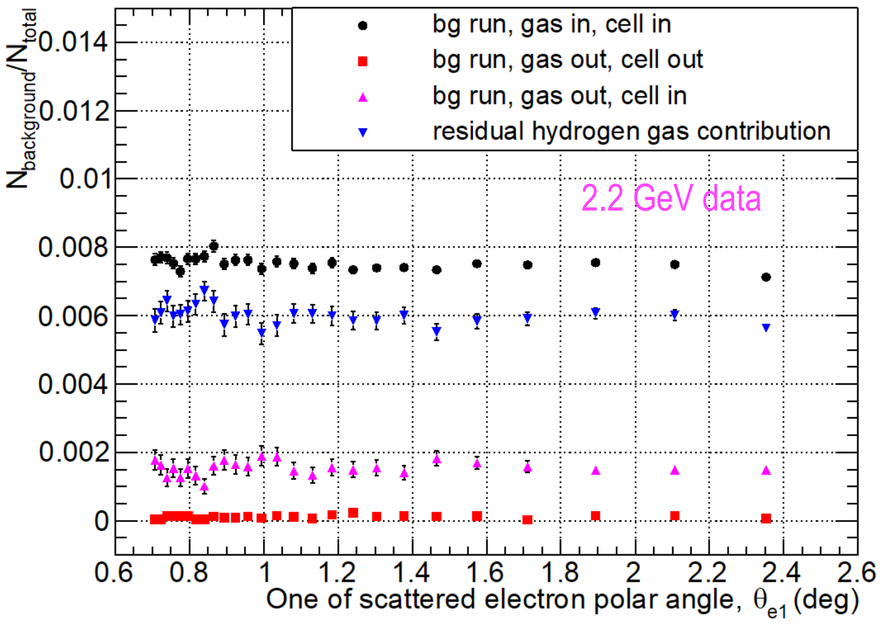


Data Analysis – Background Subtraction

- *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 .



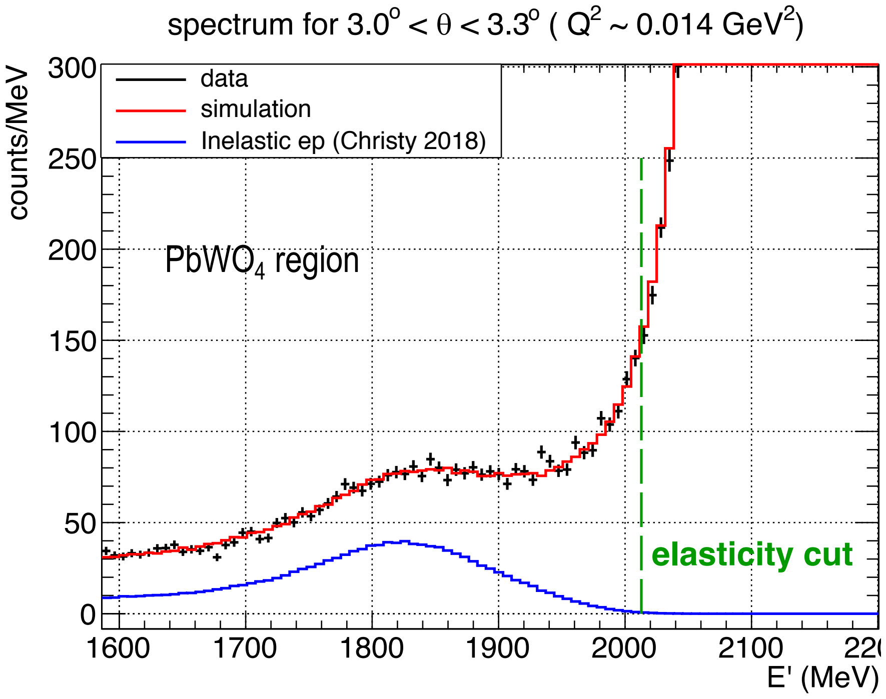
ep **Background Contribution**

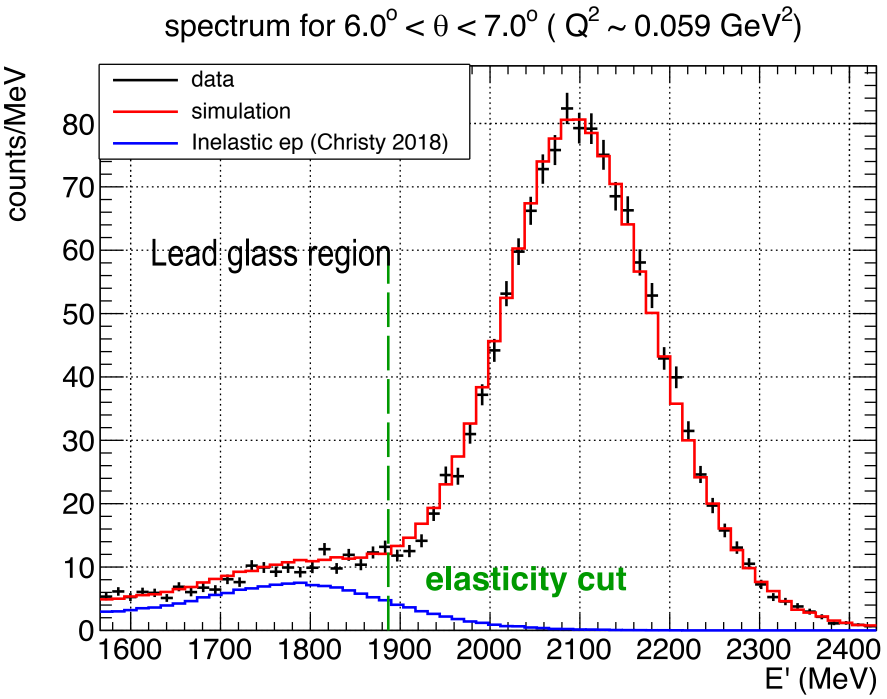


ee **Background Contribution**

Data Analysis – Inelastic *ep* 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

