



Proton Charge Radius (PRad) Experiment at Jefferson Lab

Weizhi Xiong

Duke University

For the PRad Collaboration

Spokespersons: A. Gasparian(contact person), D. Dutta, M. Khandaker, H. Gao

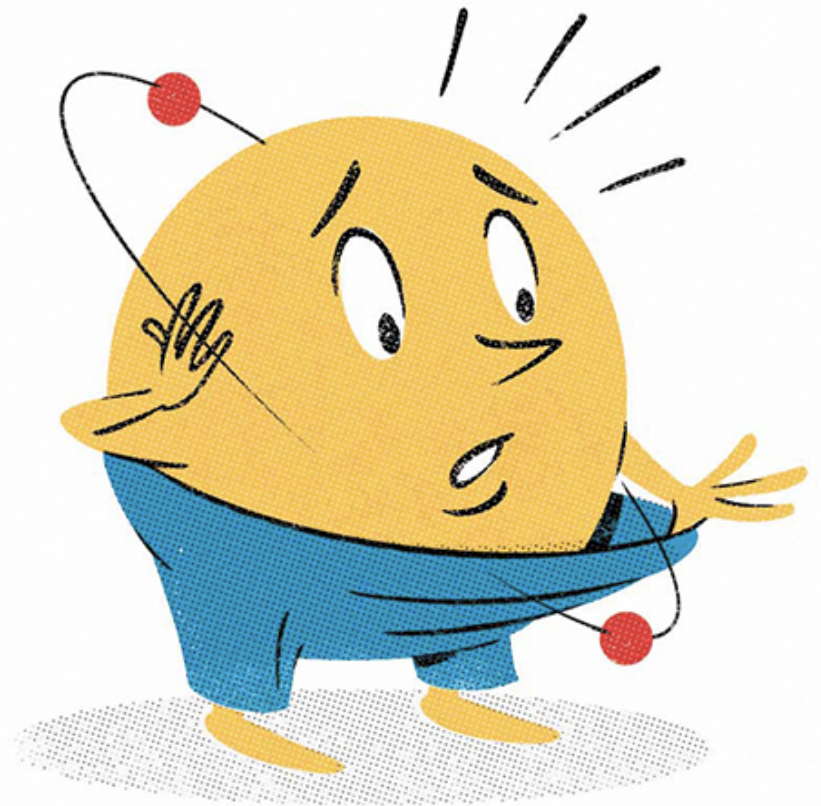
SPIN 2016

September 27th, 2016



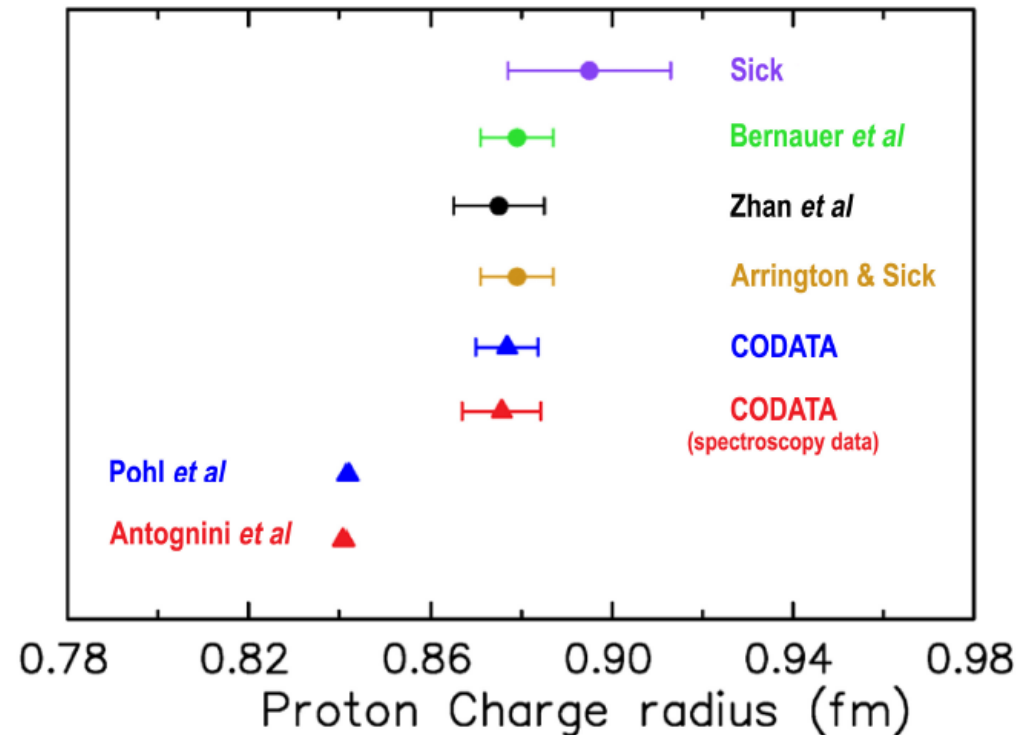
Outline

- The proton charge radius puzzle
- PRad experiment at Jefferson Lab
 - Experimental goal and approach
 - PRad apparatus
 - Collected data
- Preliminary online analysis results



Proton Charge Radius Puzzle

- Electronic measurement (ep elastic + ordinary H spectroscopy) v.s. muonic measurement (muonic H spectroscopy)
- μp Lamb shift measurements by CREMA (2010, 2013)
 - Unprecedented precision, $<0.1\%$
 - 7σ away from CODATA 2012 recommended value
- New preliminary result from ordinary H spectroscopy (from PRP 2016 Trento) seems to agree with muonic measurement
- The discrepancy is not understood yet. New experiments with different systematics are necessary



Proton Charge Radius from ep Elastic Scattering

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

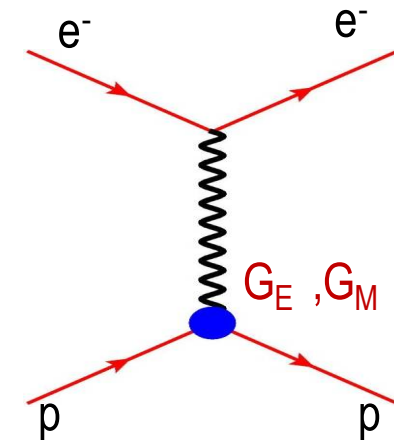
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left(\frac{E'}{E} \right) \frac{1}{1+\tau} \left(G_E^p{}^2(Q^2) + \frac{\tau}{\epsilon} G_M^p{}^2(Q^2) \right)$$

