High Precision Measurement of the Proton Charge Radius at JLab

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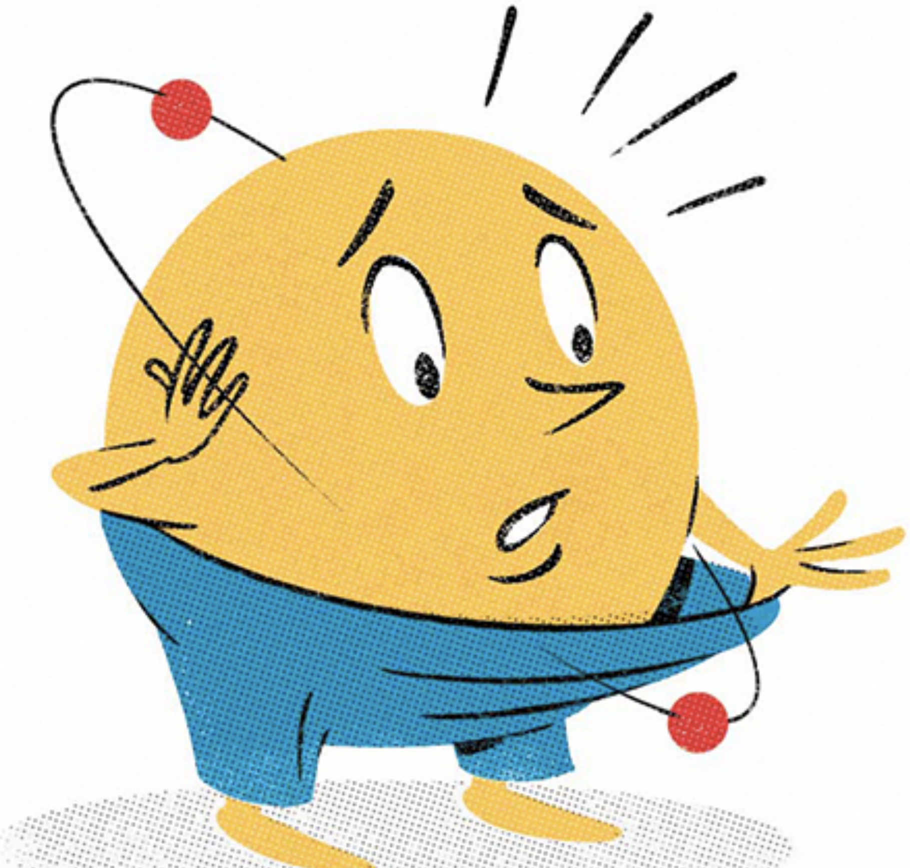
- Shandong University
- For the PRad Collaboration

- 中国物理学会高能物理分会
- August 11th 2022

Outline

- Introduction and the proton charge radius puzzle
- PRad experiment and results
- PRad-II experiment and projection
- Summary

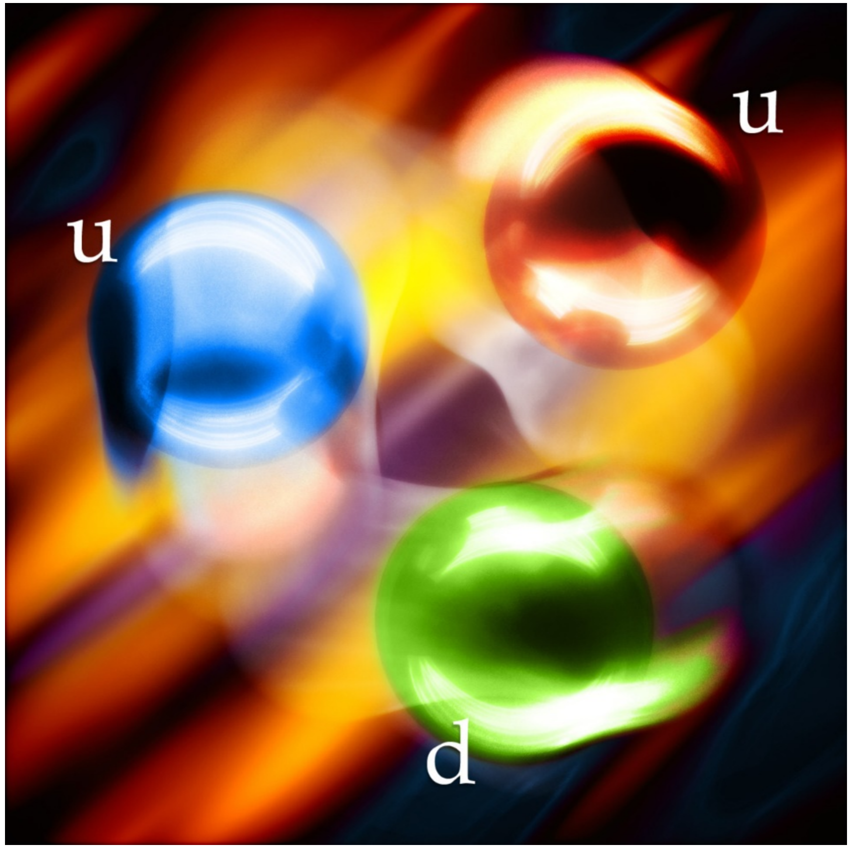


New York Times

Introduction

- Nucleons (protons and neutrons) make up over 99% of the mass of visible universe

- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. Critical in determining Rydberg constant
  4. An important physics input to the bound state QED calculation for atomic hydrogen energy levels



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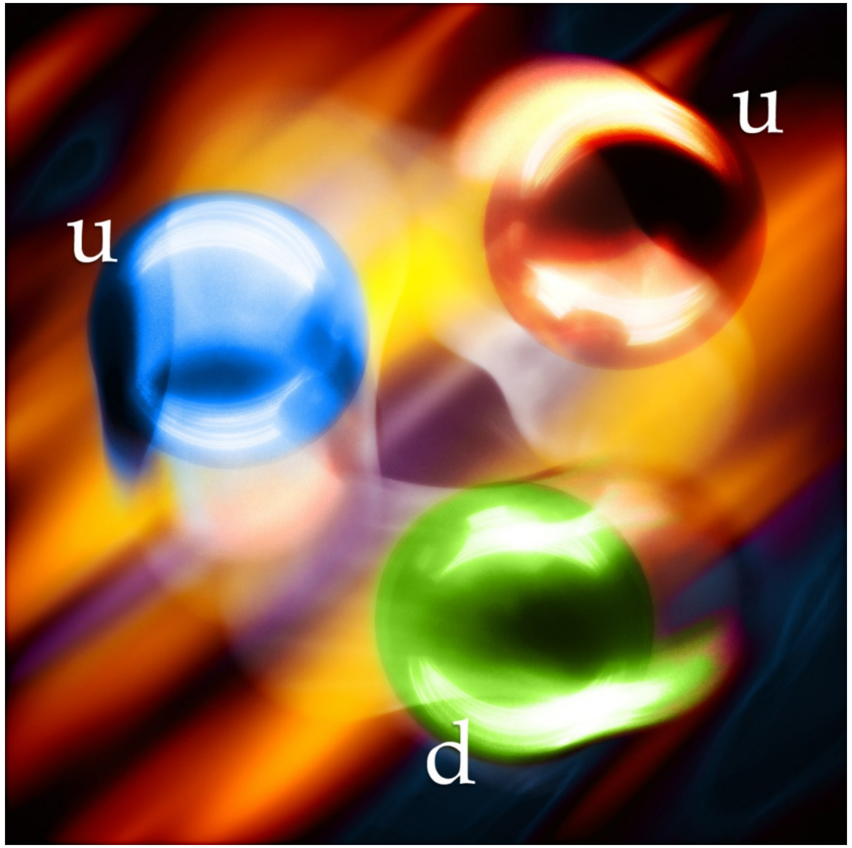
- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - ➢ Ordinary hydrogen
     - ➢ Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics)
     - ➢ *ep* elastic scattering (like PRad)
     - ➢ *μp* elastic scattering (like MUSE)



Unpolarized *ep* Elastic Scattering

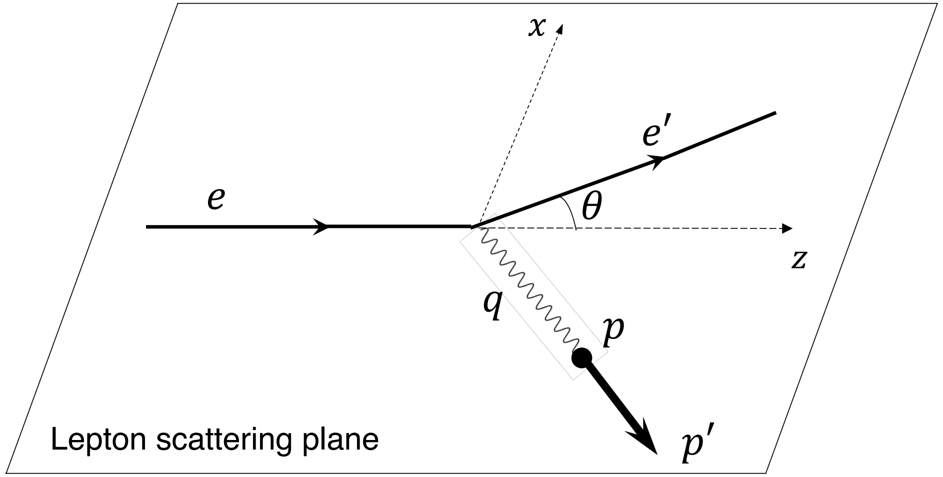
- Elastic ep scattering, in the limit of Born approximation (one photon exchange):

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

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

- Structure-less and spin-less proton:

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



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 low Q^2 limit

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

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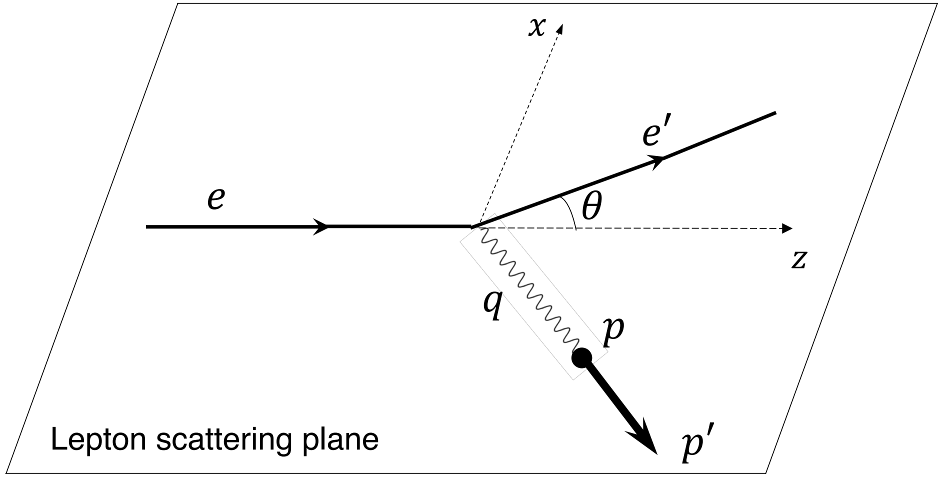
- G_E^p and G_M^p can be extracted using Rosenbluth separation
- For PRad, cross section dominated by G_E^p



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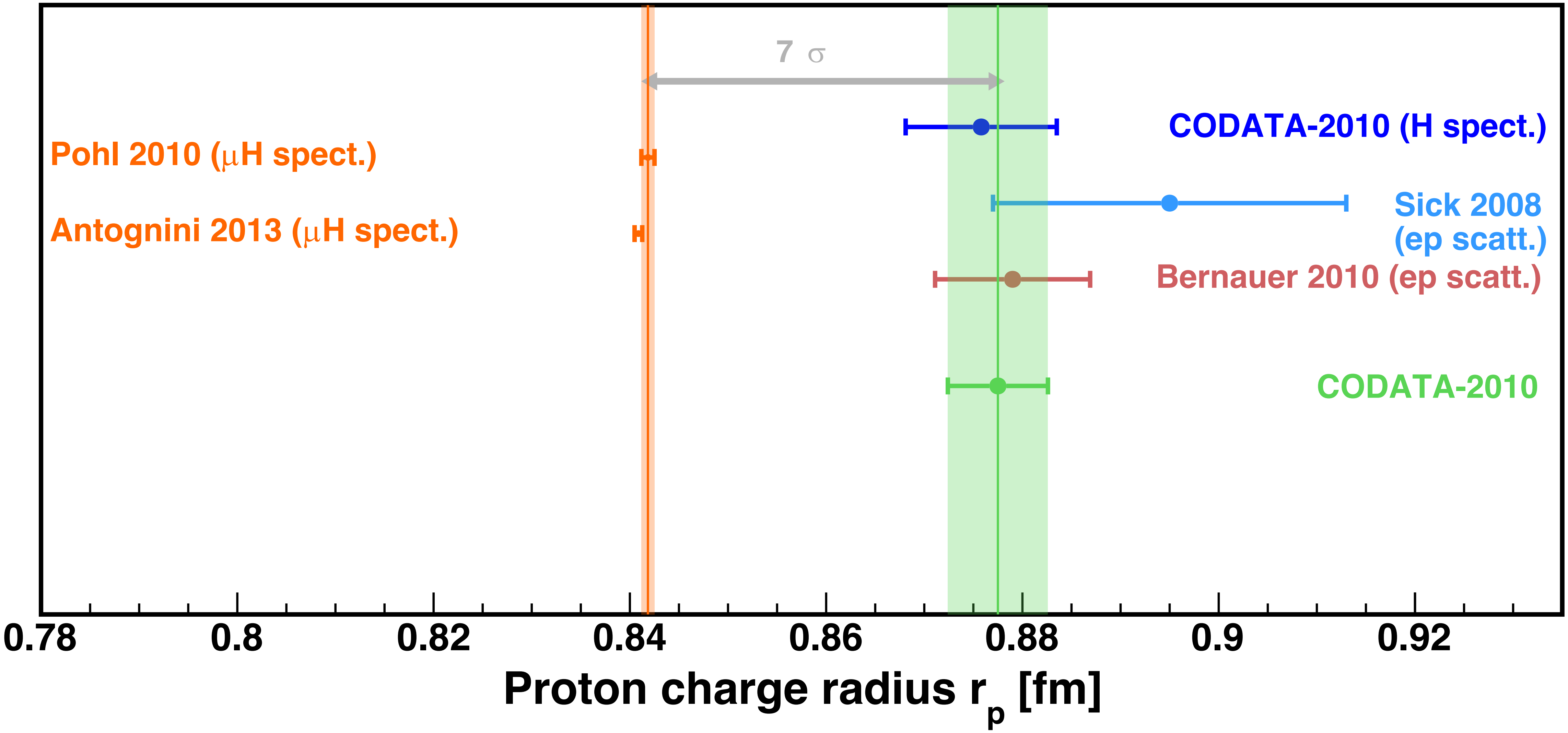
Proton Charge Radius Puzzle



PRad Experiment Overview

PRad goal: Measuring proton charge radius using unpolarized *ep* elastic scattering

- Covers two orders of magnitude in low Q^2 with the same detector setting
  - ~2×10^{-4} - 6×10^{-2} GeV^2

