



Proton Radius Puzzle and the PRad Experiment at JLab

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for the PRad collaboration

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Outline

- The “*Proton Radius Puzzle*”
- Recent status
- The PRad experiment
- Status of the run and the data quality
- Summary

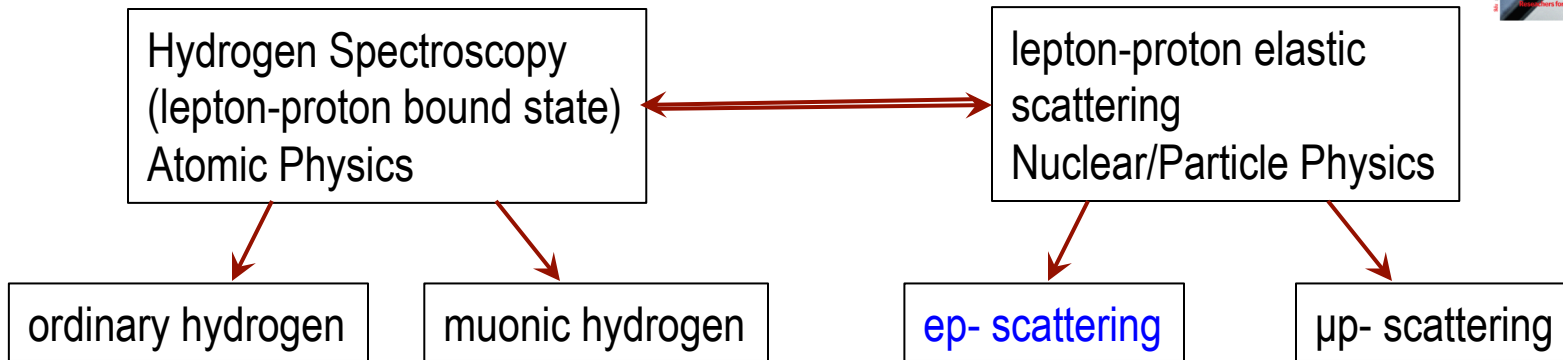
Proton Has a Structure: How to Measure the Radius?

- In 1933 Otto Stern measured proton's magnetic moment
 - ✓ Unexpectedly, it was shown that $g \neq 2$ \longrightarrow the proton is not a point-like (Dirac) particle
 - ✓ Nobel Prize in Physics 1943

- ep-scattering experiments @ SLAC

- ✓ Robert Hofstadter awarded Nobel Prize in 1961
- ✓ Proton has a structure (first form factors were measured)!

- Methods to measure the Proton Radius:

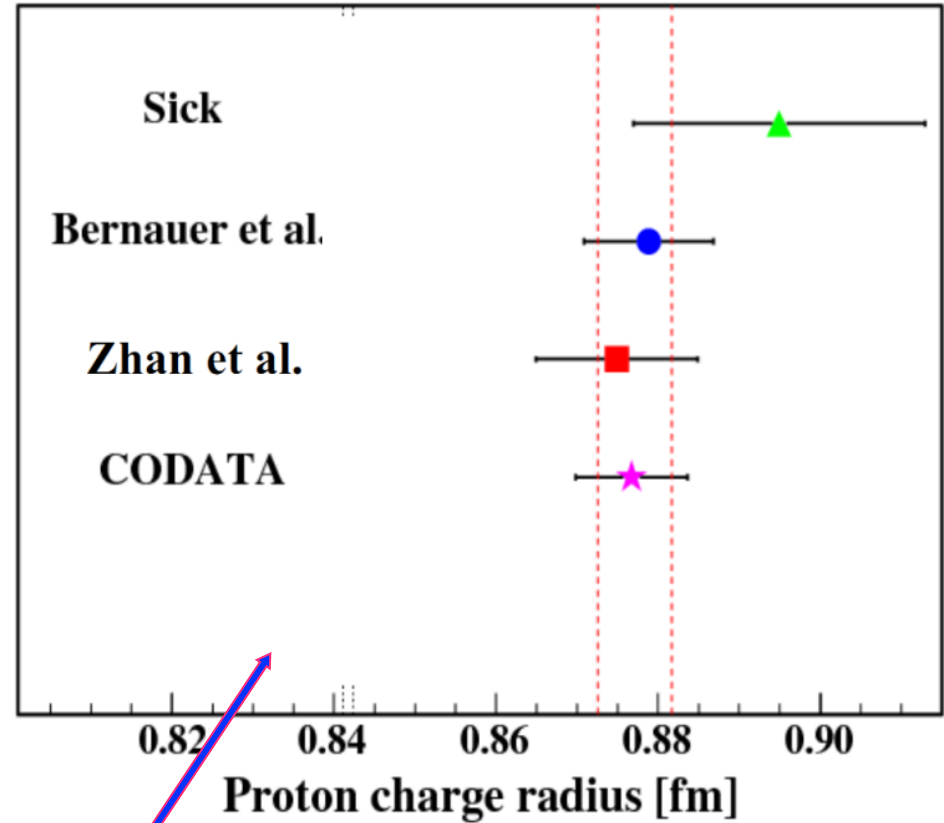


- Over 60 years of experimentation!

The Proton Radius Puzzle (2010)

- Proton radius is one of the most fundamental quantities in physics:
 - ❖ critically important for atomic physics in precision spectroscopy of atom (**Rydberg constant**)
 - ❖ precision test of nuclear/particle models
 - ❖ connects atomic and subatomic physics
- **~ 8 σ discrepancy** between the new muonic-hydrogen measurements and all previous results

The Proton Radius Puzzle



muonic-hydrogen result:

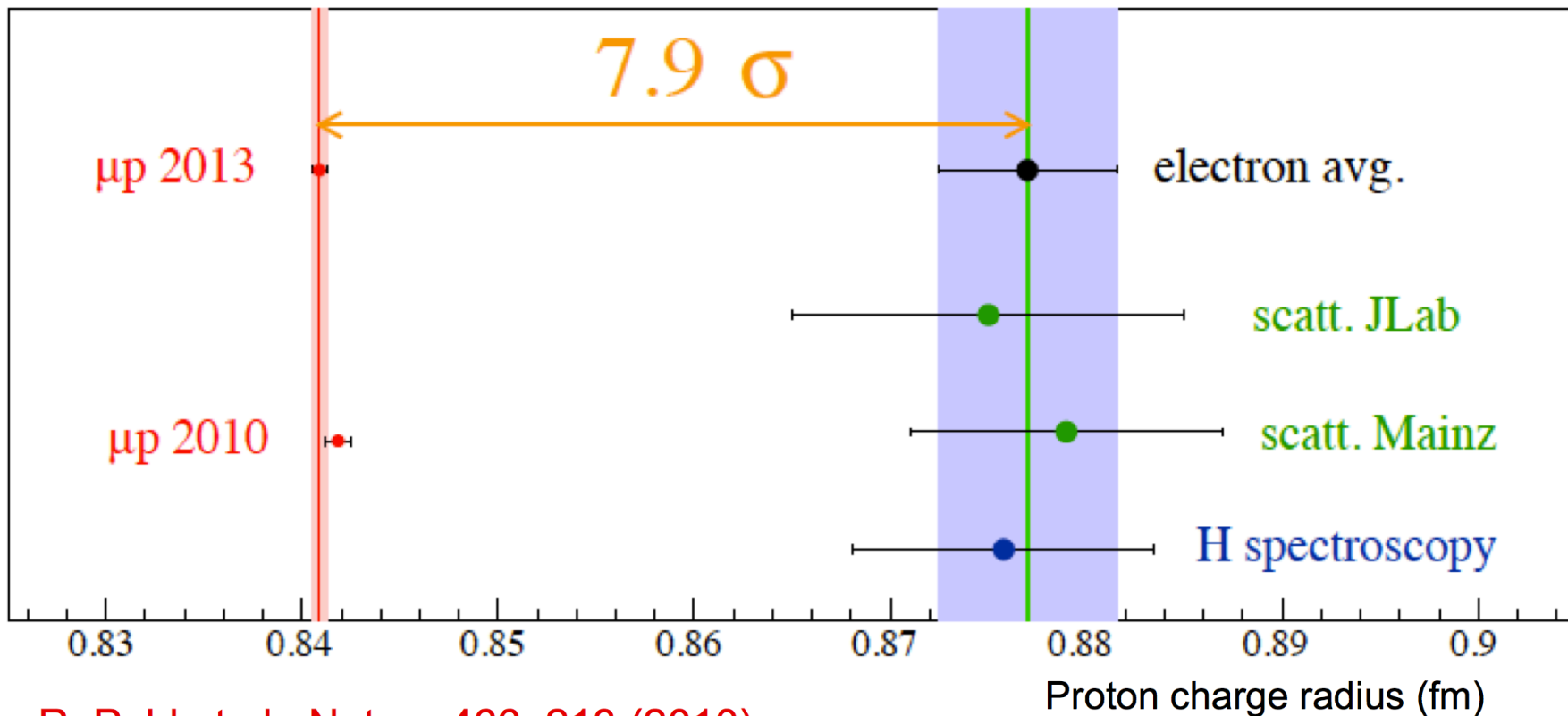
$$r_p = 0.8409(4) \text{ fm}$$

R. Pohl et al., Nature 466, 213 (2010).

CODATA-2010:

$$r_p = 0.8775(51) \text{ fm}$$

The Proton Radius Puzzle (2013)



