# The PRad Experiments at Jefferson Lab

## (PRad, PRad-II, DRad, and more)

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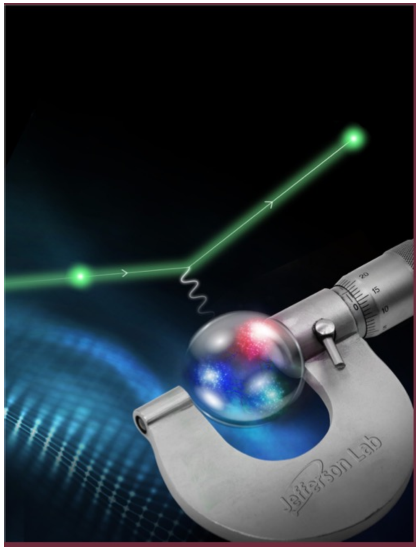
for the PRad collaboration

## Outline

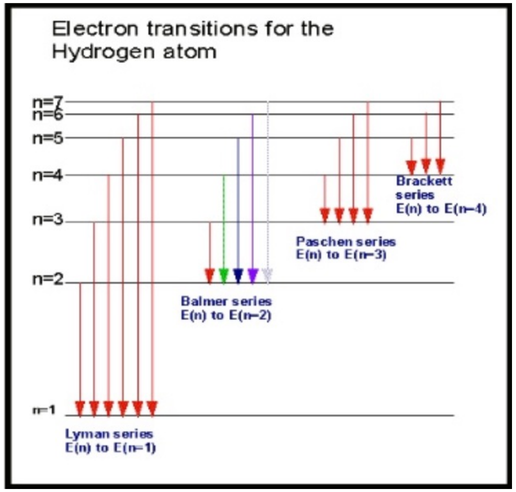
- the PRad approach for new ep-experiments
- PRad experiment and the results
- new approved experiment, PRad-II
- new proposal, DRad
- Summary and outlook



# Proton Charge Radius

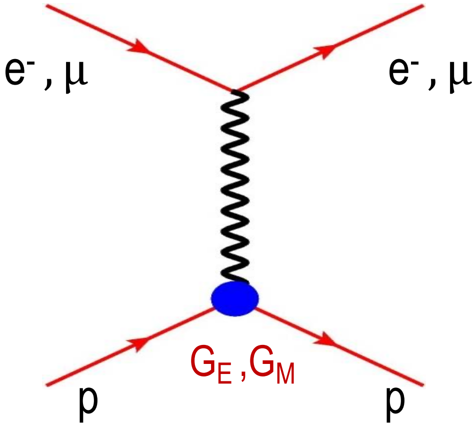
One of the most fundamental quantities in physics:

- atomic physics:
  - ✓ precision atomic spectroscopy (QED, Lamb shifts, Rydberg constant $R_\infty$);
  - ✓ $r_p$ is strongly correlated to $R_\infty$
- 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):
  - ordinary hydrogen
  - muonic hydrogen
- Lepton-proton elastic scattering (Nuclear Physics):
  - ep- scattering (like MAMI, PRad, ULQ2, …)
  - μp- scattering (like MUSE, AMBER, …)

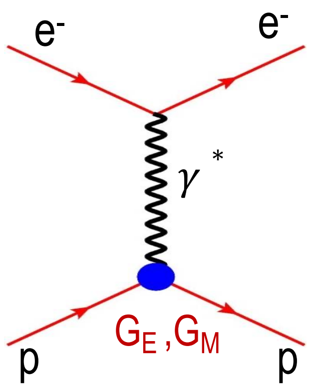


# Proton Radius from ep→ep Scattering Experiments

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

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

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



- Structureless proton:

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

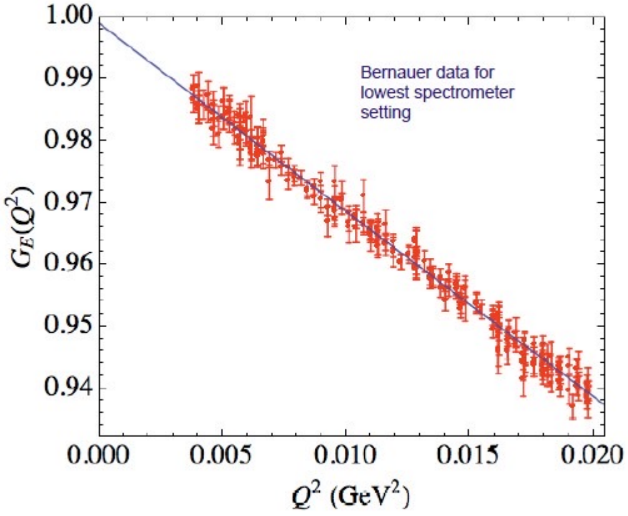
- $G_E$ and $G_M$ can be extracted using Rosenbluth separation
- for extremely low $Q^2$, the cross section is dominated by $G_E$
- Taylor expansion of $G_E$ at low $Q^2$

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

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:

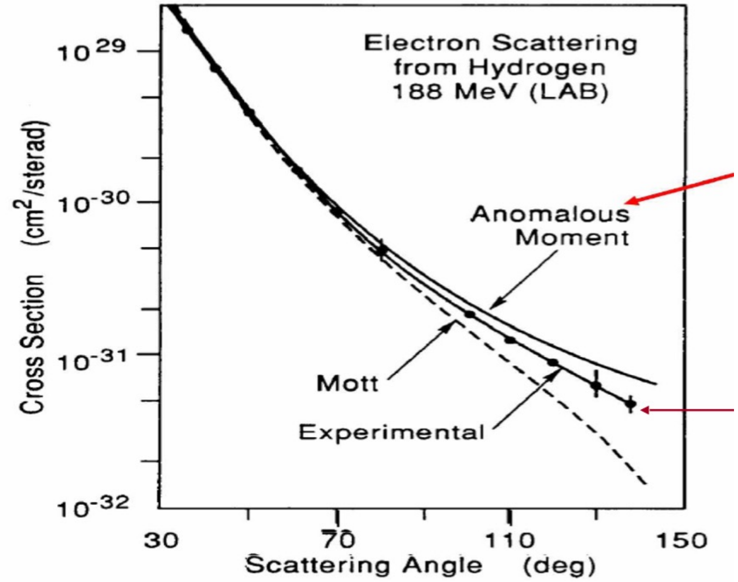
  “*for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the **structure of nucleons***”

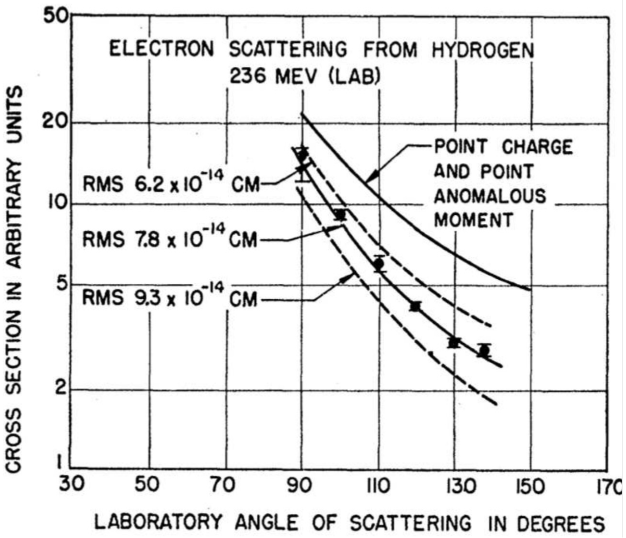
“***proton has a diameter of $0.74 \mp 0.24$ x $10^{-13}$ cm***”

$r_p$ = 0.74 fm with a 32% uncertainty

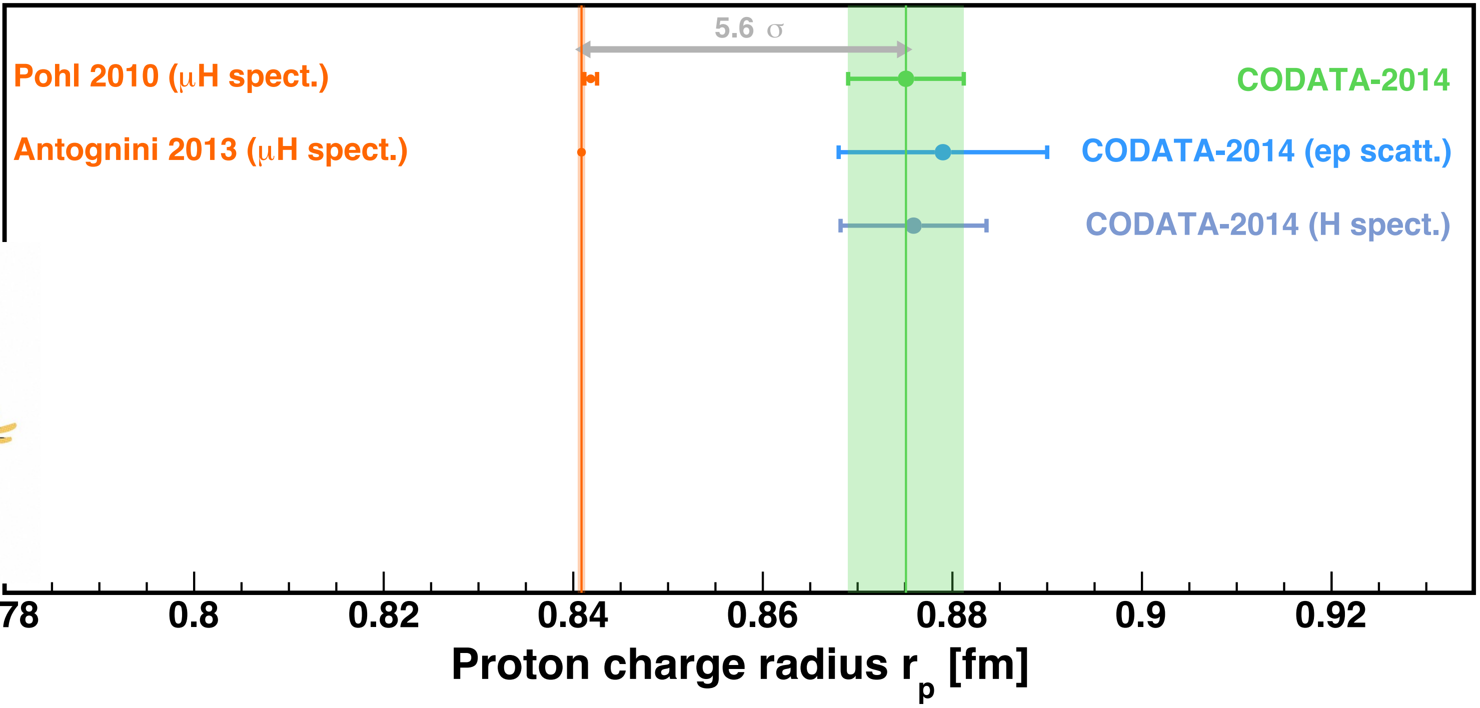
Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956)

- Over 60 years of experimentation!
  - ✓ started from 0.74 fm in 1956
  - ✓ raised to 0.895 fm by 2010.
  - ✓ ended to 0.8414 fm in 2018





# The Proton Radius Puzzle before the PRad Experiment (2016)



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

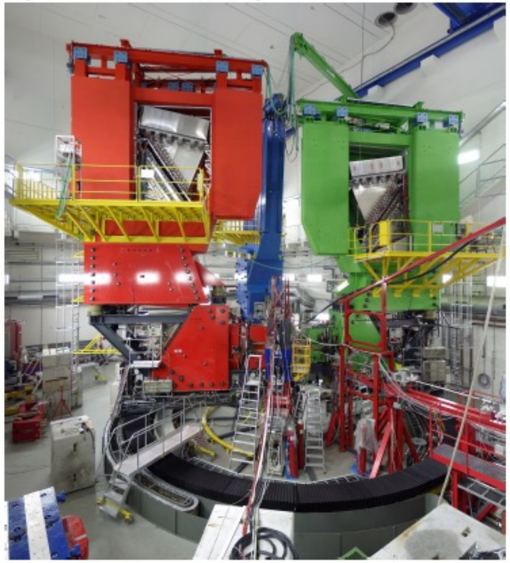
# Possible Resolutions to the *Proton Radius Puzzle*

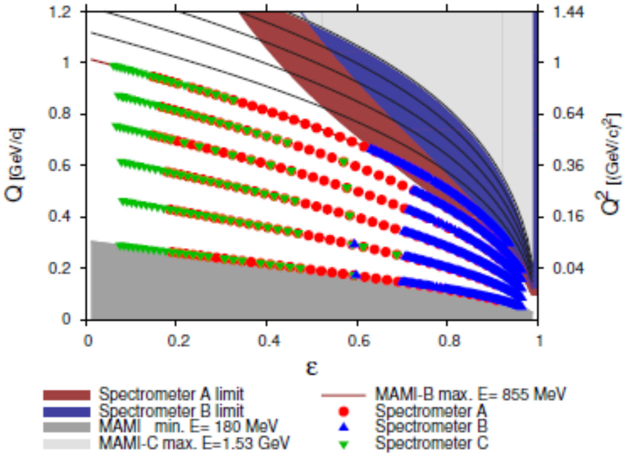
- Some initial open questions about QED calculations:
  - additional corrections to muonic-hydrogen. Not found
  - missing contributions to electronic-hydrogen. Not found
  - higher moments in electric form factor; Not significant
  - …
- Is the ep-interaction the same as μp-interaction (the lepton universality 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 ($\Theta_e$) , 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:





# The PRad Experimental Approach

1) Use large acceptance, high resolution electromagnetic calorimeter (together with a GEM coordinate detector):

   - ✓ measure all angles in one experimental setting ($\vartheta_e = 0.6^0 - 7.0^0$)
     ($Q^2 = 2\text{x}10^{-4} \div 6\text{x}10^{-2}$) GeV/c$^2$ ;
   - ✓ access to smaller angles ($\vartheta_e \approx 0.6^0$)
   - ✓ calibrate with a well-known QED process: azimuthal symmetry of the calorimeter, simultaneous detection of ee → ee Moller scattering (best known control of systematics).

2) 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.