- At each beam energy, different Q^2 data collected at the same time

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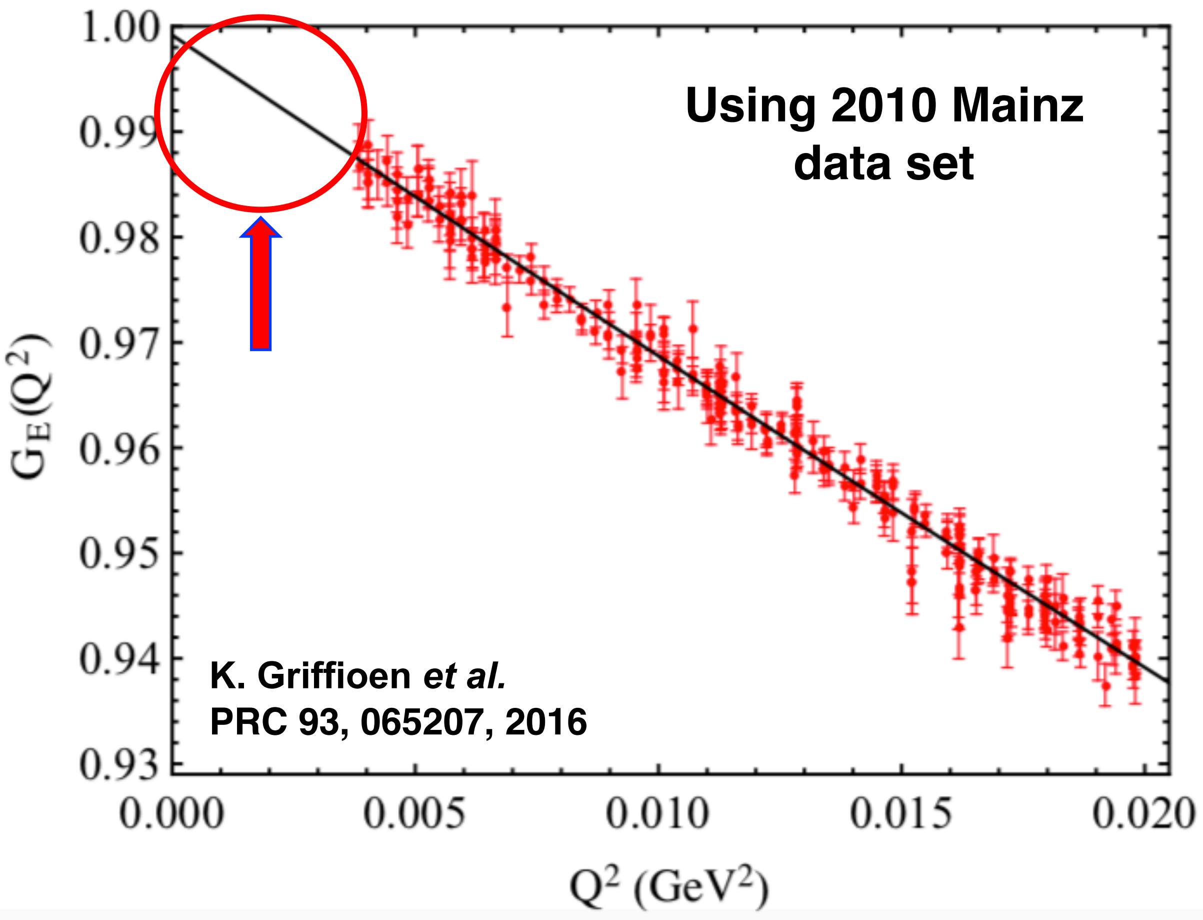

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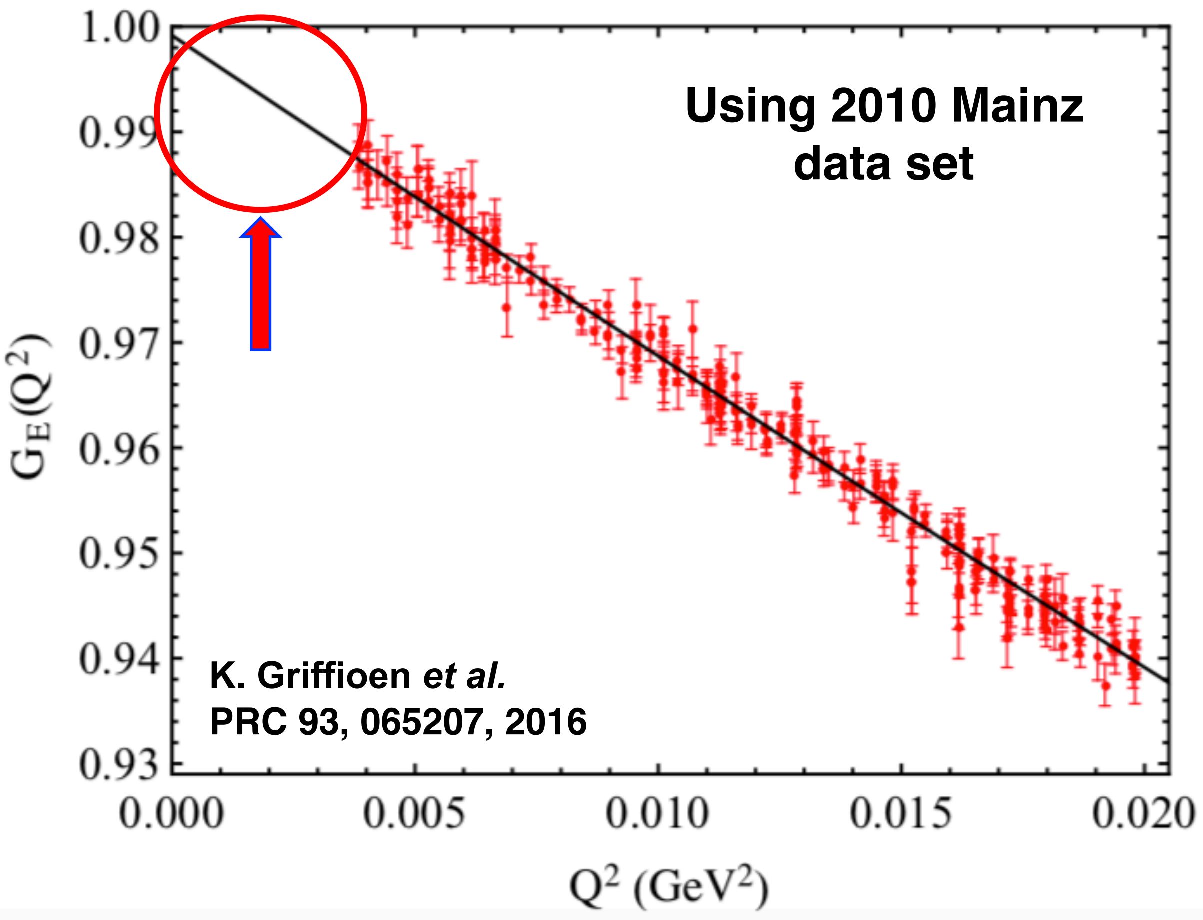
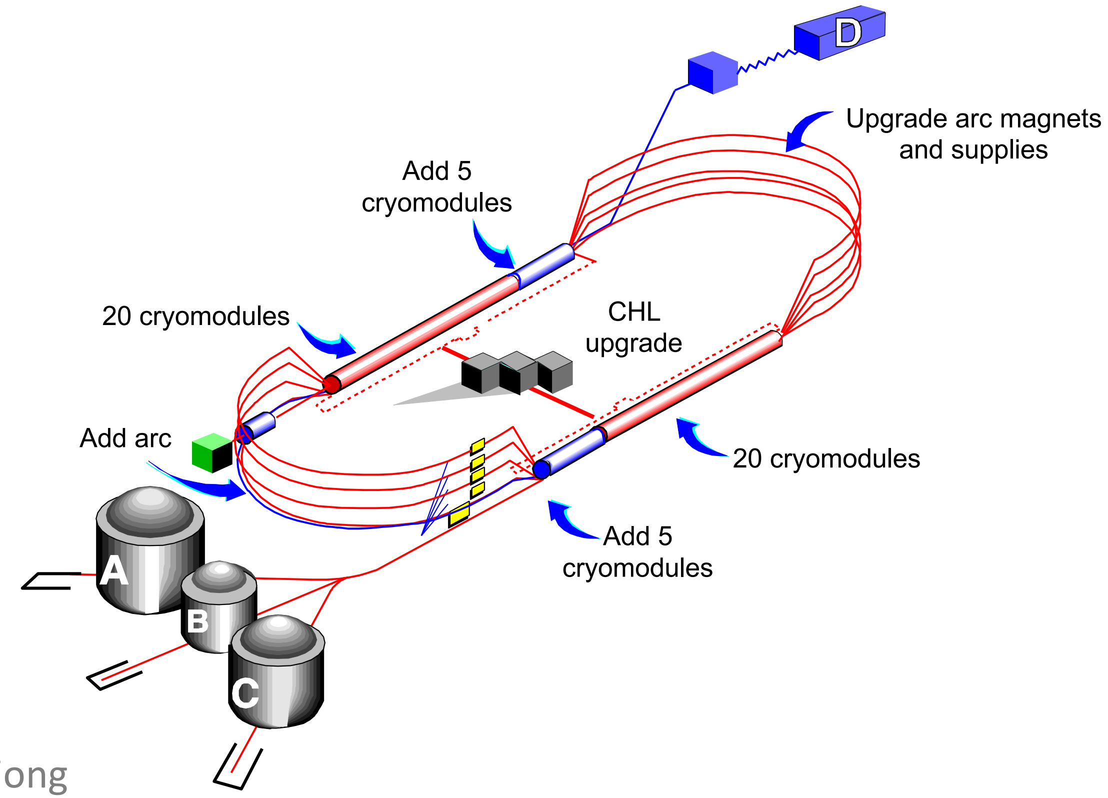
- At each beam energy, different Q^2 data collected at the same time
- Unprecedented low Q^2 (~2×10^{-4} GeV^2)
- Normalize to the simultaneously measured Møller scattering process
- Windowless H_2 gas-flow target removes major background source
- Extreme forward angles (0.7^o to 7^o), minimize G_M contribution

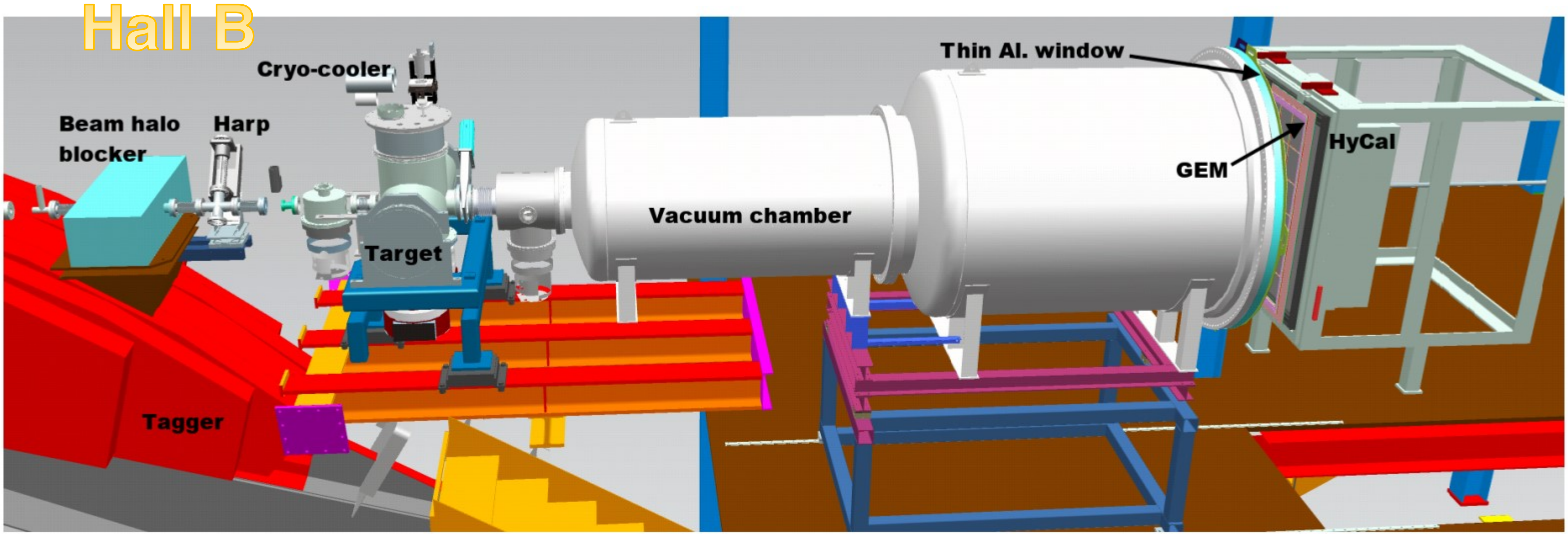


Jefferson Lab

- Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA
- Completed 6 GeV to 12 GeV upgrade in 2015
- 4 experimental Halls
- PRad data taking May/June 2016, with 1.1 GeV and 2.2 GeV electron beams