R. Pohl et al., Nature 466, 213 (2010)

A. Antognini et al., Science 339, 417 (2013)

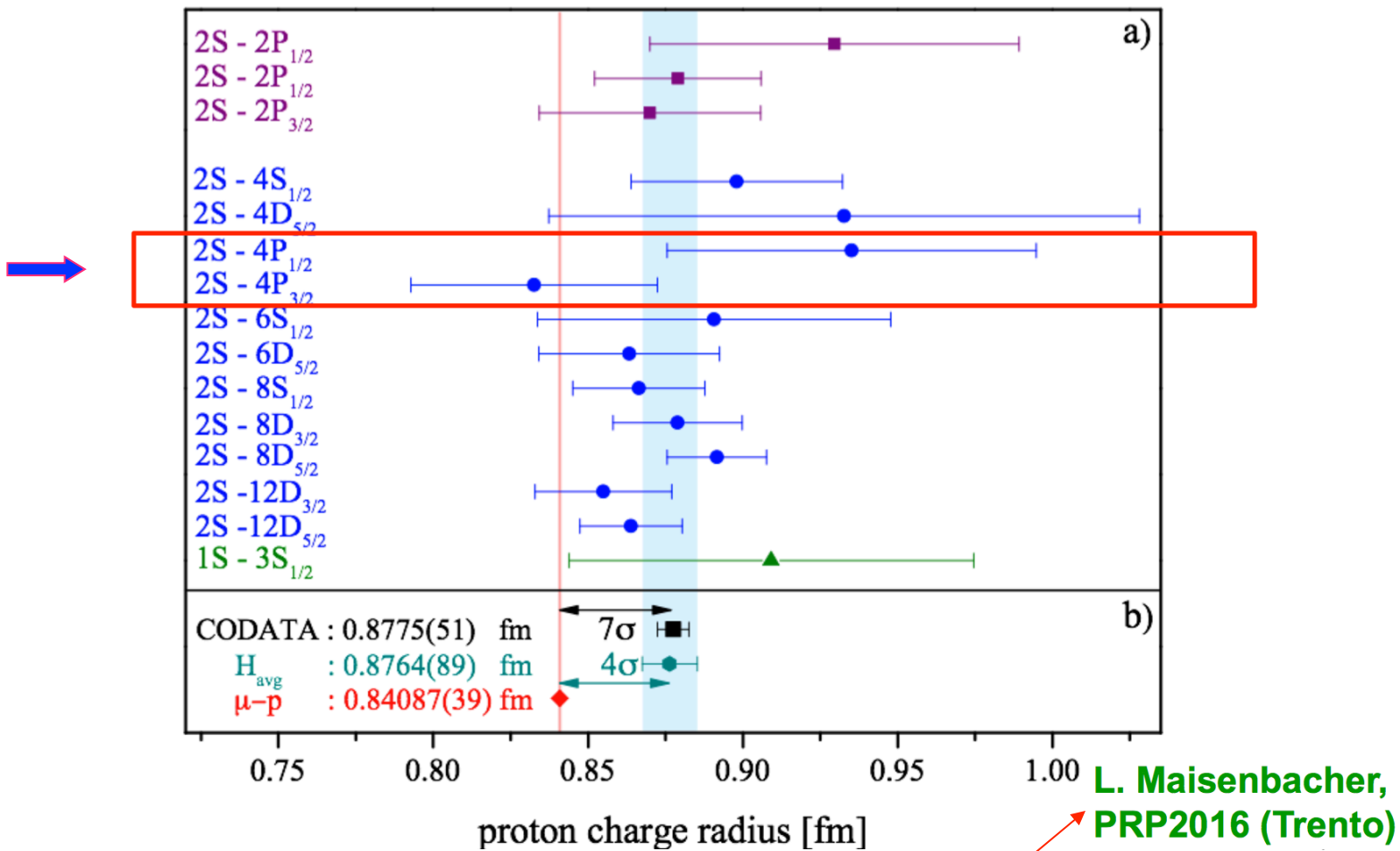
M. Kohl

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

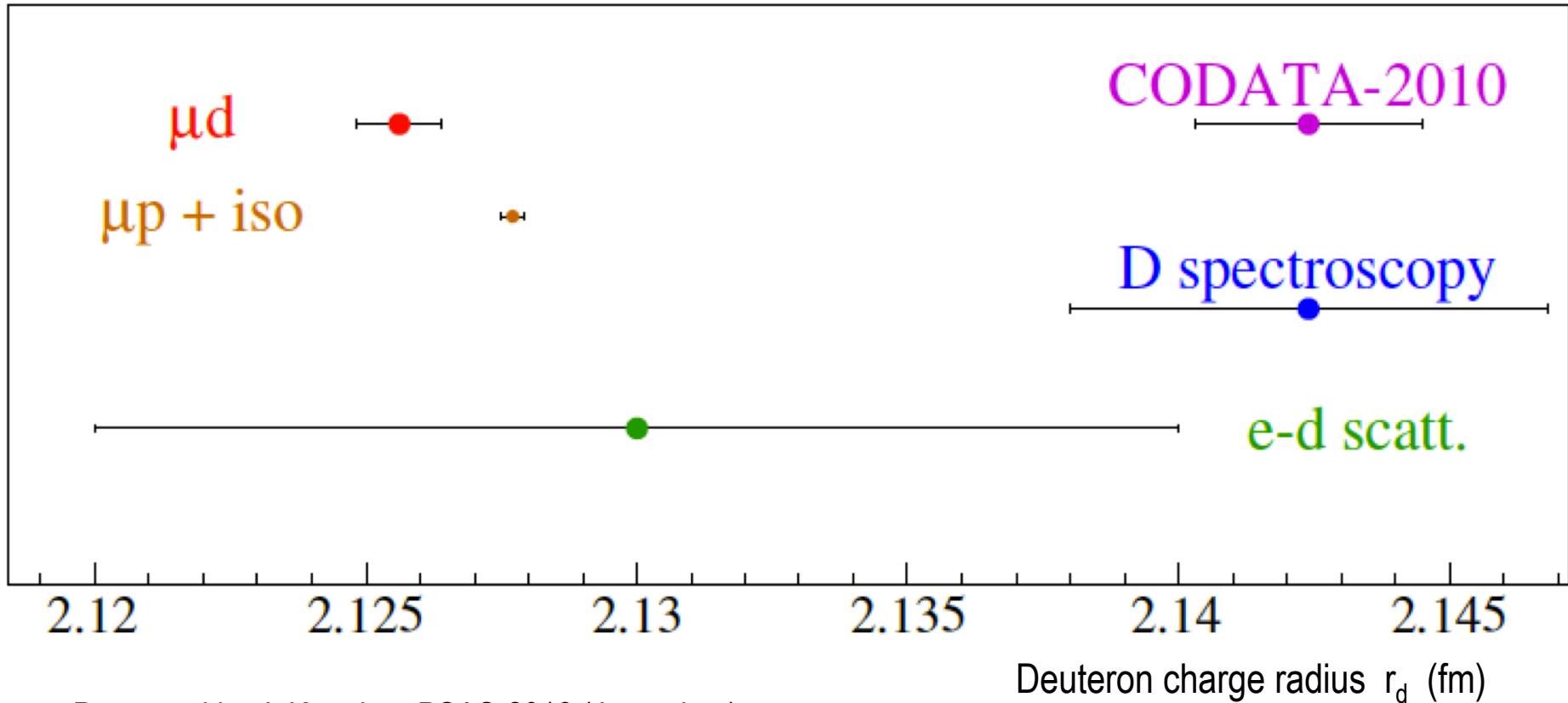
muons: 0.8409 ± 0.0004 fm

The Proton Radius Puzzle (June 2016)



- New, preliminary value for r_p was reported in PRP-2016 Workshop (Trento, Italy) from ordinary hydrogen
- Consistent with the muonic-hydrogen result !
- Is the Puzzle solved? No, new measurements are needed (spectroscopy, ep-scattering)

Muonic Deuterium: A New Puzzle?



- ✓ Presented by J. Krauth at PSAS-2016 (Jerusalem) and PRP-2016 (Trento)

➤ Reported in Workshop only, unpublished yet!

➤ New high precision experiments are needed (both in spectroscopy and scattering)

from M. Kohl

Extraction of r_p from $ep \rightarrow ep$ Scattering Experiments

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

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

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

- Structureless proton:

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

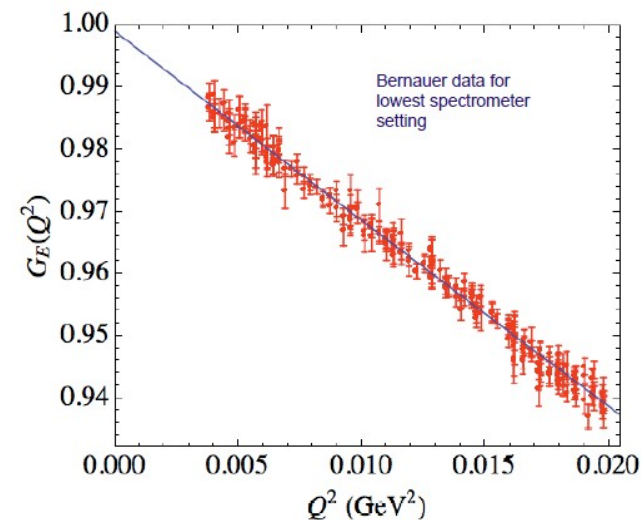
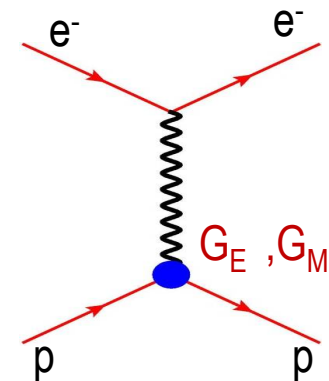
- G_E and G_M were extracted using Rosenbluth separation (or at extremely low Q^2 the G_M can be ignored, like in the PRad experiment)
- The Taylor expansion at low Q^2 :

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



derivative in $Q^2 \rightarrow 0$ limit:

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



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

A New $ep \rightarrow ep$ Experiment?

- ❑ Practically all ep -scattering experiments are done with the magnetic spectrometers!
- Limitation on minimum Q^2 : $10^{-3} \text{ GeV}^2/C^2$
 - ✓ limitation on min. scattering angle: $\theta_e \approx 5^\circ$
 - ✓ Typical beam energies: $\sim 0.1 \div 1 \text{ GeV}$
- Absolute cross section measurement is needed ($d\sigma/d\Omega$):
 - ✓ Statistics is not a problem ($< 0.2\%$)
 - ✓ Control of systematic errors???
 - electron beam flux;
 - target thickness and windows;
 - geometrical acceptances;
 - detection efficiencies, ...
 - Typical uncertainty: $\sim 2 \div 3\%$
- A possible solution (the PRad approach):
 - ✓ Non-magnetic-spectrometer method
 - ✓ No target windows
 - ✓ Calibrate with other well-known QED processes

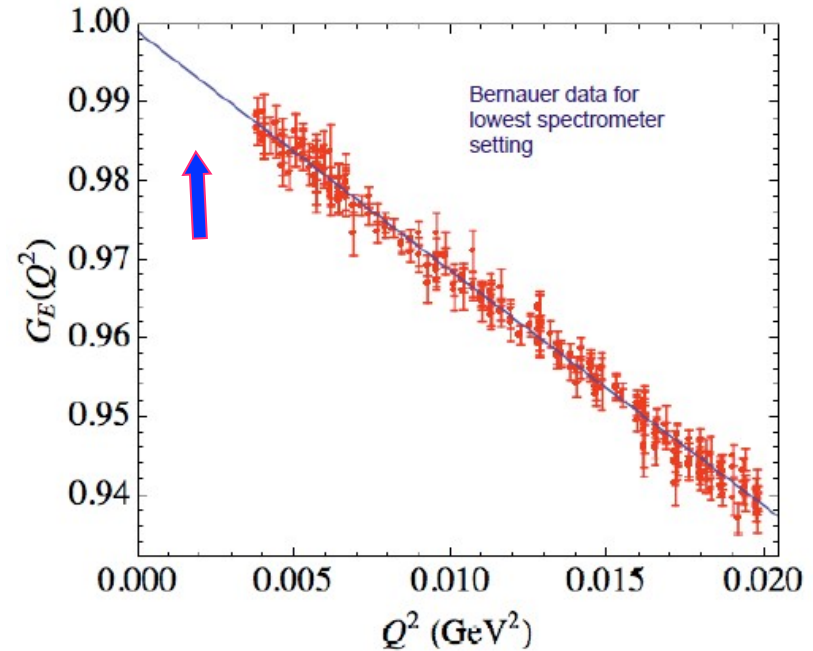
Three spectrometer facility of the A1 collaboration:



Mainz magnetic spectrometers

The PRad Experimental Approach

- Experimental goals:
 - reach to very low Q^2 range ($\sim 10^{-4}$ GeV/c²)
 - reach to sub-percent precision in cross section
 - large Q^2 range in one experimental setting
- Suggested solutions:
 - ✓ use high resolution high acceptance calorimeter:
 - ❖ reach smaller scattering angles: ($\Theta = 0.7^\circ - 7.0^\circ$)
($Q^2 = 1 \times 10^{-4} \div 6 \times 10^{-2}$) GeV/c²
large Q^2 range in one experimental setting!
essentially, model independent r_p extraction
 - ✓ Simultaneous detection of $ee \rightarrow ee$ Moller scattering
 - ❖ (best known control of systematics)
 - ✓ Use high density windowless H₂ gas flow target:
 - ❖ beam background fully under control
 - ❖ minimize experimental background