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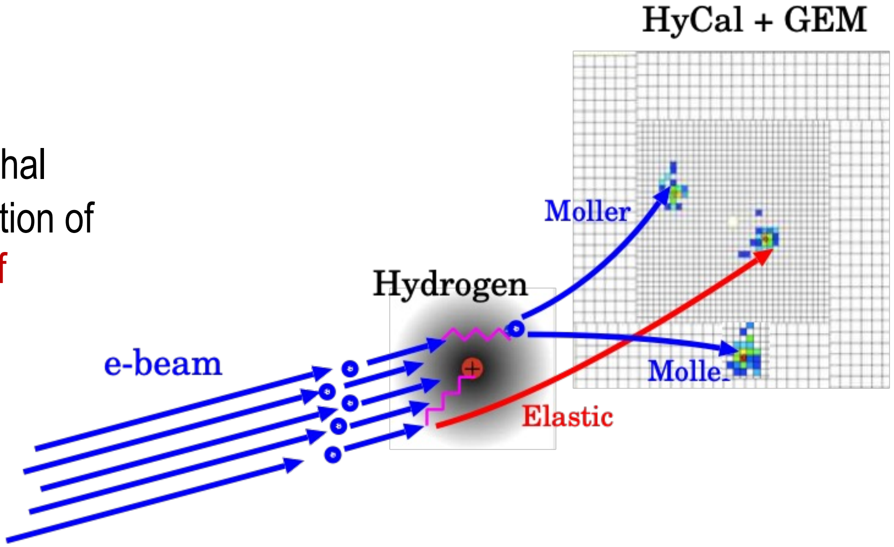

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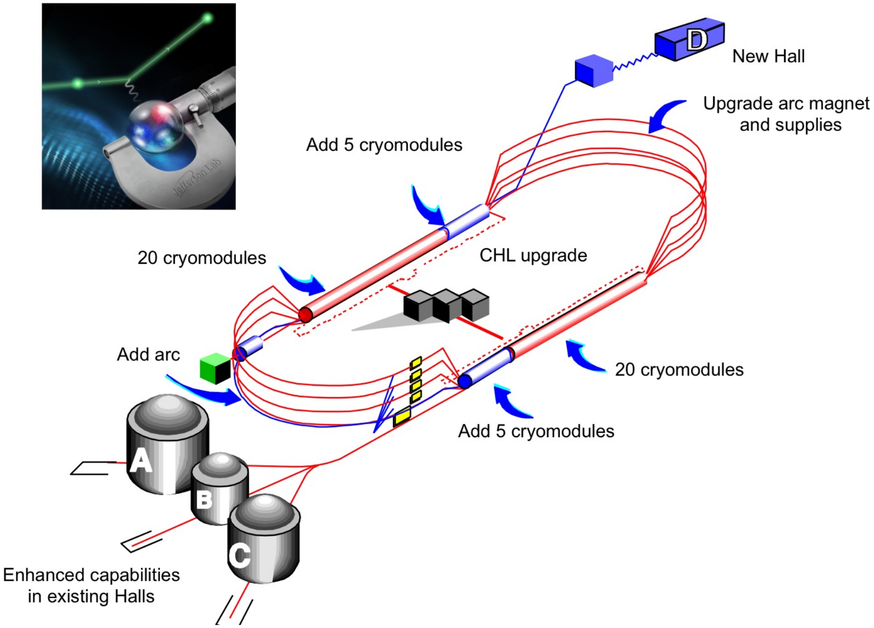
   - ✓ minimize experimental background.

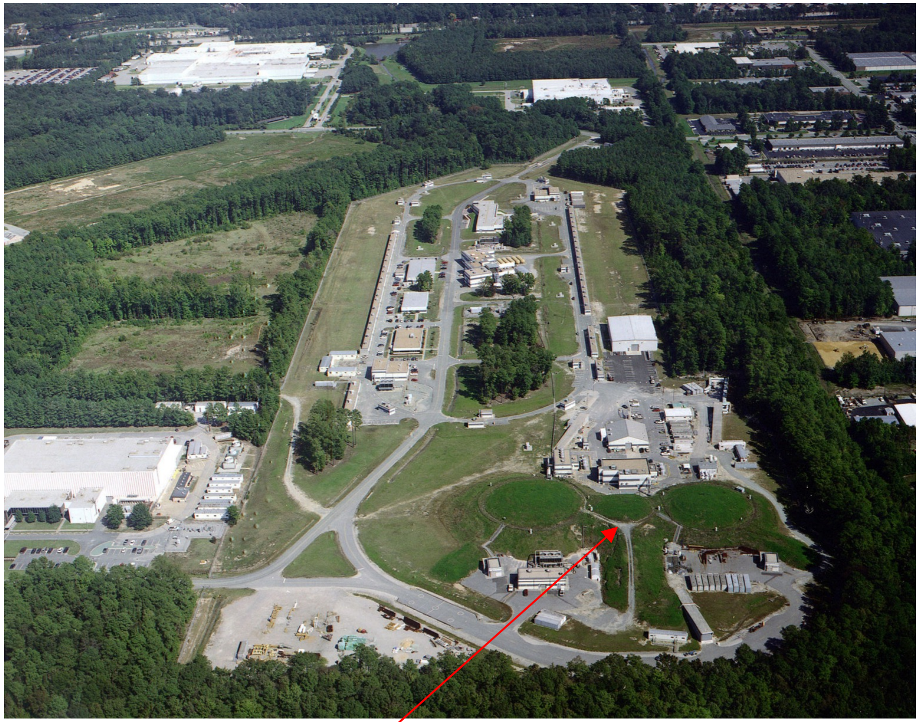
- Use two beam energies only: $E_0$ = 1.1 GeV and 2.2 GeV to check the consistency of experimental data.

# 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 |
| ✓ | Preliminary results released | Summer 2018 (Mainz workshop) |
| ✓ | Publication in Nature, 575, 145–150 (2019) | November, 2019 |

# PRad Experiment Performed in Hall B at Jefferson Lab



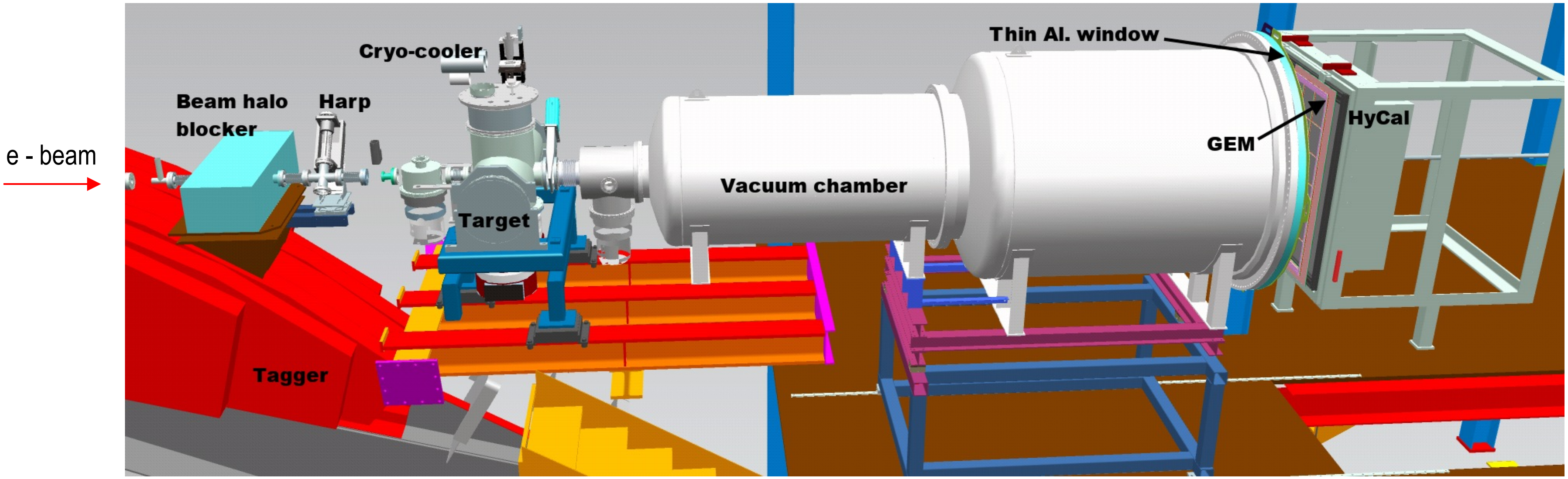


PRad was performed in Hall B at JLab
in January – June of 2016

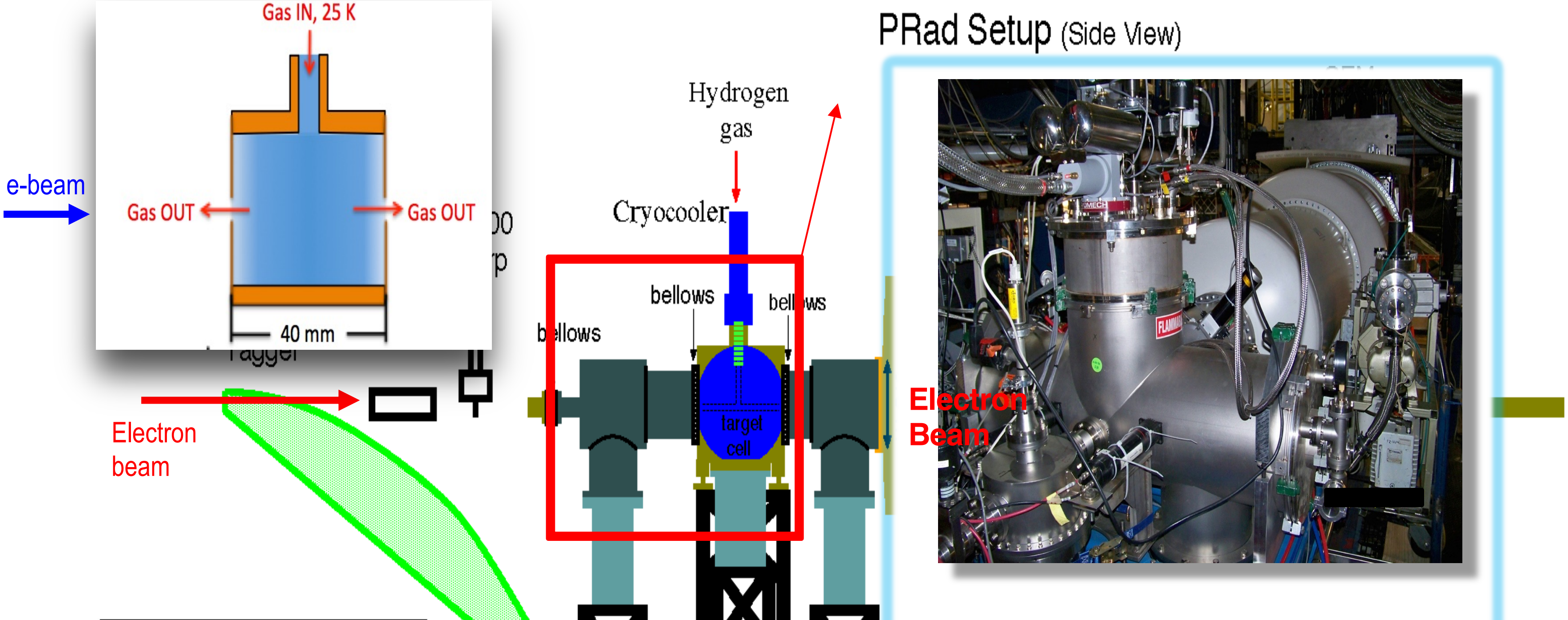
# PRad Experimental Setup in Hall B at JLab (schematics)

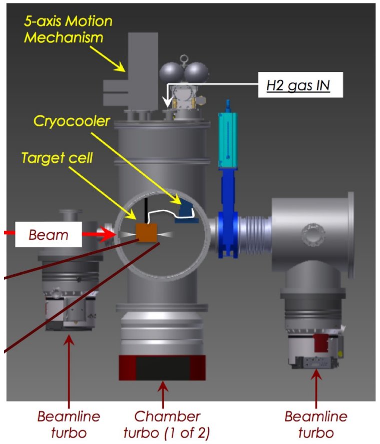
- Main detector elements:
  - windowless $H_2$ gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- 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



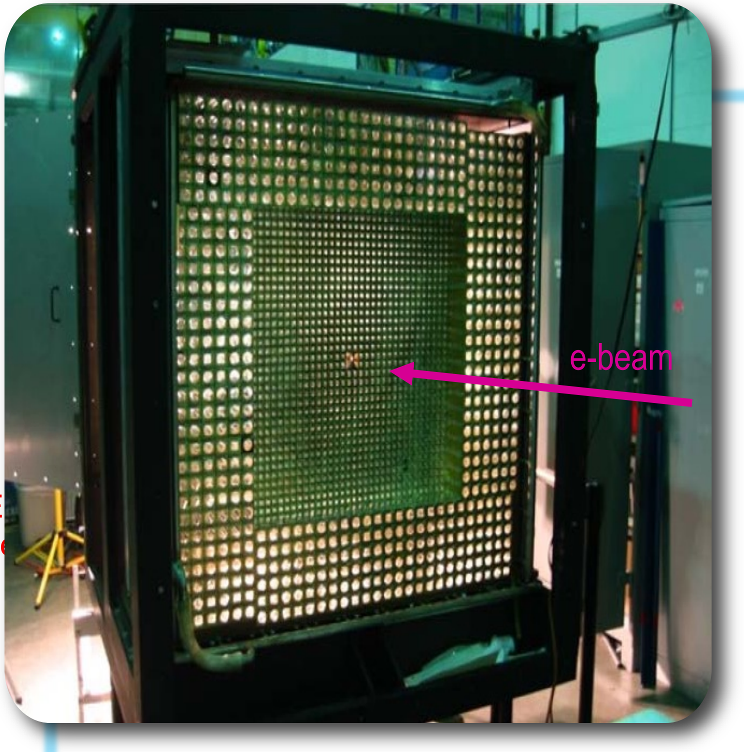
# Windowless Hydrogen Gas Flow Target





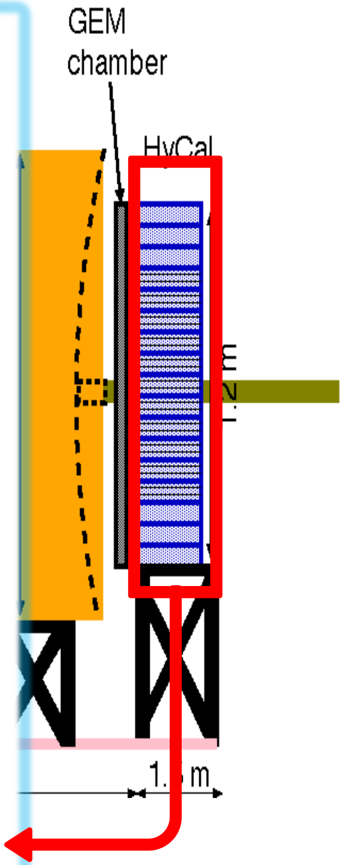
- 8 cm diam. X 4 cm long target cell
- 2 mm holes open at front and back of kapton foils for the beam passage
- areal density: 1.8x10$^{+18}$ H atoms/cm$^2$
  - cell pressure: 471 mTorr
  - chamber pressure: 2.34 mTorr: cell vs. chamber pressures: 200:1
  - vacuum tank pressure 0.3 mTorr: cell vs. vacuum tank pressures: 1000:1
  - at temperature: 19.5 K