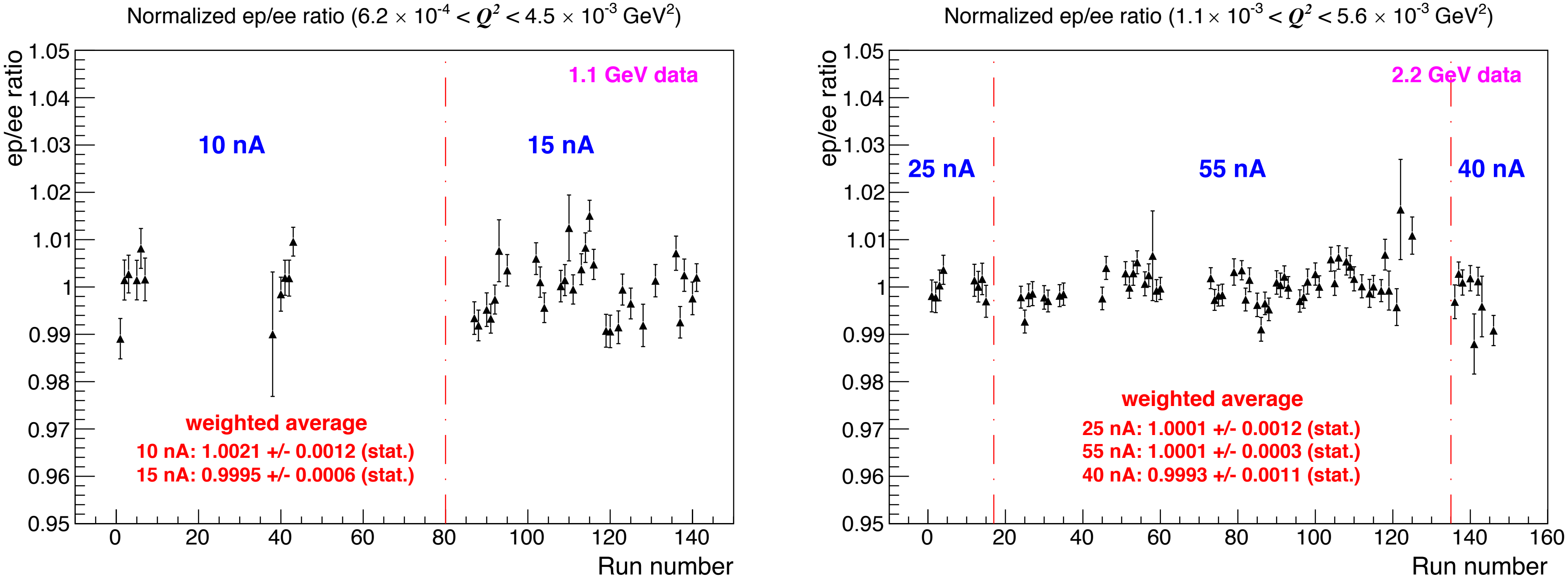

spectrum for $3.0^{o} < \theta < 3.3^{o}$ ($Q^2 \sim 0.014$ GeV^2)


spectrum for $6.0^{o} < \theta < 7.0^{o}$ ($Q^2 \sim 0.059$ GeV^2)

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

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, …


Normalized ep/ee ratio ($6.2 \times 10^{-4} < Q^2 < 4.5 \times 10^{-3}$ GeV^2)

Normalized ep/ee ratio ($1.1 \times 10^{-3} < Q^2 < 5.6 \times 10^{-3}$ GeV^2)

weighted average

10 nA: 1.0021 +/- 0.0012 (stat.)

15 nA: 0.9995 +/- 0.0006 (stat.)

weighted average

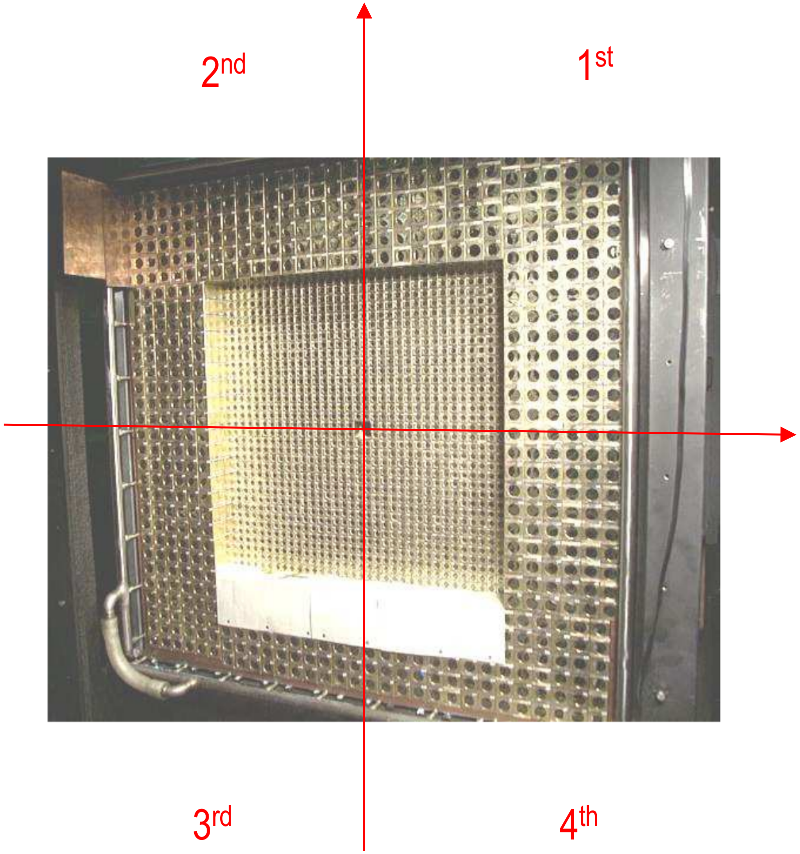
25 nA: 1.0001 +/- 0.0012 (stat.)

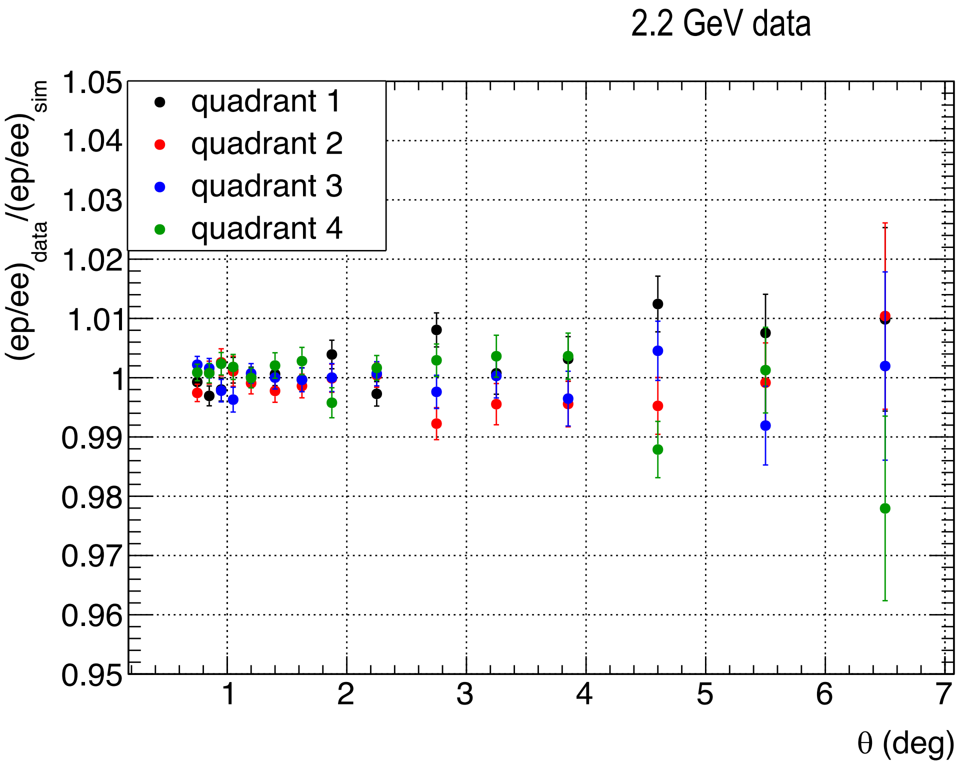
55 nA: 1.0001 +/- 0.0003 (stat.)

40 nA: 0.9993 +/- 0.0011 (stat.)