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

- Two beam energies: $E_0 = 1.1$ GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision in r_p extraction
- Approved by JLab PAC39 (June, 2012) with high “A” scientific rating

PRad Experiment Timeline

- ✓ Initial proposal development: 2011-12
- ✓ Approved by JLab PAC39: 2012
- ✓ Funding proposal for windowless H₂ 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
- ✓ Experiment Readiness Reviews: 2015, 2016
- ✓ Beam line installation: January /April 2016
- ✓ Beam Commissioning: May 2016
- ✓ Experimental data taking: May, June 2016

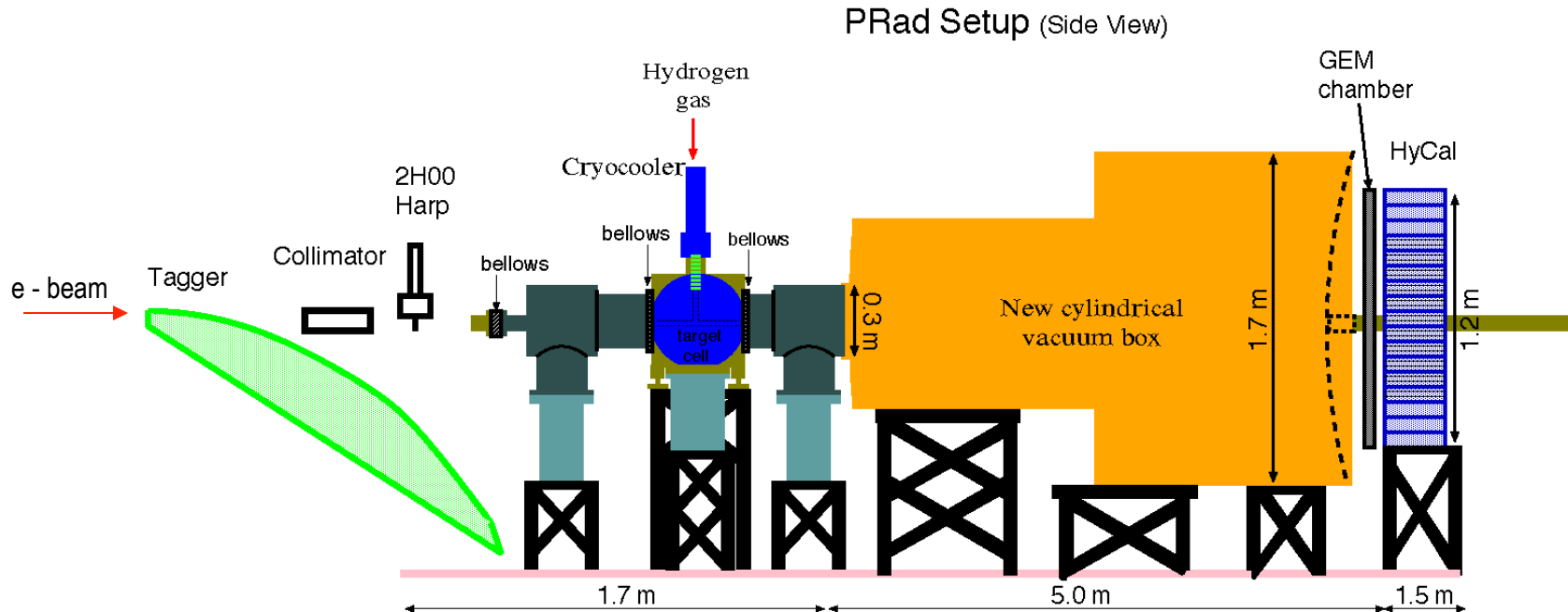
PRad Experimental Setup (schematics)

■ Main detector elements:

- windowless H₂ gas flow target
- PrimEx HyCal calorimeter
- vacuum box with one thin window at HyCal end
- X,Y – GEM detector on front of HyCal

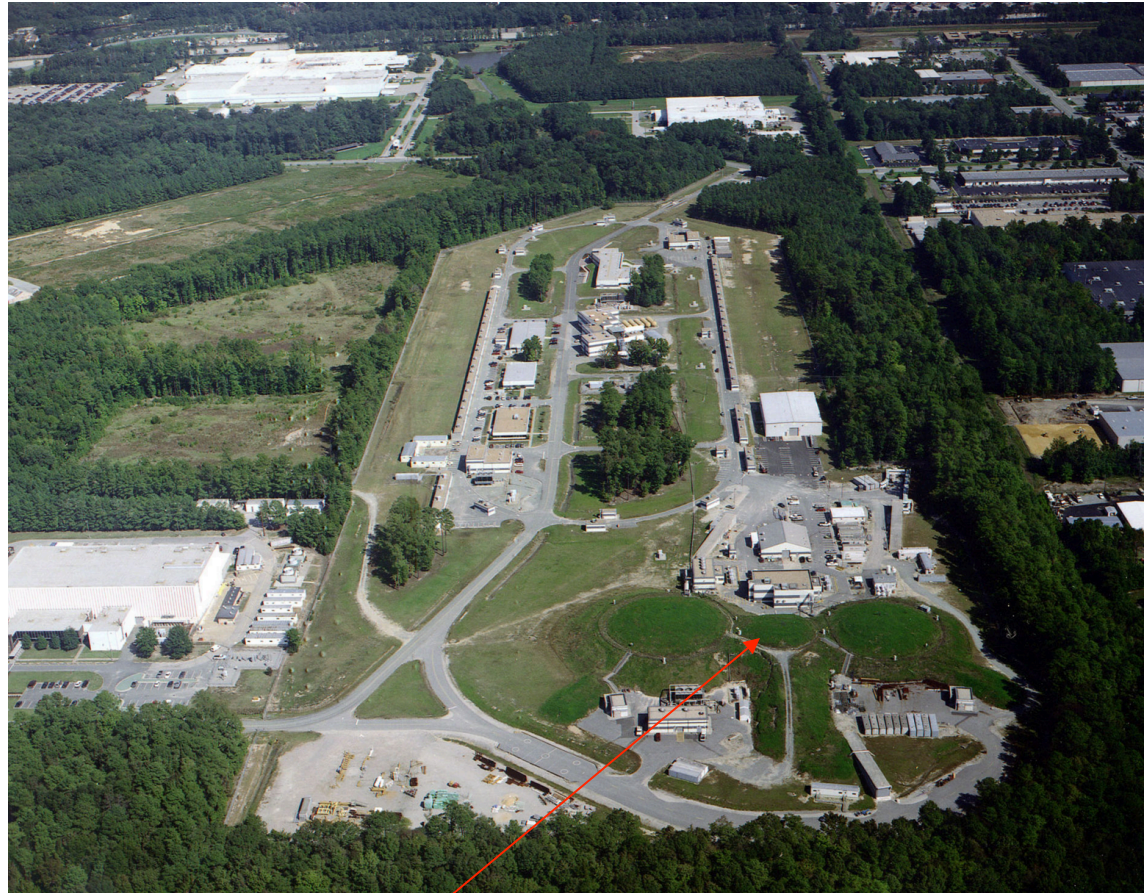
■ Beam line equipment:

- standard beam line elements (0.1 – 10 nA)
- photon tagger for HyCal calibration
- collimator box (6.4 mm collimator for photon beam, 12.7 mm for e⁻ beam halo “clean-up”)
- Harp 2H00
- pipe connecting Vacuum Window through HyCal



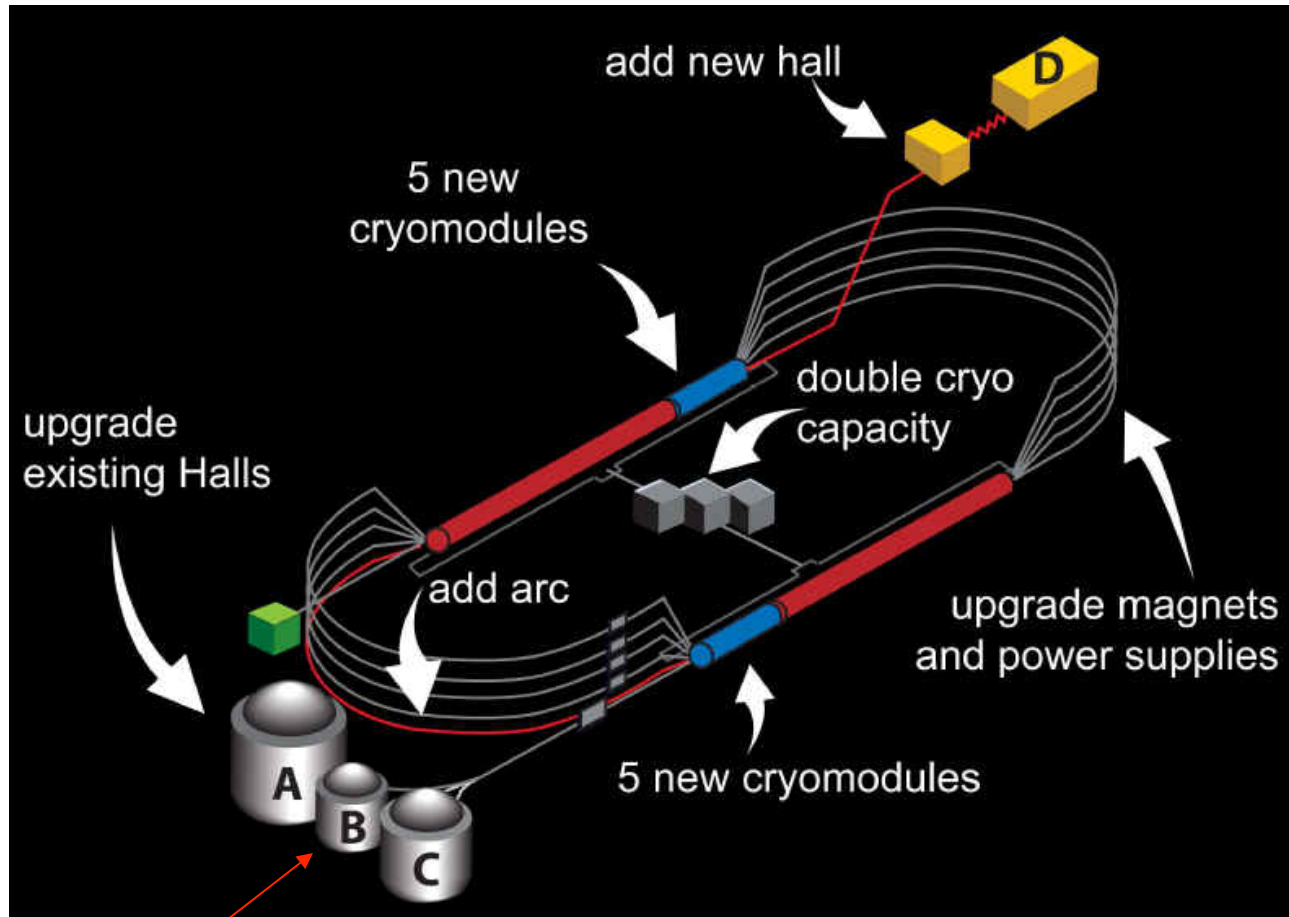
Jefferson Lab CEBAF Accelerator Facility (aerial view)