PRad Experimental Apparatus



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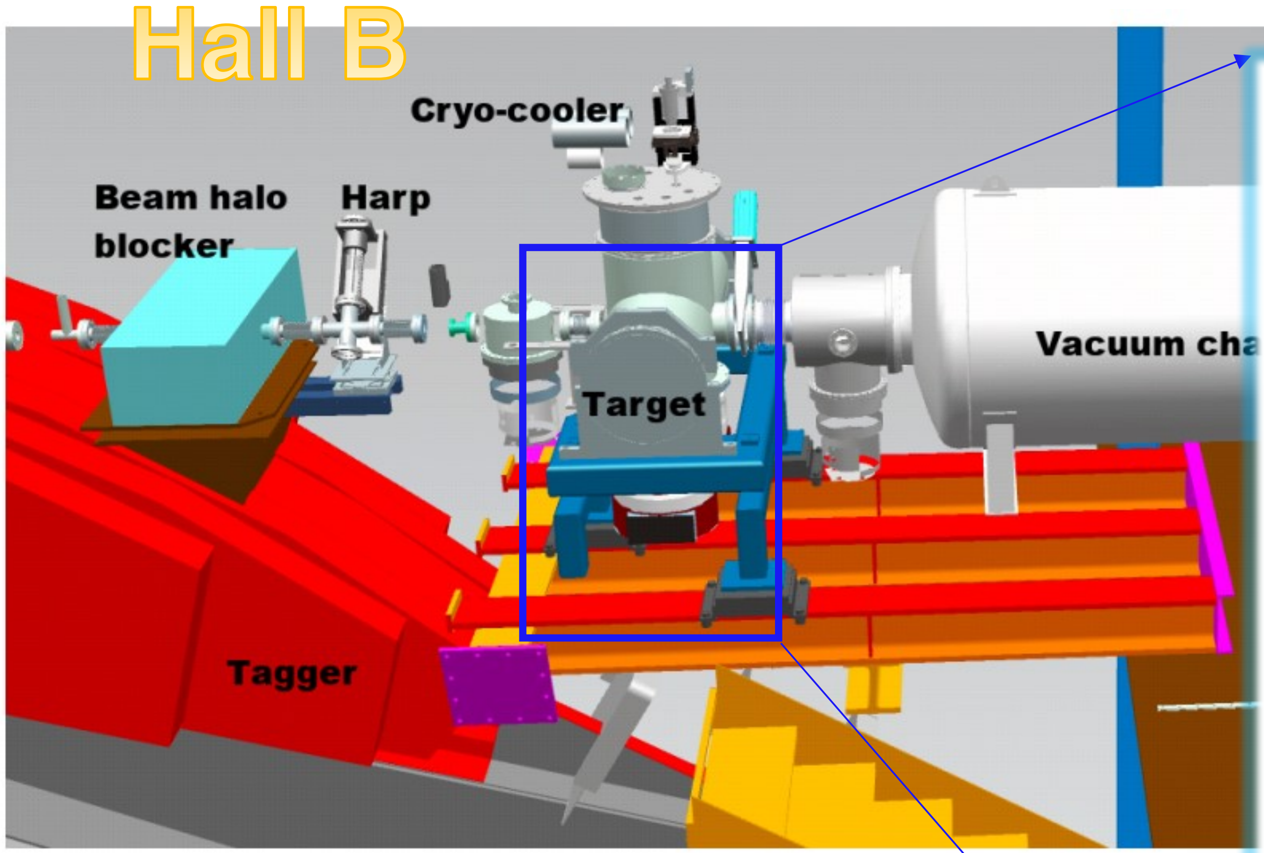
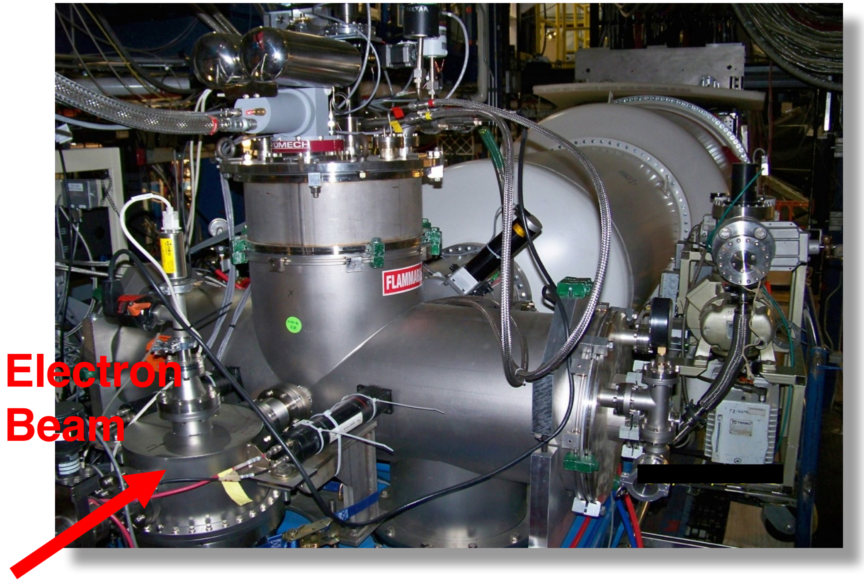
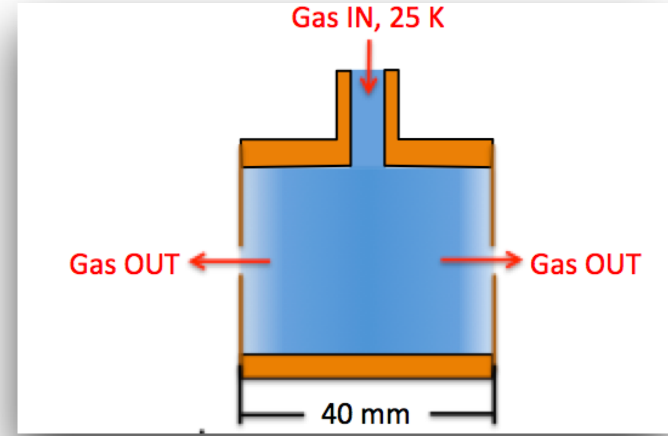
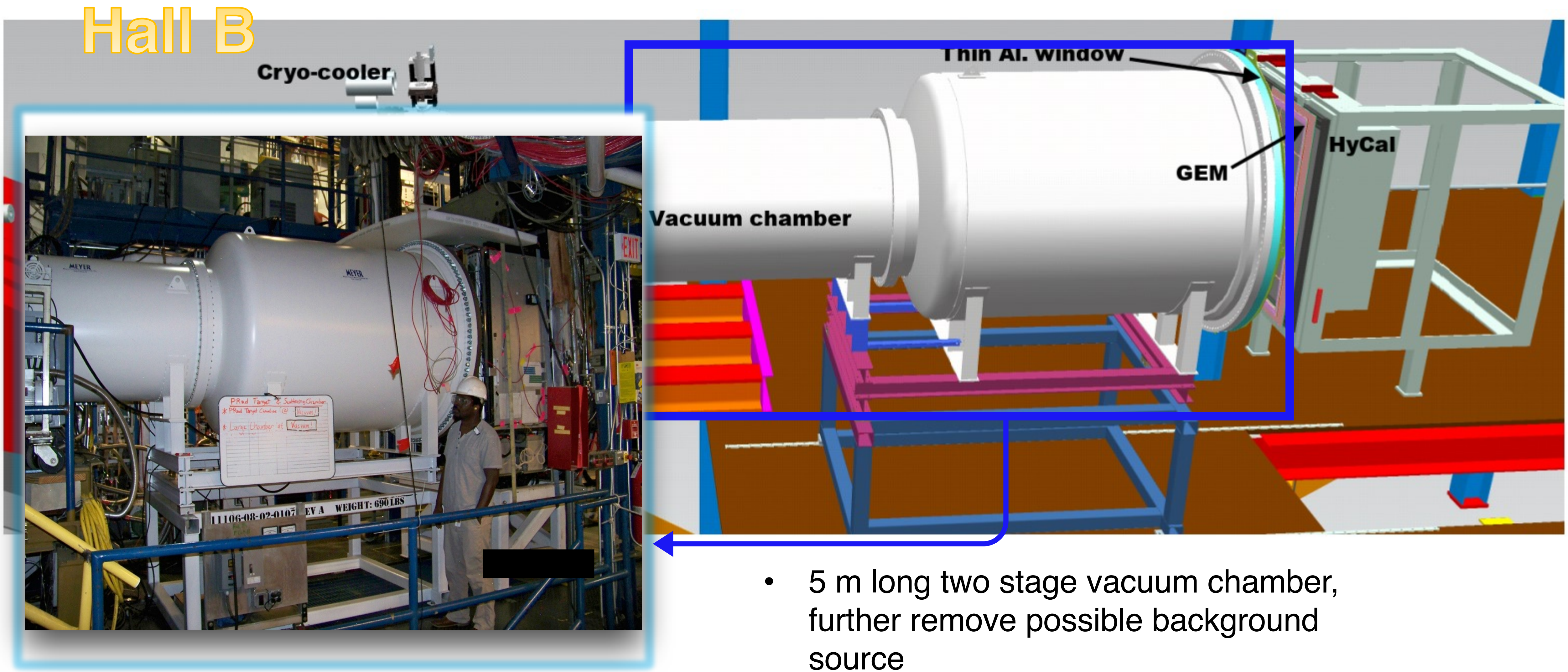






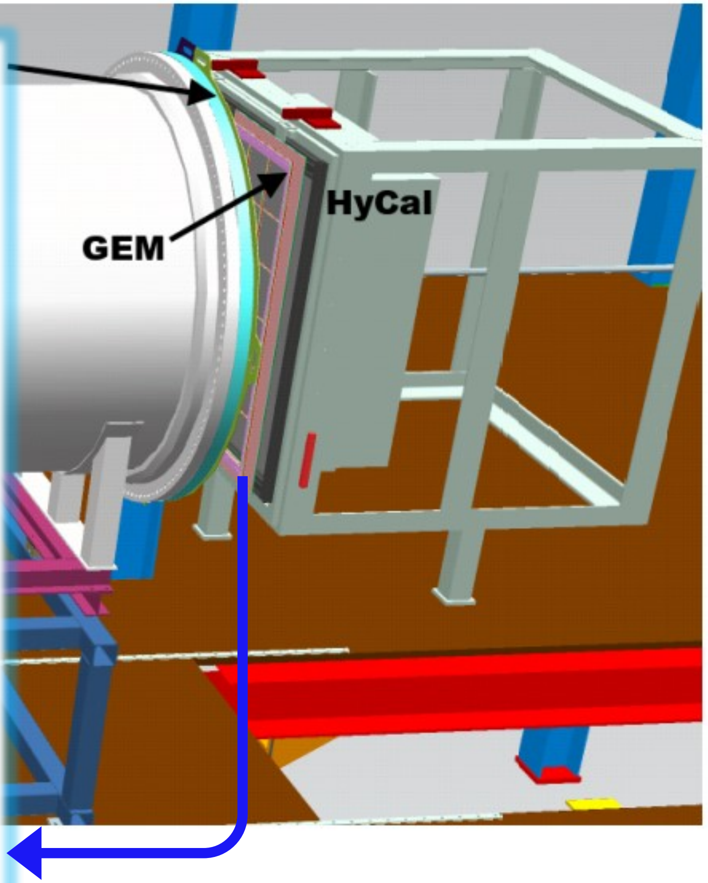
- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2

PRad Experimental Apparatus



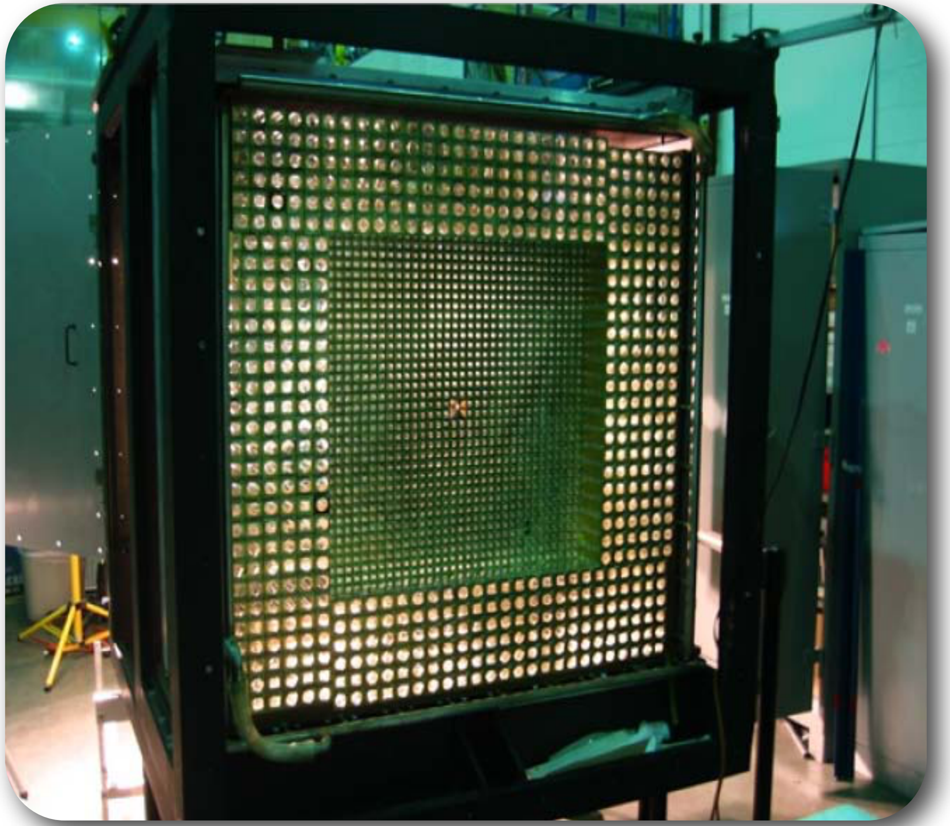
- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum chamber pressure: 0.3 mTorr

PRad Experimental Apparatus

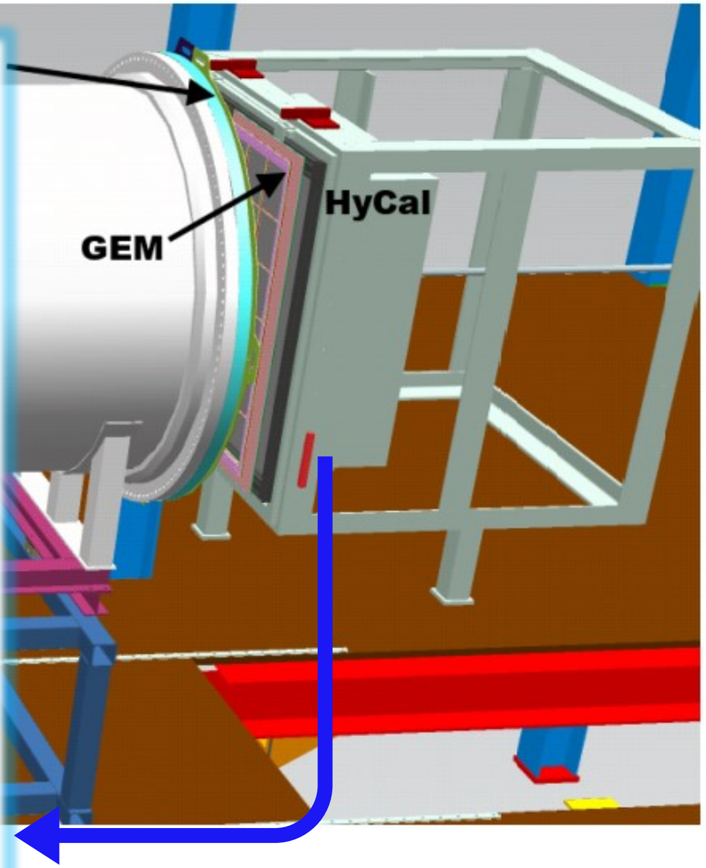


- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)

PRad Experimental Apparatus



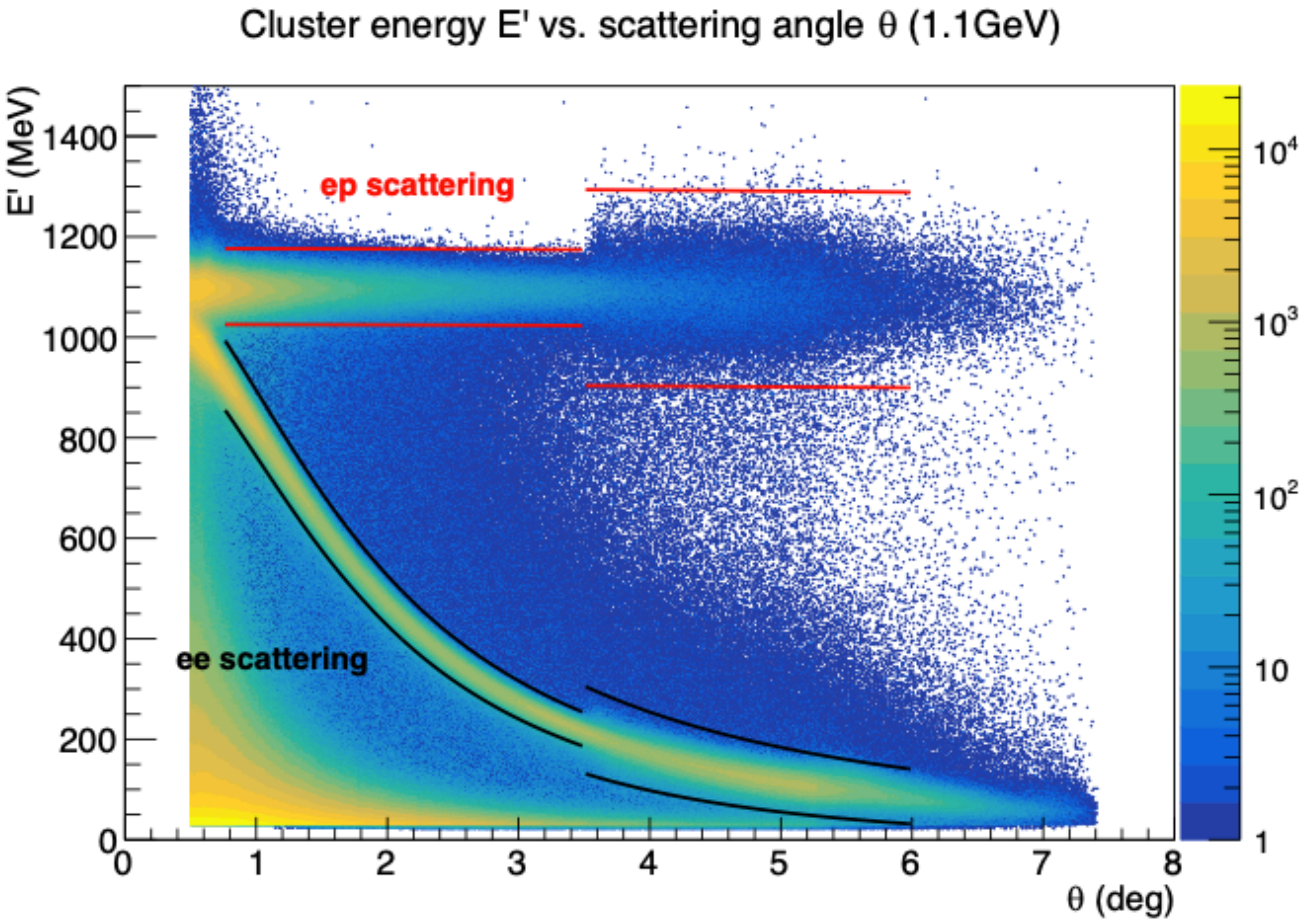
- Hybrid EM calorimeter (HyCal)
  - Inner 1156 $PbWO_4$ modules
  - Outer 576 lead glass modules
- Scattering angle coverage: ~ 0.7° to 7.0°
- Full azimuthal angle coverage
- High resolution and efficiency