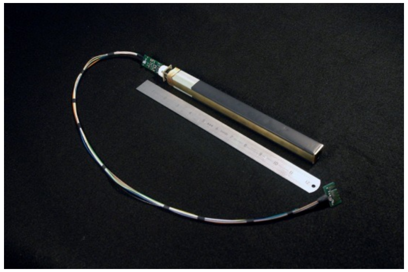
# PRad Experimental Apparatus: HyCal El. Mag. Calorimeter



PRad Setup (Side View)

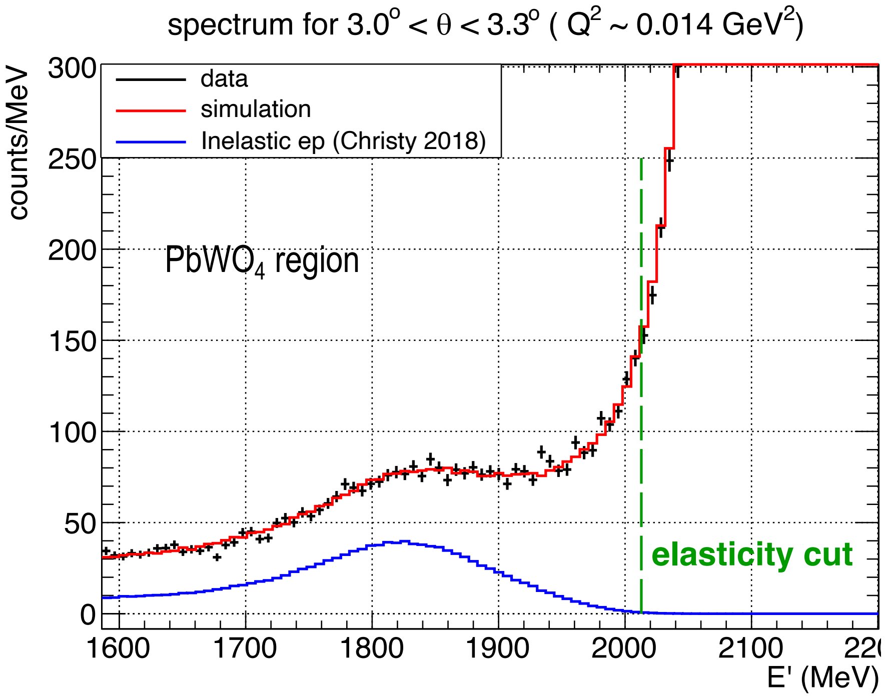
- hybrid EM calorimeter (HyCal)
  - ✓ inner 1156 $PbWO_4$ modules.
  - ✓ outer 576 lead glass modules.
- 5.8 m from the target.
- scattering angle coverage: ~ 0.6˚ to 7.5˚
- full azimuthal angle coverage
- high resolution and efficiency
  - ✓ 2.5% at 1 GeV for crystal part
  - ✓ 6.1% at 1 GeV for lead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

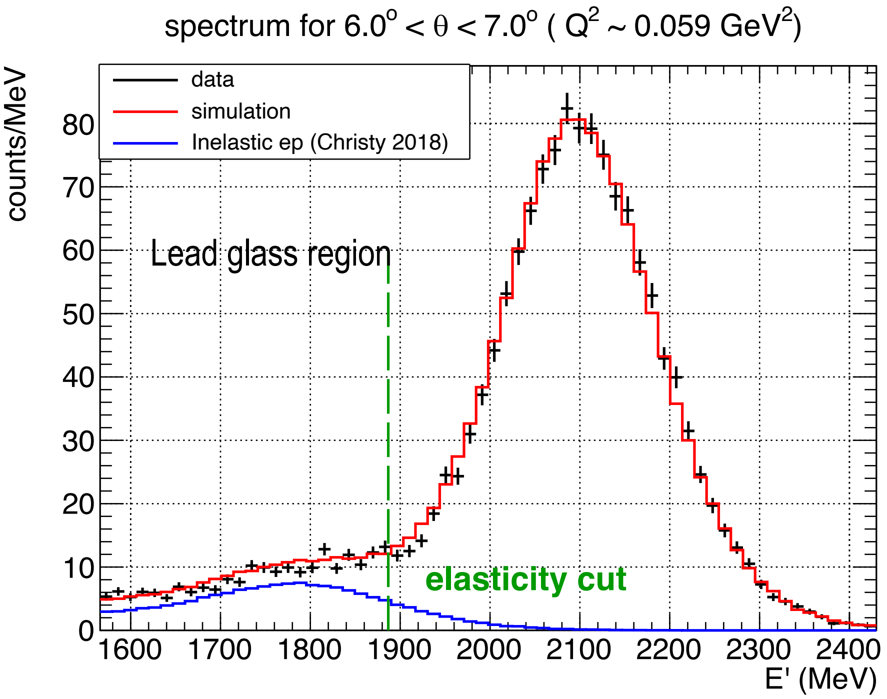




# Data Analysis: *ep-inelastic* Contribution

- 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

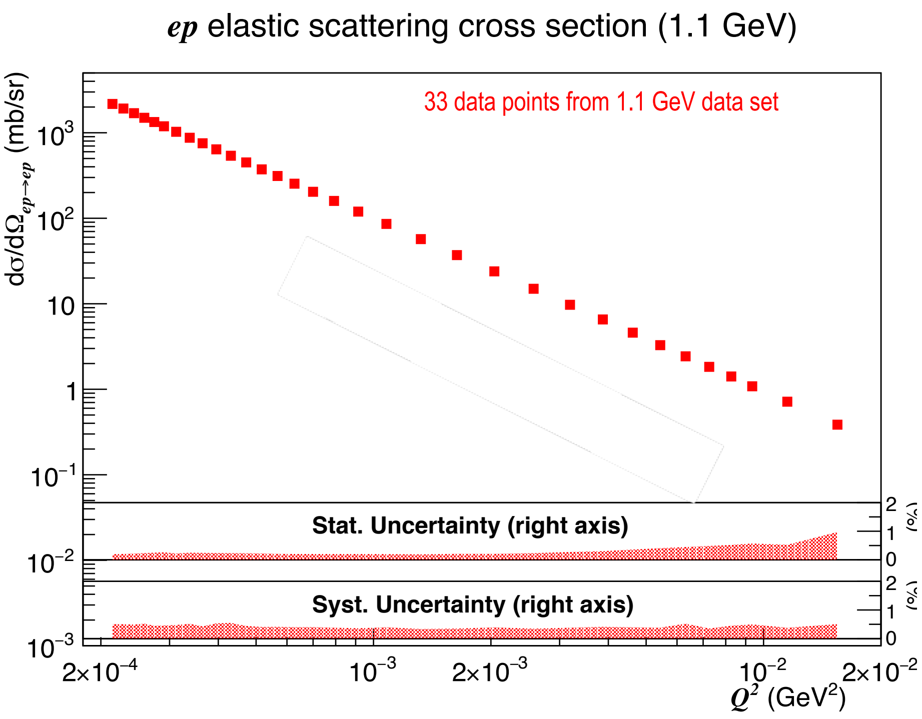


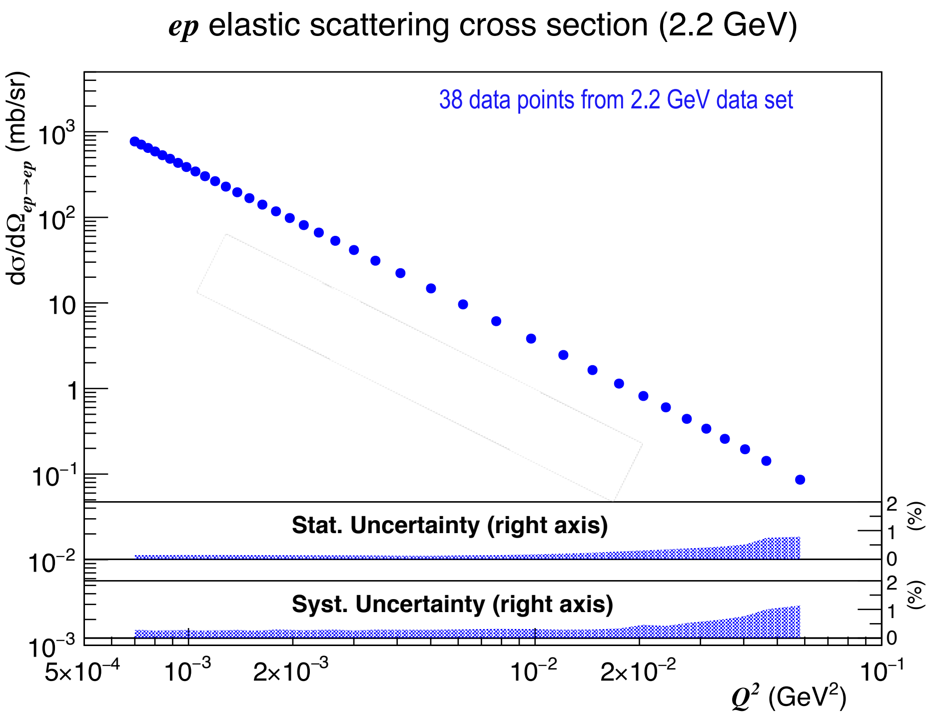


* M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)

# 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.





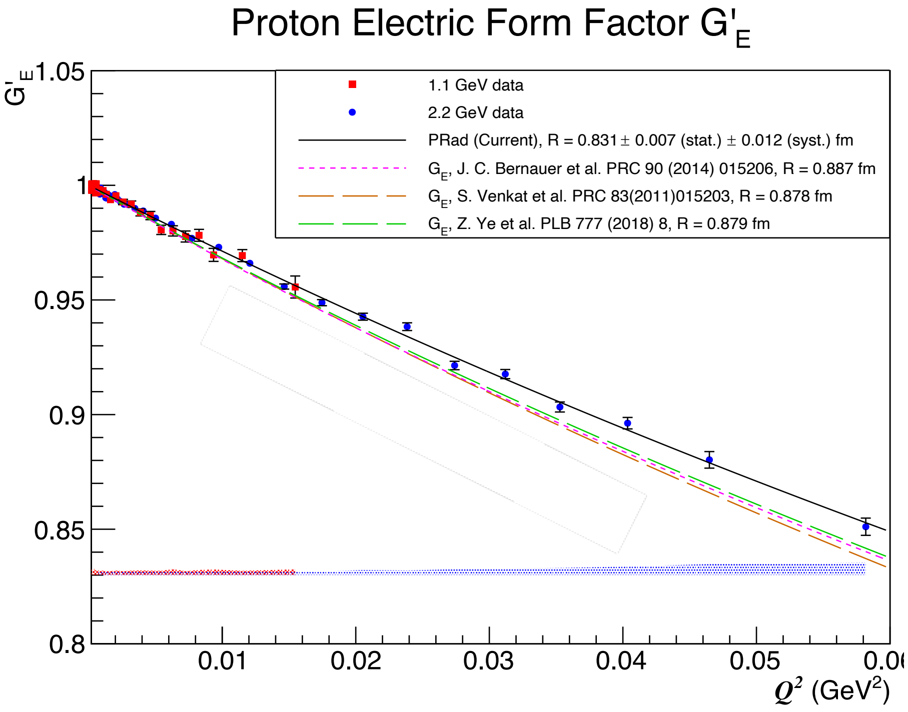
# Extracted Charge Form Factor (fit to extract the Proton Radius)

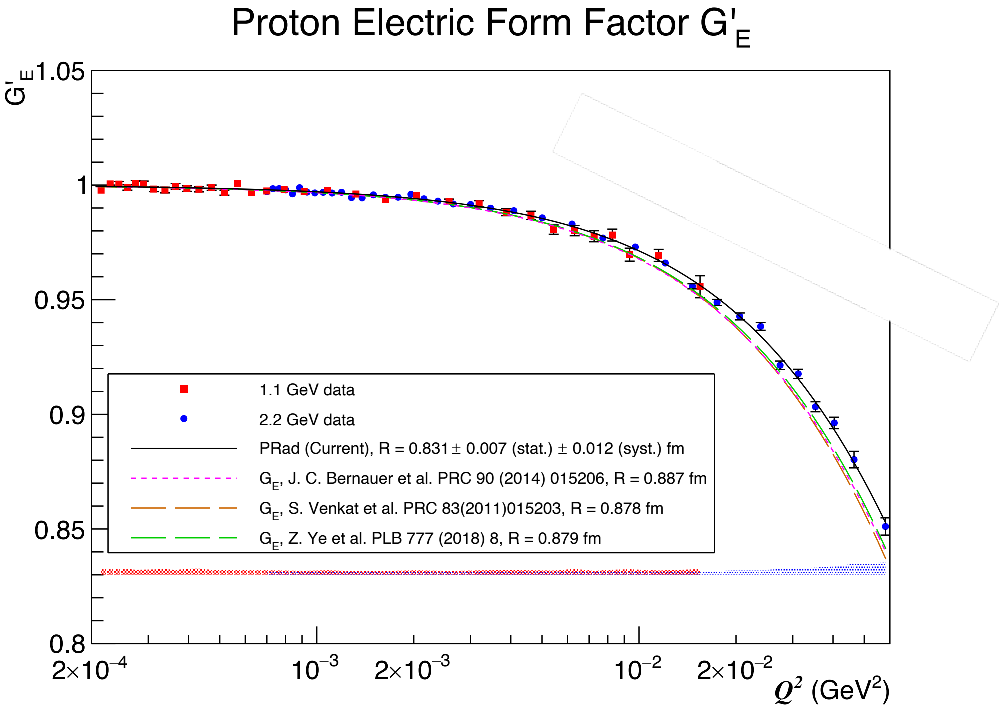
$n_1$ and $n_2$ obtained by fitting PRad $G_E$ to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