Data Analysis: Azimuthal Uniformity

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





Extraction of the *ep* → *ep* Elastic Scattering Cross Section

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

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

- Radiative effects corrected by Monte Carlo method:
  - ✓ GEANT4 based simulation package with full geometry setup
  - ✓ event generators with complete calculations of radiative corrections1),2)
  - ✓ iterative procedure applied for radiative corrections

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

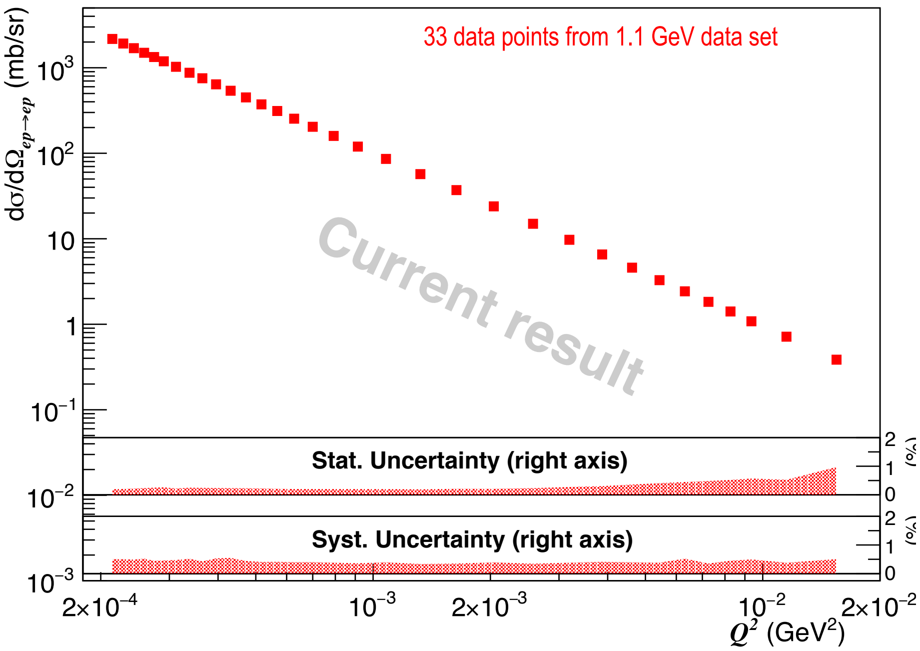
1) A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001;

2) I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (fully beyond ultra relativistic approximation).

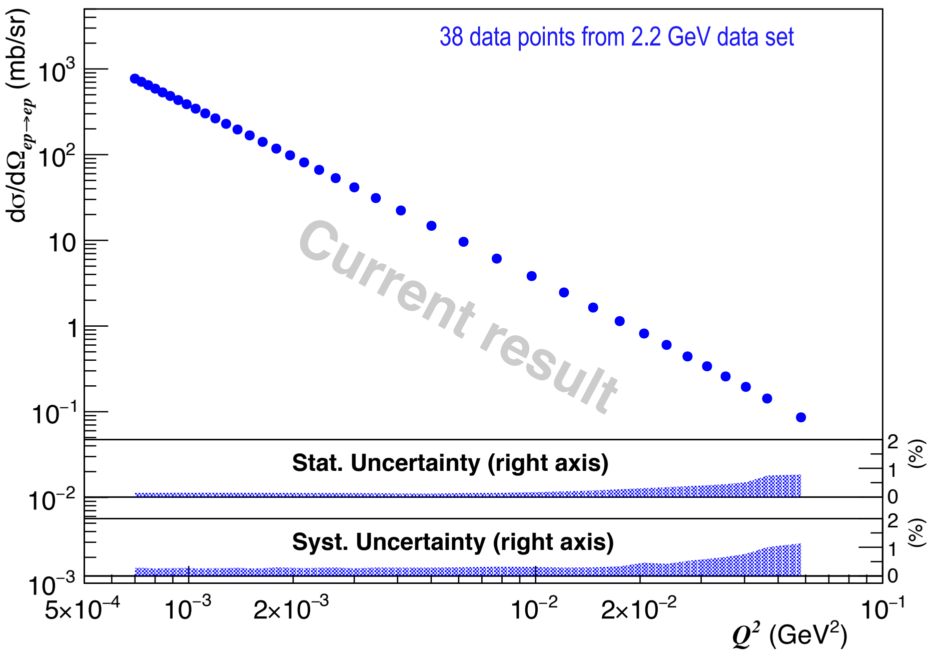
Elastic ep⟶ep Differential Cross Sections (Current)

- Extracted differential cross sections vs. Q^2, with 1.1 and 2 GeV data (current).
- 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.

ep **elastic scattering cross section (1.1 GeV)**



ep **elastic scattering cross section (2.2 GeV)**



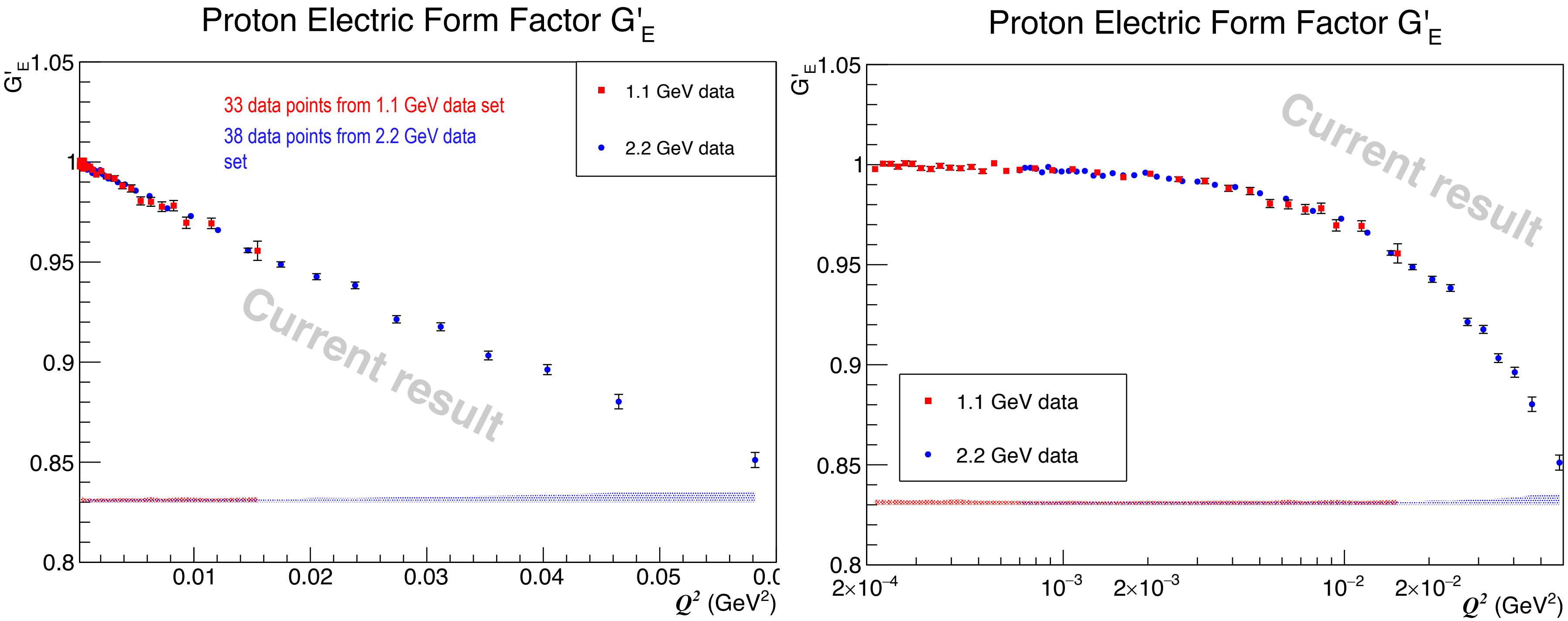
Extracted Proton Electric Form Factor, G_E vs. Q^2

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

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

Using rational (1,1)