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

- Structure-less proton:

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

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



Taylor expansion of G_E at low Q^2

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

Derivative at low Q^2 limit

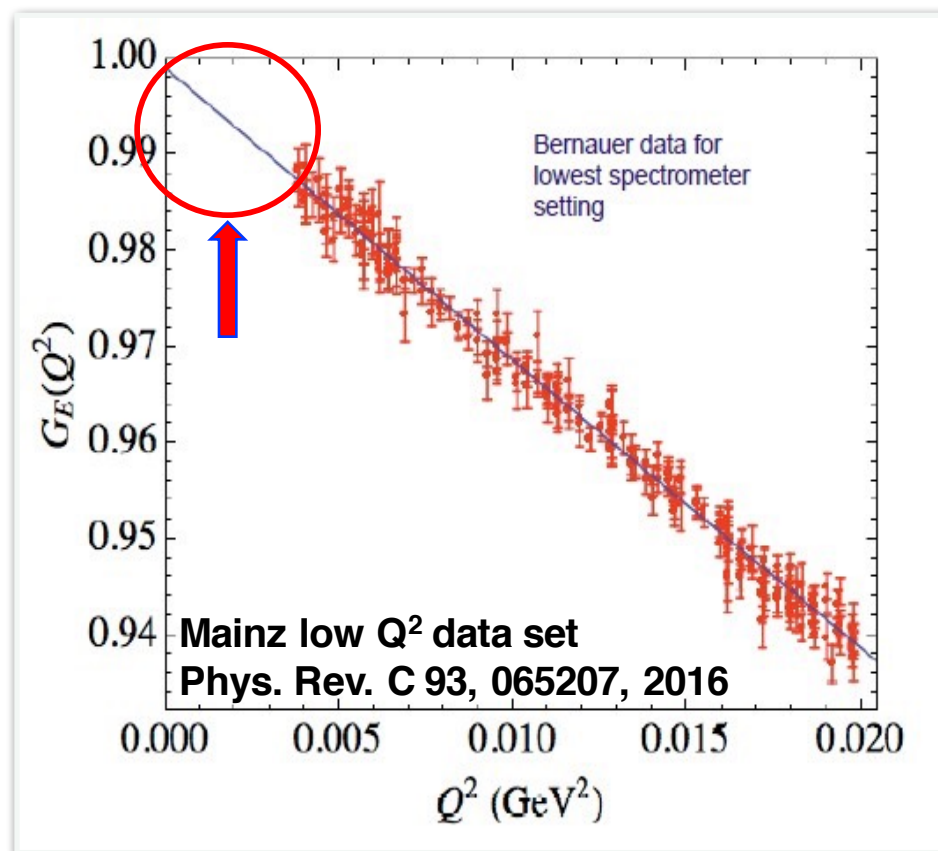
$$\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

PRad Experiment Overview

- PRad goal: Measuring proton charge radius using ep elastic scattering
- Unprecedented low Q^2 ($\sim 2 \times 10^{-4} \text{ GeV}^2$)
 - Fill in very low Q^2 region
- Large Q^2 range in a single setting
 - $\sim 2 \times 10^{-4} - 6 \times 10^{-2} \text{ GeV}^2$
- Calibrate to the simultaneously measured Møller scattering process
 - best known control of systematics
- Aims to extract cross section and radius to **sub-percentage** level

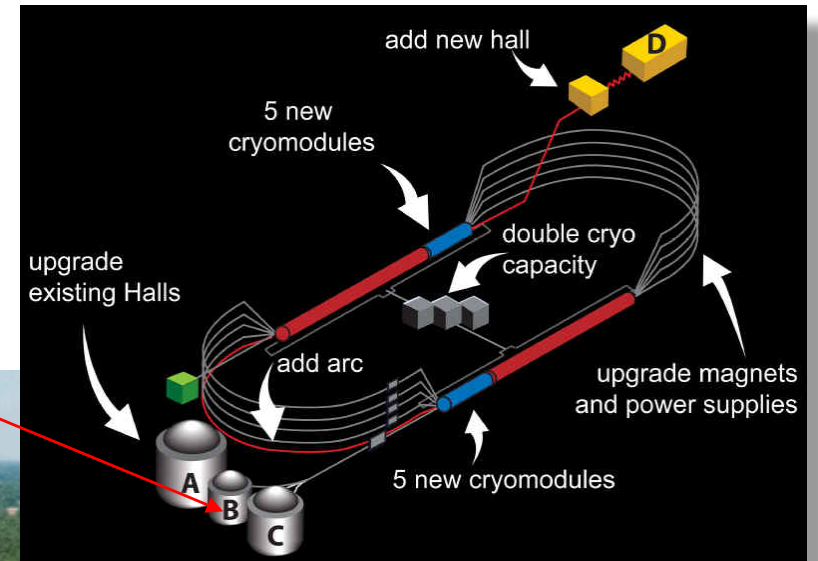
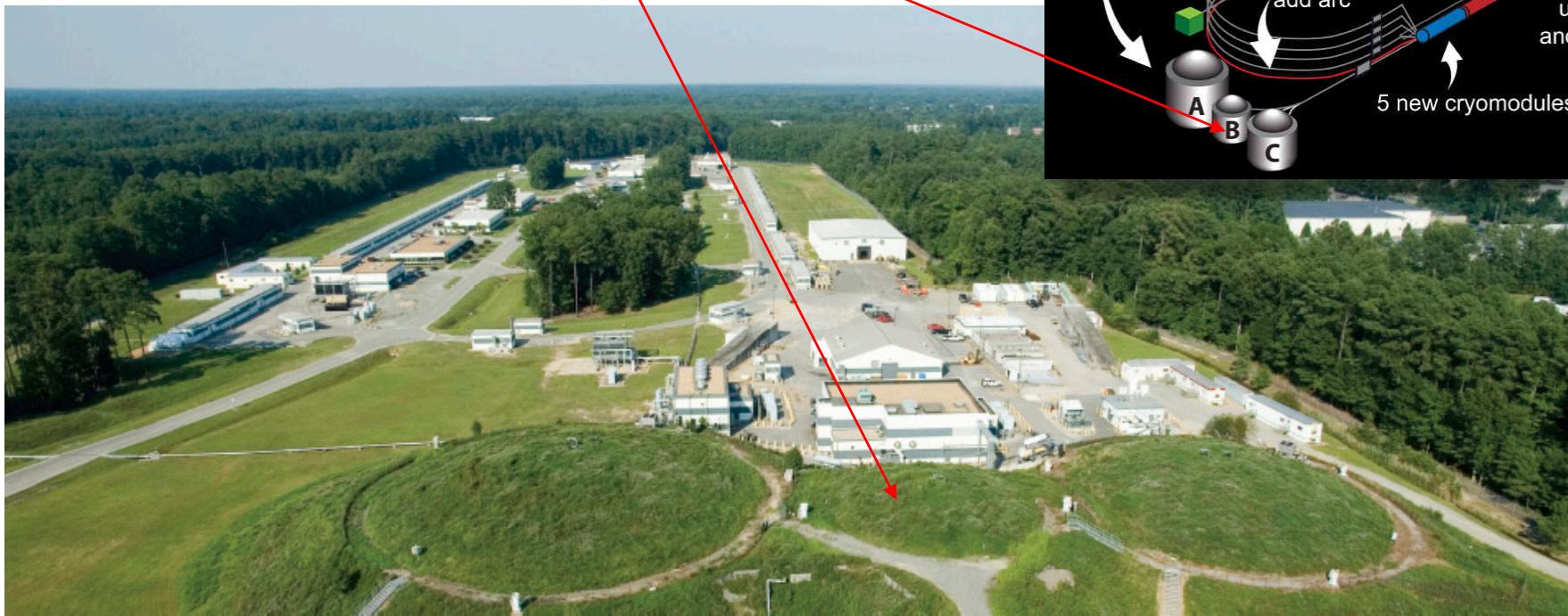
PRad Experiment Overview