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

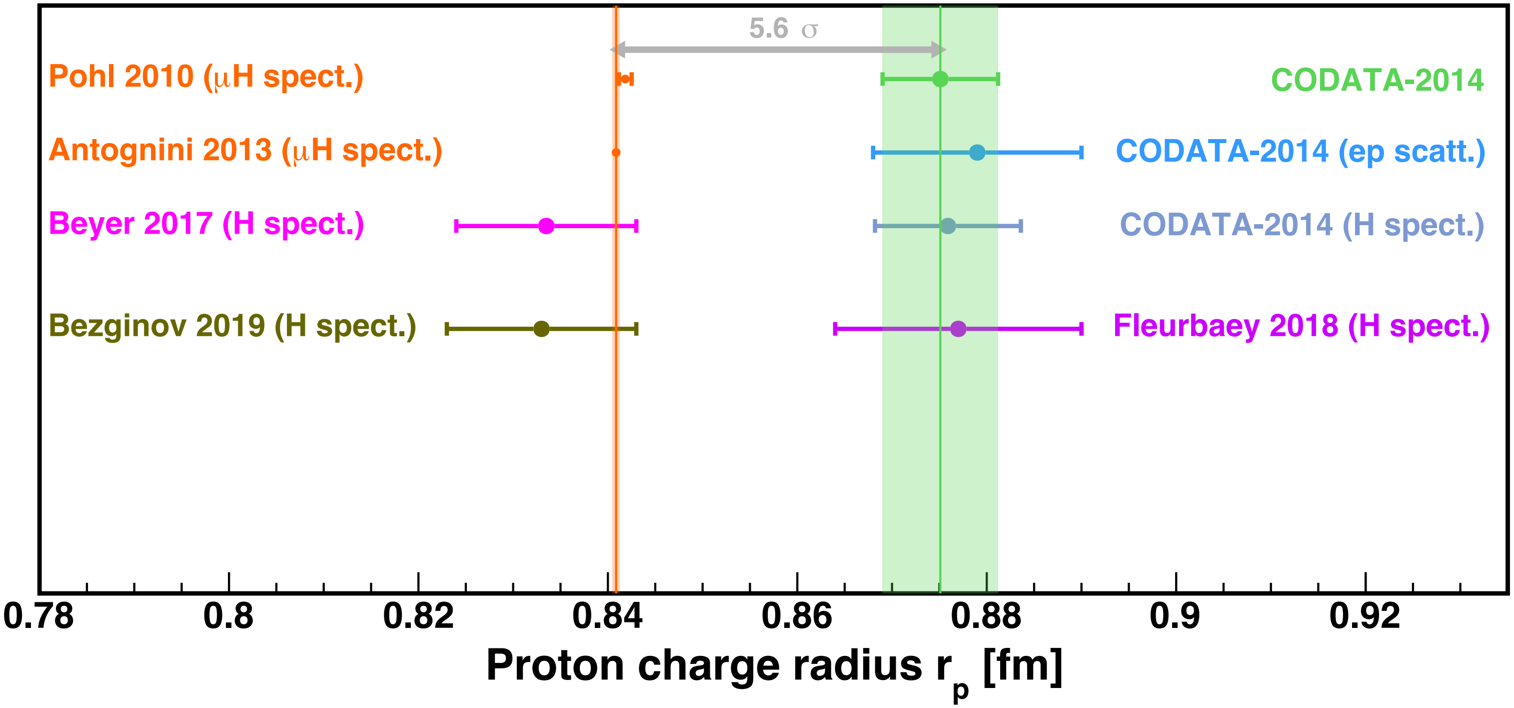
PRad fit shown as $f(Q^2)$ $r_p$ = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm





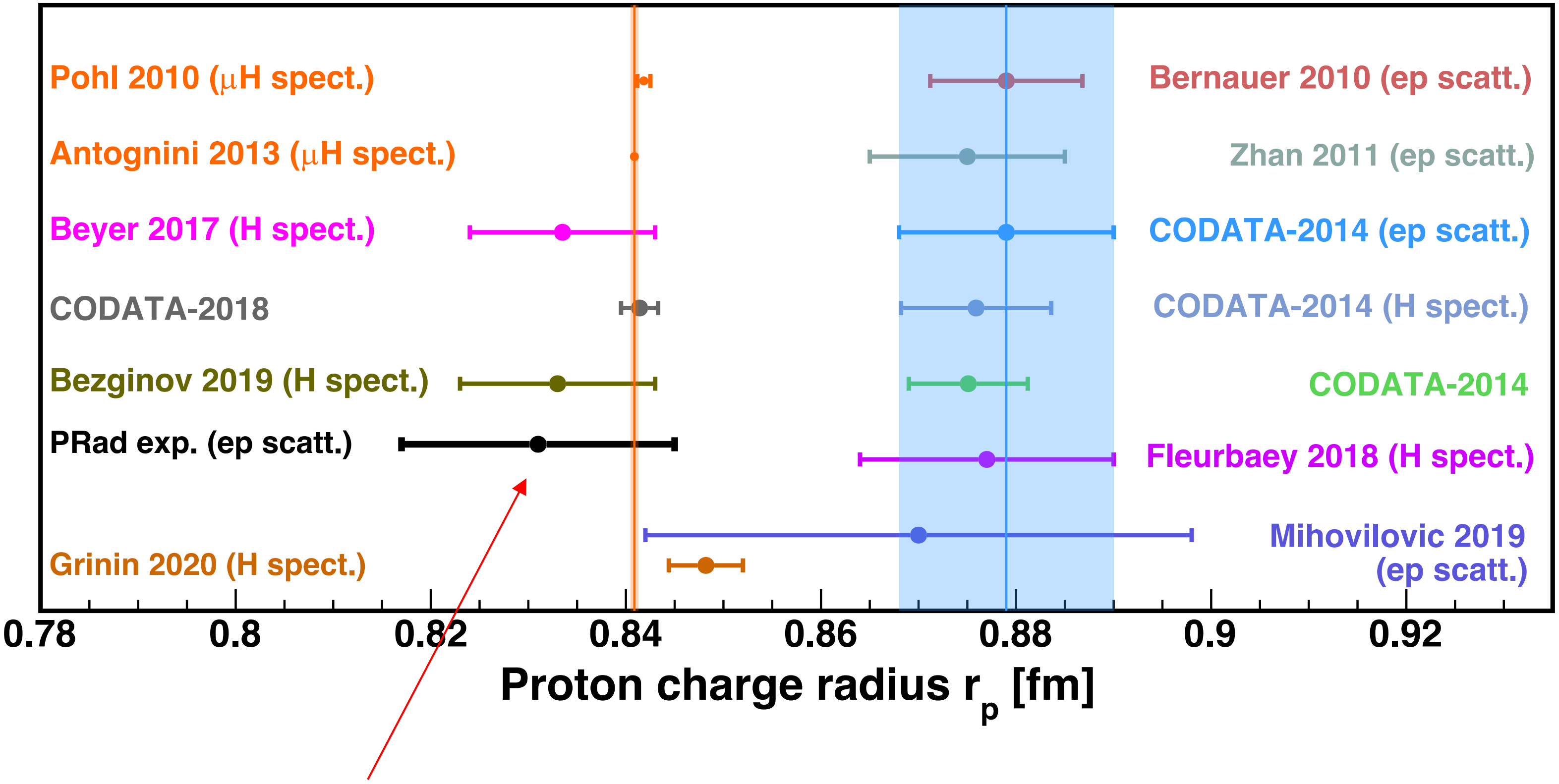
**PRad final result: $R_p$ = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm**

# 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

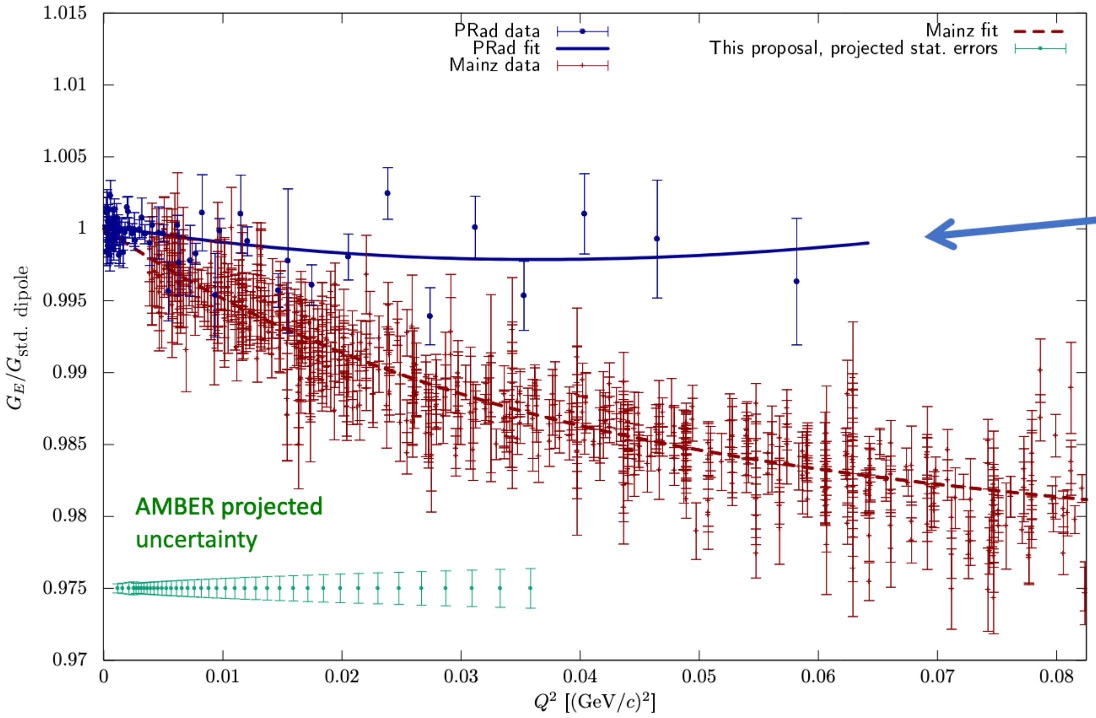


**PRad final result:** $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm

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

# What is Next? Or the Current Open Questions

- The “Puzzle” is still not fully resolved!
- There is certain discrepancy between the very recent FF measurements.



Proton Radius Experiment at Jefferson Lab

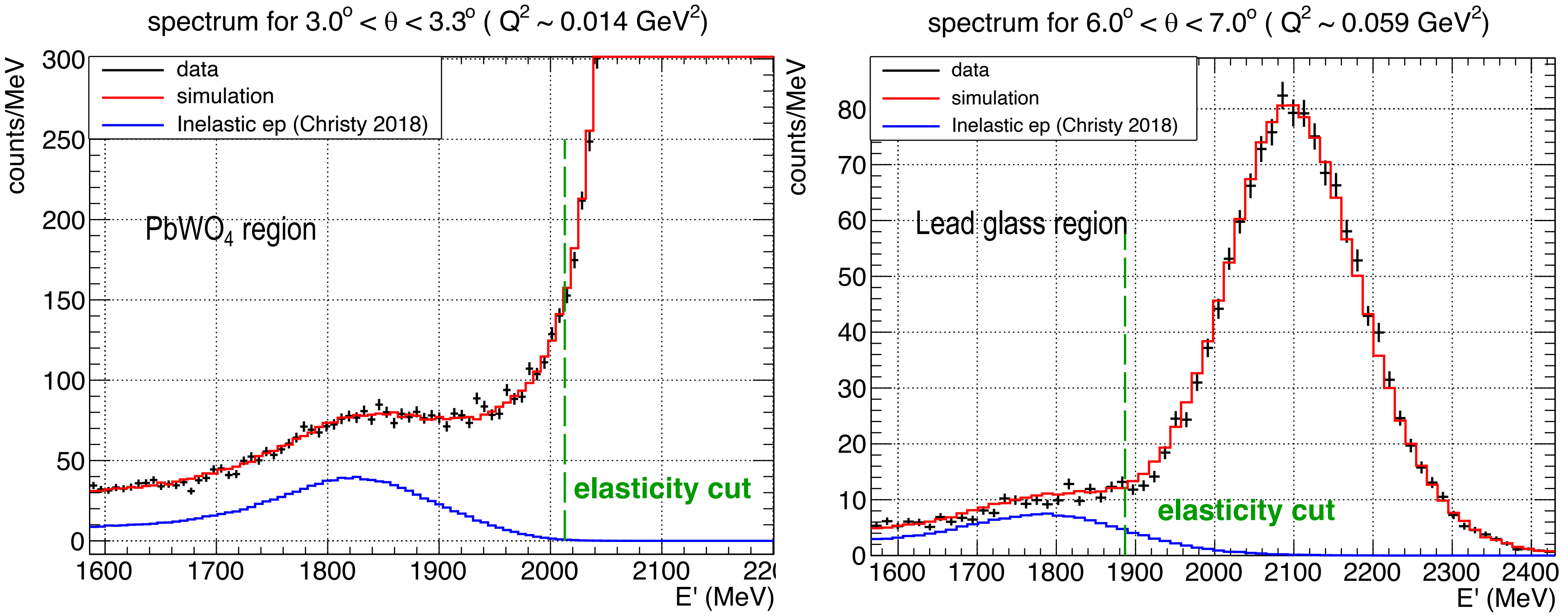
PRoton Radius

mami
MAINZER MIKROTRON

*figure: J. Bernauer*

# 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



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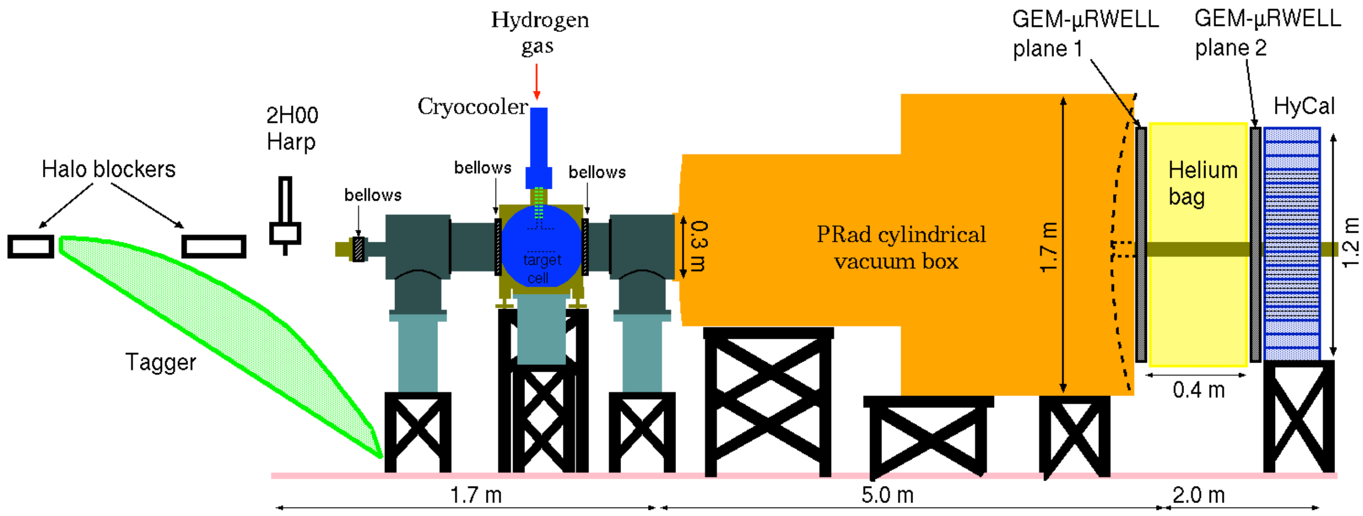
# Planed New Experiment: PRad-II at JLab (E12-20-004)