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



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

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

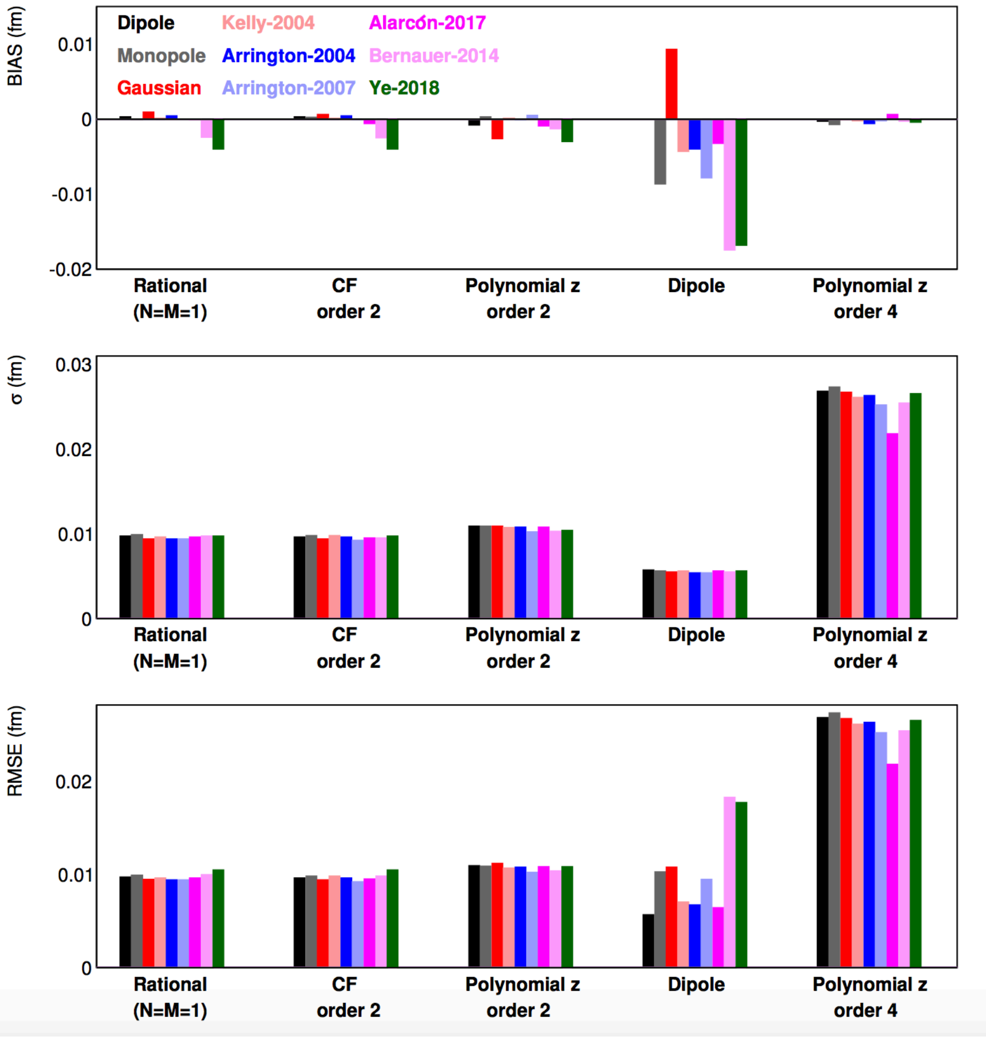
Recent Developments in Fitting Procedures

- 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 = sqrt(bias^2 + σ^2)

- X. Yan, et al. "*Robust extraction of the proton charge radius from electron-proton scattering data*", *PRC 98, 2, 025204, 2018*

Fit to Extract the Proton Radius

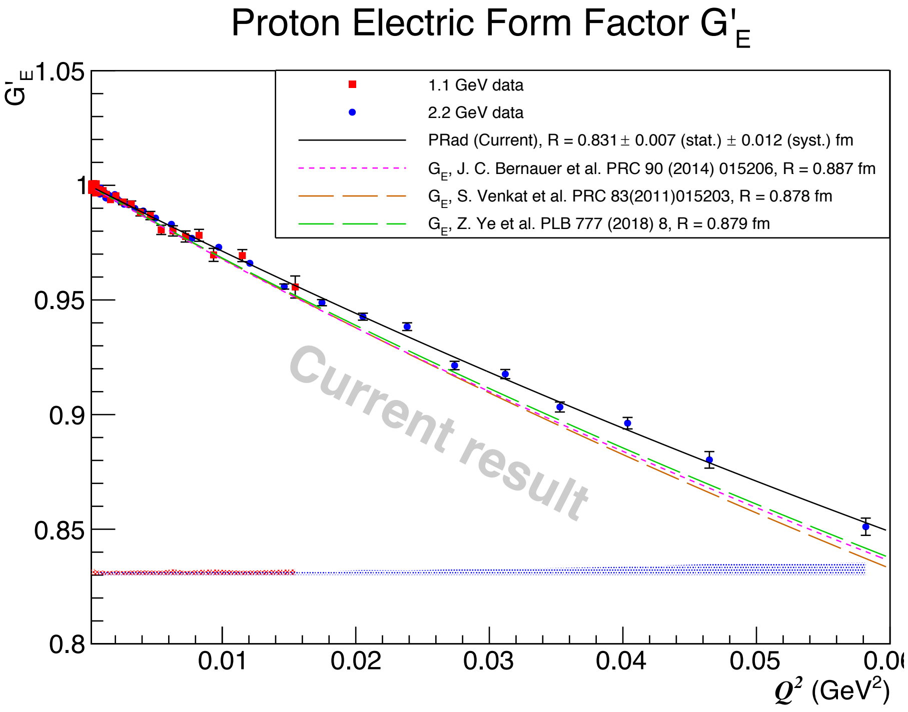
n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

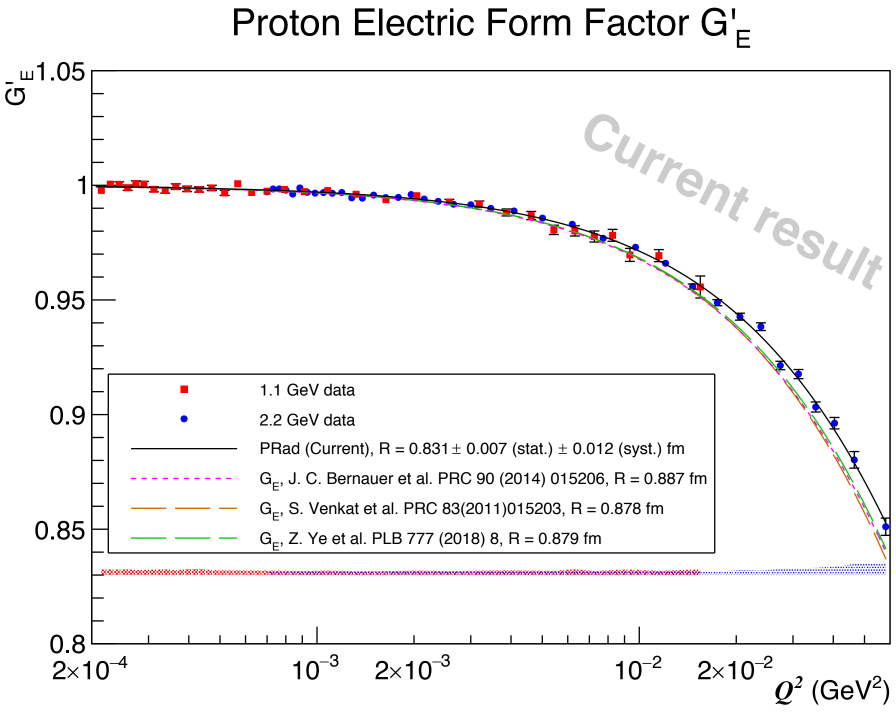
Using rational (1,1)