- PRad goal: Measuring proton charge radius using ep elastic scattering
 - Unprecedented low Q^2 ($\sim 2 \times 10^{-4} \text{ GeV}^2$)
 - Fill in very low Q^2 region
 - Large Q^2 range in a single setting
 - $\sim 2 \times 10^{-4} - 6 \times 10^{-2} \text{ GeV}^2$
 - Calibrate to the simultaneously measured Møller scattering process
 - best known control of systematics
 - Aims to extract cross section and radius to **sub-percentage** level

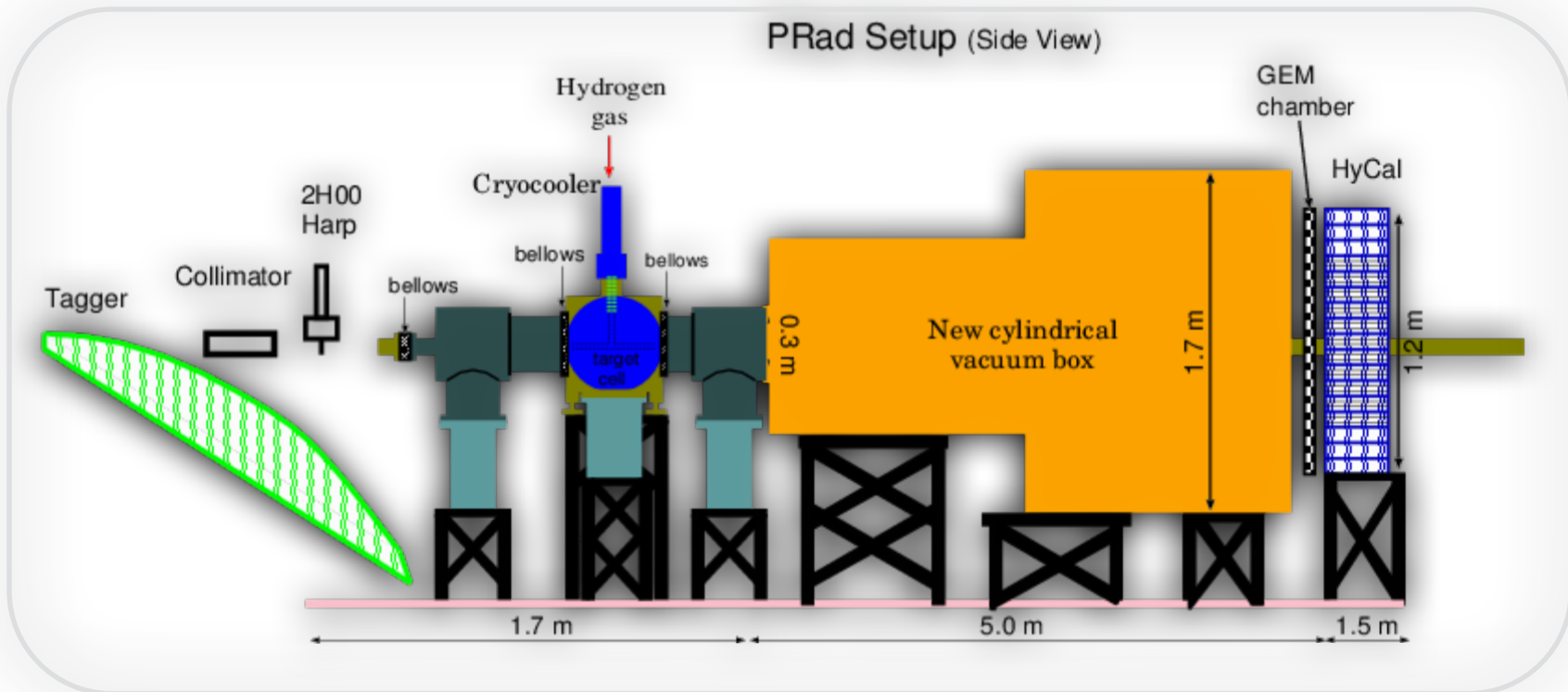


Jefferson Lab CEBAF Accelerator Facility

PRad experiment was performed in Hall B at
Jefferson Lab



PRad Experimental Apparatus

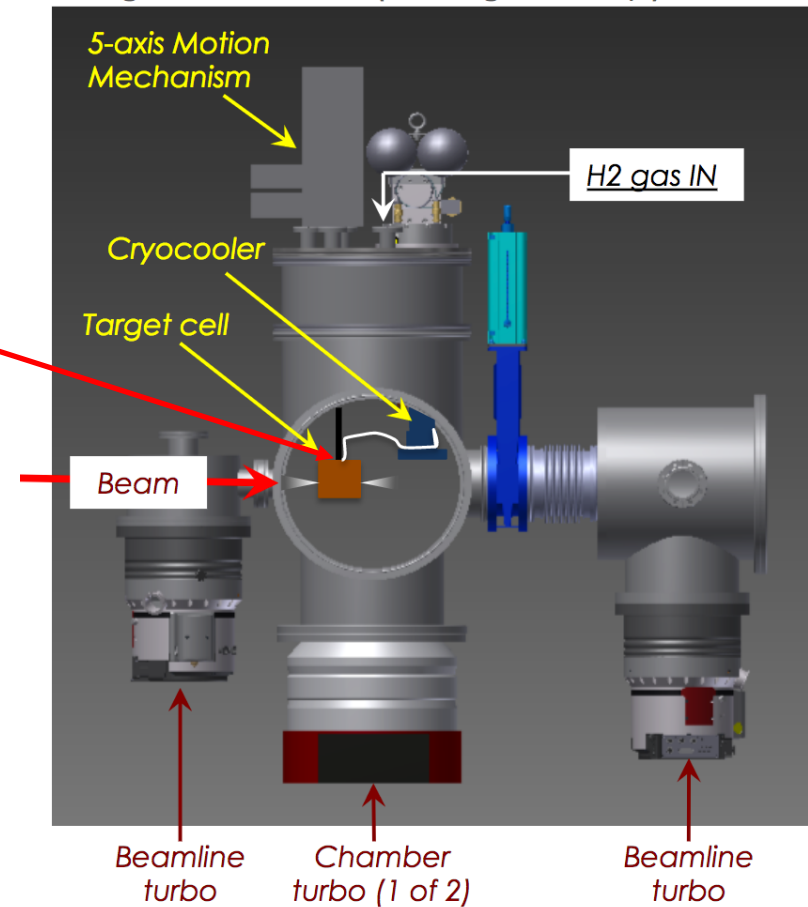