In Newport News, VA USA



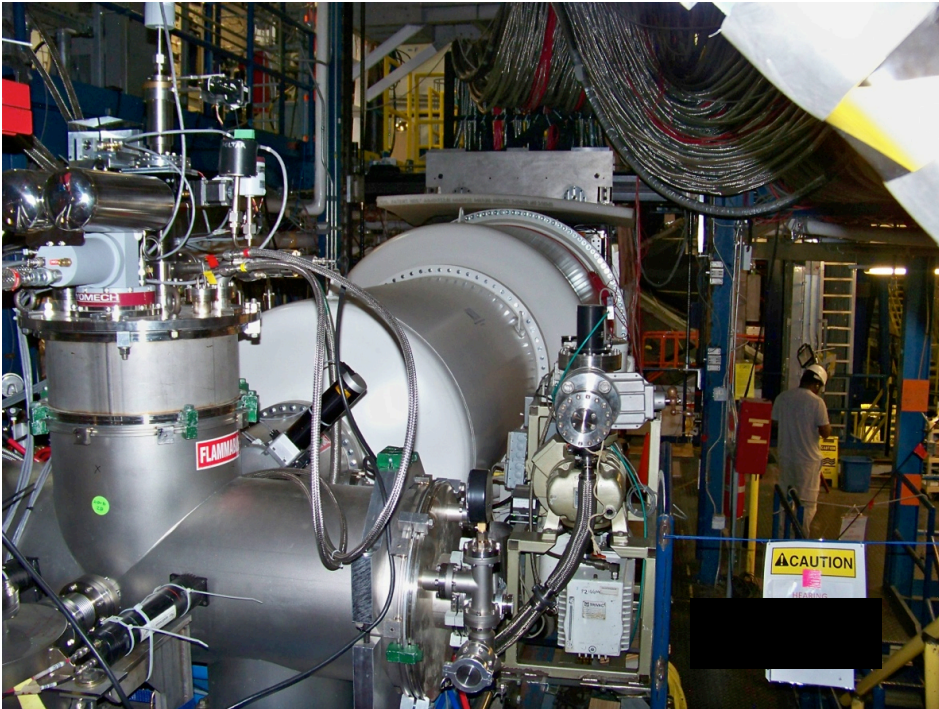
PRad was performed in Hall B at JLab

Jefferson Lab CEBAF Accelerator Facility (schematic view, with 12-GeV upgrade)



PRad was performed in Hall B

PRad Experimental Setup Installed in the Hall B Beam Line



Beam-down view

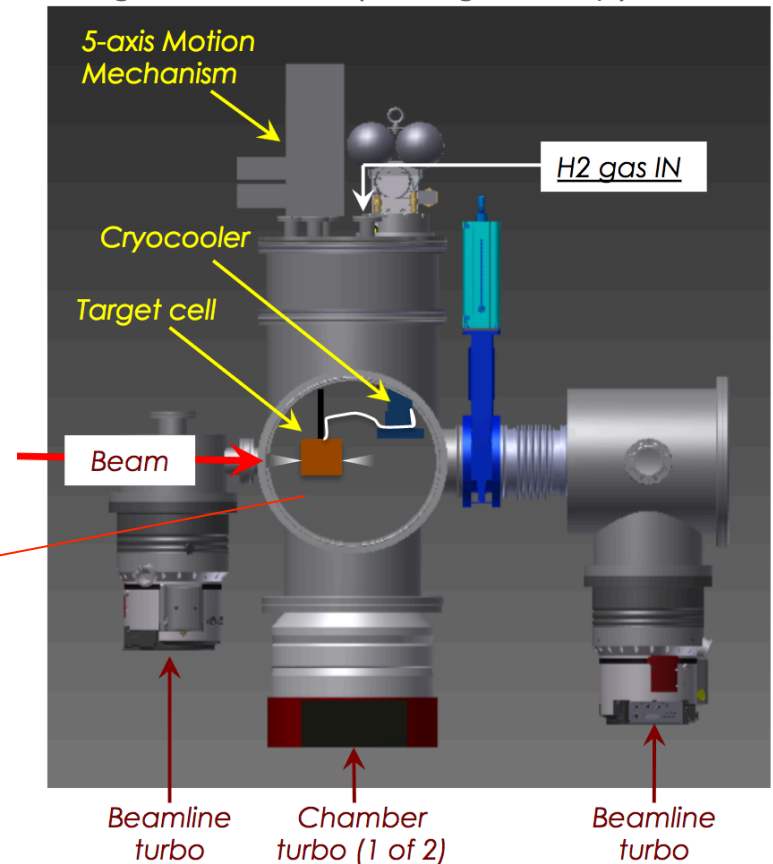
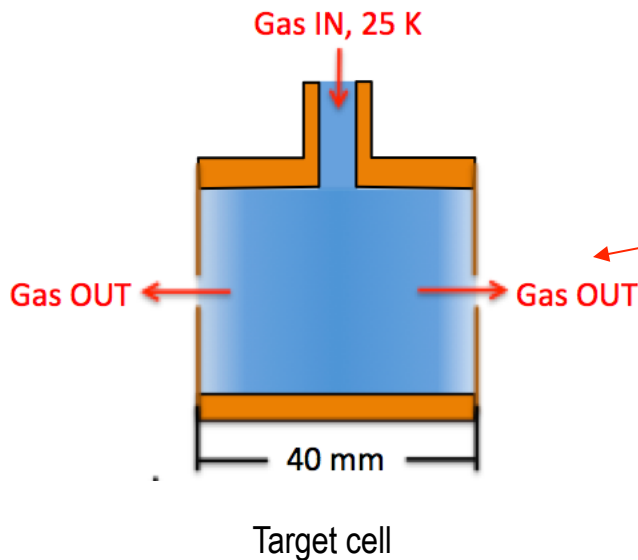


Beam-side view

- Beam line installation completed in May of 2016

Windowless H₂ Gas Flow Target (Schematics)

- A **windowless** gas target of cryogenically cooled hydrogen
 - Target cell is 4 cm long copper, attached to cryocooler via heat strap
 - Cell diameter: 8 cm
 - Cell covers are 7.5 μm kapton with **2 mm beam orifices**
 - Two additional solid target foils: $1\ \mu\text{m}$ ¹²C and Al
 - H₂ input gas temp. 19.5 K



Windowless H₂ Gas Flow Target Installed in Hall B Beam Line

✓ Areal density: 1.8×10^{18} H atoms/cm²

cell pressure: 471 mtorr

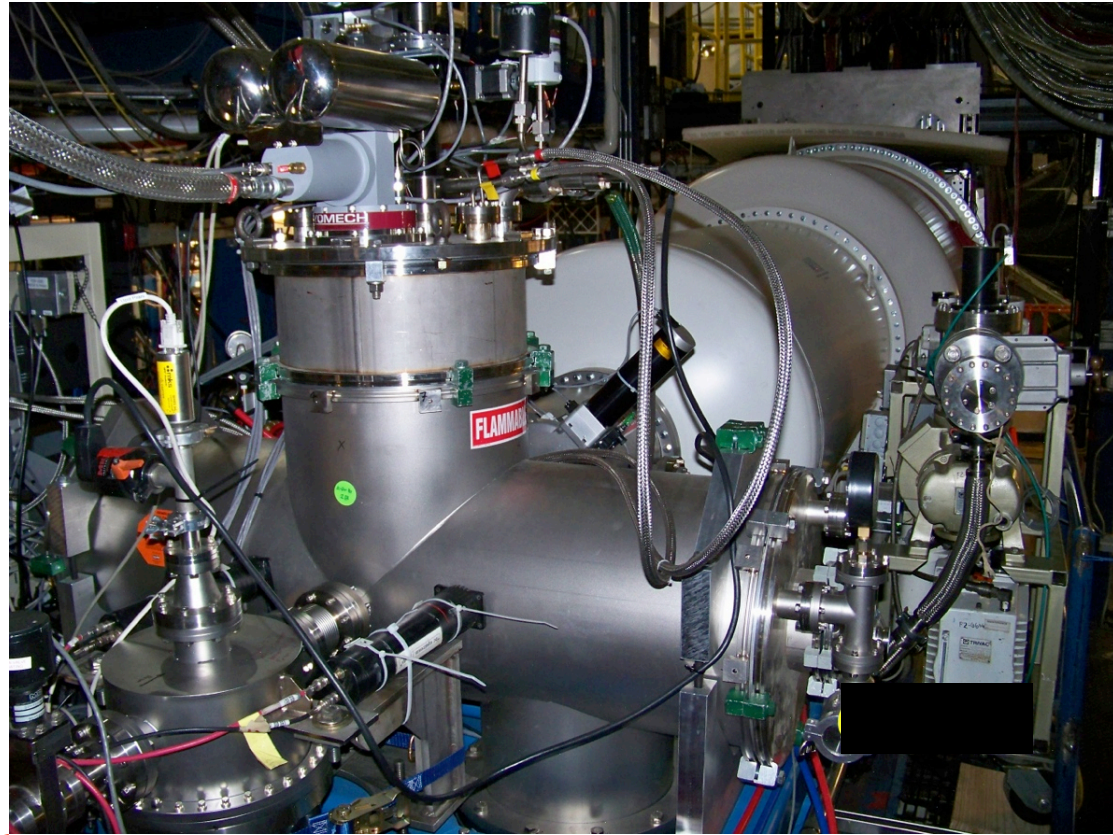
chamber pressure: 2.34 mtorr

cell vs. chamber pressures:

200:1 has been reached.