Analysis – Event Selection

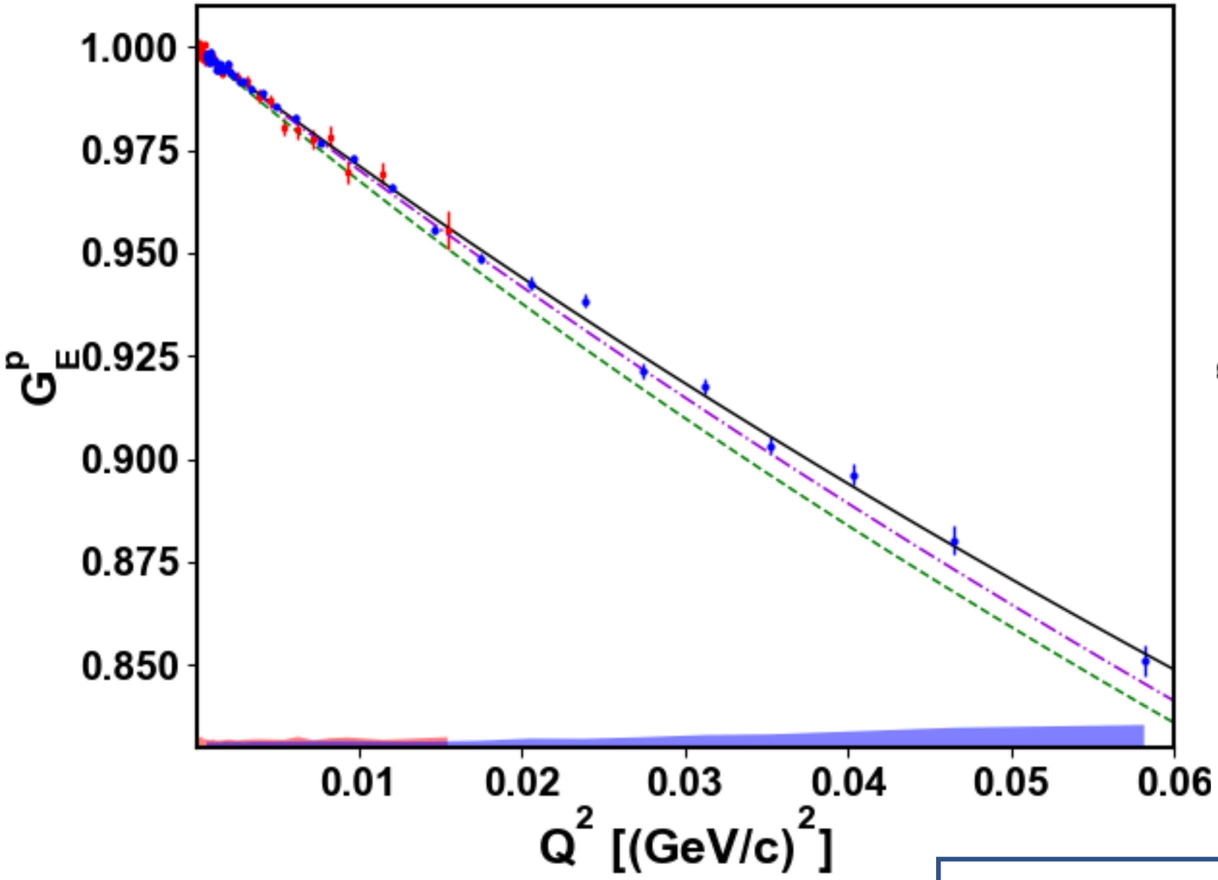
Event selection method

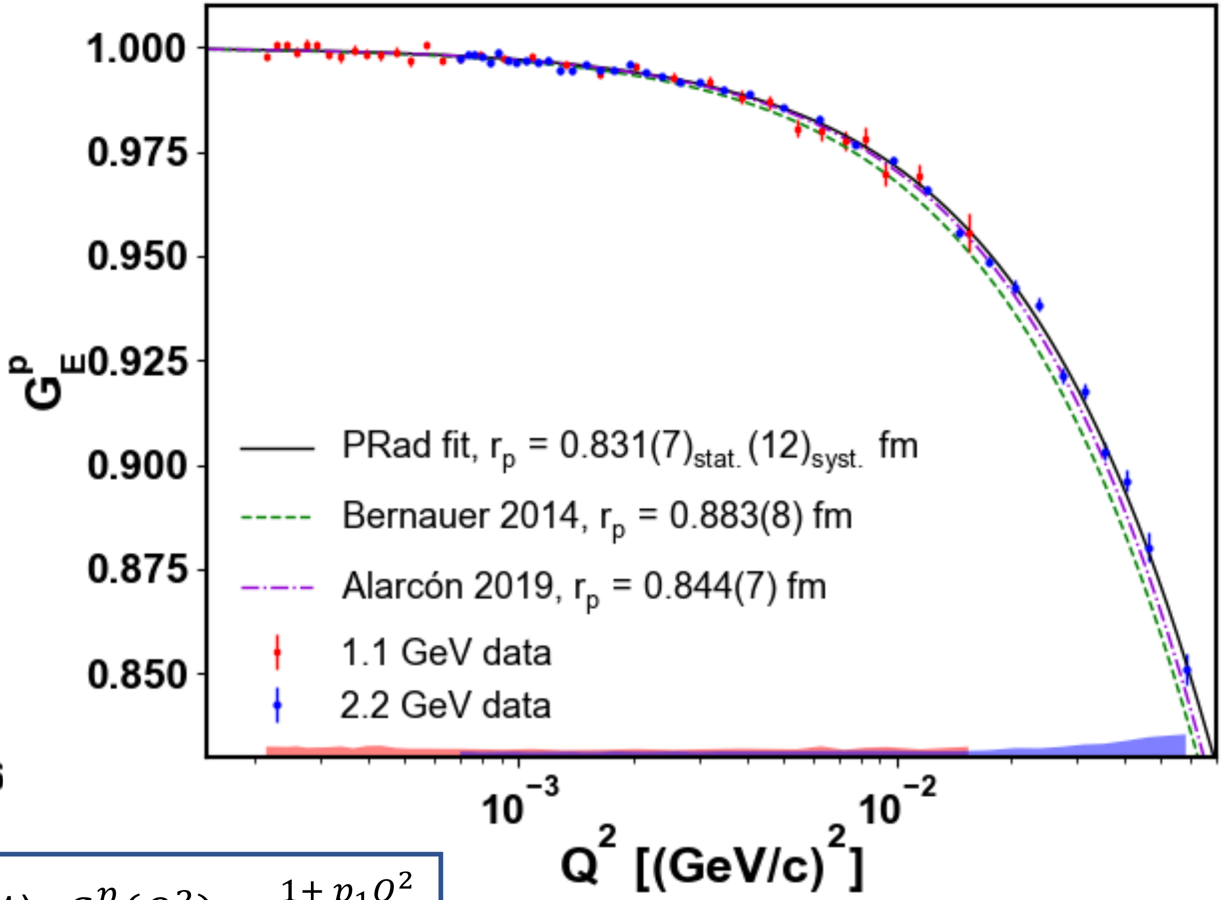
1. Hit matching between GEMs and HyCal
2. Apply angle dependent energy cut based on kinematics
   1. Cut size depend on local detector resolution
3. For *ee*, requiring double-arm events, and apply additional cuts
   1. Elasticity
   2. Co-planarity
   3. Vertex z



Proton Electric Form Factor G_E^p

r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

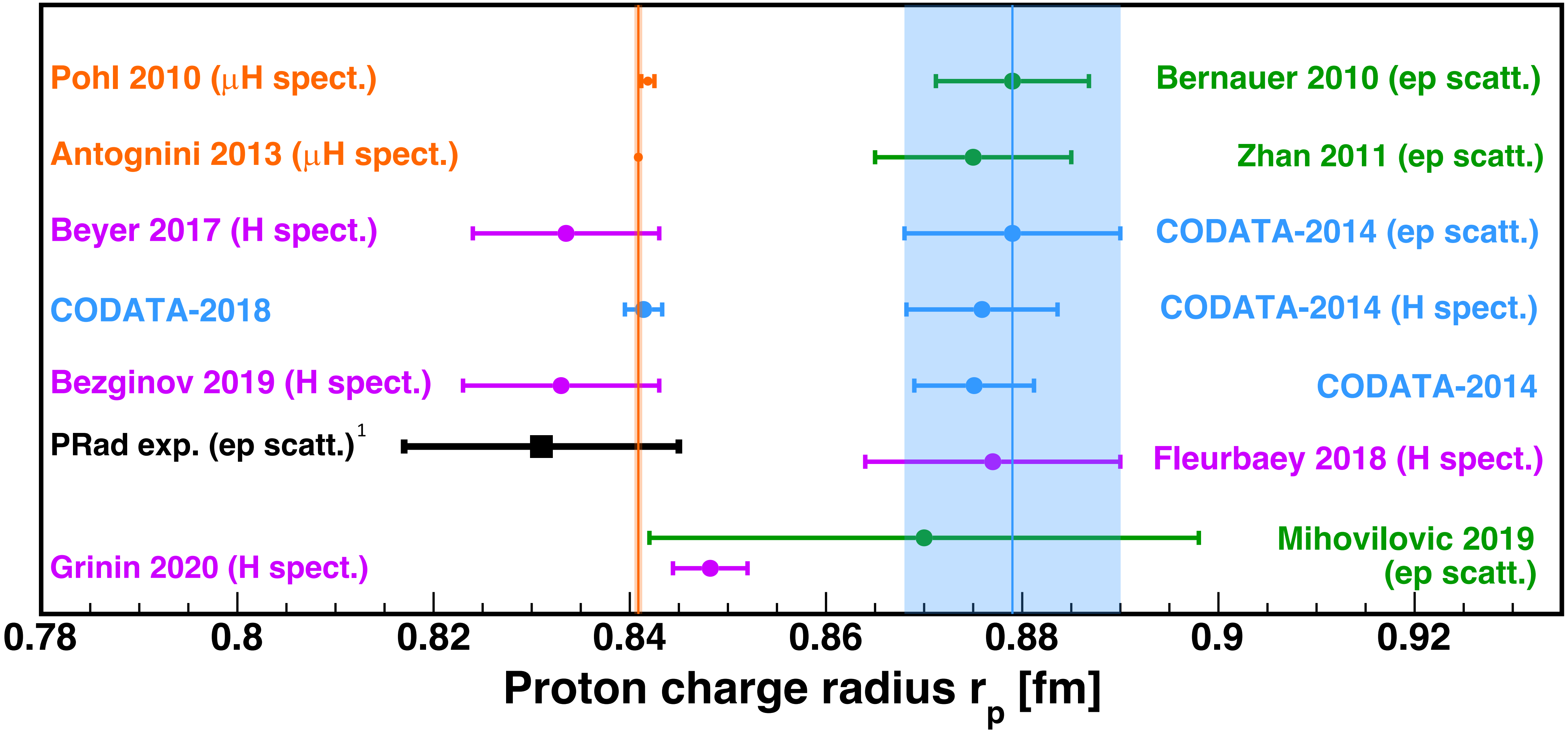




Rational (1,1): $G_E^p(Q^2) = \frac{1+ p_1 Q^2}{1+ p_2 Q^2}$

PRad Proton Charge Radius

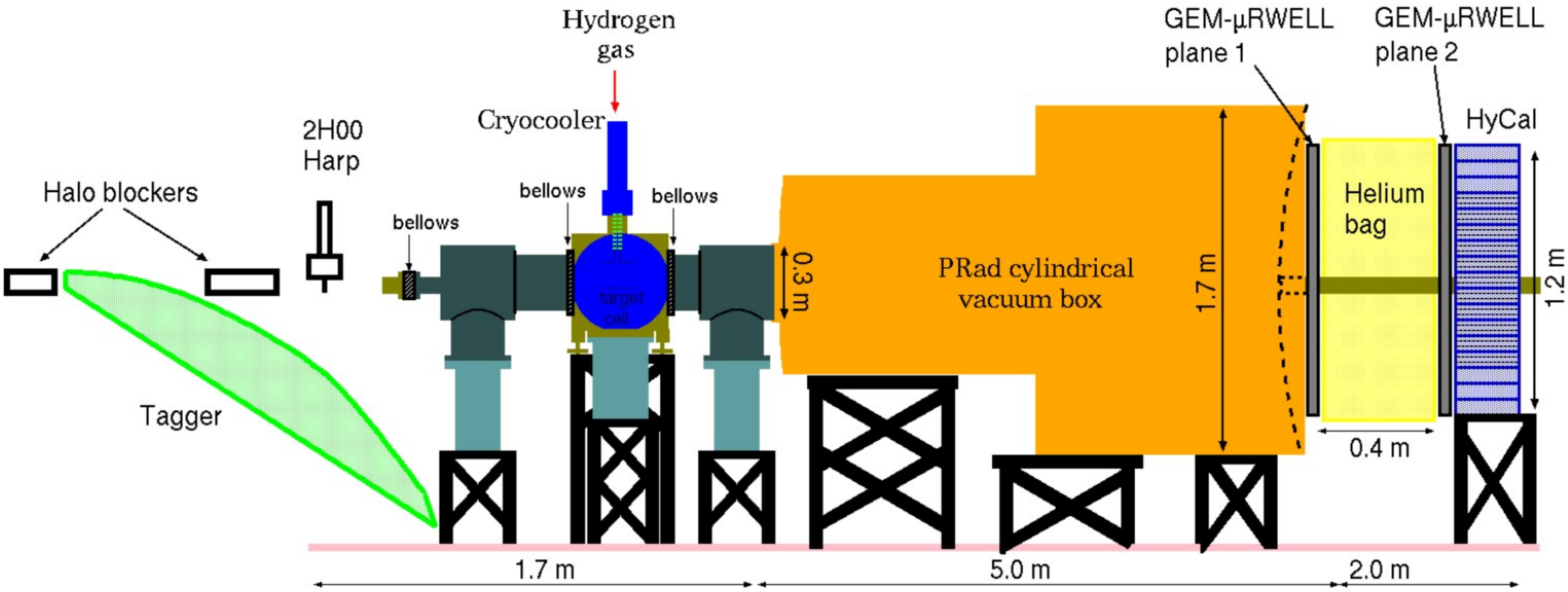
PRad result: r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



1: W. Xiong et al. Nature **575**, no. 7781, 147 (2019)