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

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

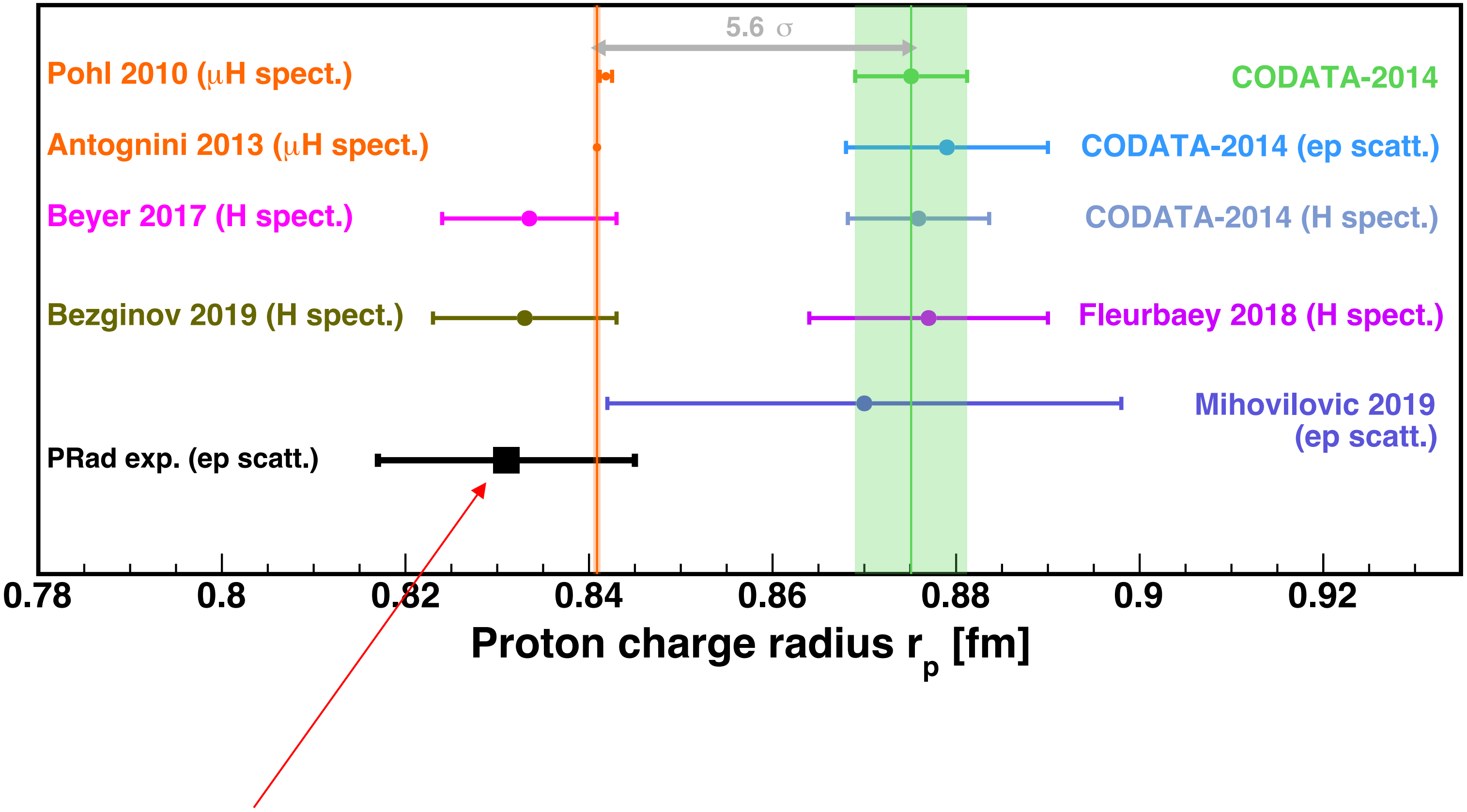
PRad fit shown as $f(Q^2)$ r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm





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

The PRad Final Result on the Radius with the Mainz ISR



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

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:**

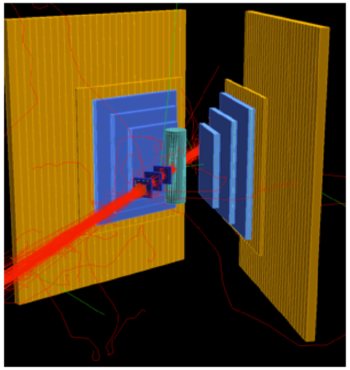
Chao Peng (Duke), Weizhi Xiong (Duke),
Xinzhan Bai (UVa), Li Ye (MSU)

- **Postdocs:**

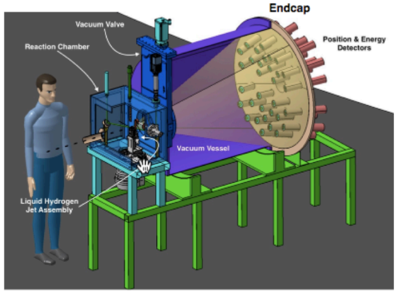
Chao Gu (Duke), Xuefei Yan (Duke),
Mehdi Meziane (Duke), Zhihong Ye (Duke),
Maxime Lavilain (NC A&T), Krishna Adhikari (MSU),
Latif-ul Kabir (MSU), Chandra Akondi (NC A&T)

New Experiments in Progress

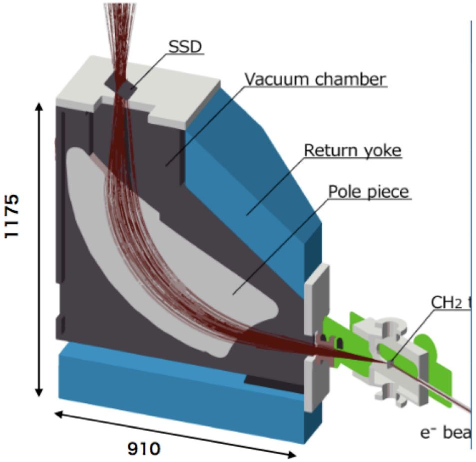
- MUSE at PSI: measure μp and ep scattering (Q^2 range $2x10^{-3} \div 10-2$ GeV^2):
    - test of lepton universality;
    - extraction of proton radius;
    - first results expected very soon.



- ProRad at IPNO, France (Q^2 ,$10^{-6} - 10^{-4}$ GeV^2):
    - 30 ÷ 70 MeV electron beam;
    - extract the proton radius;
    - in a preparation stage.

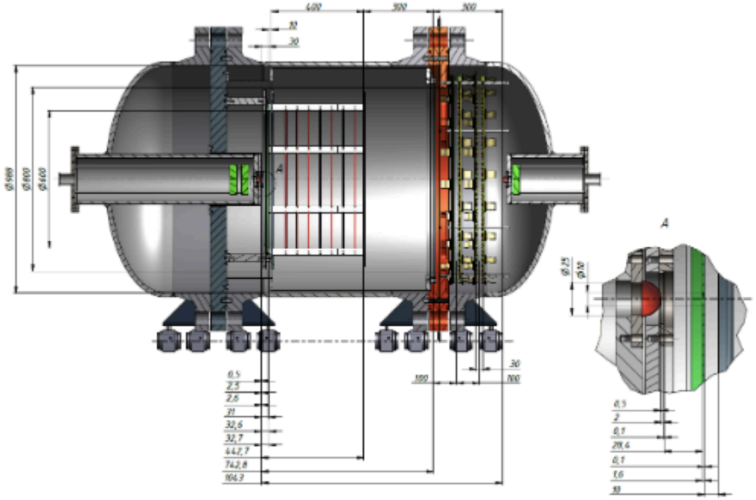


- ULQ^2 at Tohoku Univ. Japan (Q^2 ,$10^{-4} - 10^{-3}$ GeV^2):
    - 20 ÷ 60 MeV electron beam;
    - extract the proton radius
    - in commissioning stage.