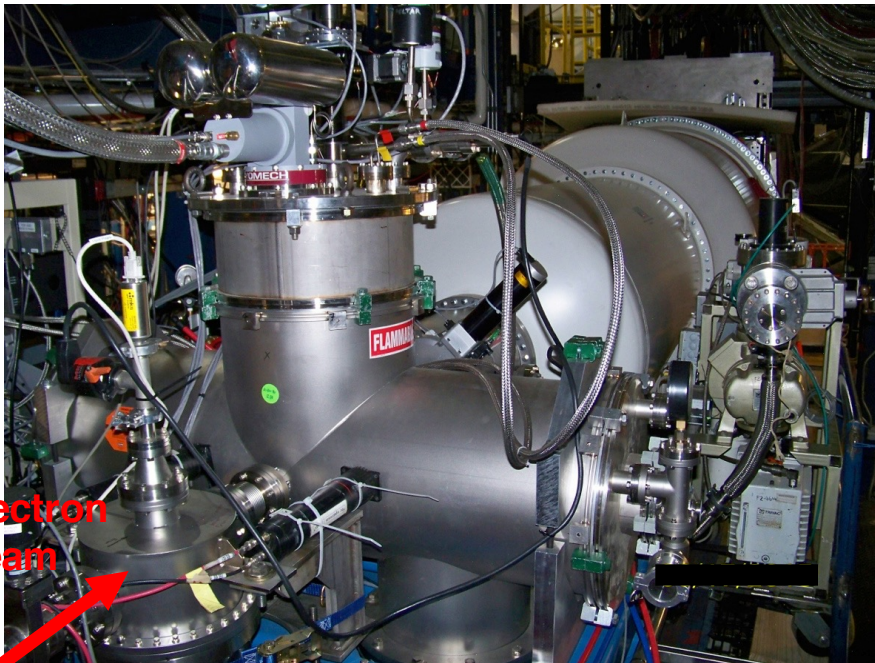
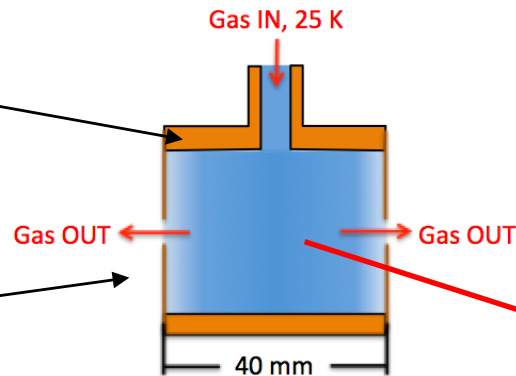


- Windowless, high density H_2 gas flow target (background control)
- Vacuum box, one thin window at downstream
- High resolution and high efficiency, Hybrid calorimeter (HyCal)
- Two large area Gas Electron Multipliers, improve position resolution

Windowless Gas Target

Target cell
(8 cm dia x 4 cm long
copper)

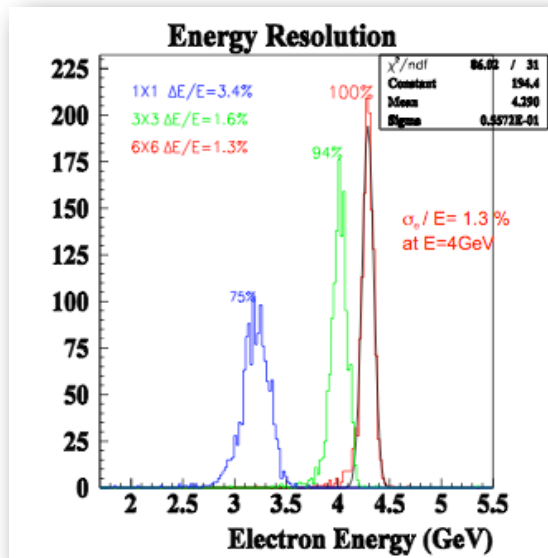
7.5 μm kapton foil
with 2mm hole



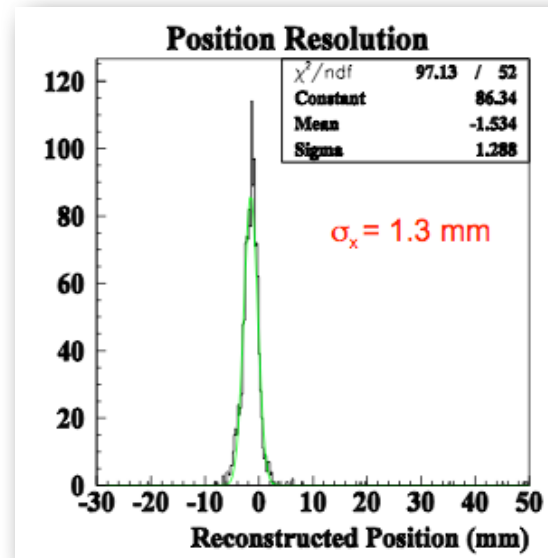
Areal density: $\sim 2 \times 10^{18}$ H atoms / cm^2
Cell / chamber / vacuum tank pressure:
470 mtorr / 2.3 mtorr / 0.3 mtorr