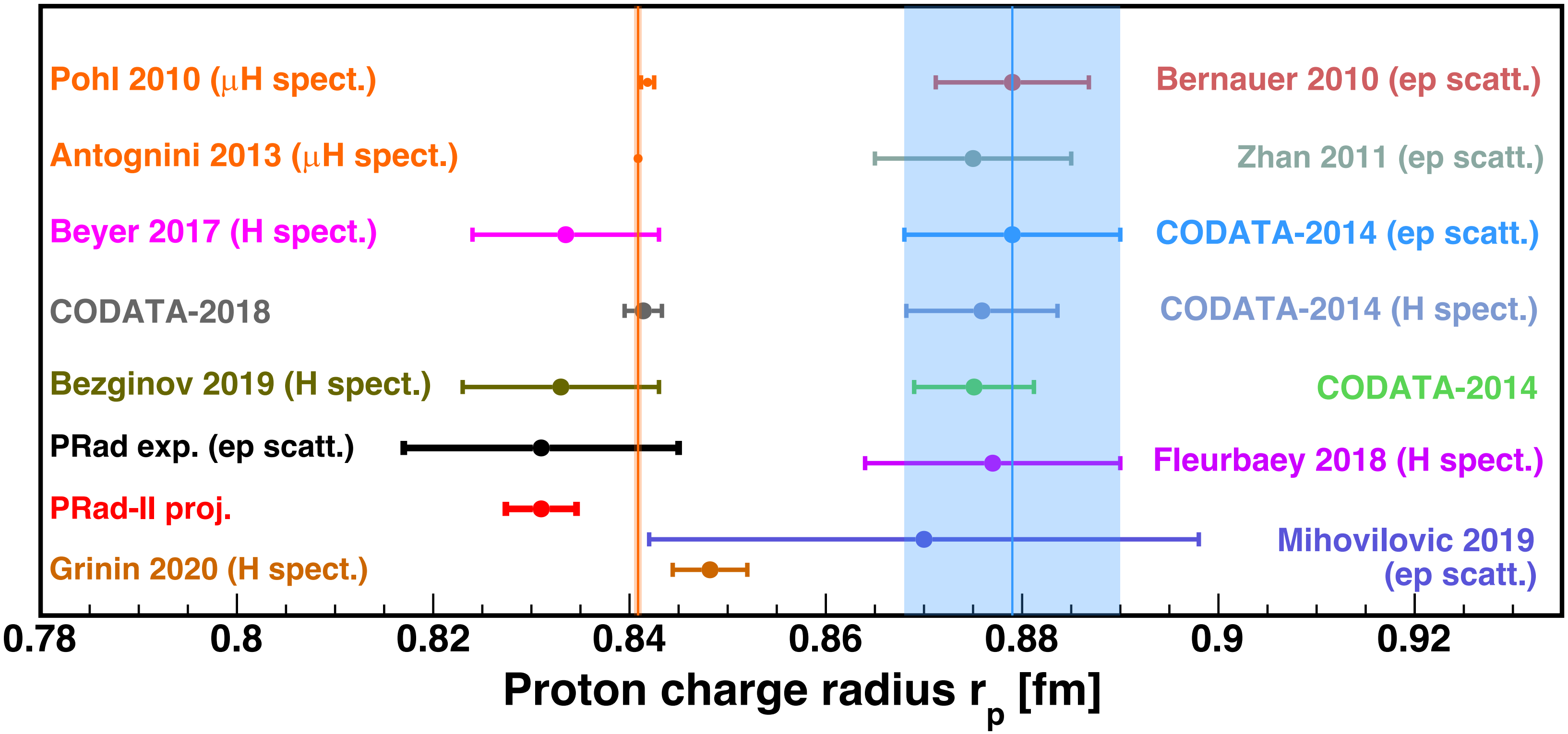
- PRad-II is planning to improve the PRad accuracy by a factor of 3.8 (to $\pm 0.43\%$ on $r_p$) by:
  - Significantly improved statistics (4 times less uncertainties);
  - Hardware upgrades (systematics):
    - adding full tracking capability (second plane of GEM/μRwell detectors).
    - small-size 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: 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 PAC48 in August, 2020, (E12-20-004)

- Order for new electronics and DAQ (fADC based) is in progress at JLab.
- Funding for new GEMs (second plane) is released by JLab, parts ordering is in progress.

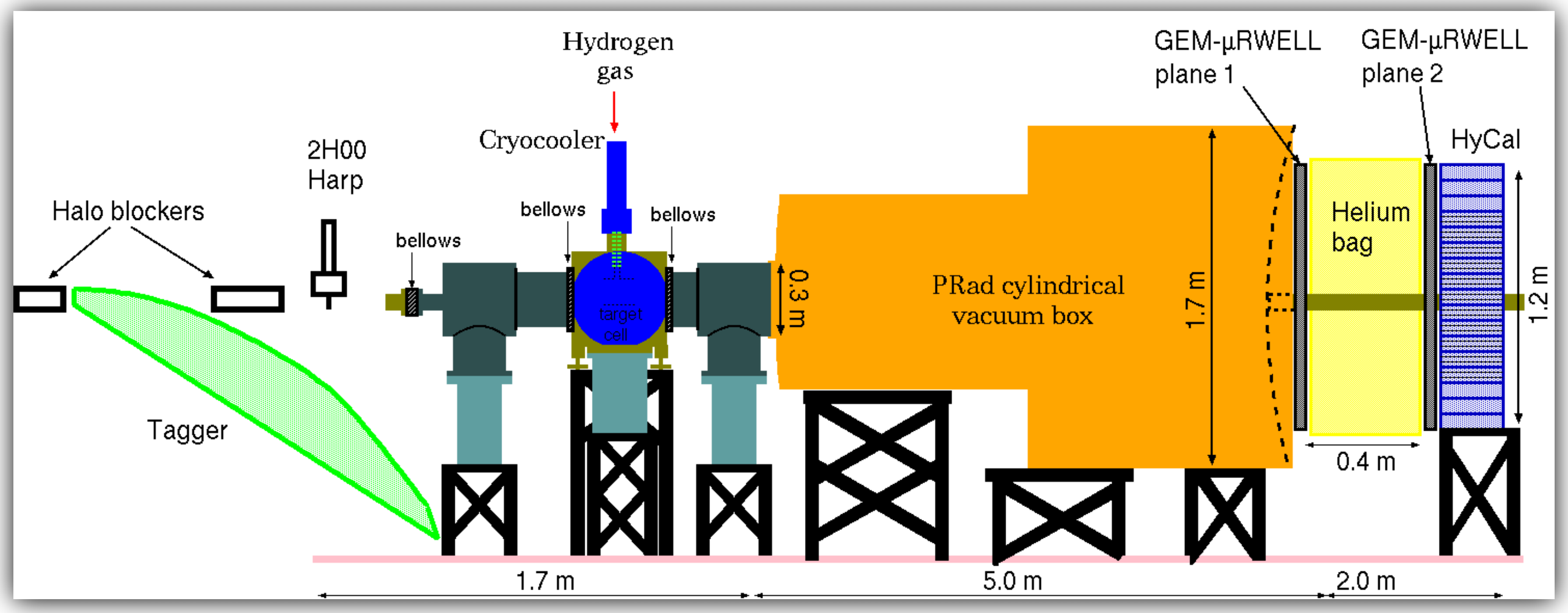
- NSF funding proposal is submitted in February 2023 for HyCal upgrade:
  - ✓ Major Research Instrumentation (MRI) Track-2 development type proposal, ~$4M total for:
    - ➢ HyCal partial upgrade to $PbWO_4$ crystals
    - ➢ second plane of GEM detectors
    - ➢ scintillator detectors to veto the Moller electrons at very small $Q^2$ range ($\approx 10^{-5}$ GeV$^2$)
  - ✓ NSF decision is expecting in July 2023

- For the calorimeter upgrade, we are also looking for possible collaborations with experimental groups and institutions willing to provide $PbWO_4$ part of the HyCal calorimeter.

- Current optimistic prediction for the run is Summer of 2025

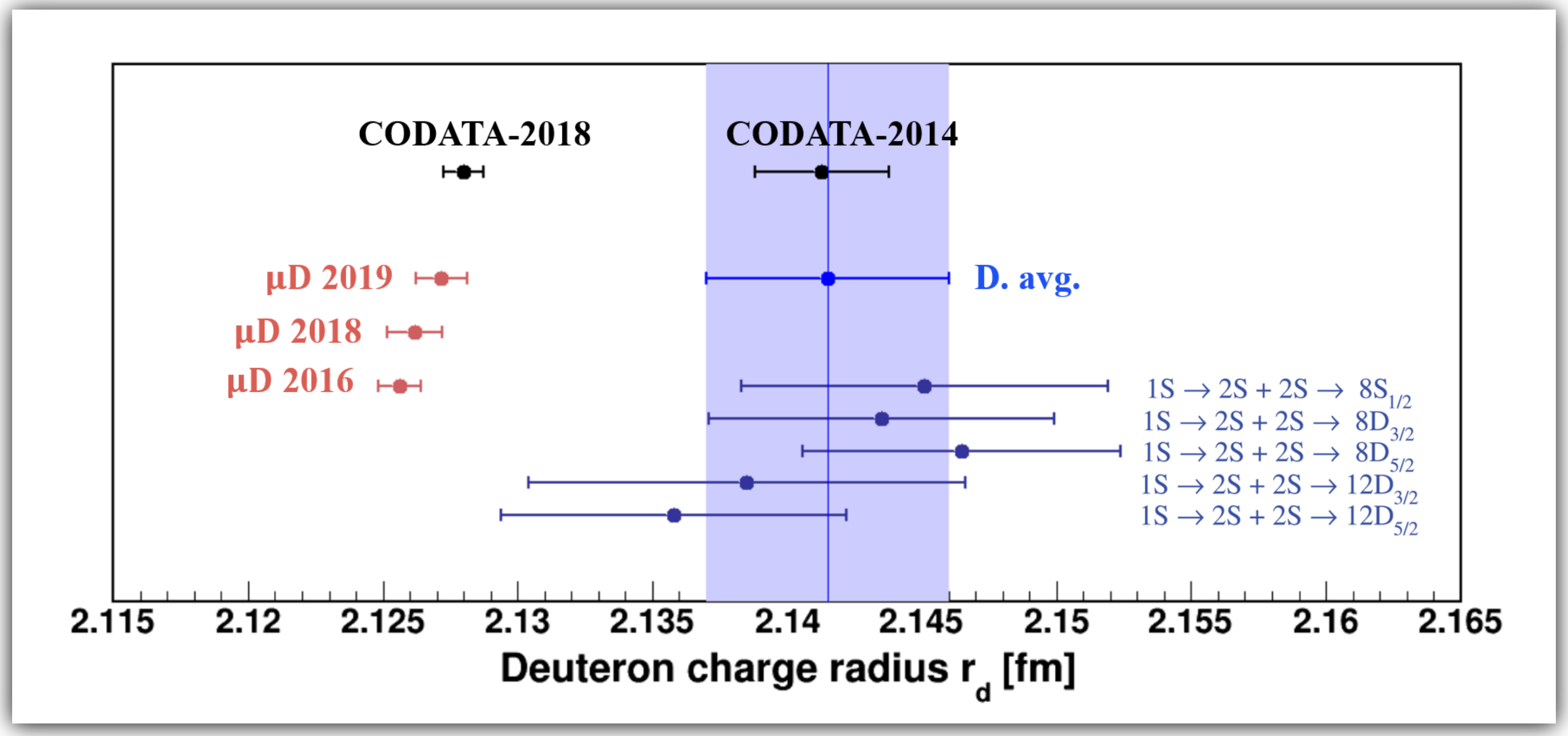
# DRad: New Proposal for Deuteron Charge Radius (PR12-23-011)

- Use (PRad-II setup) + (cylindrical recoil detector) for the control of reaction elasticity
- Electron beam energy: 1.1 GeV and 2.2 GeV
- $Q^2$ range: $2\text{x}10^{-4}$ – $5\text{x}10^{-2}$ $\text{GeV}^2$
- Simultaneous detection of scattered elastic and Moller electrons (control of systematics)



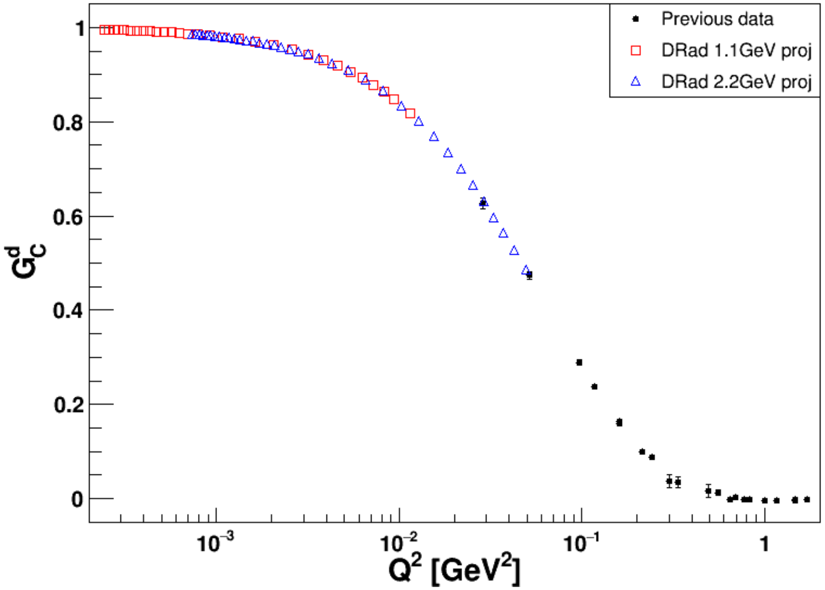
# The Deuteron Radius Puzzle (spectroscopy results)