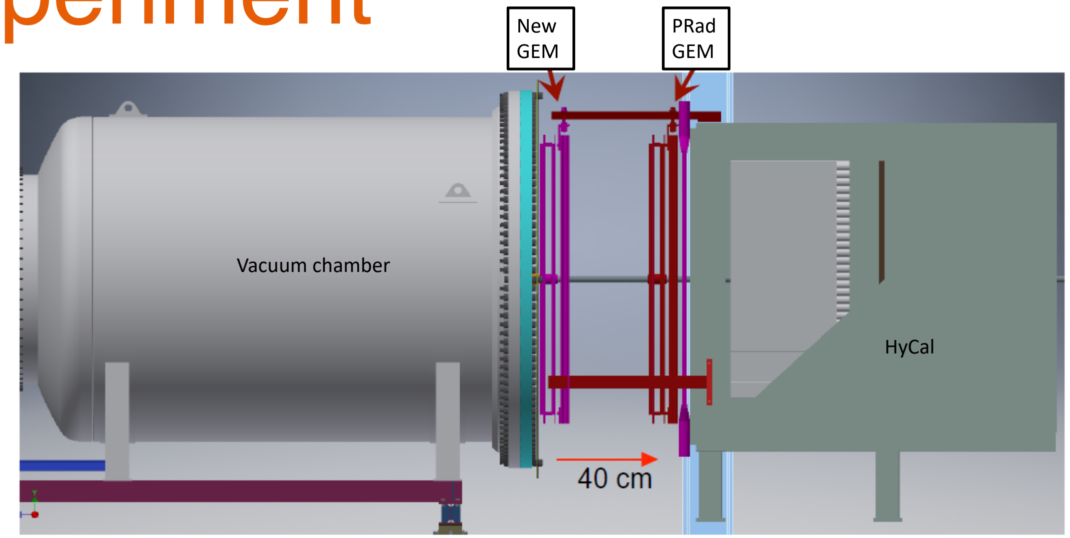
PRad-II Experiment

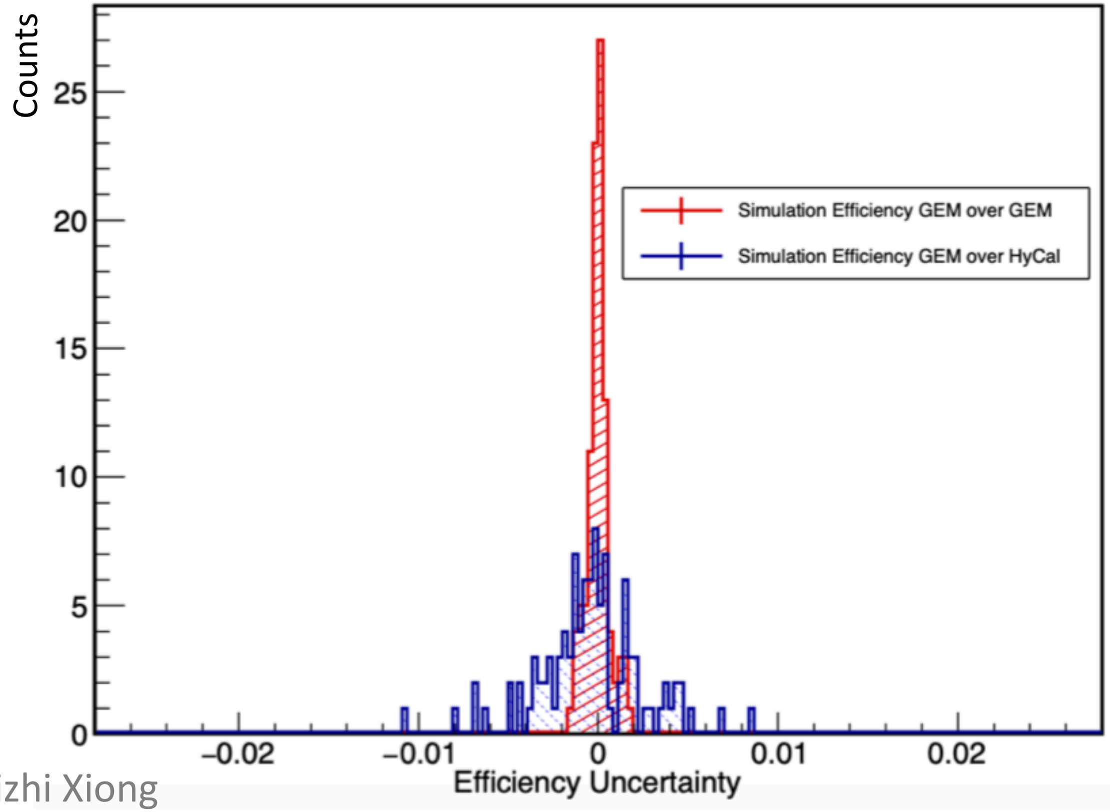
- JLab PAC 48 approved PRad-II (PR12-20-004) with the highest scientific rating "A"
- Goal: reach ultra-high precision (~4 times smaller total uncertainty), resolve tension with modern *e-p* scattering results, examine μH spectroscopic results

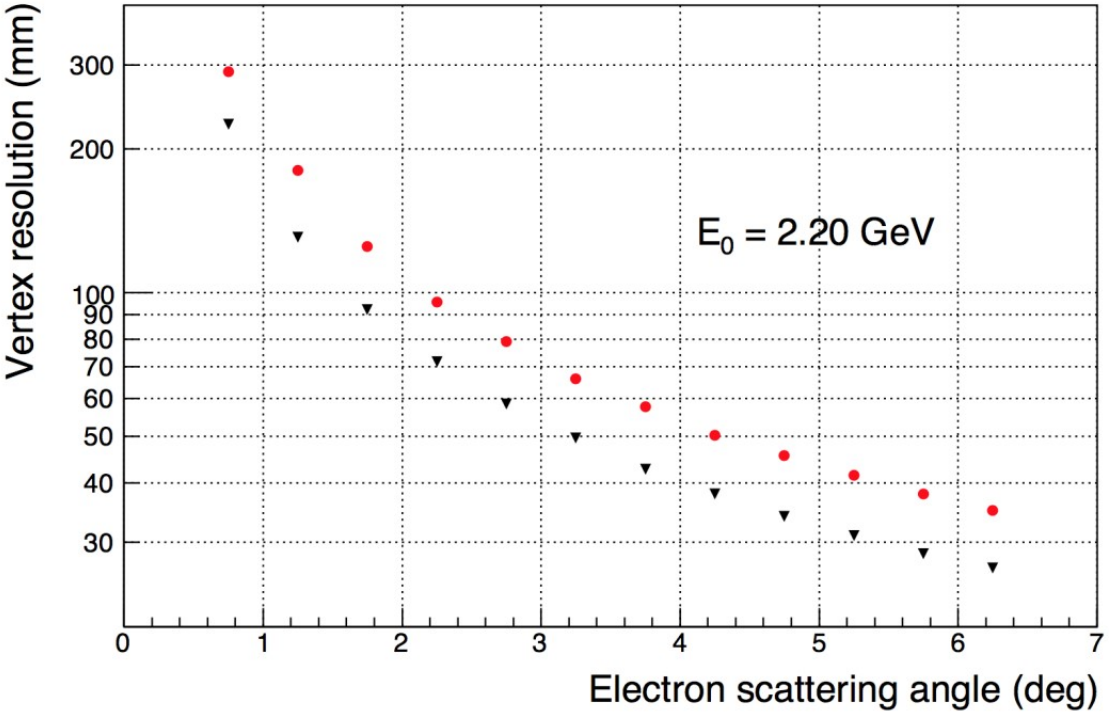


PRad-II Experiment

- Adding tracking capacity (second GEM plane)
  - ➢ Improve GEM efficiency measurement
  - ➢ Vertex-z reconstruction for *ep* to reject upstream background

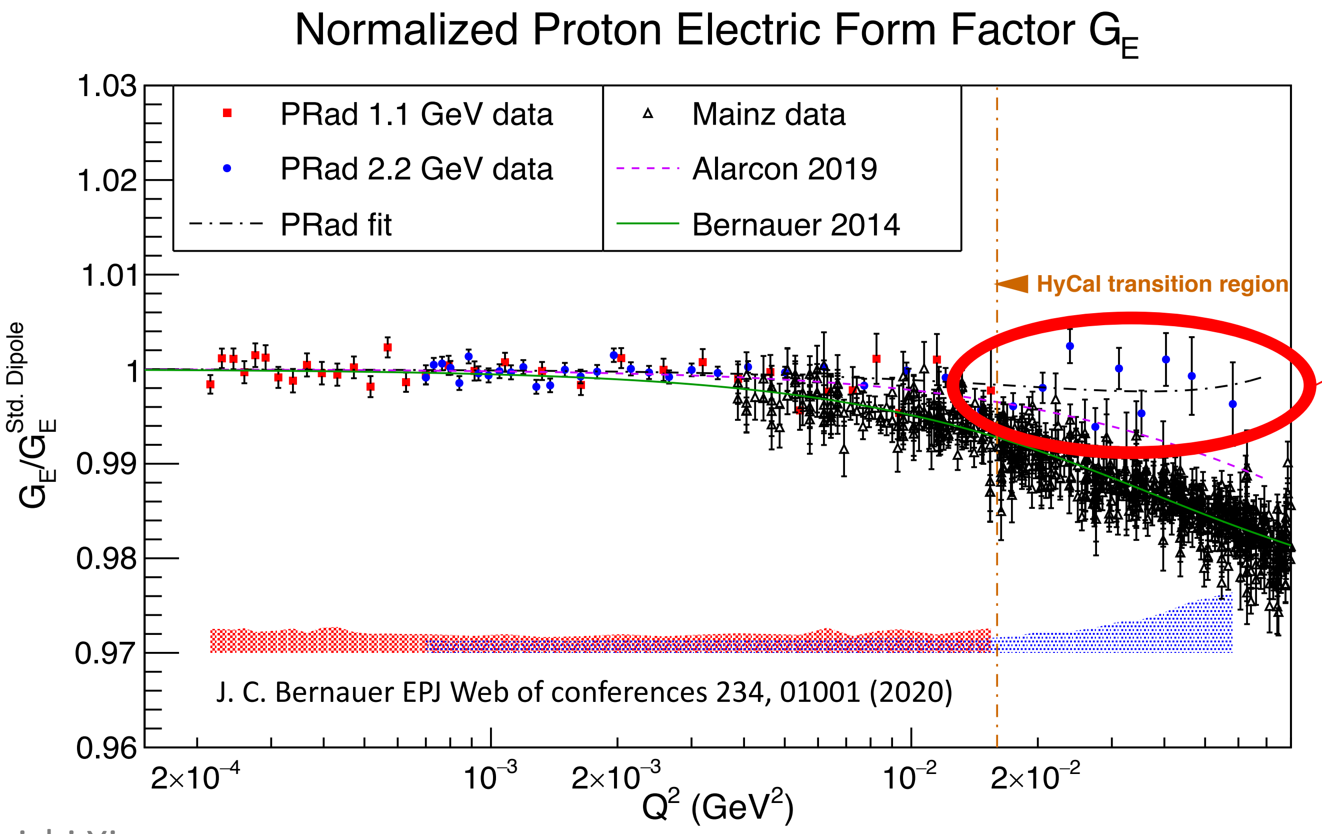


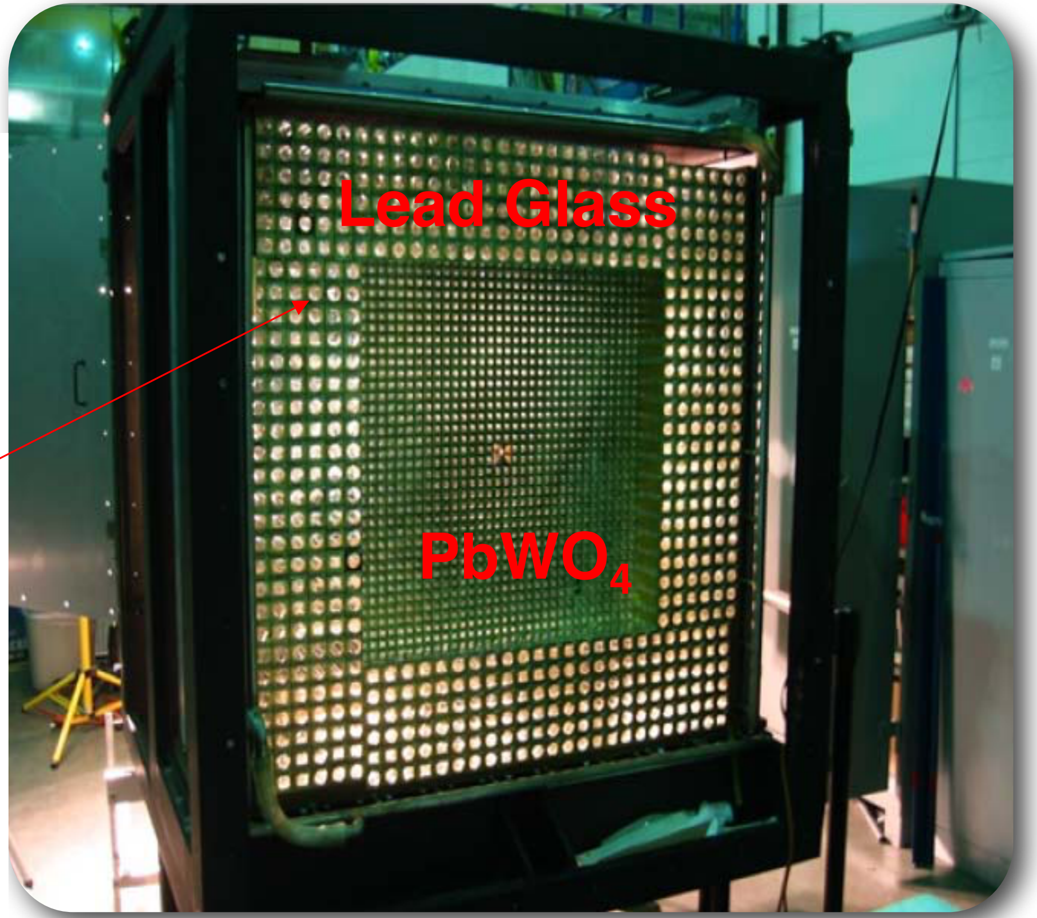




PRad-II Experiment – Cont.

- Upgraded HyCal with all high resolution $PbWO_4$ modules
  - ➢ Better energy resolution: 2.4% v.s. 6.0% from LG
  - ➢ Better position resolution
  - ➢ Better non-linearity response





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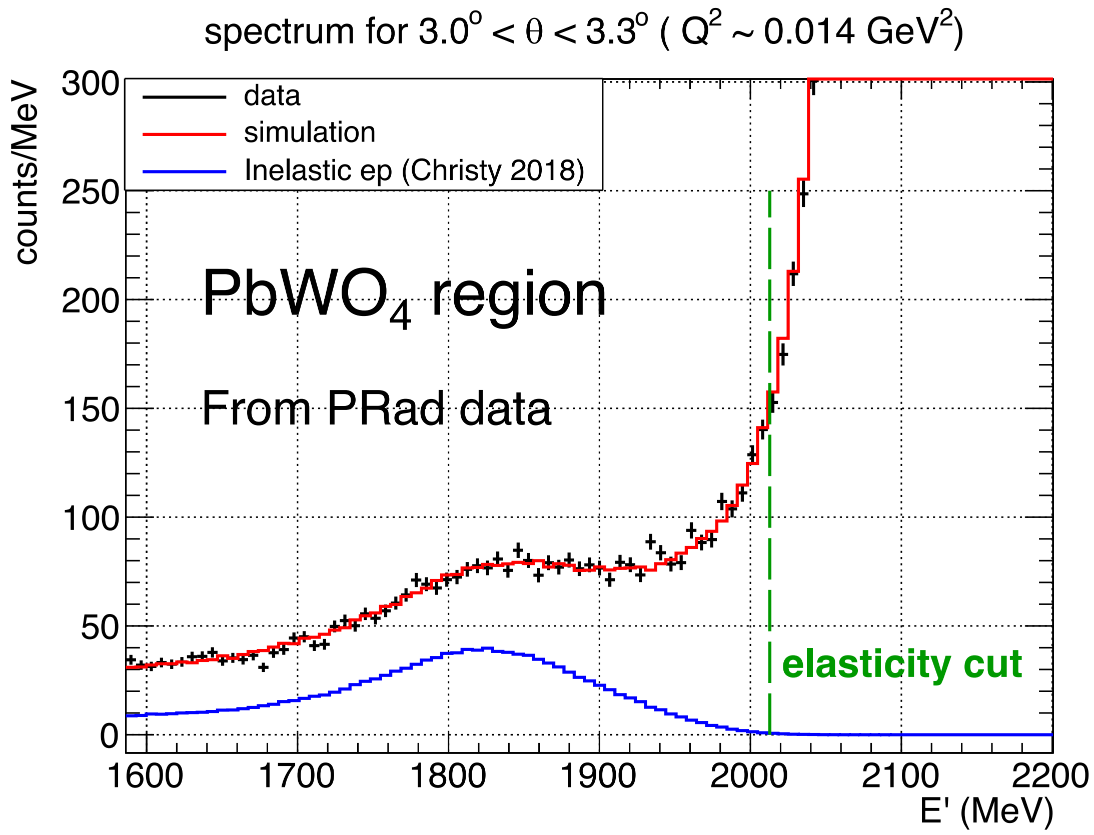