Hybrid Calorimeter (HyCal)

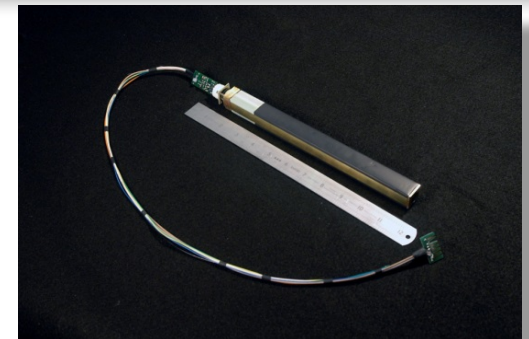
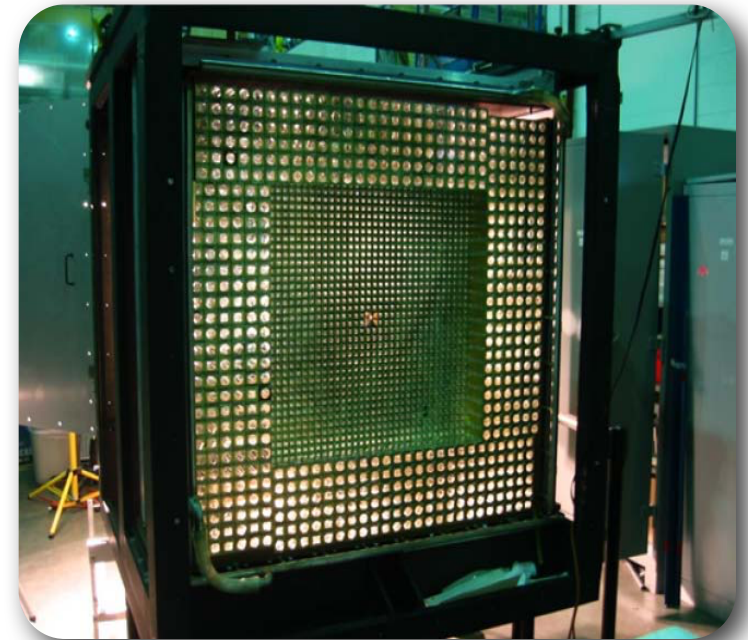
- Used in the PrimEx experiment
- PbWO_4 and Pb-glass calorimeter ($118 \times 118 \text{ cm}^2$)
- 576 Pb-glass modules ($3.82 \times 3.82 \text{ cm}^2 \times 45 \text{ cm}$)
- 1152 PbWO_4 modules ($2.05 \times 2.05 \text{ cm}^2 \times 18 \text{ cm}$)
- 5.8 m from the target
- Polar angle coverage: $\sim 0.5^\circ$ to 7.5°
- Azimuthal angle coverage: 2π



PbWO₄ resolution:
 $\sigma_E/E = 2.6\%/\sqrt{E}$
 $\sigma_{xy} = 2.6 \text{ mm}/\sqrt{E}$

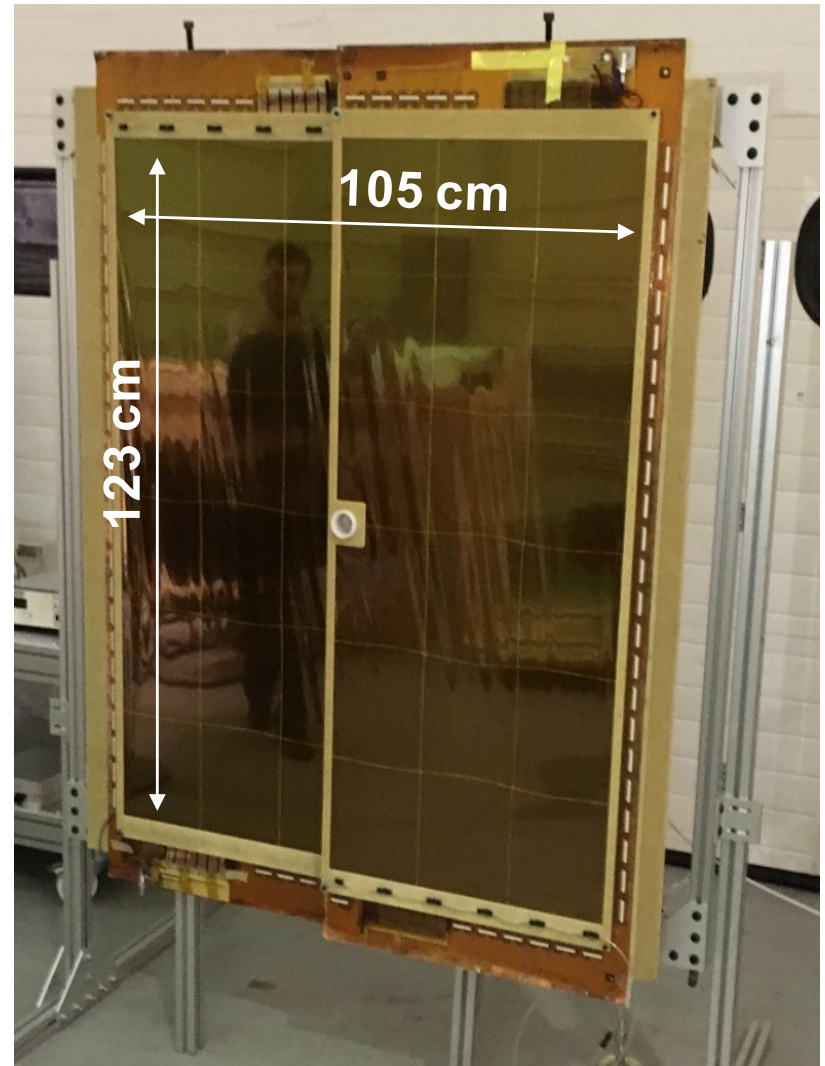
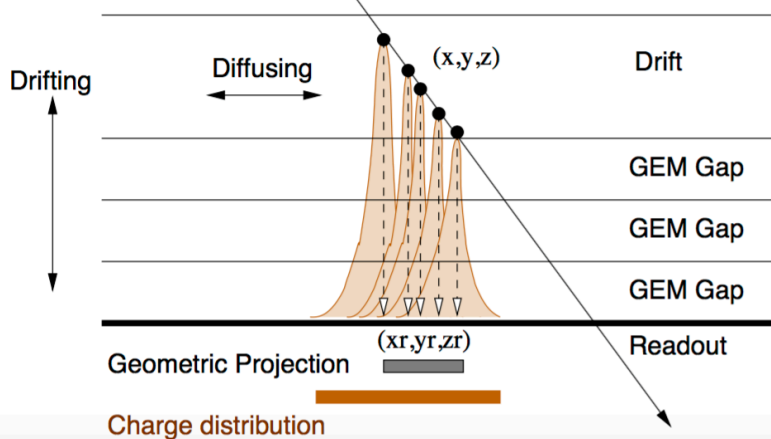