✓ cell vs. first vacuum tank pressures:

1000:1 has been reached
(471 mtorr:0.3 mtorr);

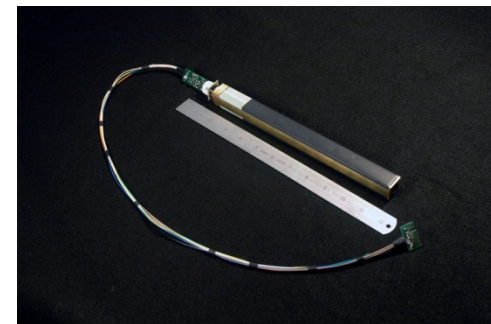
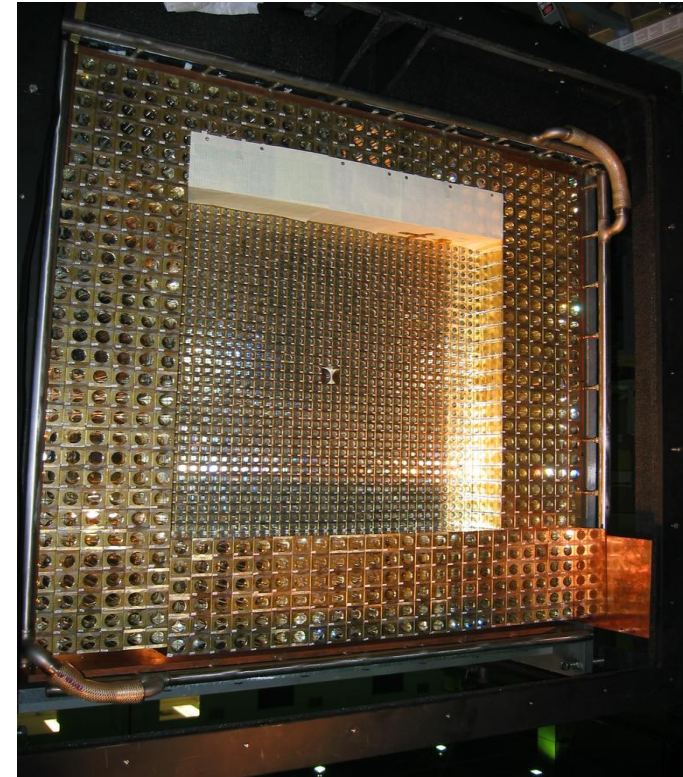


e - beam

Target installed in Hall B beam line, May 2016

Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of PbWO_4 and Pb-glass detectors ($118 \times 118 \text{ cm}^2$)
 - 34 x 34 matrix of $2.05 \times 2.05 \times 18 \text{ cm}^3$ PbWO_4 shower detectors
 - 576 Pb-glass shower detectors ($3.82 \times 3.82 \times 45.0 \text{ cm}^3$)
 - 2 x 2 PbWO_4 modules removed in middle for beam passage
 - 5.5 m from H_2 target ($\sim 0.5 \text{ sr}$ acceptance)
- Resolutions:
 - for PbWO_4 shower detectors:
 - ✓ energy: $\sigma/E = 2.6 \text{ \%}/\sqrt{E}$
 - ✓ position: $\sigma_{xy} = 2.5 \text{ mm}/\sqrt{E}$
 - for Pb-glass shower detectors factor of ~ 2.5 worse



PbWO_4 crystal cell

HyCal Electromagnetic Calorimeter in Hall B beam Line



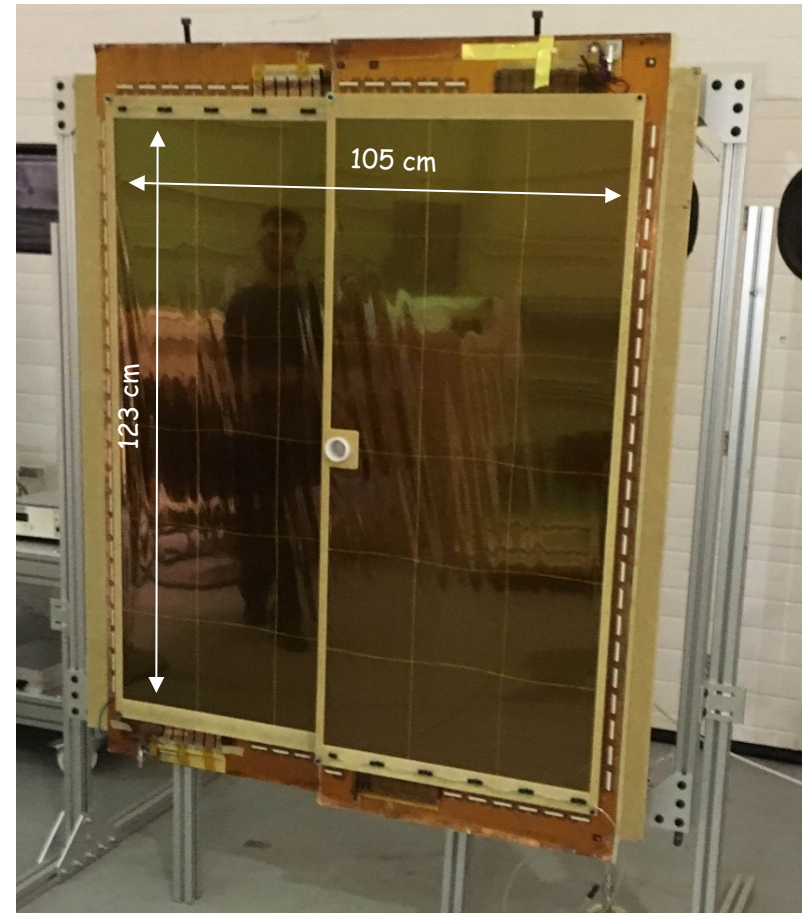
GEM Coordinate Detectors

■ Tasks for GEM:

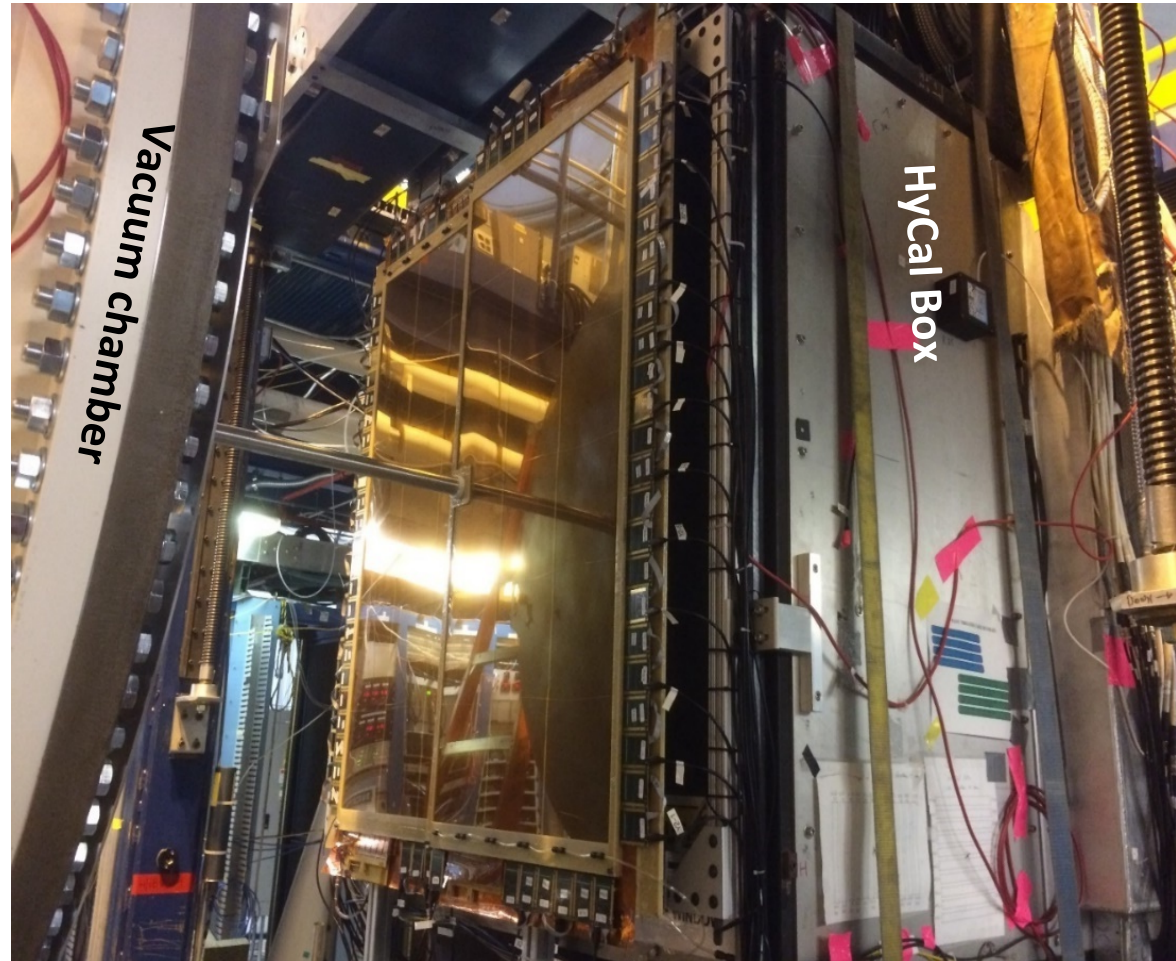
- factor of **>20 improvements in coordinate resolutions**
- similar improvements in Q^2 resolution (**very important**)
- unbiased coordinate reconstruction (including HyCal transition region)
- increase Q^2 range by including HyCal Pb-glass part

■ Designed and built at University of Virginia (UVa)

■ Two large size GEM X and Y- coordinate detectors with $100\ \mu\text{m}$ position resolution



GEM Coordinate Detectors in Hall B Beam Line

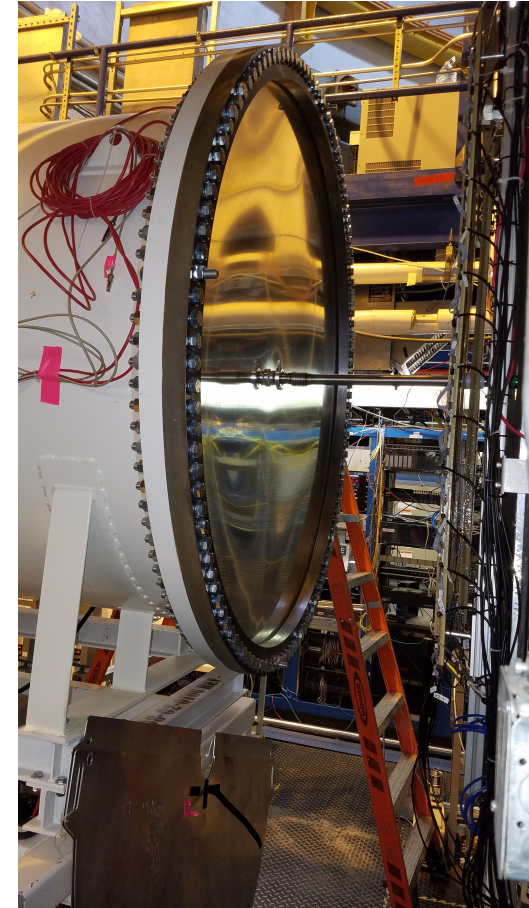


2 GEM detectors installed in Hall B beam line, May 2016

Vacuum Box with a Large Window



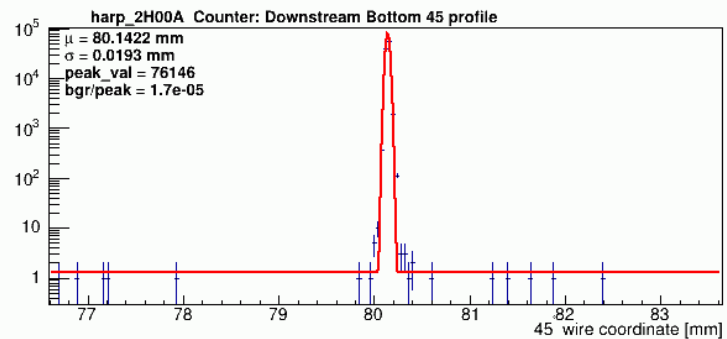
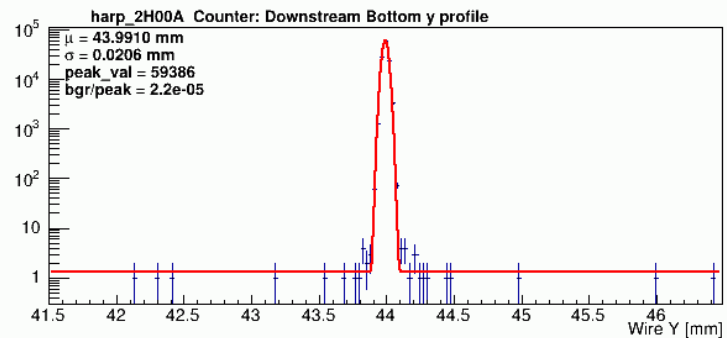
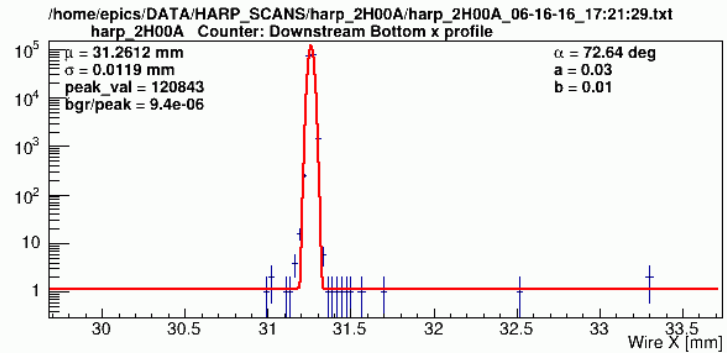
2-stage vacuum box in Hall B beam line