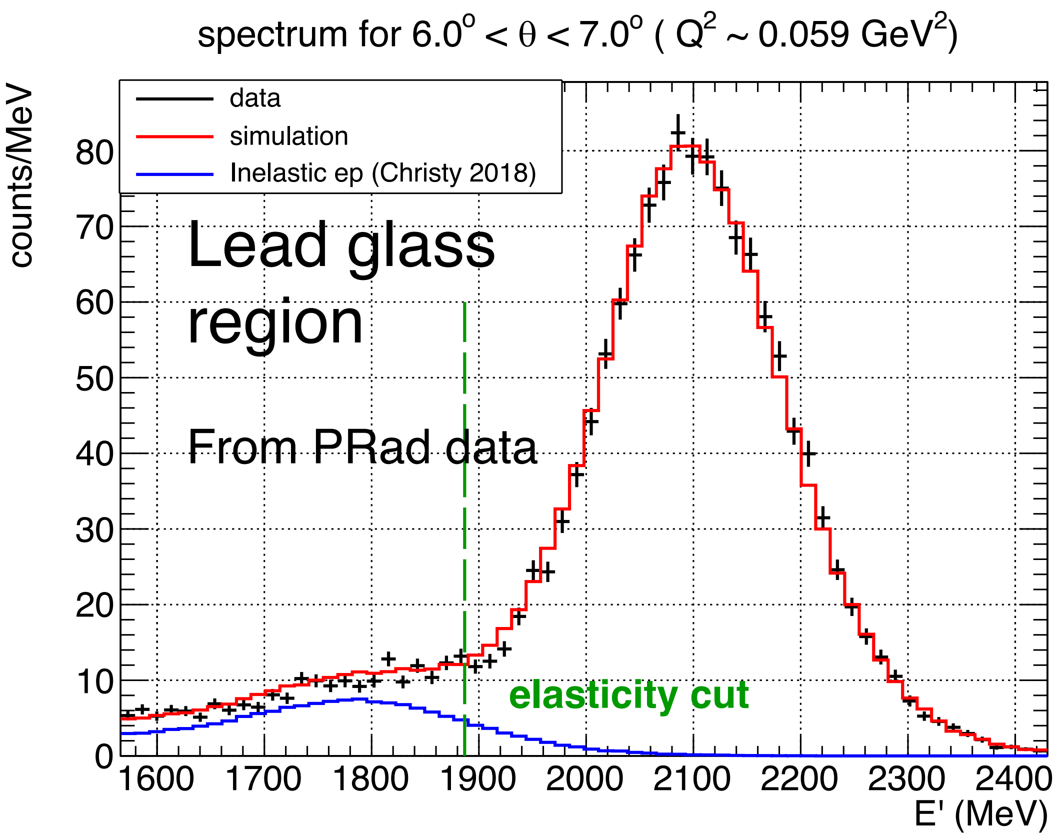

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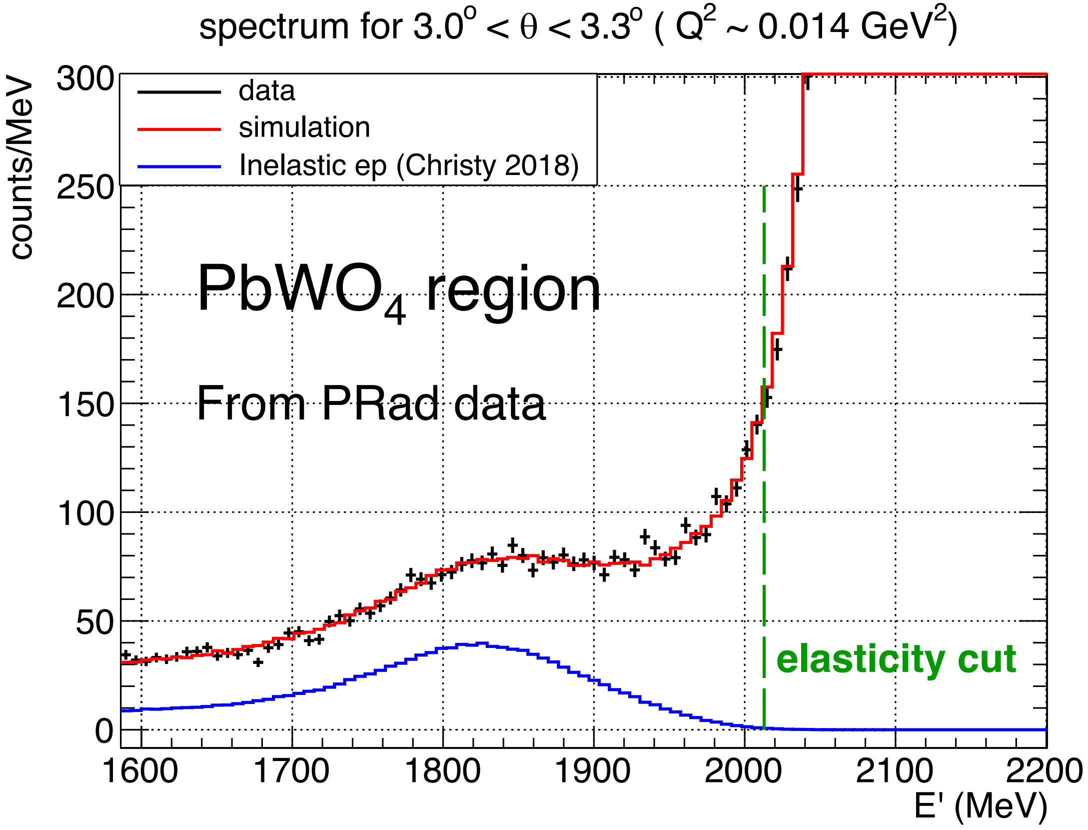
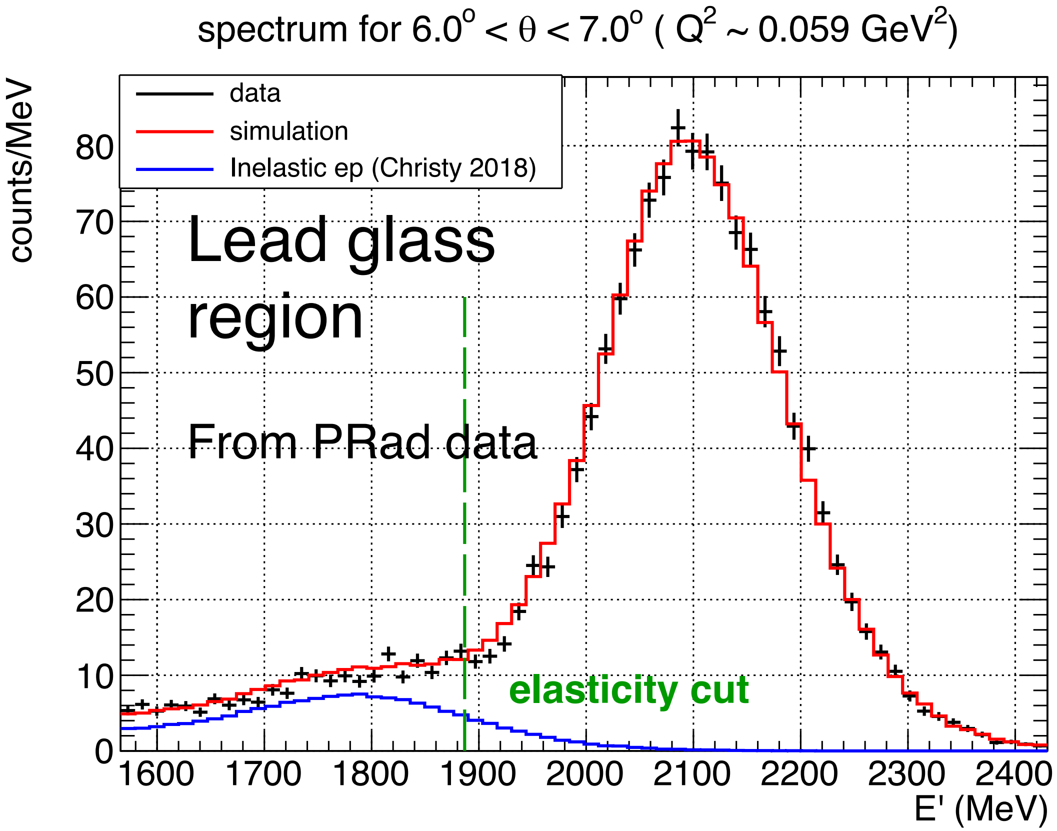
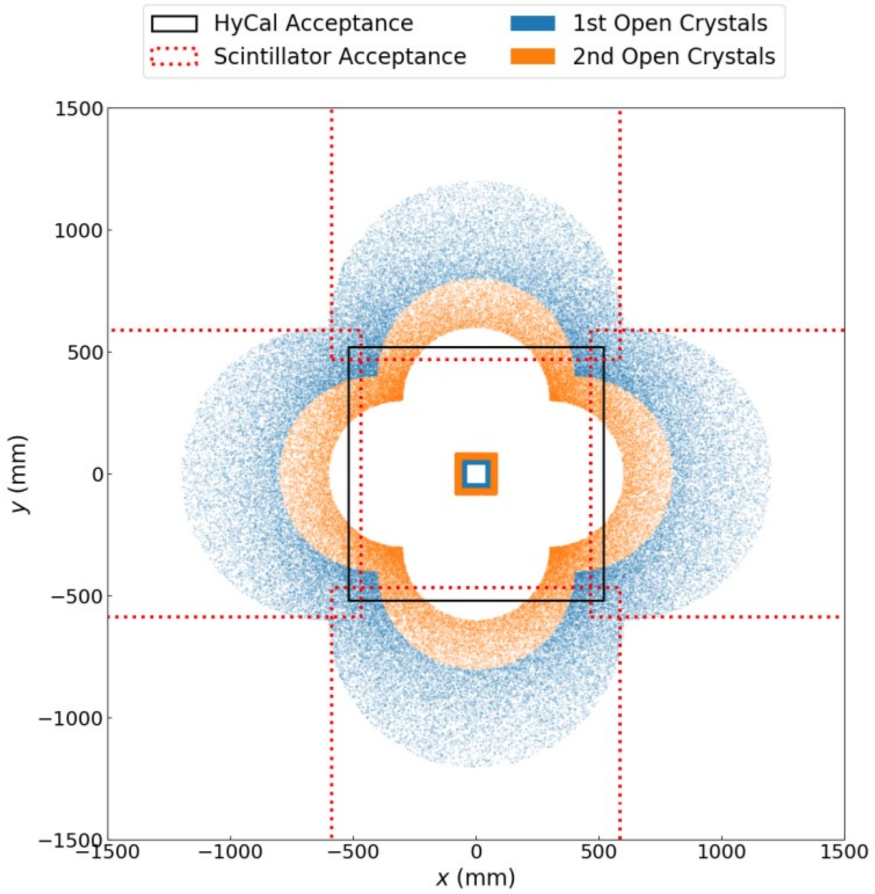
  - Better energy resolution: 2.4% v.s. 6.0% from LG
  - Better position resolution
  - Better non-linearity response
- Currently seeking funding or used modules for the upgrade

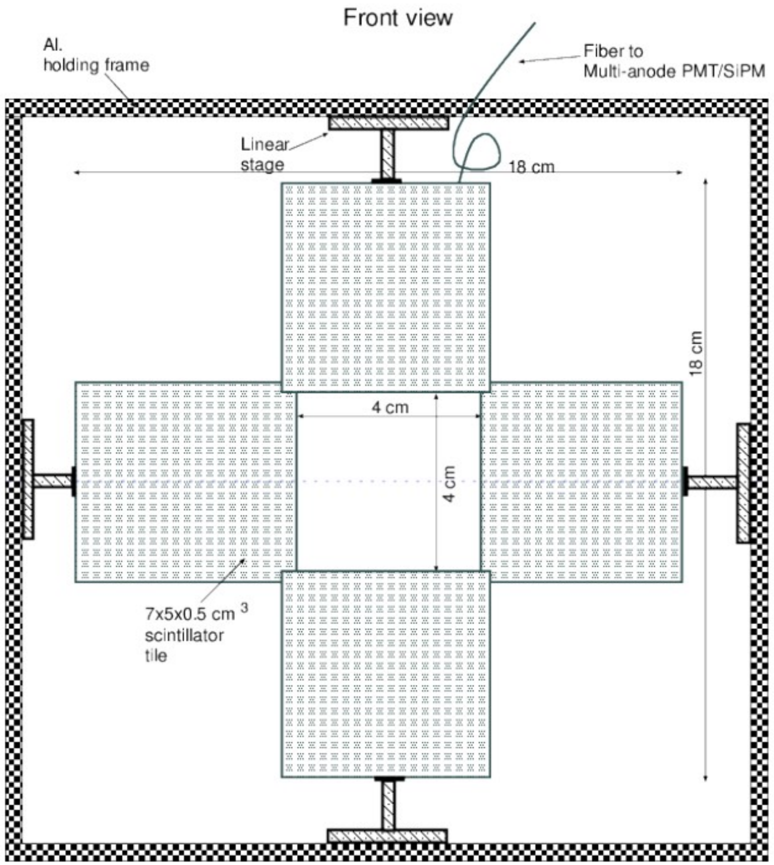




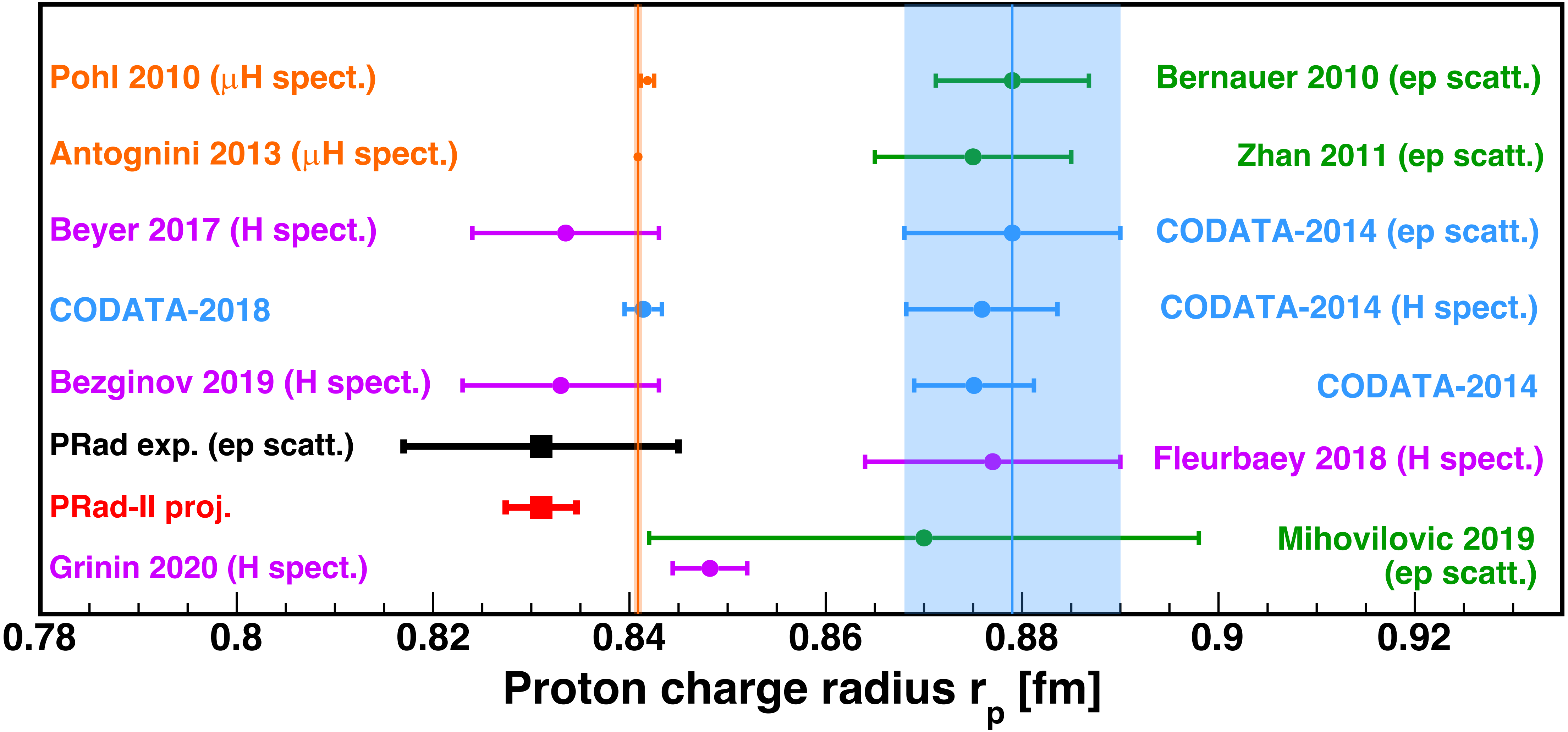
PRad-II Experiment – Cont.