Pb-glass:
 2.5 times worse



Gas Electron Multipliers (GEM)

- Two large area GEM detectors with 2D Cartesian readout planes
- $\sim 100 \mu\text{m}$ position resolution
- The GEM detectors can provide:
 - >20 times improvement on position resolution
 - Similar improve for Q^2 resolution at small angle



PRad in Jefferson Lab Hall B

Beam-side view



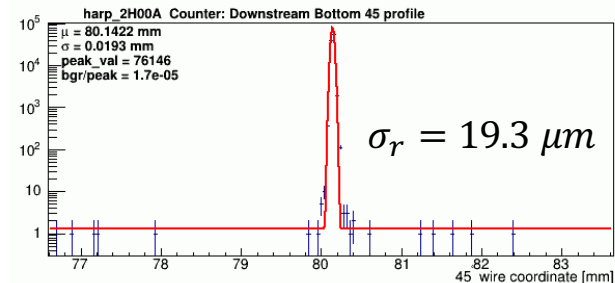
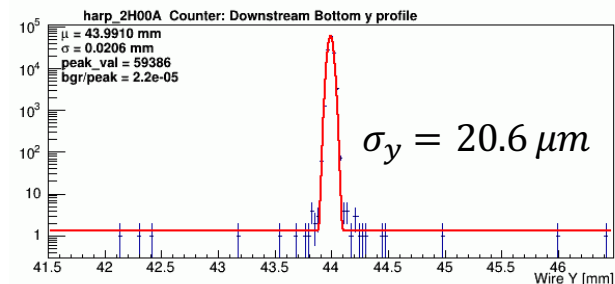
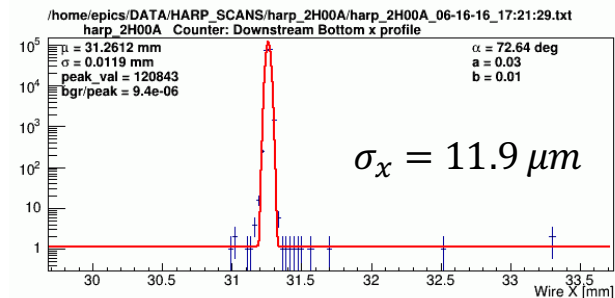
GEMs mounted on HyCal



Experimental Data Collected

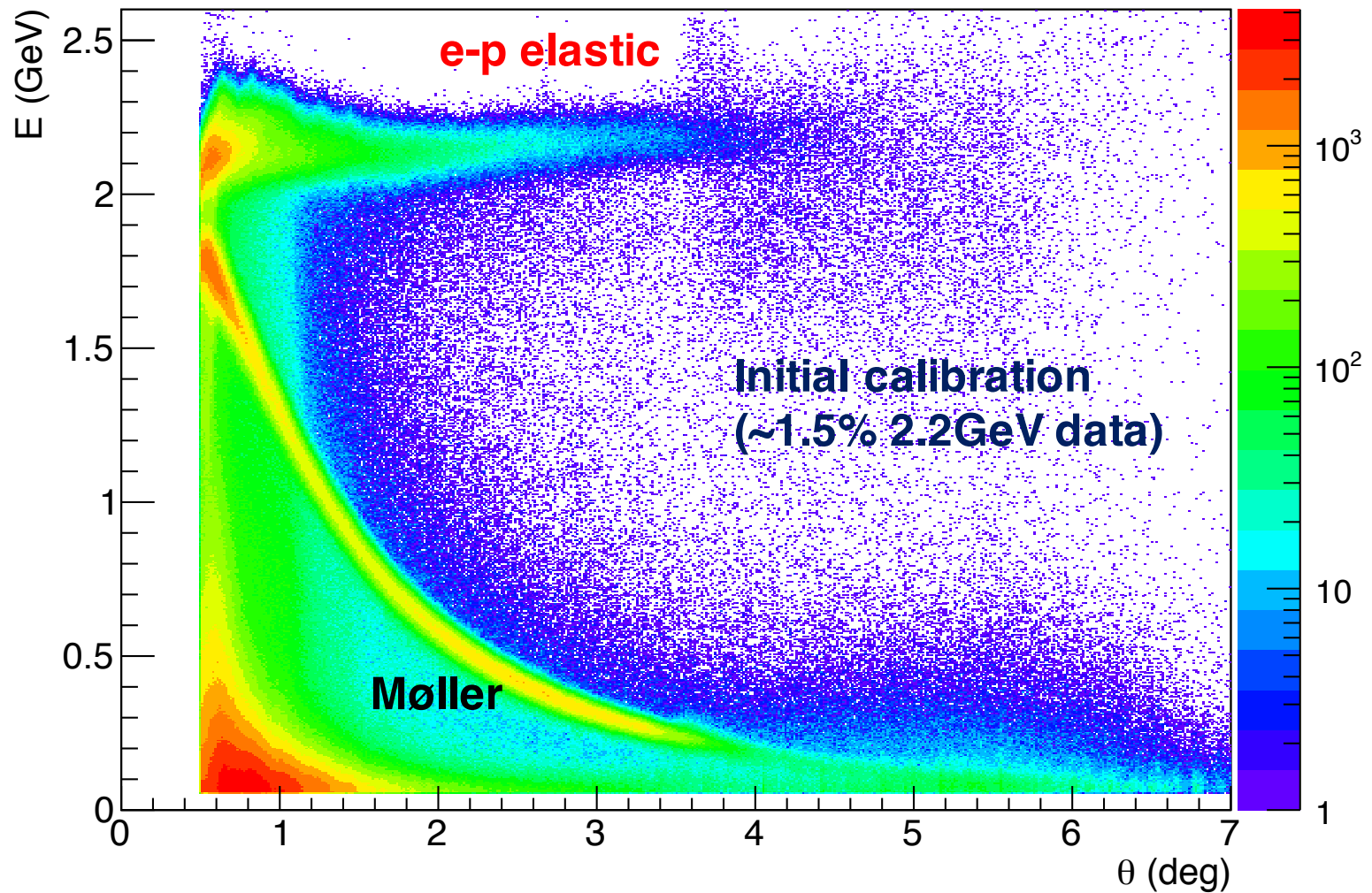
- Experiment ran in May - June 2016
- Large amount of data taken with high quality and stable electron beam from CEBAF
 - Beam position stability: $\sim 250 \mu\text{m}$
 - Beam width: $\sim 25 \mu\text{m}$
- Data taking with **1.1 GeV** beam:
 - 604 M events with H_2 in cell
 - 53 M events without H_2 in cell
 - 25 M events with $1 \mu\text{m}$ carbon foil target
 - Collected 4.2 mC on target (2×10^{18} H atoms/ cm^2)
- Data taking with **2.2 GeV** beam
 - 756 M events with H_2 in cell
 - 38 M events without H_2 in cell
 - 10.5 M events with $1 \mu\text{m}$ carbon foil target
 - Collected 14.3 mC on target (2×10^{18} H atoms/ cm^2)