1.7 m diameter, 2 mm Al vacuum window

The CEBAF Electron Beam at Jlab

- The e-beam profile at the target measured by “harp” scan before the target:
 - ✓ typical size, 25 μm
 - ✓ position stability, $\pm 200 \mu\text{m}$



Experimental Data Collected

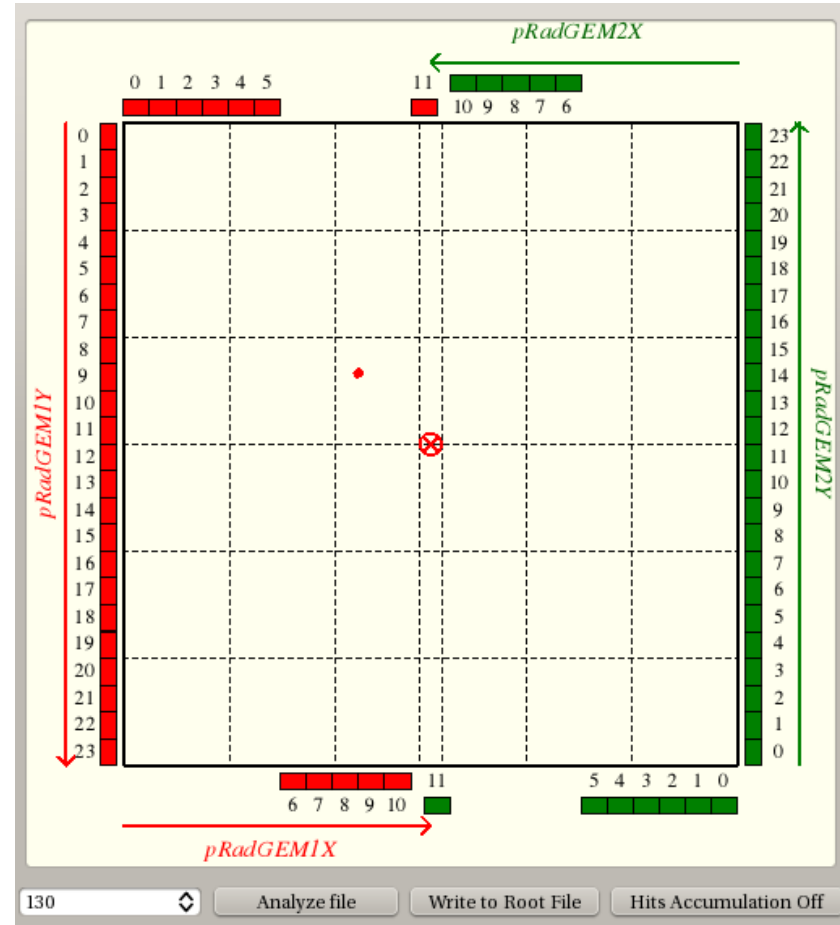
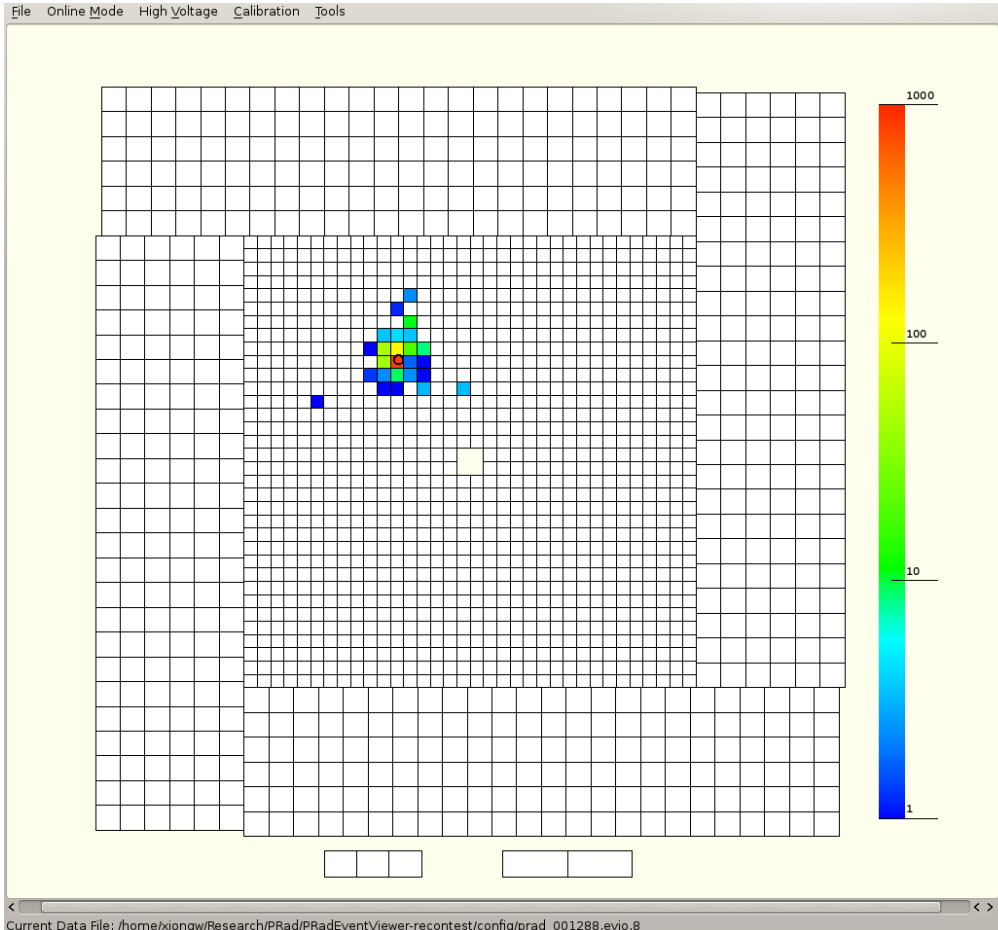
(May/June 2016 Run)

- with $E_e = 1.1$ GeV beam:
 - ✓ 4.2 mC (target areal density: 2×10^{18} H atoms/cm²)
 - ✓ 604 M events with target;
 - ✓ 53 M events with “empty” target;
 - ✓ 25 M events with ¹²C target for calibration.

- with $E_e = 2.2$ GeV beam:
 - ✓ 14.3 mC (target areal density: 2×10^{18} H atoms/cm²)
 - ✓ 756 M events with target;
 - ✓ 38 M events with “empty” target;
 - ✓ 10.5 M events with ¹²C target for calibration.

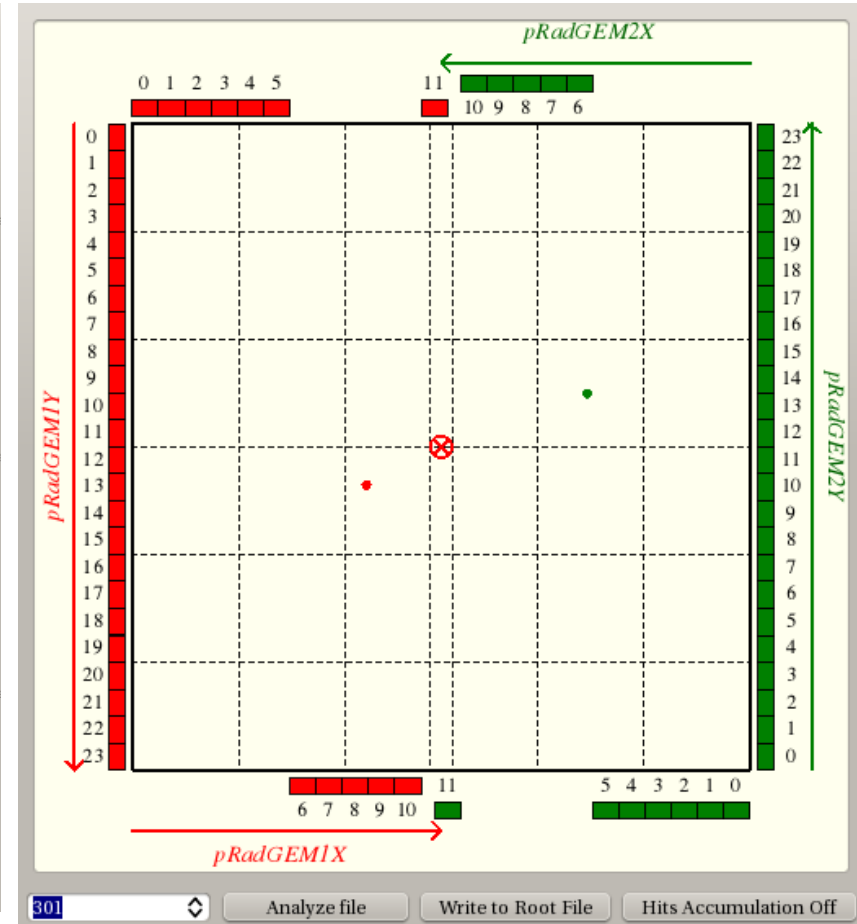
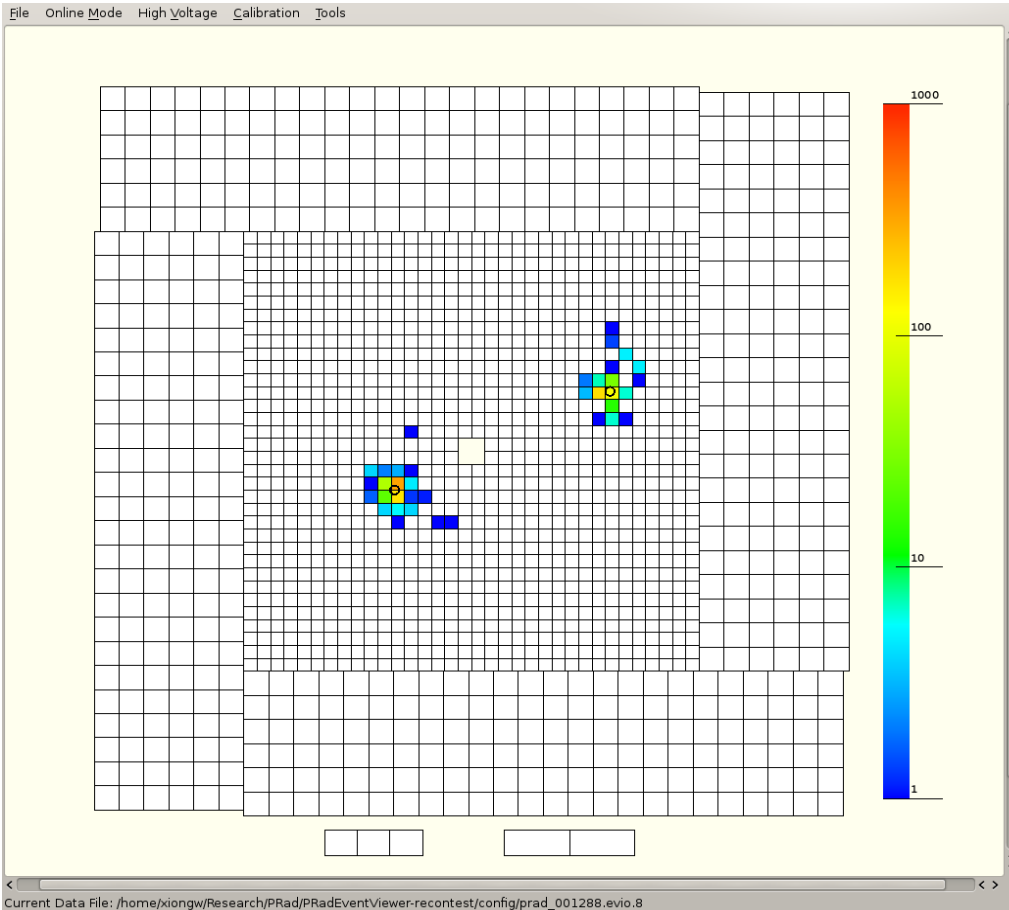
Fresh Results from On-Line Analysis (HyCal - GEM single-cluster event matching)