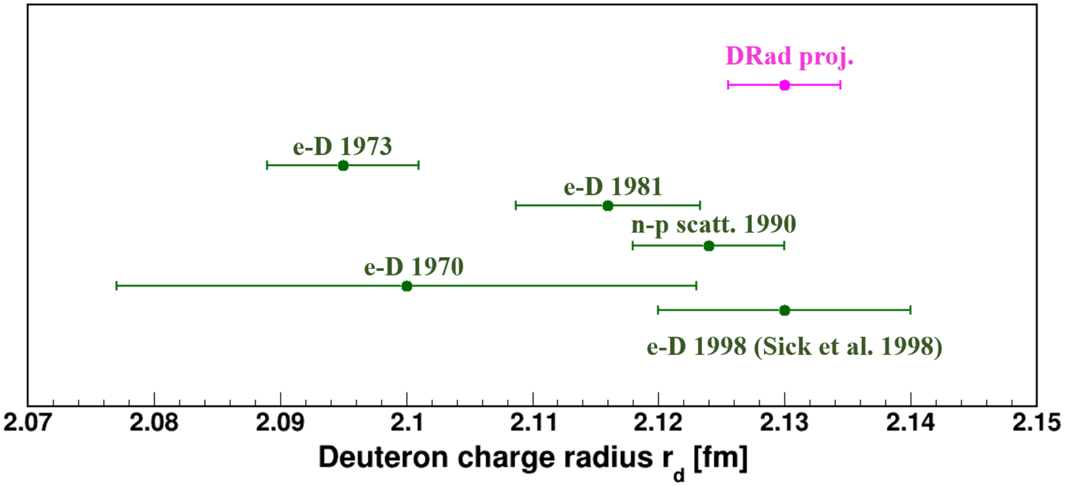
- ~ 6 $\sigma$ discrepancy between $R_d$ from ordinary and muonic spectroscopy results.



# Expected Results

- Submitted to JLab PAC51 for July 2023 meeting
- Expected total uncertainty on Rd: 0.21%





# Search for Hidden Sector New Particles in the 3 - 60 MeV Mass Range

## (JLab Experiment E12-21-003)

- The experiment has two experimental objectives:
  1) Validate existence or establish an experimental upper limit on the electroproduction of the hypothetical X17 particle claimed in two ATOMKI low-energy proton-nucleus experiments.
  2) Search for "hidden sector" intermediate particles (or fields) in [3 – 60] MeV mass range produced in electron-nucleus collisions and detected in $e^+e^-$ (or $\gamma\gamma$) channels.

- The method:
  - ✓ "bump hunting" in the invariant mass spectrum over the beam background.
  - ✓ direct detection of all final state particles (e', $e^+e^-$ and/or $\gamma\gamma$) → full control of kinematics

- Electroproduction on heavy nucleus in forward directions:

$e^- + \mathrm{Ta} \rightarrow e' + \gamma^* + \mathrm{Ta} \rightarrow e' + X + \mathrm{Ta}$, with $X \rightarrow e^+e^-$ (with tracking)

and $X \rightarrow \gamma\gamma$ (without tracking)

in mass range of: [3 - 60] MeV, target: Tantalum, (${}_{73}\mathrm{Ta}^{181}$), 1 $\mu$m ($2.4\times10^{-4}$ r.l.) thick foil.

- All 3 final state particles will be detected in this experiment:
  - ✓ scattered electrons, e' , with 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ decay e+ and e- particles, with 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ or decay $\gamma\gamma$ pairs, with $PbWO_4$ calorimeter (and GEMs for veto).

- Expected run: Summer 2025

# Summary and outlook

- 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, $[2x10^{-4} \div 6x10^{-2}]$ 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 is the best control of 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 4
  - ➢ 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, helping radius extraction more robust.
  - ➢ optimistic run period: summer, 2025

- New proposal has been developed for JLab PAC51 to measure the $R_d$ with 0.21% precision

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!

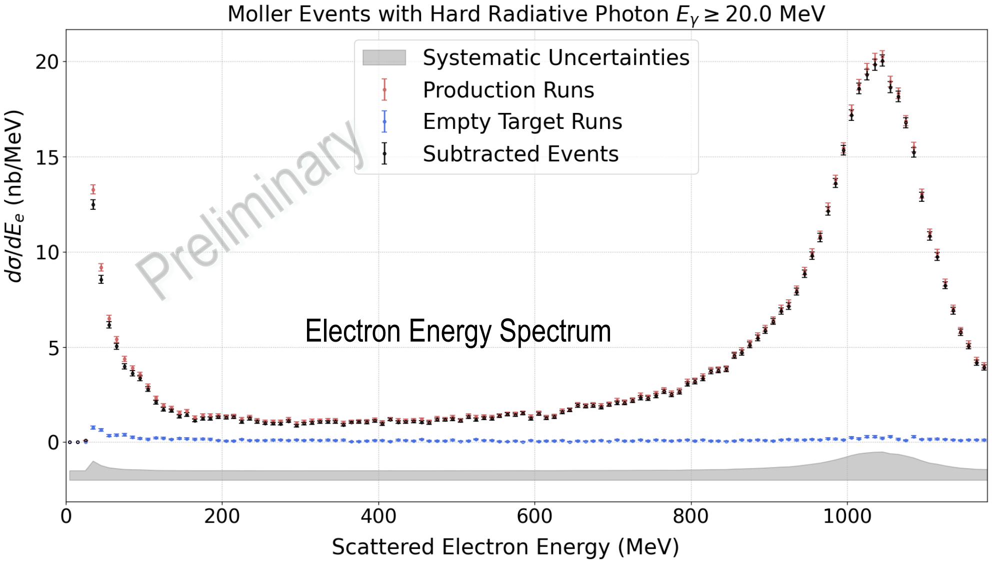
# PRad Systematic Uncertainties

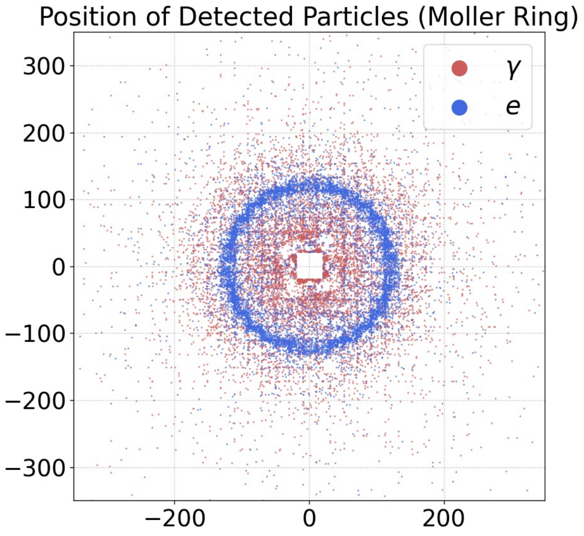
| Item | $r_p$ uncertainty [fm] | $n_1$ uncertainty | $n_2$ uncertainty |
|---|---|---|---|
| Event selection | 0.0070 | 0.0002 | 0.0006 |
| Radiative correction | 0.0069 | 0.0010 | 0.0011 |
| Detector efficiency | 0.0042 | 0.0000 | 0.0001 |
| Beam background | 0.0039 | 0.0017 | 0.0003 |
| HyCal response | 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 |

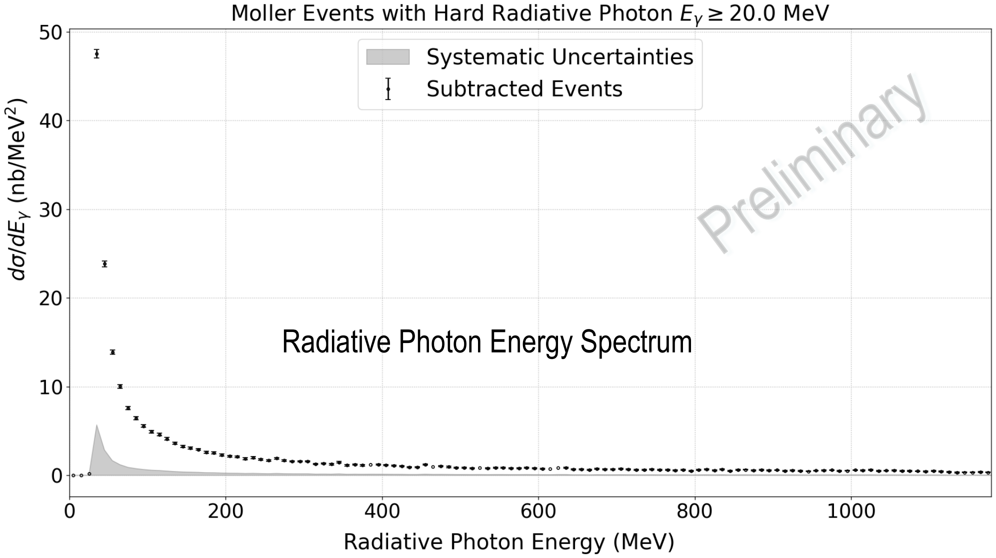
# Radiative Tail Measurement from Moller

## Data from PRad-I experiment ($E_e$ = 2.2 GeV)

- PID by GEMs and HyCal
- Event selection:
  - ✓ two e- and one or more $\gamma$ (dominated by one only)
  - ✓ $\Sigma E_{\text{clusters}} = E_{\text{beam}} \mp 4\sigma$
  - ✓ One e- is in the Moller ring
  - ✓ $E_{e-} \in \frac{1}{2} E_{\text{beam}} \mp 4\sigma$
  - ✓ $E_\gamma > 20$ MeV
- Theory simulations in progress

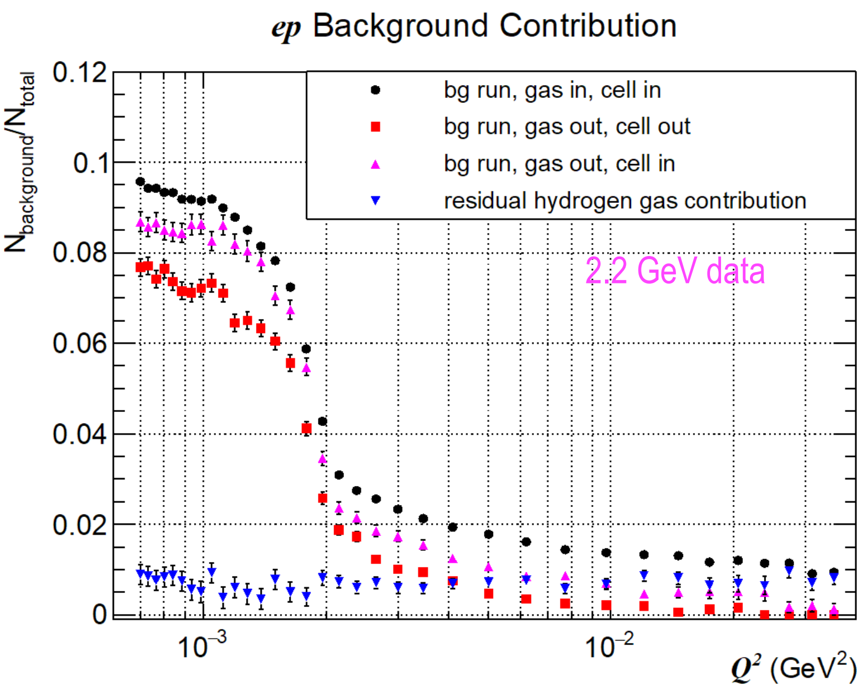

Moller Events with Hard Radiative Photon $E_\gamma \geq 20.0$ MeV

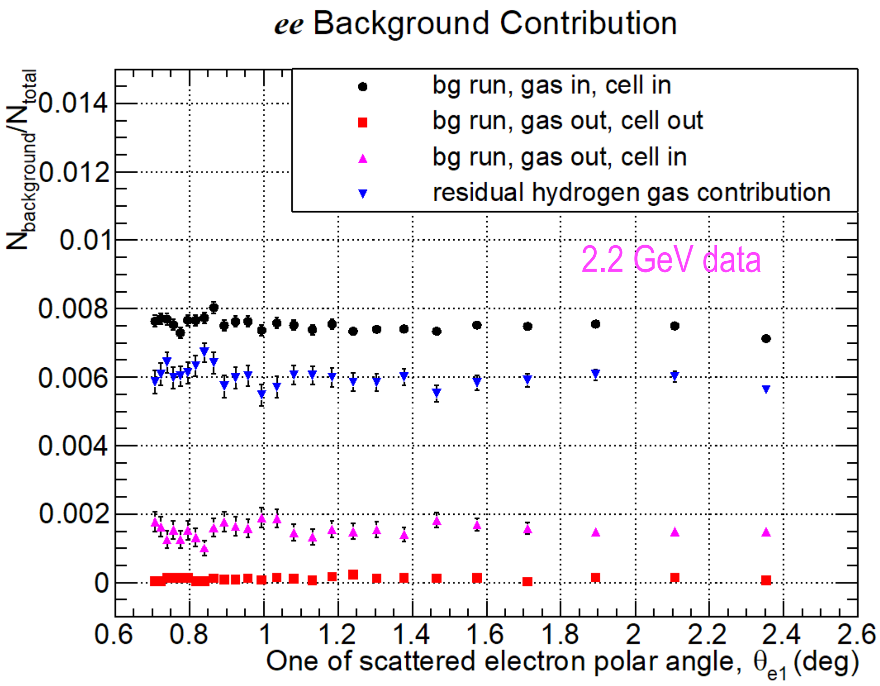

Position of Detected Particles (Moller Ring)