- Convert to FADC based readout for HyCal
- Four times smaller stat. uncertainty
- Better RC calculating including NNLO diagrams
- New scintillating detectors, help reaching $Q^2 \sim 10^{-5}$ GeV^2 (new record!)





PRad-II Experiment – Projected Result



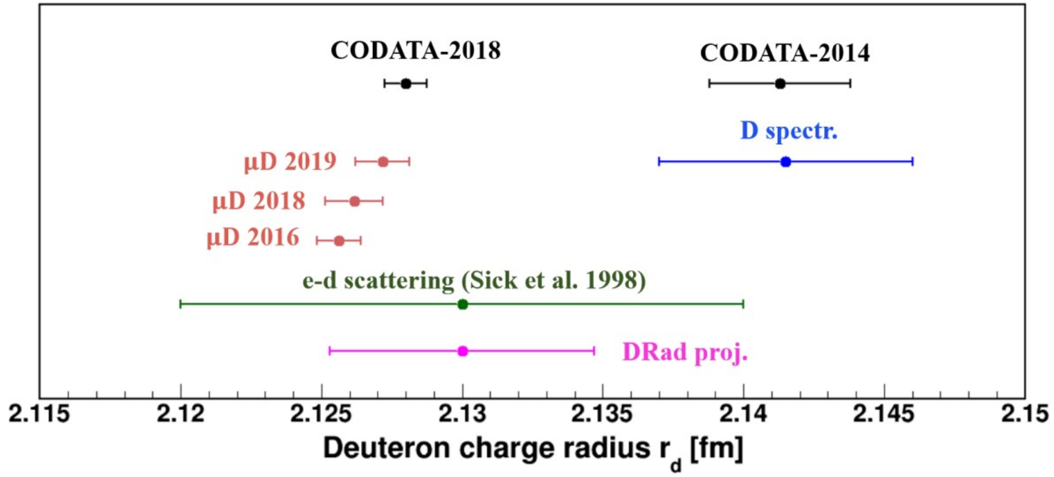
Expected total uncertainty: 0.0036 fm

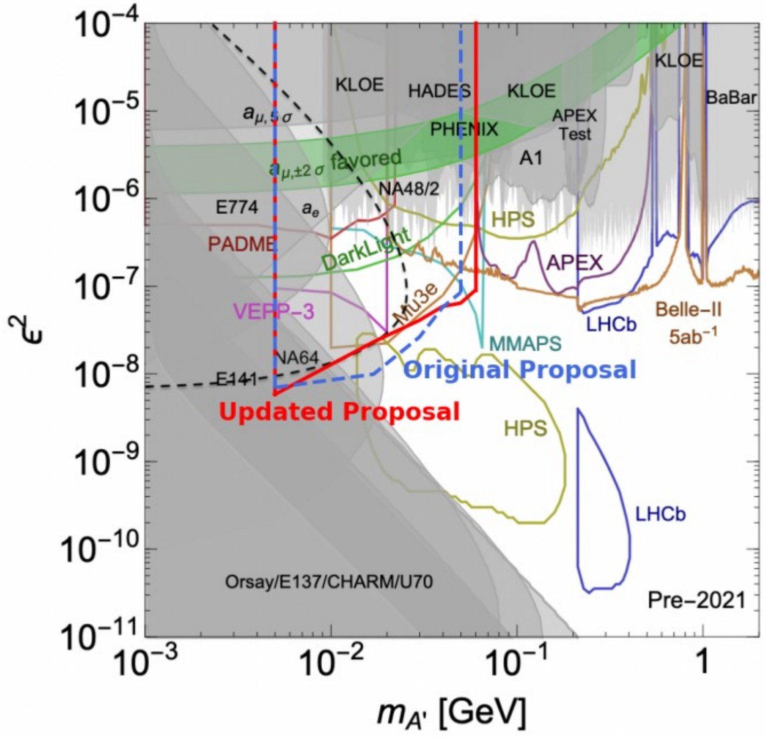
Projected result with full detector upgrades

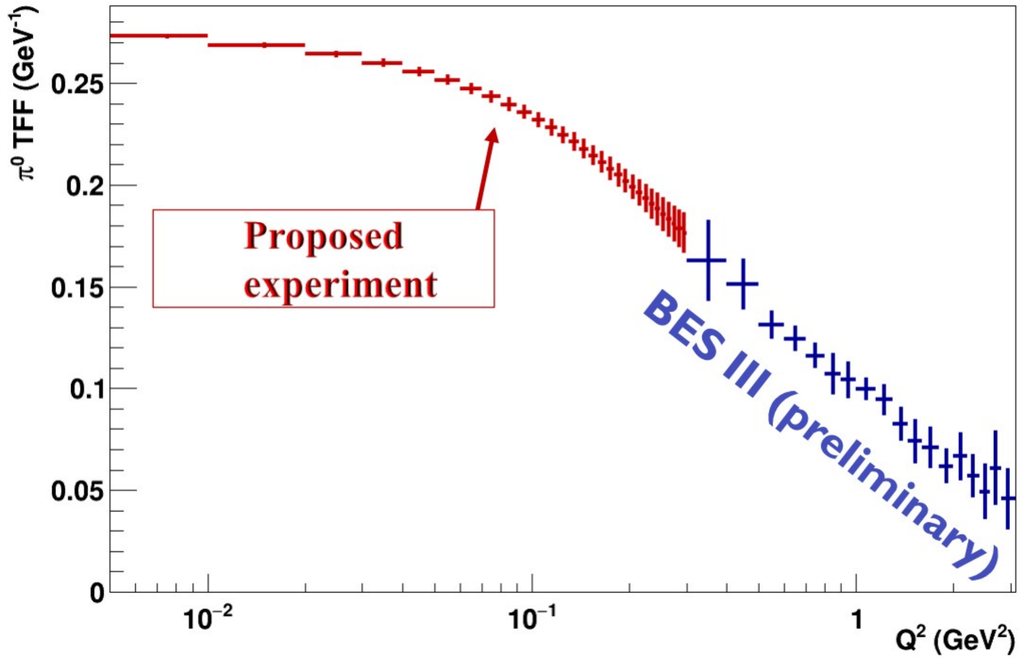
Rev. Mod. Phys. 94, 015002

Other Research Opportunities with PRad Setup

- Search for 3-60 MeV hidden sector particle
  - Approved 2022, rated A
- Neutral pion transition form factor
  - Approved 2022, rate A-
- Deuteron charge radius (DRad) experiment
  - Plan to submit next year







Summary

- The PRad collaboration carried out the first electron scattering experiment using a non-magnetic spectrometer approach – calorimeter and GEMs
- The PRad result: r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

- Planning on follow-up experiment, aim for ~4 times of improvement on total r_p uncertainty
  1. New detectors and upgrades: 2^{nd} GEM plane, possible all $PbWO_4$ calorimeter, new scintillating detector
  2. New FADC readout system for the calorimeter
  3. 4 times smaller stat. uncertainty
  4. Improved RC calculating including NNLO

This work was supported in part by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-03ER41231

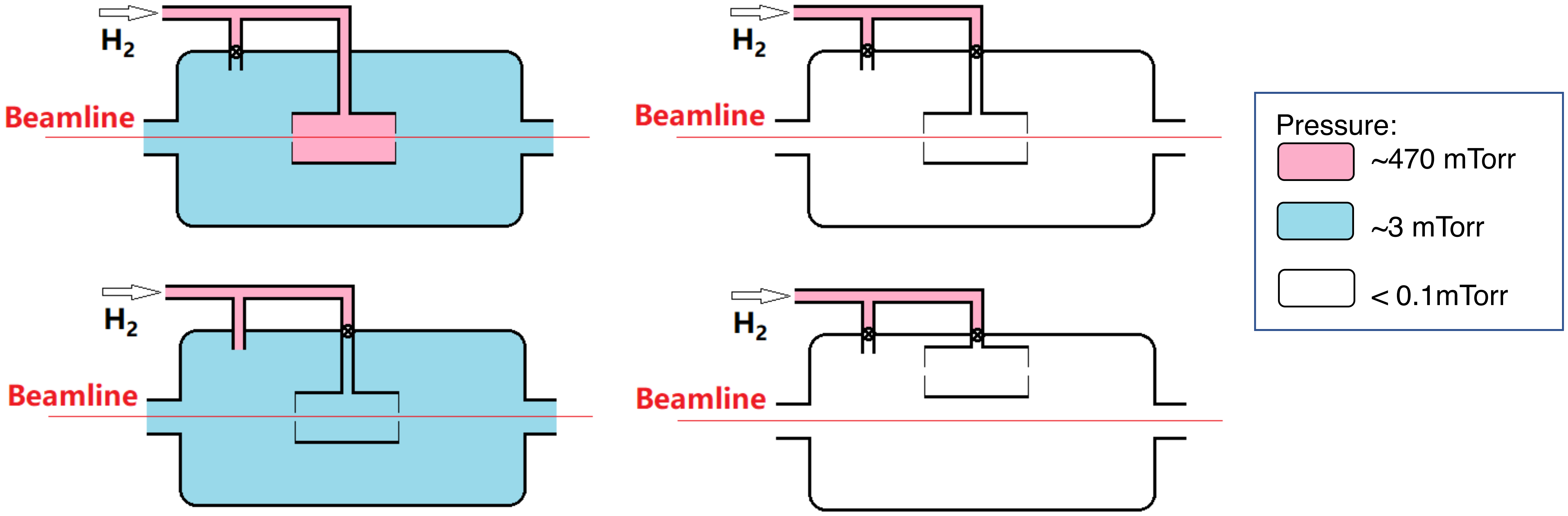
Backup

PRad-II Uncertainty Budget

Item	PRad δr_p [fm]	PRad-II δr_p [fm]	Reason
Stat. uncertainty	0.0075	0.0017	more beam time
GEM efficiency	0.0042	0.0008	2nd GEM detector
Acceptance	0.0026	0.0002	2nd GEM detector
Beam energy related	0.0022	0.0002	2nd GEM detector
Event selection	0.0070	0.0027	2nd GEM + HyCal upgrade
HyCal response	0.0029	negligible	HyCal upgrade
Beam background	0.0039	0.0016	better vacuum 2nd halo blocker vertex res. (2nd GEM)
Radiative correction	0.0069	0.0004	improved calc.
Inelastic *ep*	0.0009	negligible	-
G_M^p parameterization	0.0006	0.0005	HyCal upgrade
Total syst. uncertainty	0.0115	0.0032	
Total uncertainty	0.0137	0.0036	

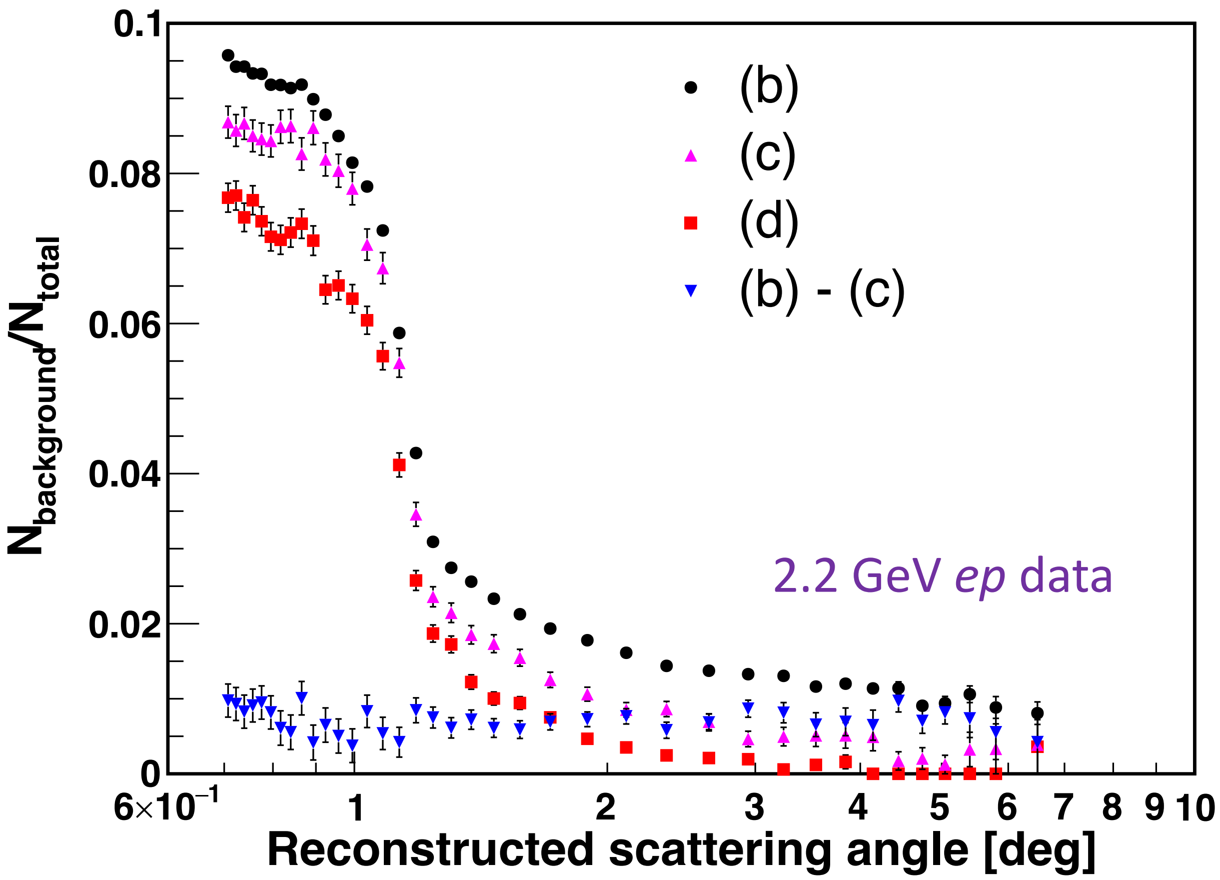
Analysis – Background Subtraction

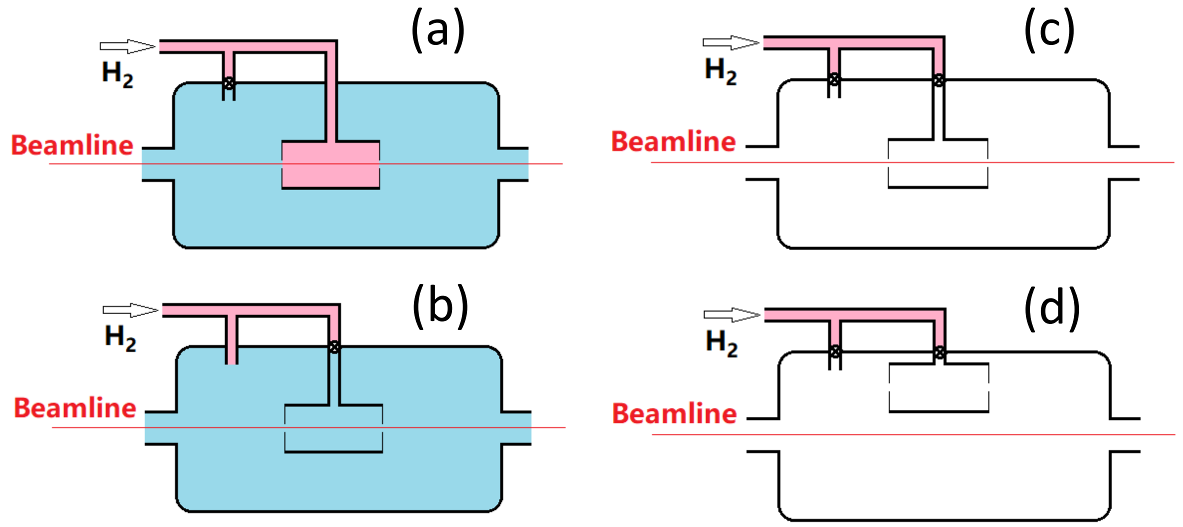
- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)



Analysis – Background Subtraction (2.2 GeV)