- $ep \rightarrow ep$ event candidate



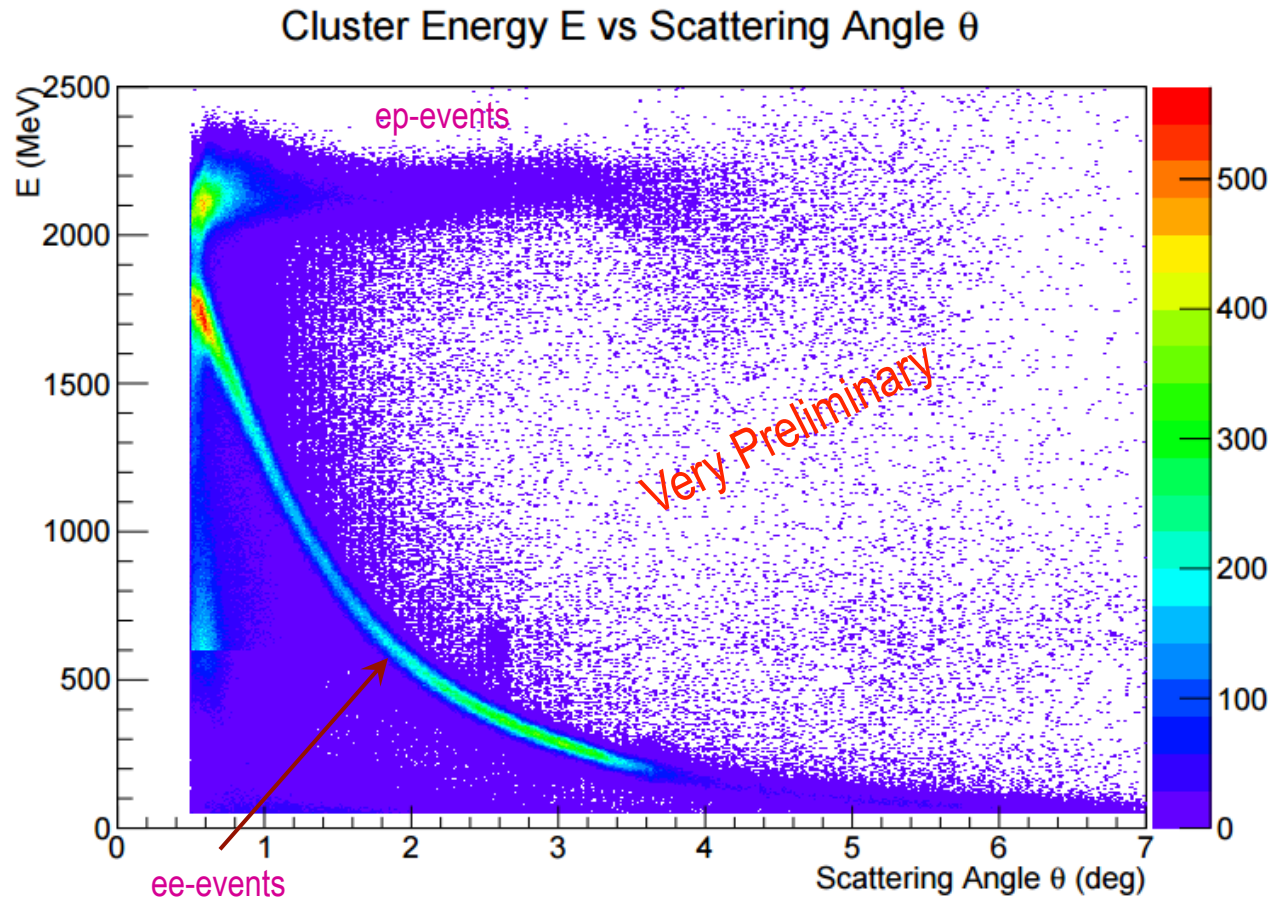
Fresh Results from On-Line Analysis (HyCal-GEM double-cluster event matching)