Example electron beam profile at target (measured with harp scan)



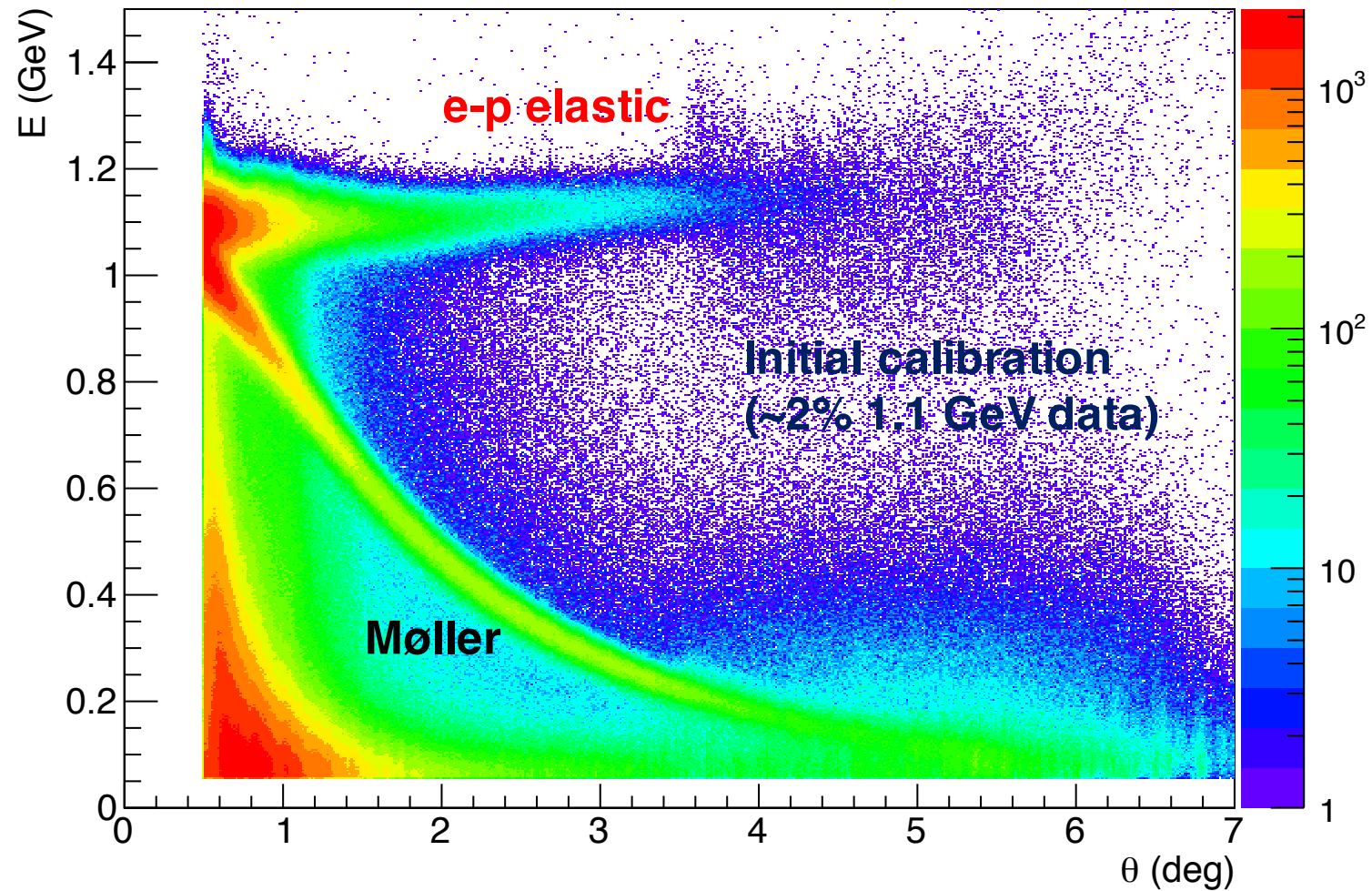
Preliminary Online Analysis Results

Cluster E vs Scattering Angle θ

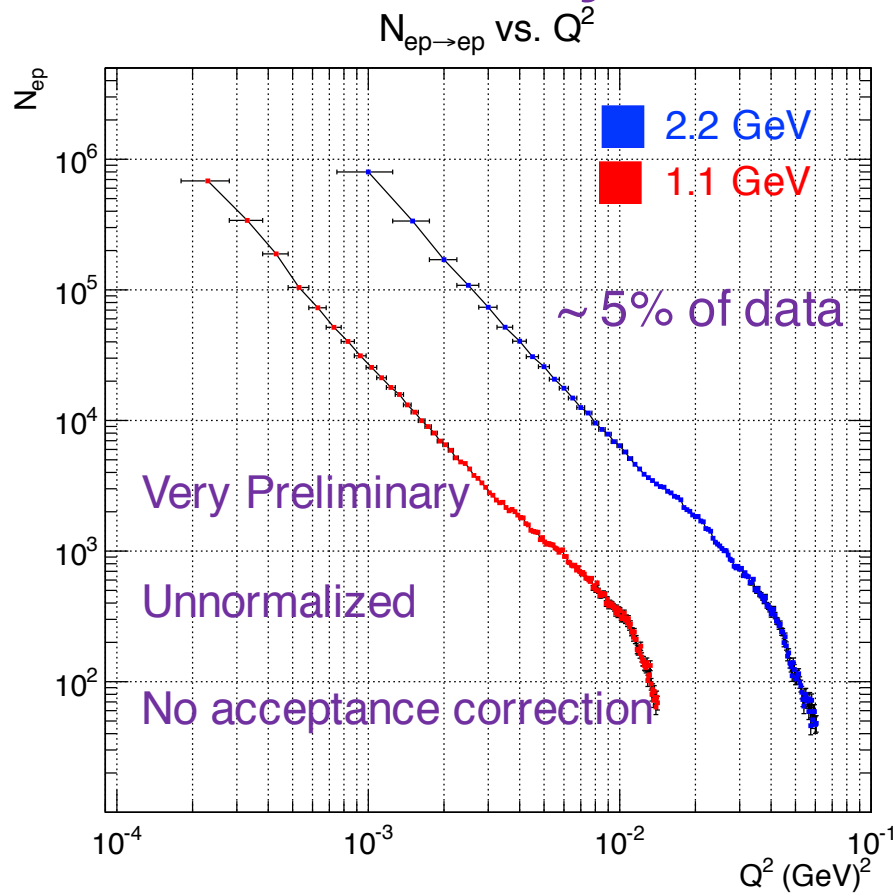


Preliminary Online Analysis Results

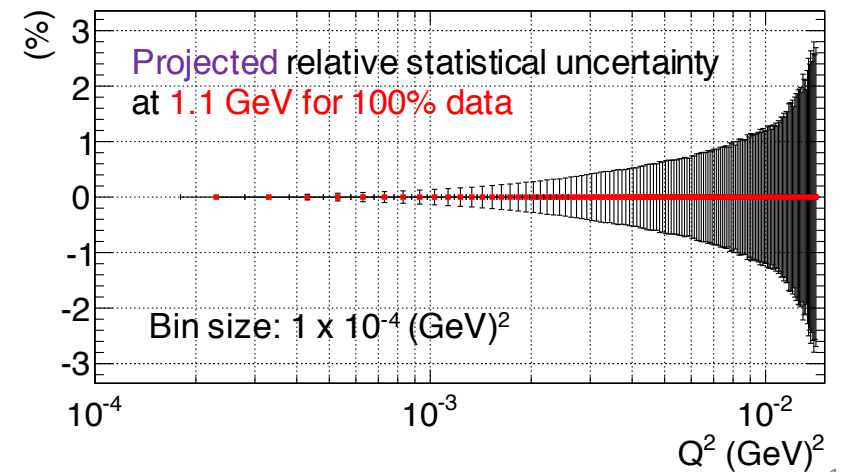
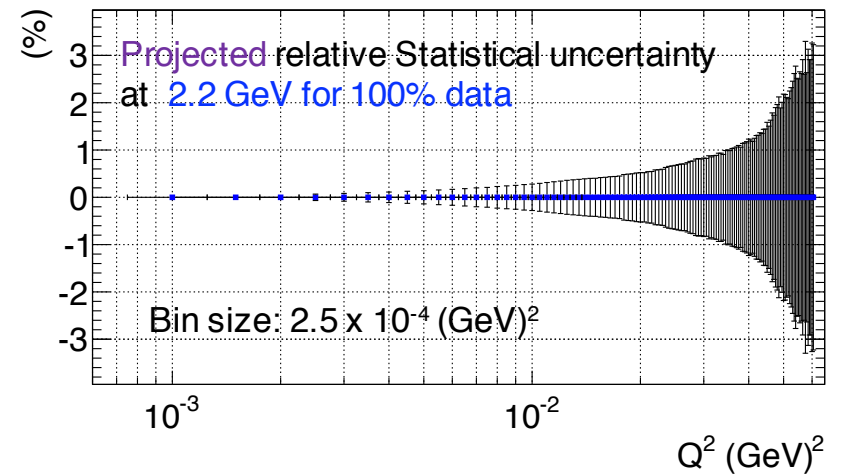
Cluster E vs Scattering Angle θ



Preliminary Online Analysis Results



- Good Q^2 resolution and large statistics at low Q^2 will allow finer binning



The PRad Collaboration

**Jefferson Lab,
NC A&T State University,
Duke University,
Idaho State University,
Mississippi State University,
Norfolk State University,
University of Virginia
University of North Carolina at Wilmington,
Old Dominion University,
University of Kentucky,
College of William & Mary,
Argonne National Lab,
Hampton University
Tsinghua University, China
ITEP, Moscow, Russia
Budker Institute of Nuclear Physics, Russia
MIT**

Graduate students

**Chao Peng (Duke)
Li Ye (MSU)
Weizhi Xiong (Duke)
Xinzhan Bai (UVa)
Abhisek Karki (MSU)**

Post-docs

**Mehdi Meziane (Duke)
Zhihong Ye (Duke)
Krishna Adhikari (MSU)
Maxime Lavillain (NC A&T)
Rupesh Silwal (MIT)**

Summary

- The *Proton Radius Puzzle* is still unsolved after six years
- The PRad experiment is a unique piece to the puzzle:
 - Lowest Q^2 data set ($\sim 2 \times 10^{-4}$ GeV) has been collected for the first time in ep elastic scattering experiment
 - Data in a large Q^2 range ($\sim 2 \times 10^{-4} - 6 \times 10^{-2}$ GeV²) have been collected with the same experimental setting
 - Large statistics, high quality, rich data has been collected
 - Systematic uncertainty well under control by simultaneous measurement of ep elastic and Møller processes
- Analysis on the first preliminary result is ongoing

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