Moller Events with Hard Radiative Photon $E_\gamma \geq 20.0$ MeV

# 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 .





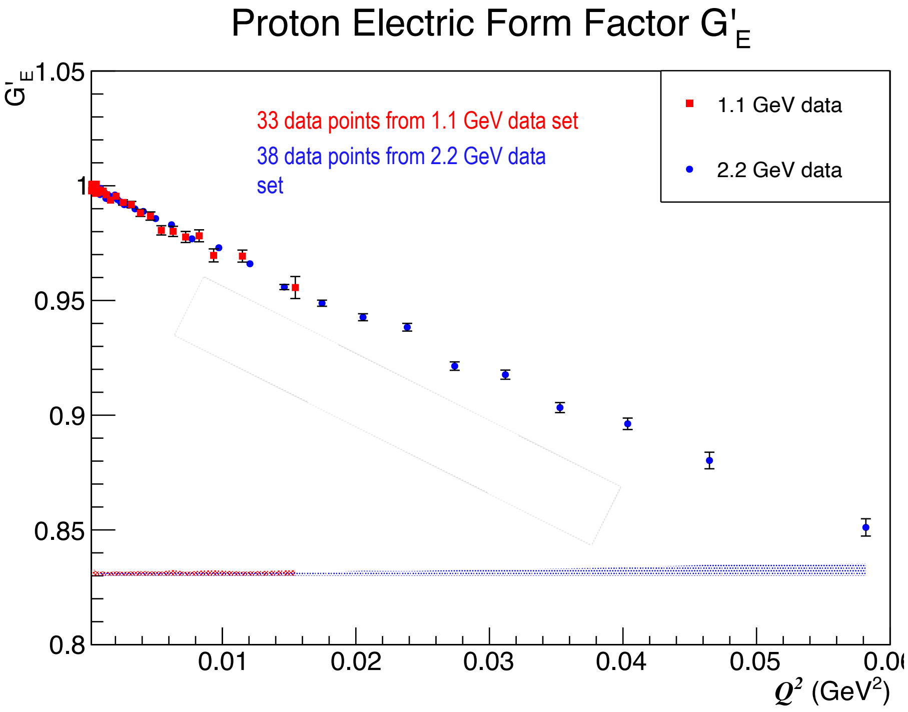
# Extracted Proton Electric Form Factor, $G_E$ vs. $Q^2$

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

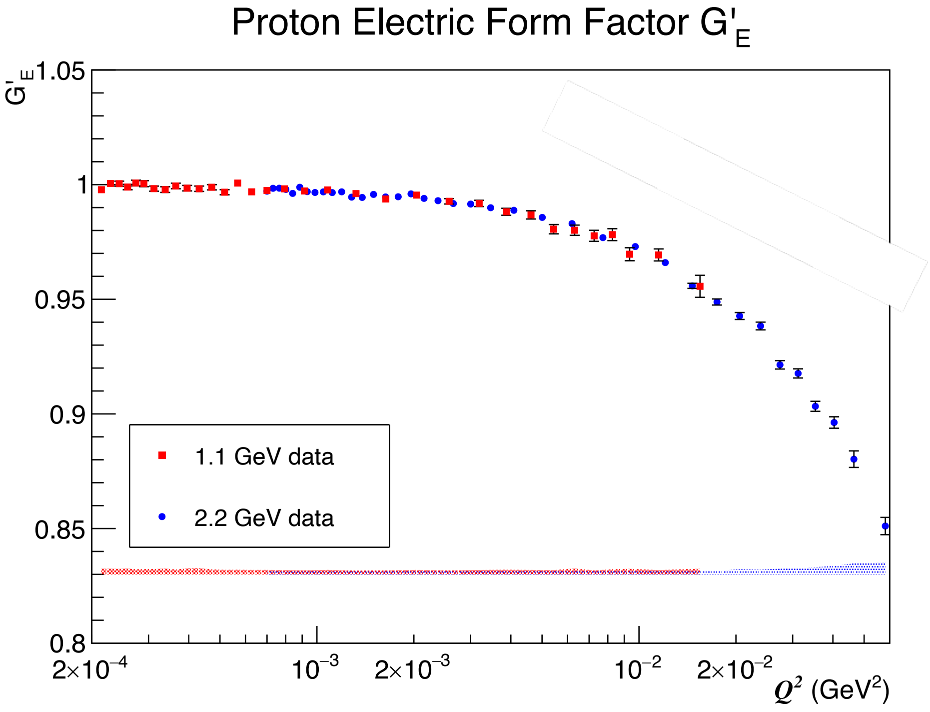
Using rational (1,1)

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



33 data points from 1.1 GeV data set

38 data points from 2.2 GeV data set



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

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

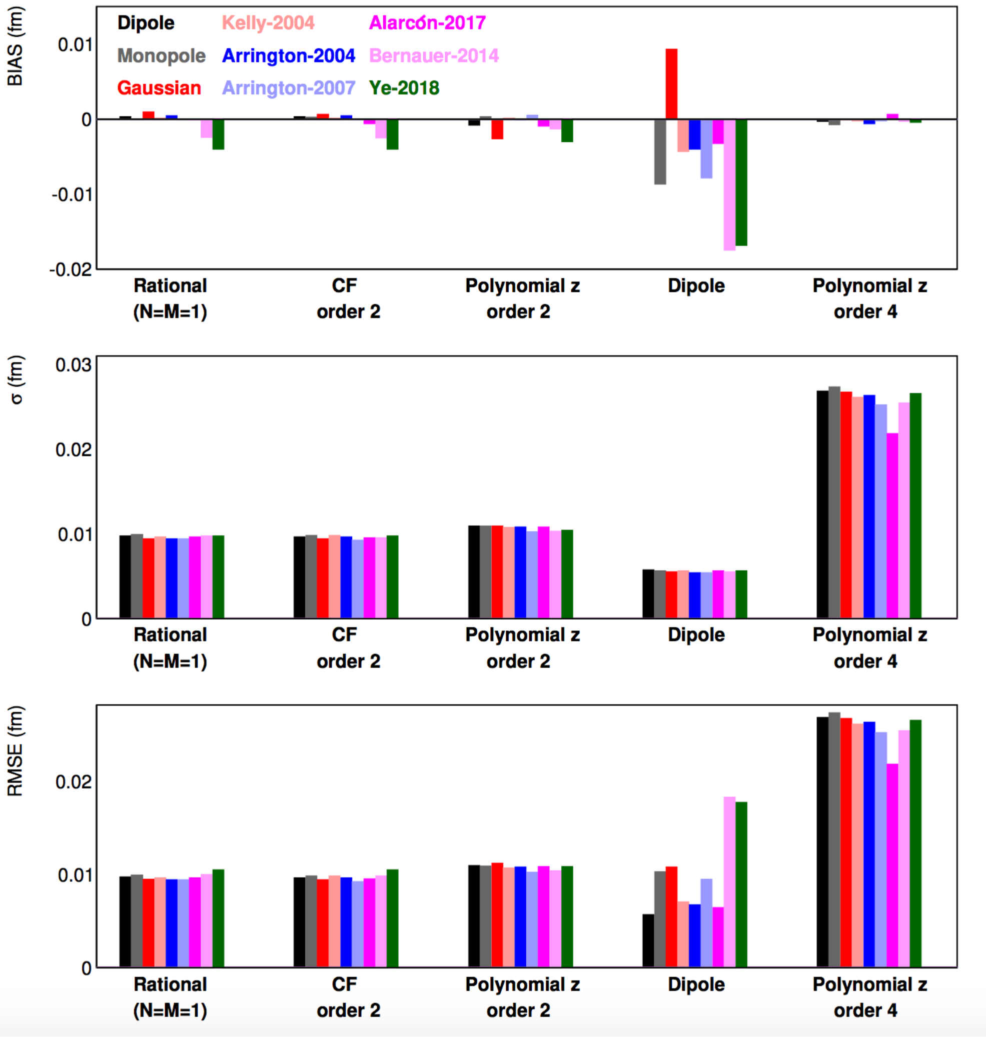
# Recent Developments in Fitting Procedures

- 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

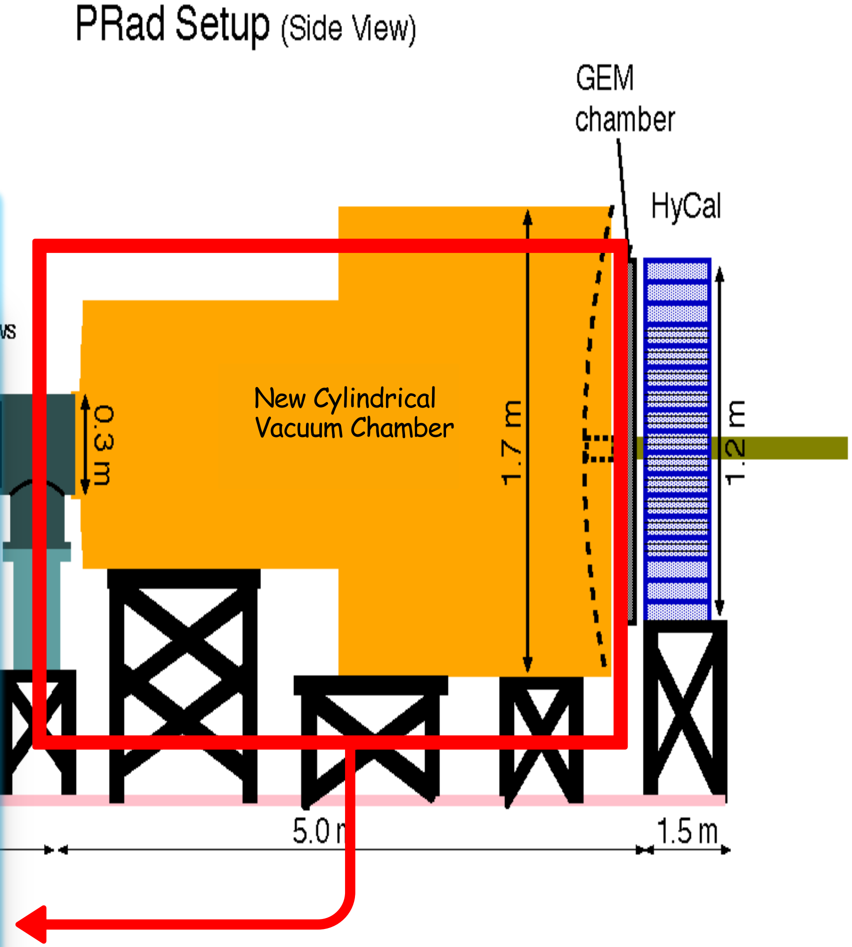


RMSE = sqrt(bias$^2$ + σ$^2$)

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

# PRad Experimental Apparatus: Vacuum Chamber

[redacted]

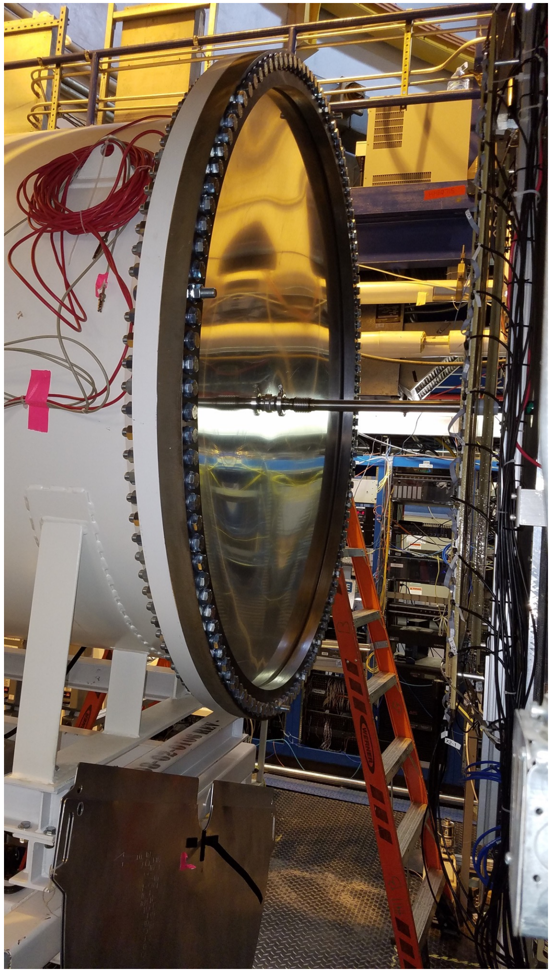


- 5 m long two stages vacuum chamber, 1.7 m diameter, 2 mm Al vacuum window vacuum chamber pressure: 0.3 mTorr

# PRad Experimental Apparatus: Vacuum Chamber and Window

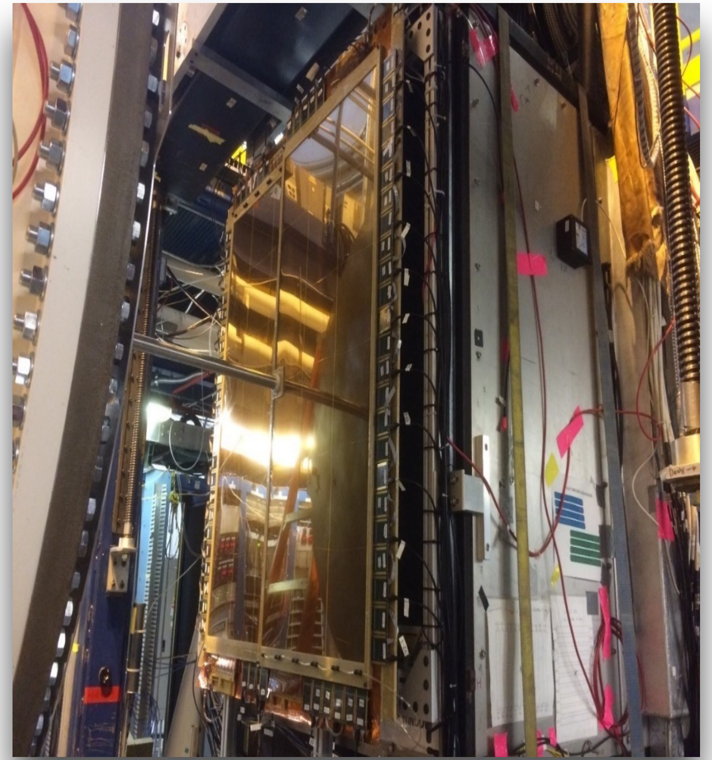

[redacted]