- *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

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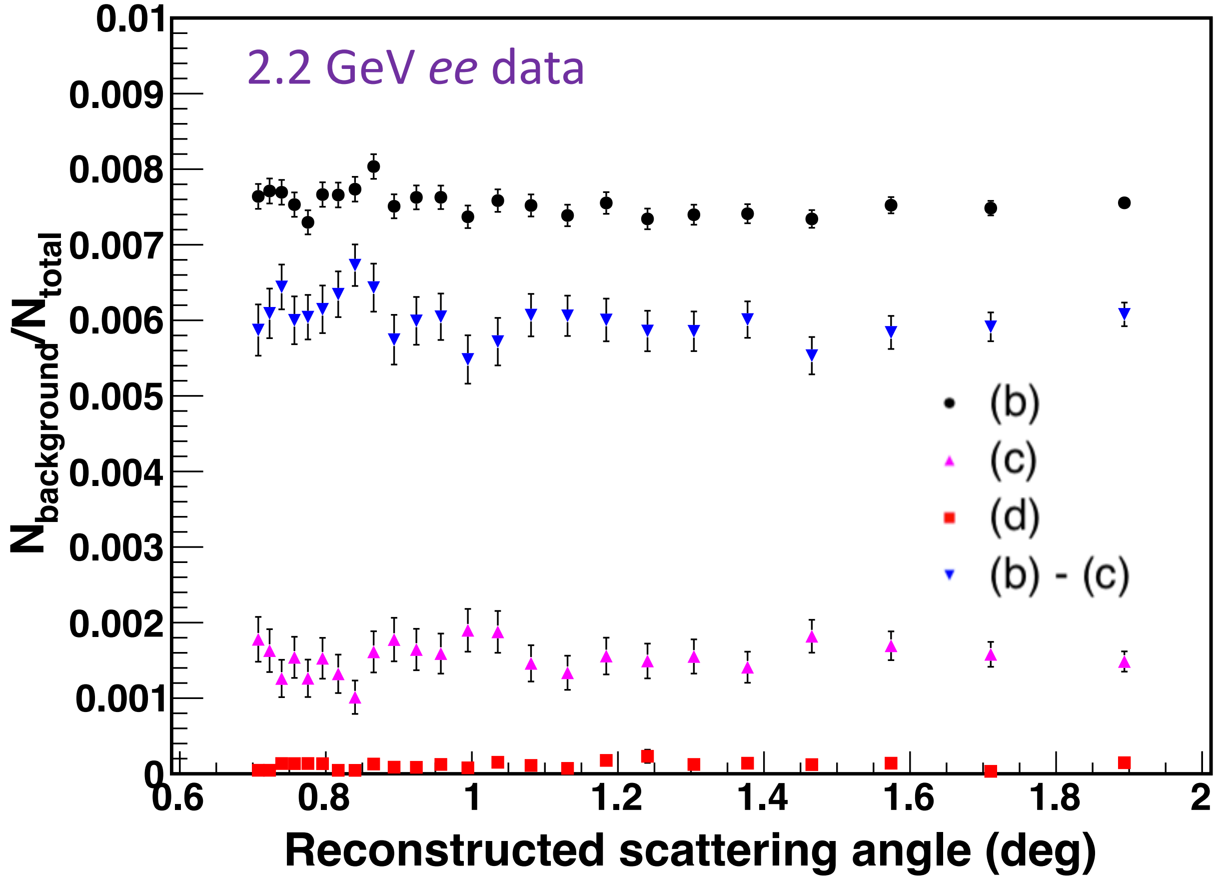

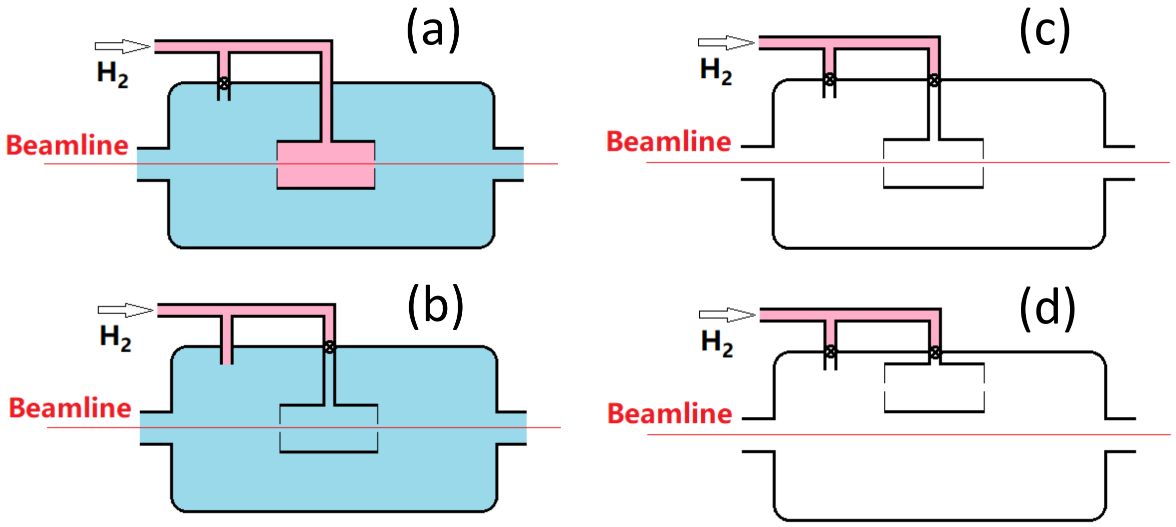

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Extraction of *ep* Elastic Scattering Cross Section

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

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

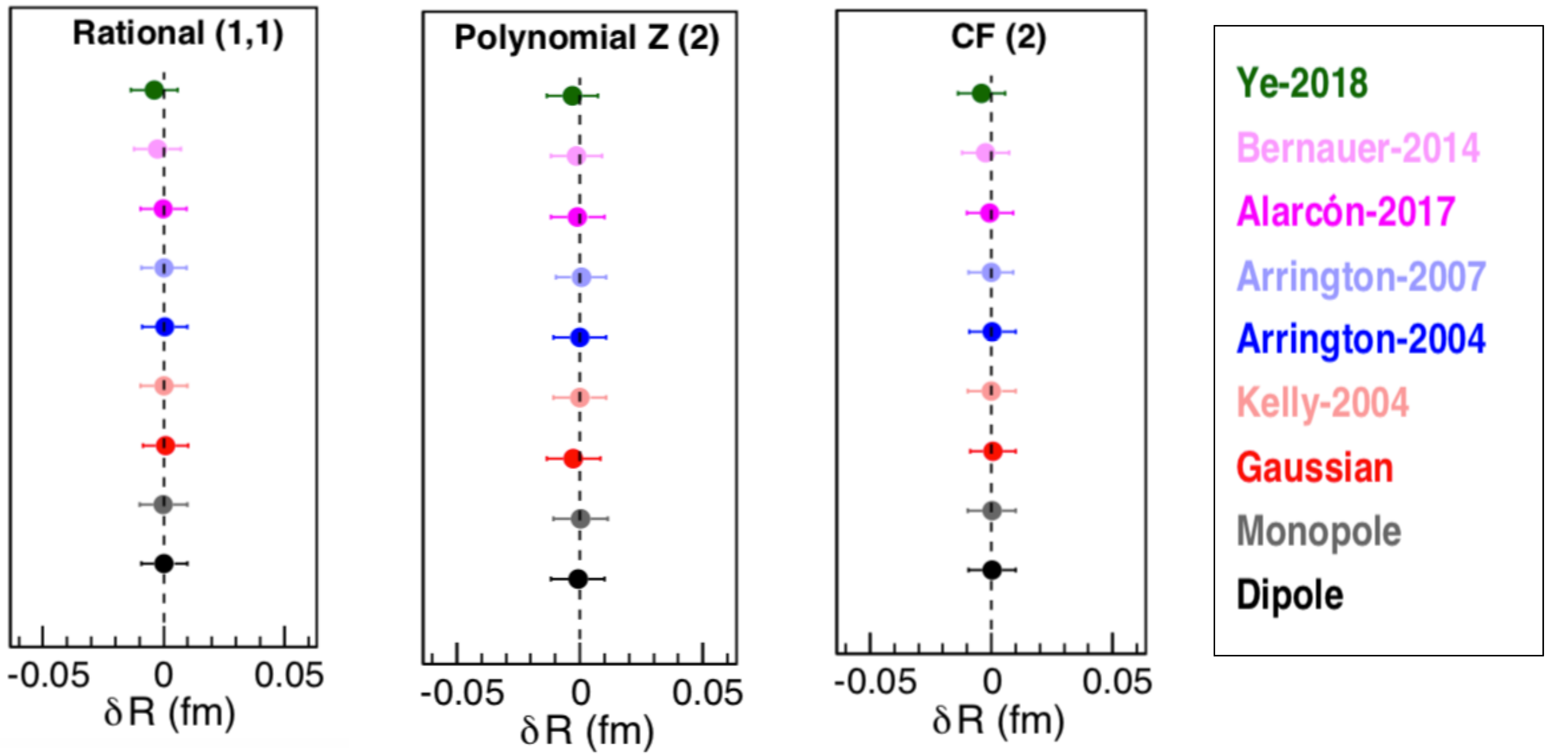
- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
  - ➢ Cancellation of energy independent part of the efficiency and acceptance
  - ➢ Limited converge due to double arm Møller acceptance
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angular bins
- Luminosity cancelled from both methods

- Bin-by-bin range: 0.7º to 1.6º for 2.2 GeV, 0.75º to 3.0º for 1.1 GeV. Larger angles use integrated Møller method

Searching the Robust fitters

- Various fitters tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties (X. Yan *et al.* Phys. Rev. C98, 025204 (2018))
- Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties
- Typically a floating parameter n is included to take care normalization uncertainties

$$f(Q^2) = n\, G_E^p(Q^2)$$



Rational (1,1)

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

2nd order z transformation

$$1 + p_1 z + p_2 z^2,$$

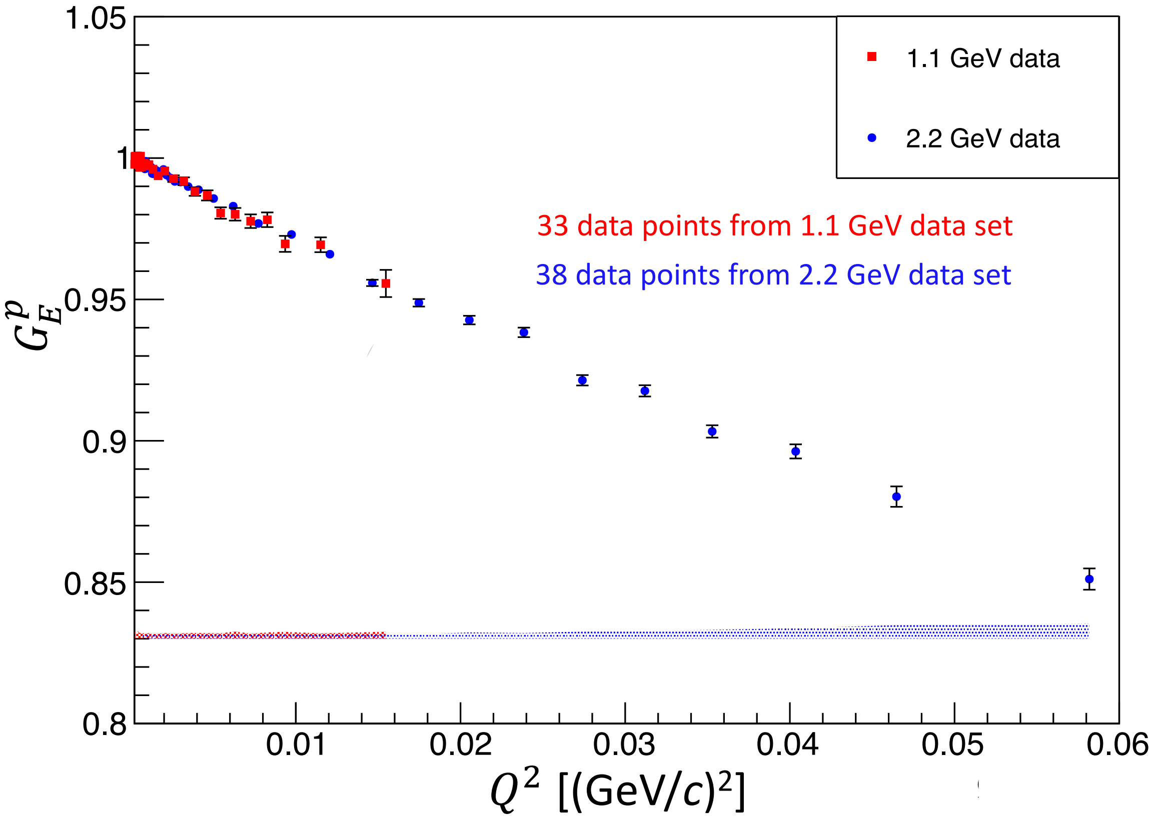
$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

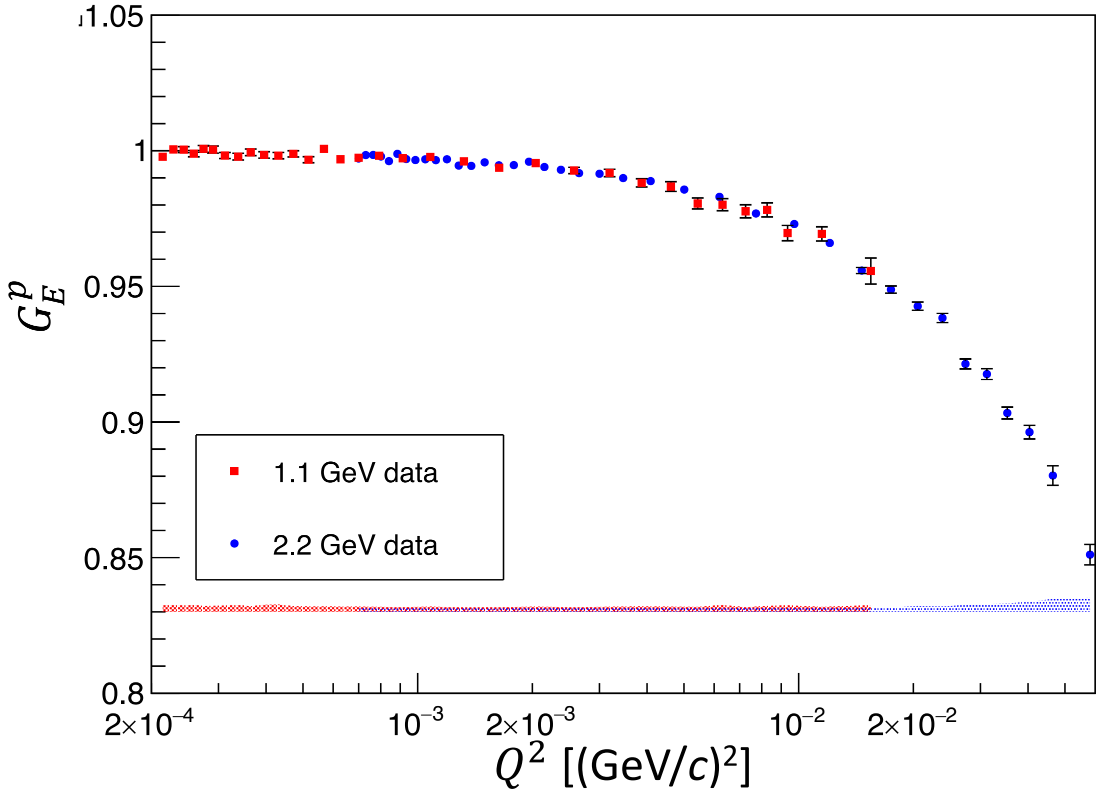
2nd order continuous fraction

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

Proton Electric Form Factor G_E^p

- n_1 and n_2 obtained by fitting PRad electric form factors to $f(Q^2) = \begin{cases} n_1 G_E^p(Q^2), & \text{for 1.1 GeV data} \\ n_2 G_E^p(Q^2), & \text{for 2.2 GeV data} \end{cases}$
- G_E^p as normalized electric form factor: $\begin{cases} f(Q^2)/n_1, & \text{for 1.1 GeV data} \\ f(Q^2)/n_2, & \text{for 2.2 GeV data} \end{cases}$
- $G_E^p(Q^2) = \frac{1+p_1 Q^2}{1+p_2 Q^2}$, the rational (1,1), a robust fitter based on X. Yan *et al.* Phys. Rev. C98, 025204 (2018)





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