- $ee \rightarrow ee$ event candidate



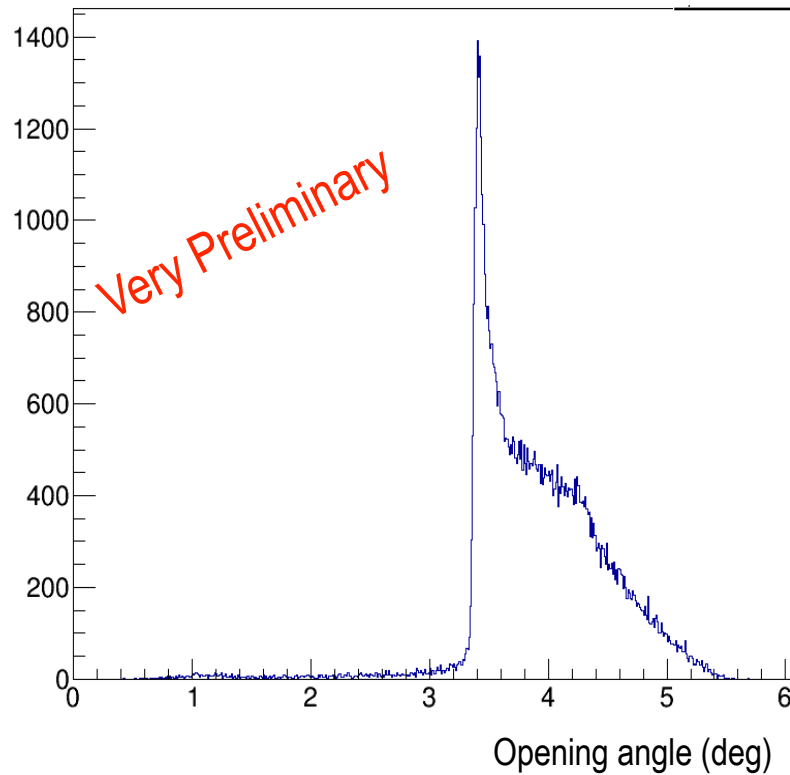
Fresh Results from On-Line Analysis

- 2d-distribution of the cluster energy vs. scattering angle

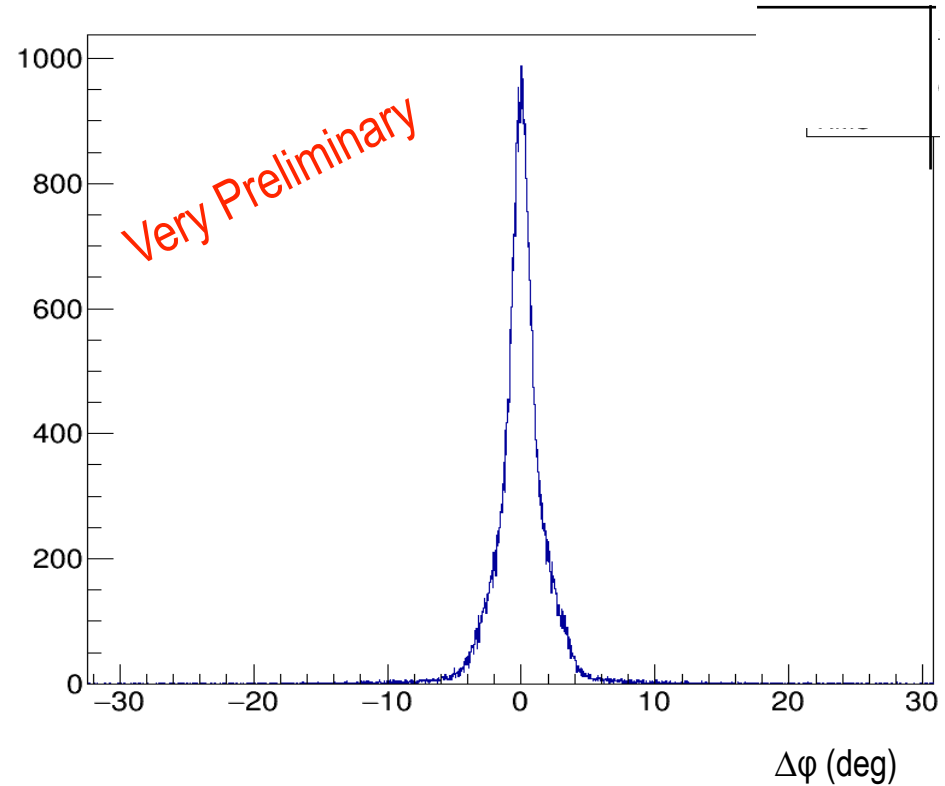


Fresh Results from On-Line Analysis

- 2-cluster events: distribution of opening angle



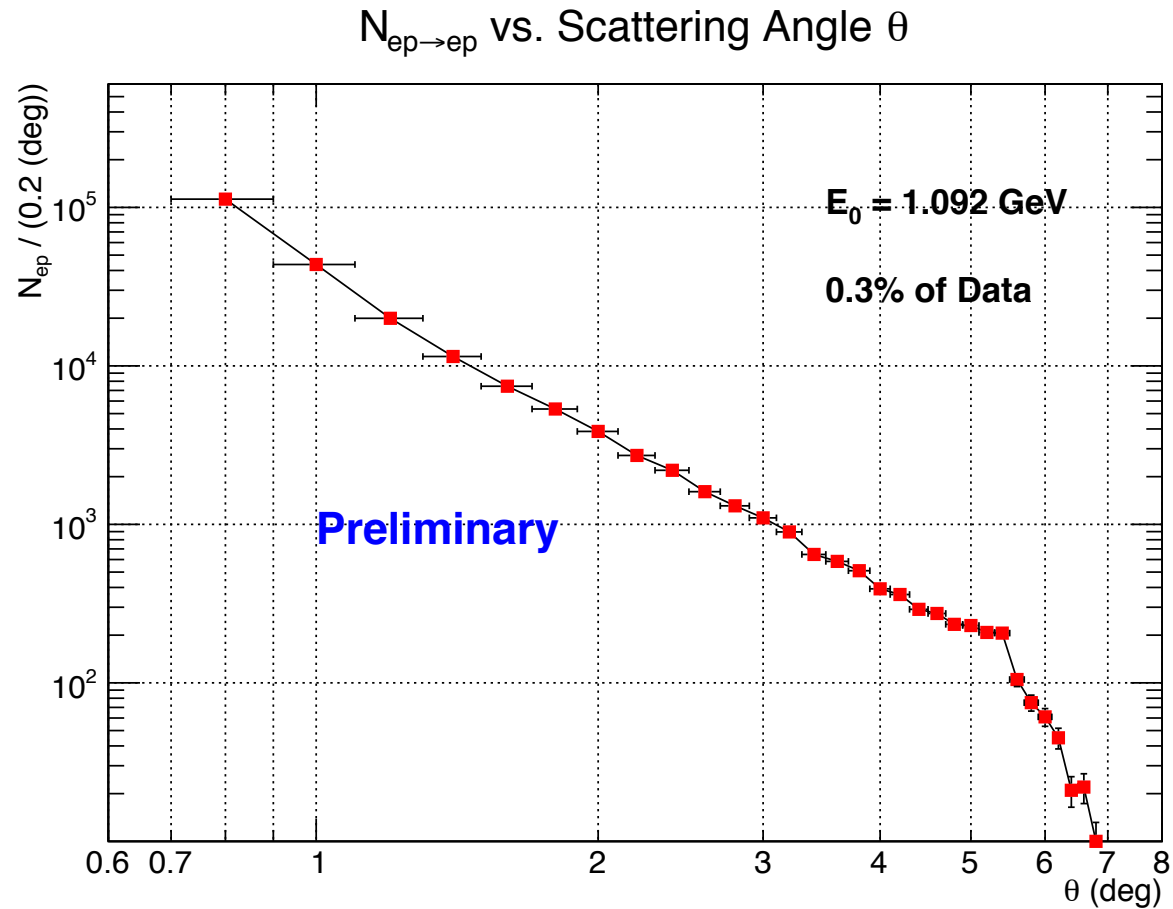
and co-planarity



- Clear signature of Møller events!

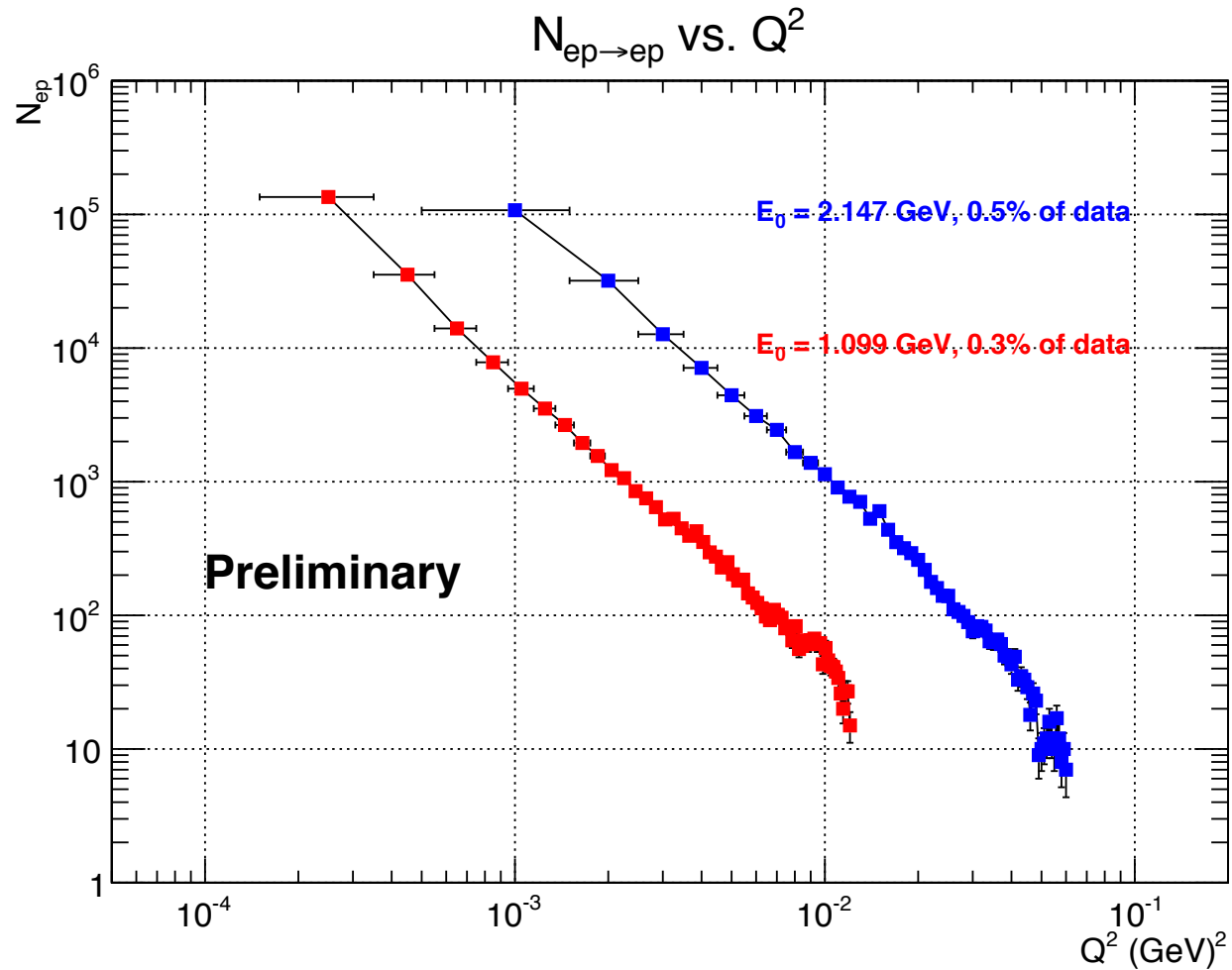
Fresh Results from On-Line Analysis

- Experimental yields for $ep \rightarrow ep$ vs. scattering angle
(not normalized, acceptance not corrected)



Fresh Results from On-Line Analysis

- Experimental yields for $ep \rightarrow ep$ vs. Q^2
(not normalized, acceptance not corrected)



PRad Collaboration Institutional List

- Currently 16 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
University of Kentucky
Hampton University
College of William & Mary
Tsinghua University, China
Old Dominion University
ITEP, Moscow, Russia
Budker Institute of Nuclear Physics , Novosibirsk, Russia

- The graduate students:

Chao Peng
Li Ya
Weizhi Xiong
Xinzhan Bai

... who carried out this experiment!

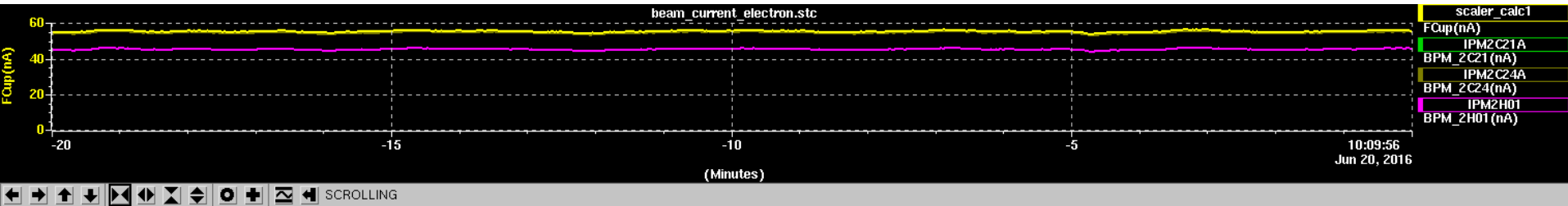
Summary

- The *Proton Radius Puzzle* is still unresolved after six years.
- PRad was uniquely designed to address the *Proton Radius Puzzle*.
- Experiment had been performed in May/June of 2016:
 - ✓ large statistics, high quality, rich data have been collected;
 - ✓ lowest Q^2 data set ($\sim 10^{-4}$ GeV/C²) 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;
 - ✓ data in a large Q^2 range have been recorded with the same experimental settings, [$10^{-4} \div 10^{-1}$] GeV/C², for the first time in ep-scattering experiments.
- Data analysis has been started, first preliminary results for this year are possible.
 - PRad is supported in part by NSF MRI award #PHY-1229153 as well as DOE awards for GEM
 - my research work is supported in part by NSF awards: PHY-1506388 and PHY-0855543

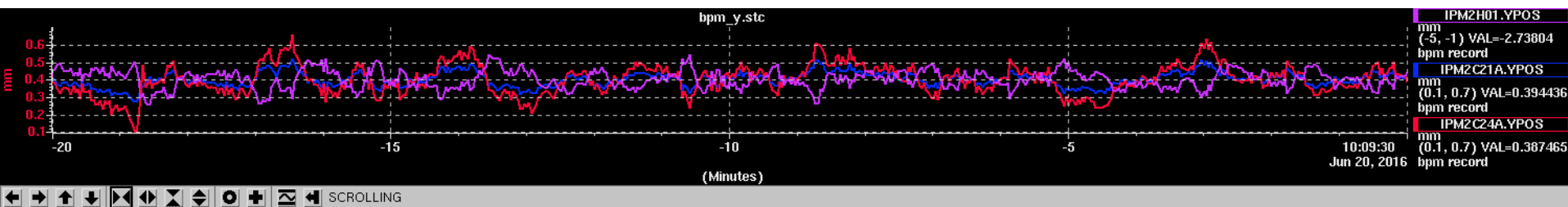
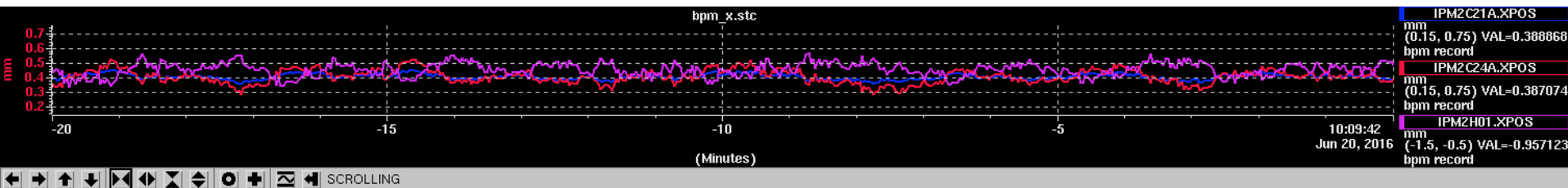
The End

The CEBAF Electron Beam at JLab

- Beam current monitoring (55 nA)



- X and Y position stability (± 0.1 mm)



The CEBAF Electron Beam at JLab (energy stability)

- Beam energy monitoring, $E_e = 2147.4 \text{ MeV}$ ($\Delta E/E = \pm 5 \times 10^{-4}$)