Planning Experiments

- High pressure hydrogen gas TPC detector at Mainz,
  - ep→ep scattering at moderate energies;
  - detection of recoil proton;
  - promising to reach Q^2 10^{-5} GeV^2 range;
  - extraction of the proton radius;
  - first collaboration meeting on March 11.

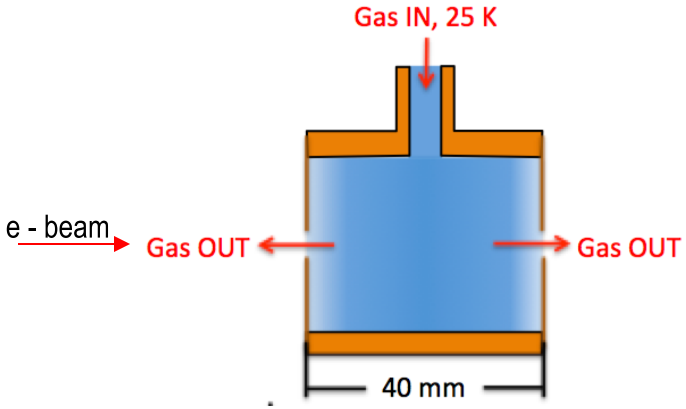


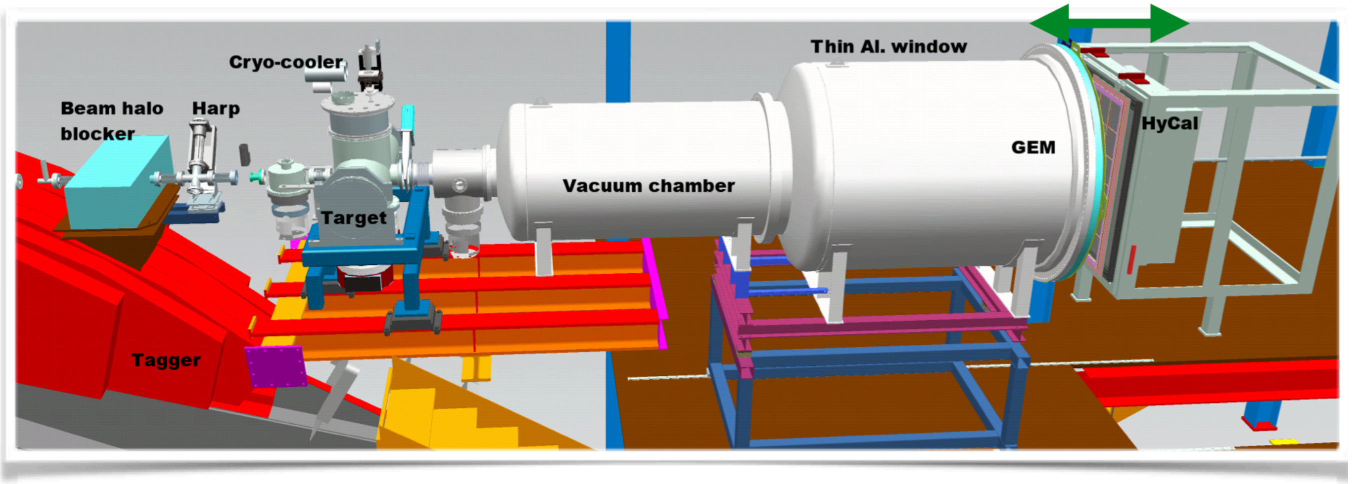
- The same high pressure hydrogen TPC detector at COMPASS (Q^2 range: $10^{-4} – 1$ GeV^2):
  - $\mu p \rightarrow \mu p$ scattering at high energies;
  - detection of the recoil proton;
  - extract the proton radius;
  - in a planning stage.

Possible Extension of the PRad Experiment: PRad-II at JLab

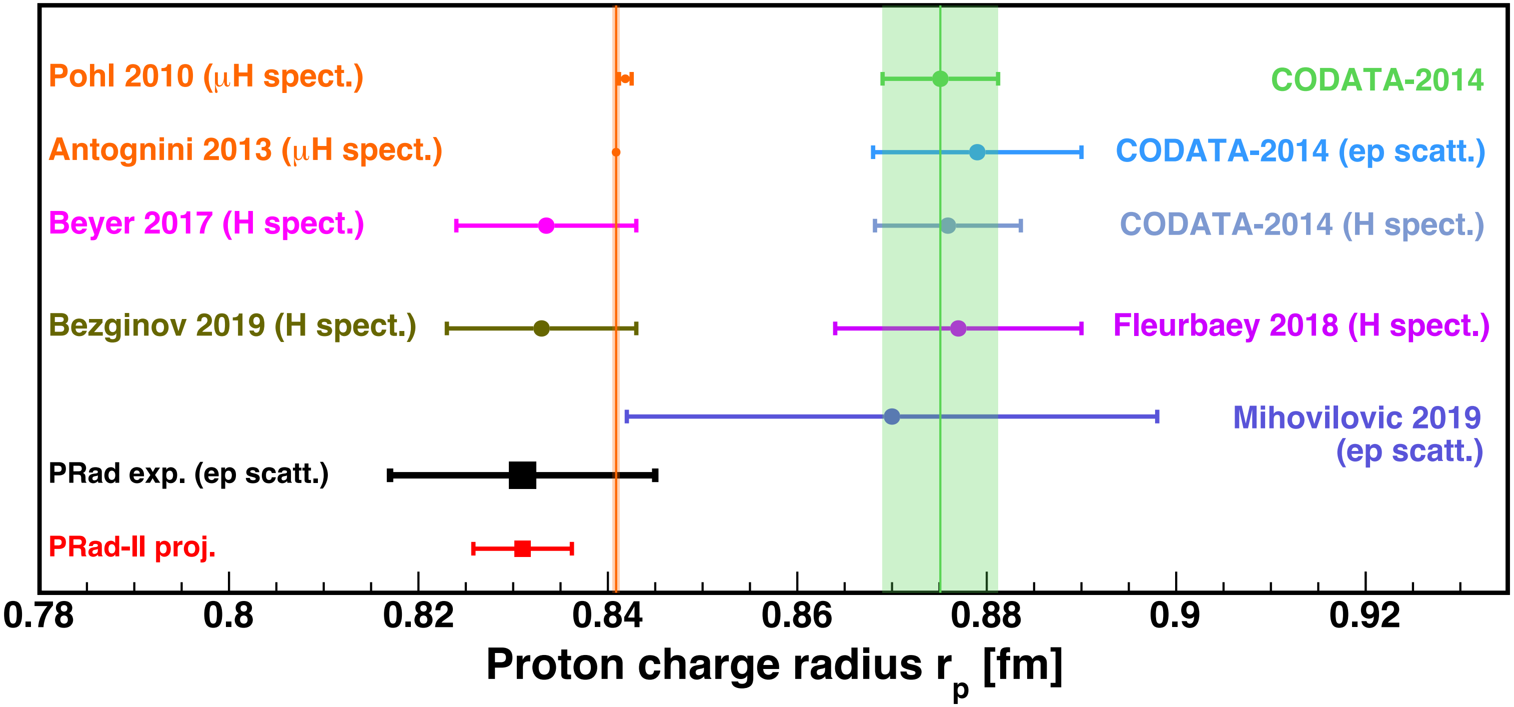
- We are preparing a proposal to JLab PAC-48 (this summer) to get maximum precision with the PRad method:
  - add second GEM detector for tracking;
  - modify the hydrogen gas target: looking for a liquid hydrogen droplet target;
  - 4 times more statistics;

  - upgrade HyCal to all $PbWO_4$ crystals;
  - upgrade DAQ based on FADC electronics;





Possible Extension of the PRad Experiment: PRad-II at JLab



PRad result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm (±1.67%)

PRad-II projected:
expect 2.5 times improvement in total uncertainty:
R_p = 0.8?? ± 0.003 (stat.) ± 0.005 (syst.) fm (±0.67%)

Summary

- The “*Proton Radius Puzzle”* is becoming more “puzzling” recently ” !?:
  - two recent experiments performed in the spectroscopy sector: not much agreement !!!
  - discrepancy between ep-scattering and muonic hydrogen experiments unchanged (before PRad).