2-stage vacuum box in Hall B beam line



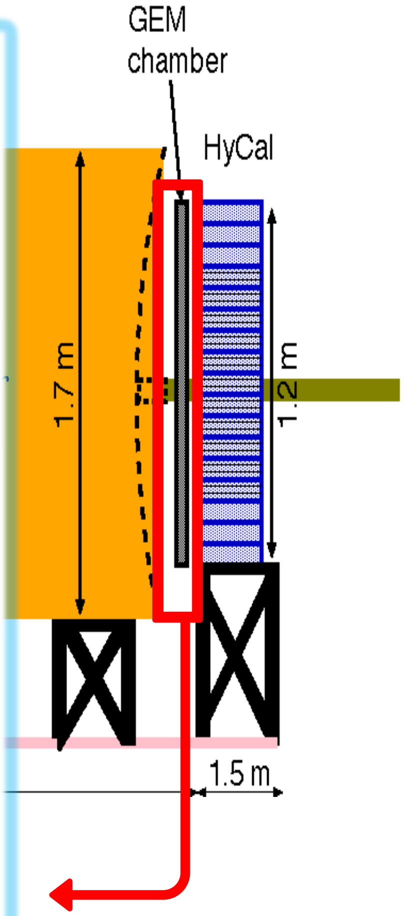
1.7 m diameter, 2 mm Al vacuum window

# PRad Experimental Apparatus: GEM Coordinate Detectors



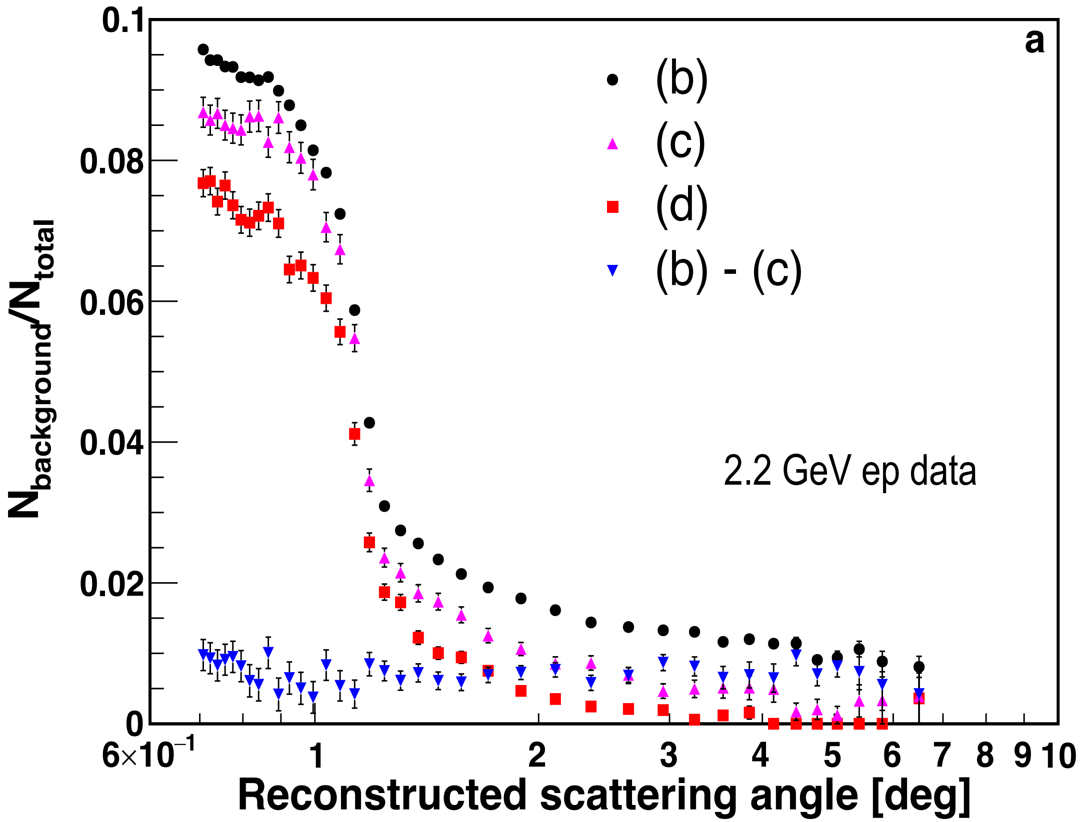
- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 µm)
- Improve position resolution of the setup by > 20 times
- Large improvements in $Q^2$ determination

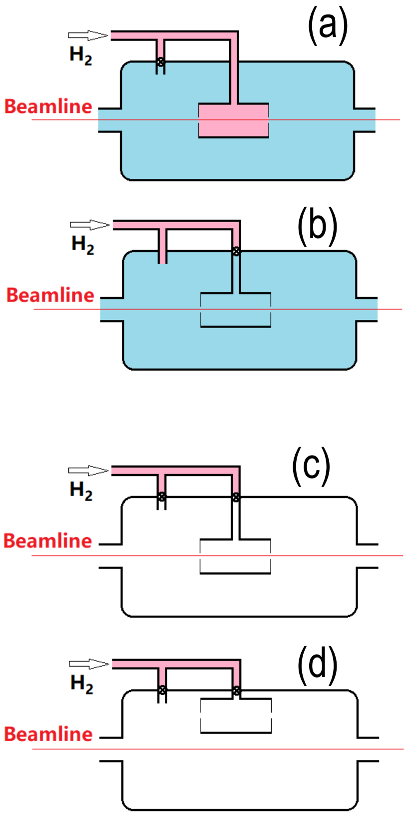
PRad Setup (Side View)



# 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

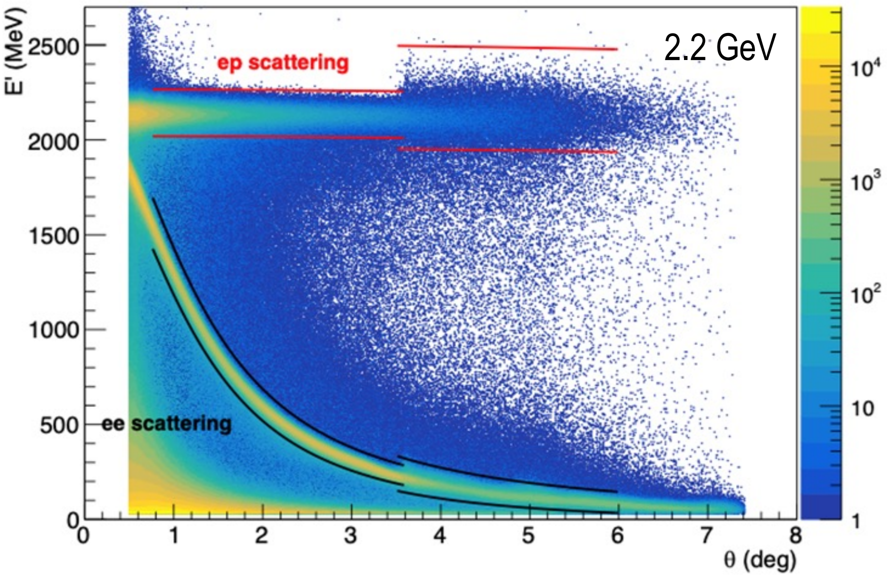


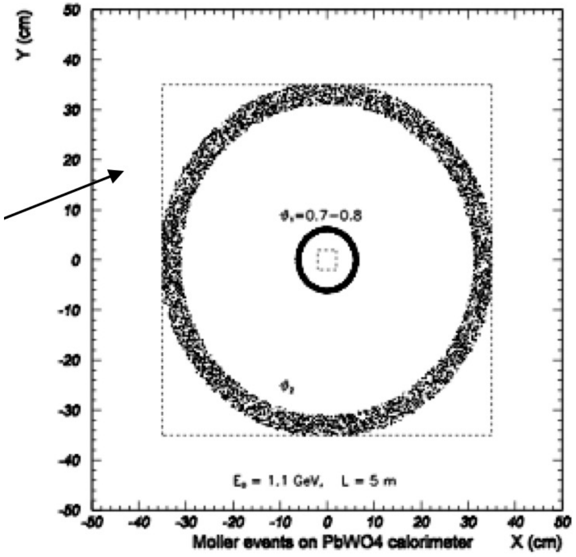


✓ Residual hydrogen gas: hydrogen gas filled during background runs

# Data Analysis: Event Selection

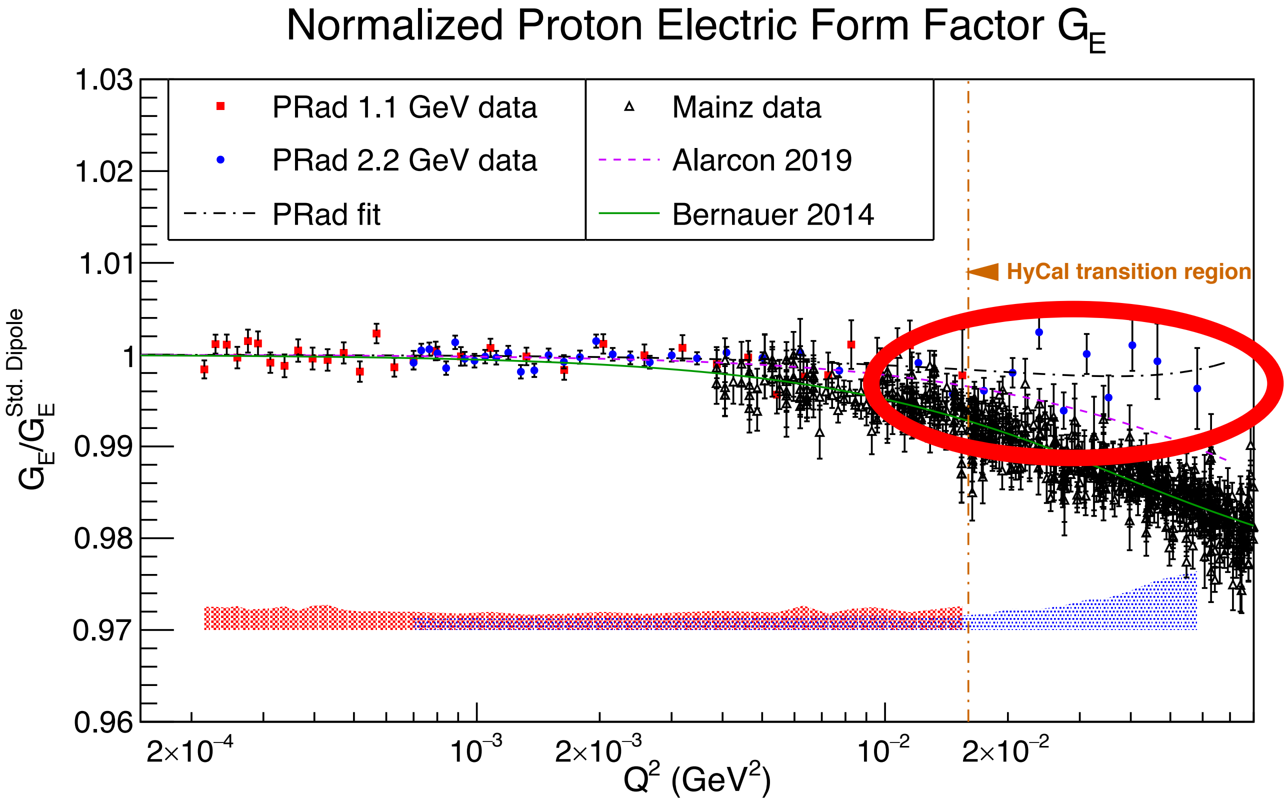
- Experimental data was taken with two beam energies:
  - ✓ 1.1 GeV (604 M events)
  - ✓ 2.2 GeV (756 M events)
- For all events, require hit matching between GEMs and HyCal
- For *ep* and *ee* events, apply angle dependent energy cut based on kinematics:
  - ➢ cut size depend on local detector resolution
- For *ee*, if requiring double-arm events, apply additional cuts:
  - ✓ elasticity
  - ✓ co-planarity
  - ✓ vertex z (kinematics)



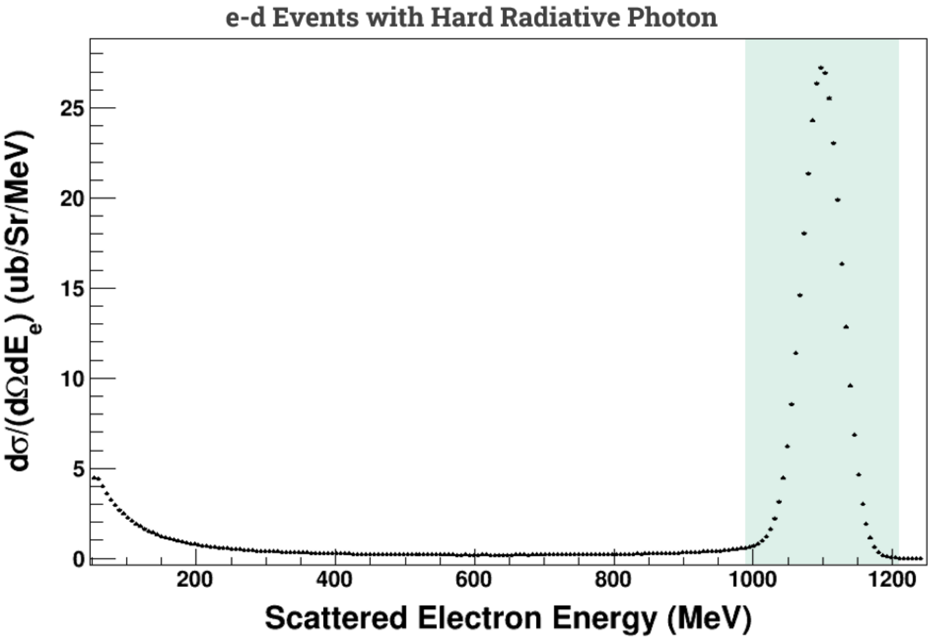


# What is Next? Or the Current Open Questions

- The "Puzzle" is still not fully resolved
- There is certain discrepancy between the very recent FF measurements



# Radiative Corrections for DRad



- The complete elastic e-d NLO cross section including the lowest order radiative corrections beyond the ultrarelativistic limit has been calculated
- Based on the ansatz in the PRad RC calculation and used the Bardin-Shumeiko infrared divergence cancellation method (I. Akushevich et al. Eur. Phys. J. A 51.1(2015), p. 1. DOI: 10.1140/epja/i2015-15001-8)
- A generator is developed and the total correction to the elastic e-d Born cross section in the DRad kinematics is calculated
- The uncertainty of the NLO calculation is estimated, taking into account higher-order contributions, calculation assumptions, and differences between various recipes
- The paper is to be submitted to arXiv and European Physical Journal A

# 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)