- 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 settings, $[2x10^{-4} \div 6x10^{-2}]$ GeV/C^2.
  - ✓ lowest Q^2 data set ($\sim 10^{-4}$ 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.

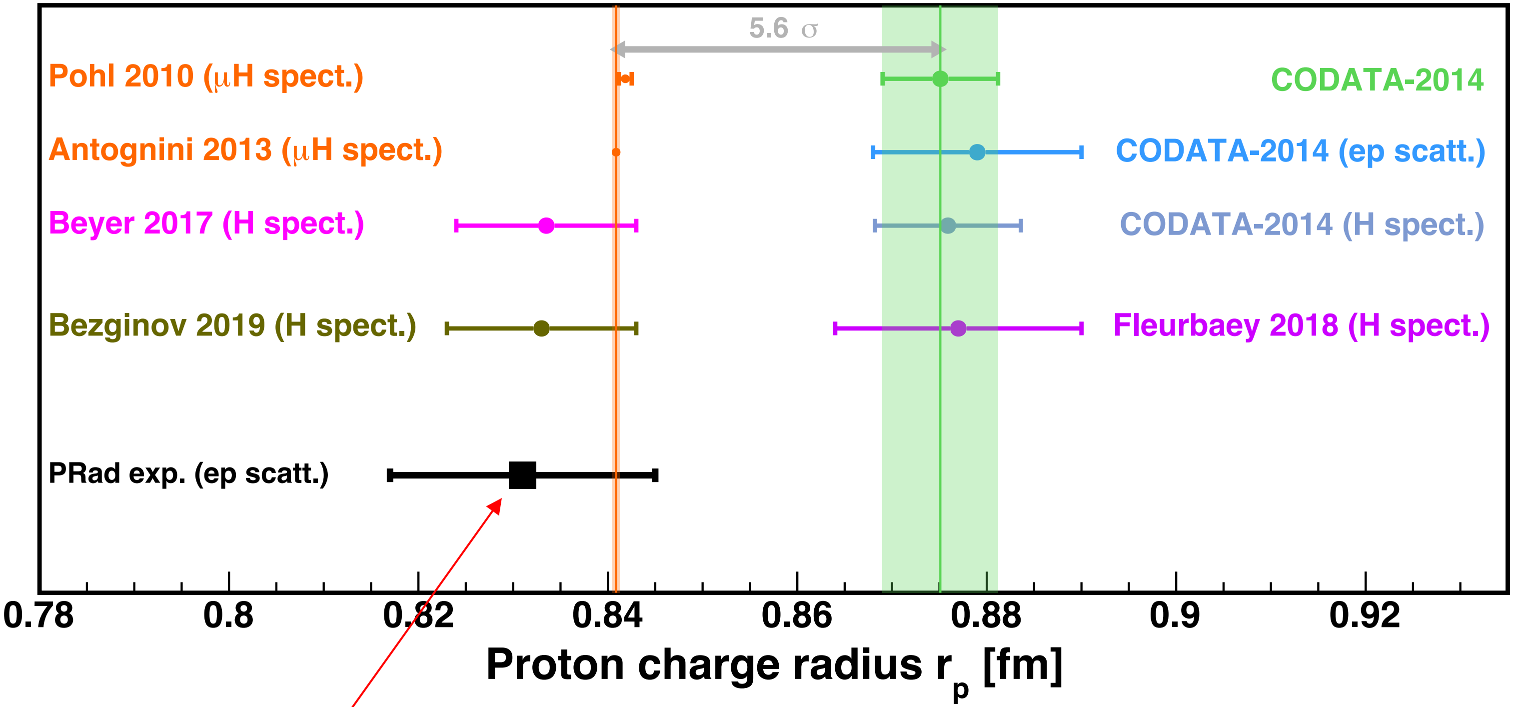
- The PRad final result supports small proton charge radius:
  - ✓ **$R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm (±1.67% total)**

- Is the “Proton Radius Puzzle” solved???
  - ➢ … wait for few more experiments!

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

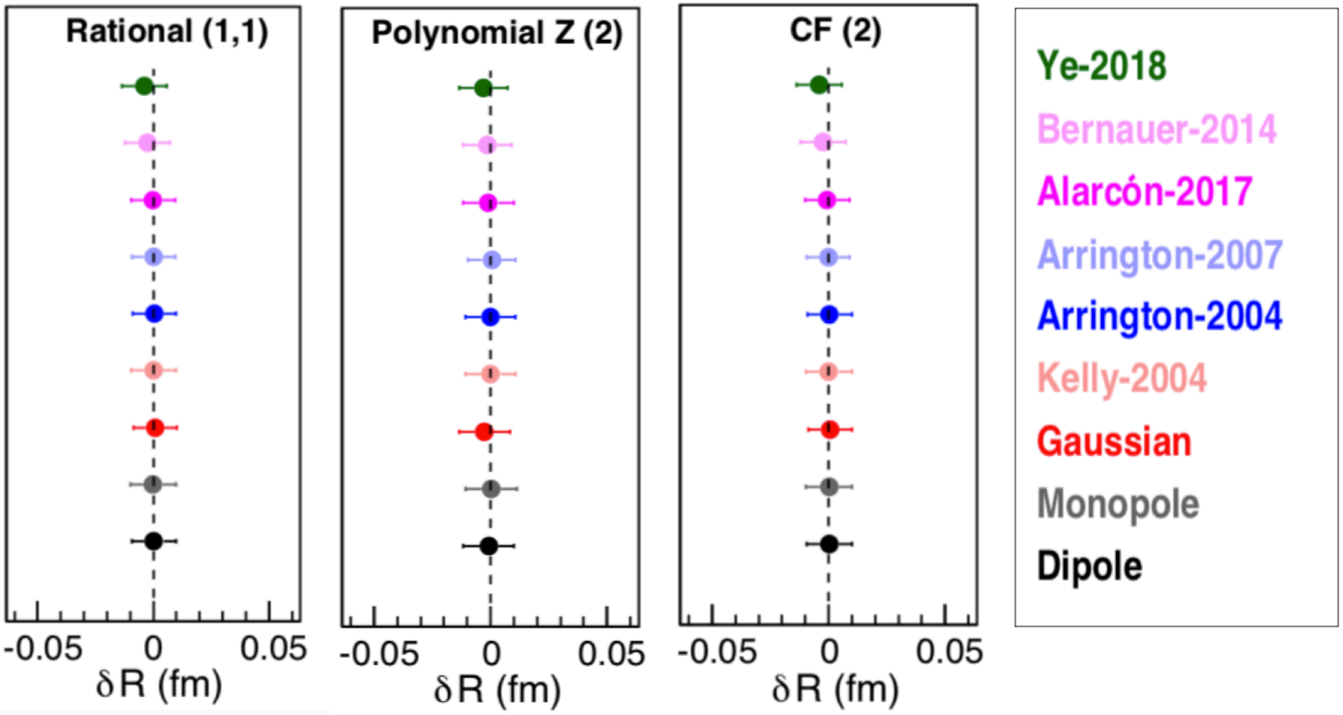
Thank you!

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

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

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

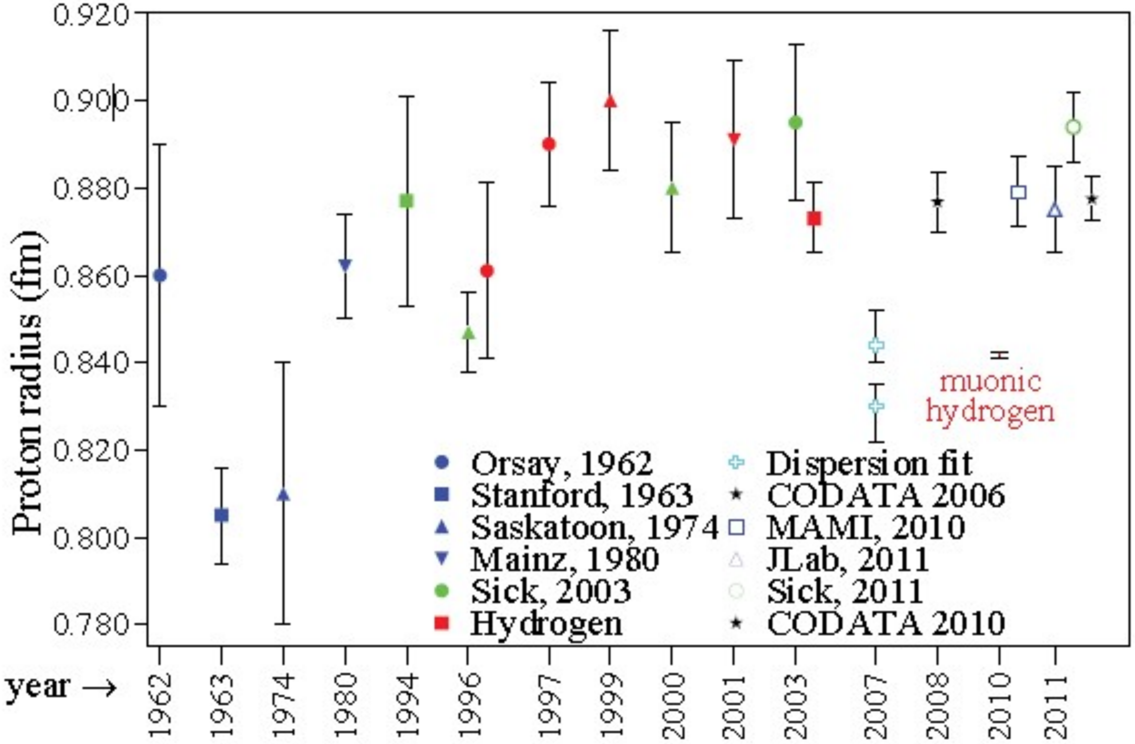
The robustness = root mean square error (RMSE)

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

Systematic Uncertainties

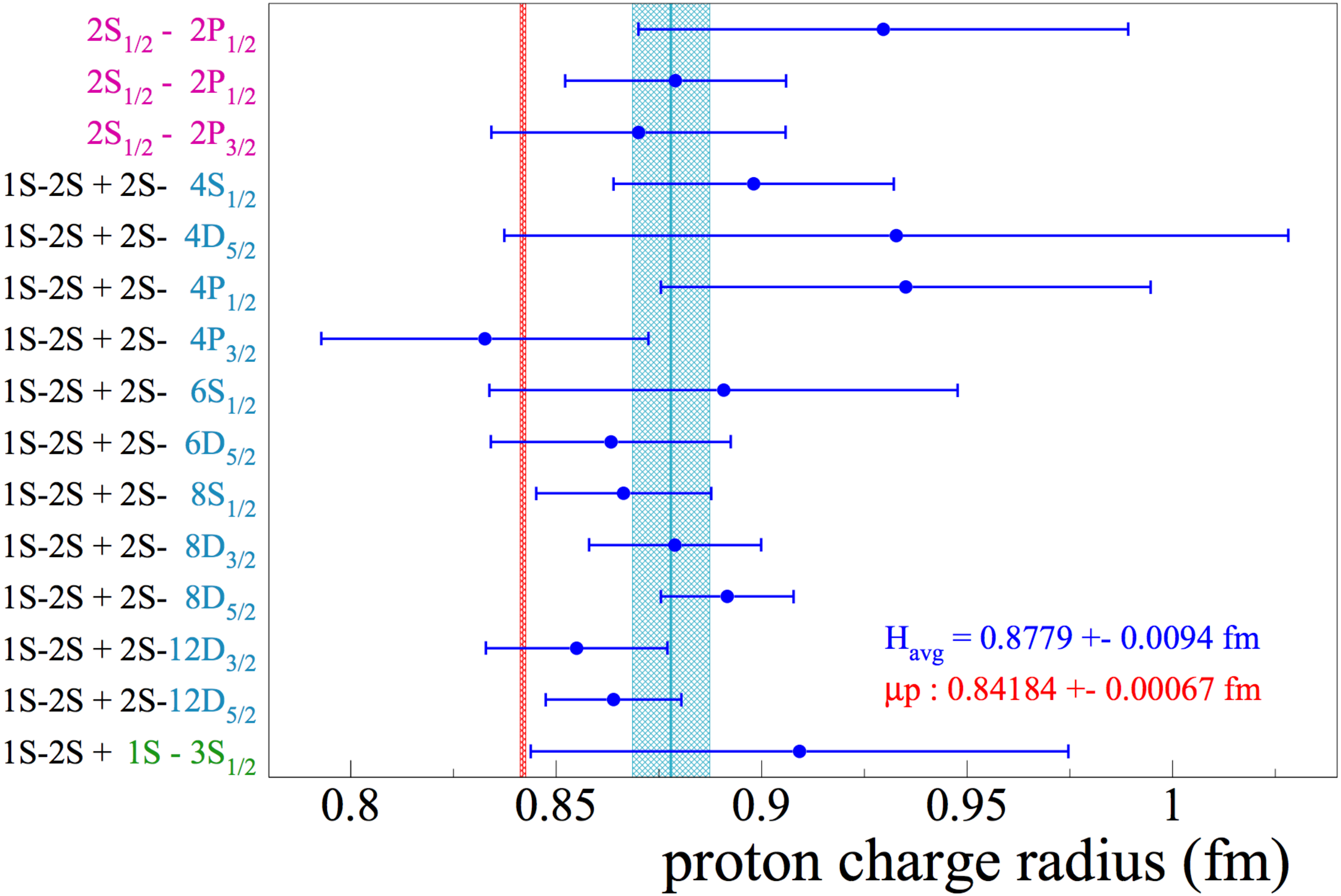
Item	R_p uncertainty (fm)	n_1 uncertainty (1.1GeV)	n_2 uncertainty (2.2GeV)
Event selection	0.0070	0.0002	0.0006
Radiative correction	0.0069	0.0010	0.0011
Detector efficiency	0.0042	0.0000	0.0001
Beam background	0.0039	0.0017	0.0003
HyCal response	0.0029	0.0000	0.0000
Acceptance	0.0026	0.0001	0.0001
Beam energy	0.0022	0.0001	0.0002
Inelastic ep	0.0009	0.0000	0.0000
Total	0.0116	0.0020	0.0013

Proton Radius Extracted From e-p Scattering Experiments



- More different analysis results than actual experiments
- Started with: $r_p \approx$ 0.81 fm in 1963
- Reached to: $r_p \approx$ 0.88 fm by 2011

Proton Radius from Regular Hydrogen Spectroscopy



A. Gasparian