The Proton Radius Experiment at Jefferson Lab (PRad)

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for the PRad collaboration

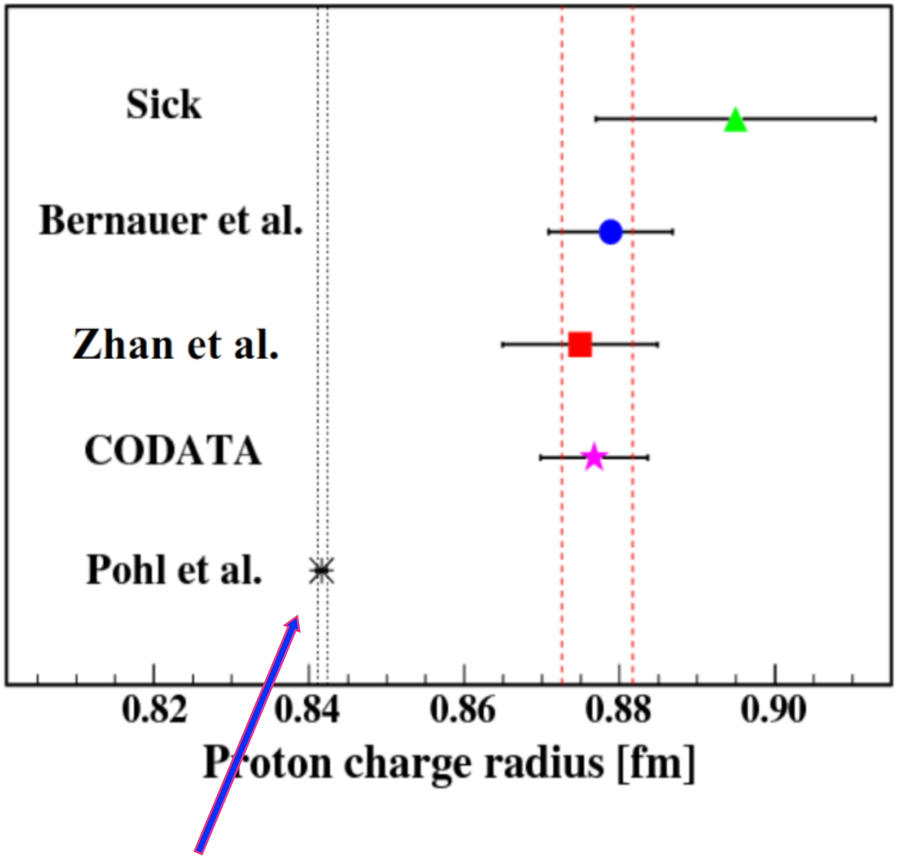
Outline

- Status of the "*Proton Radius Puzzle*"
- The PRad experiment
- Status of the run and the data quality
- Summary

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

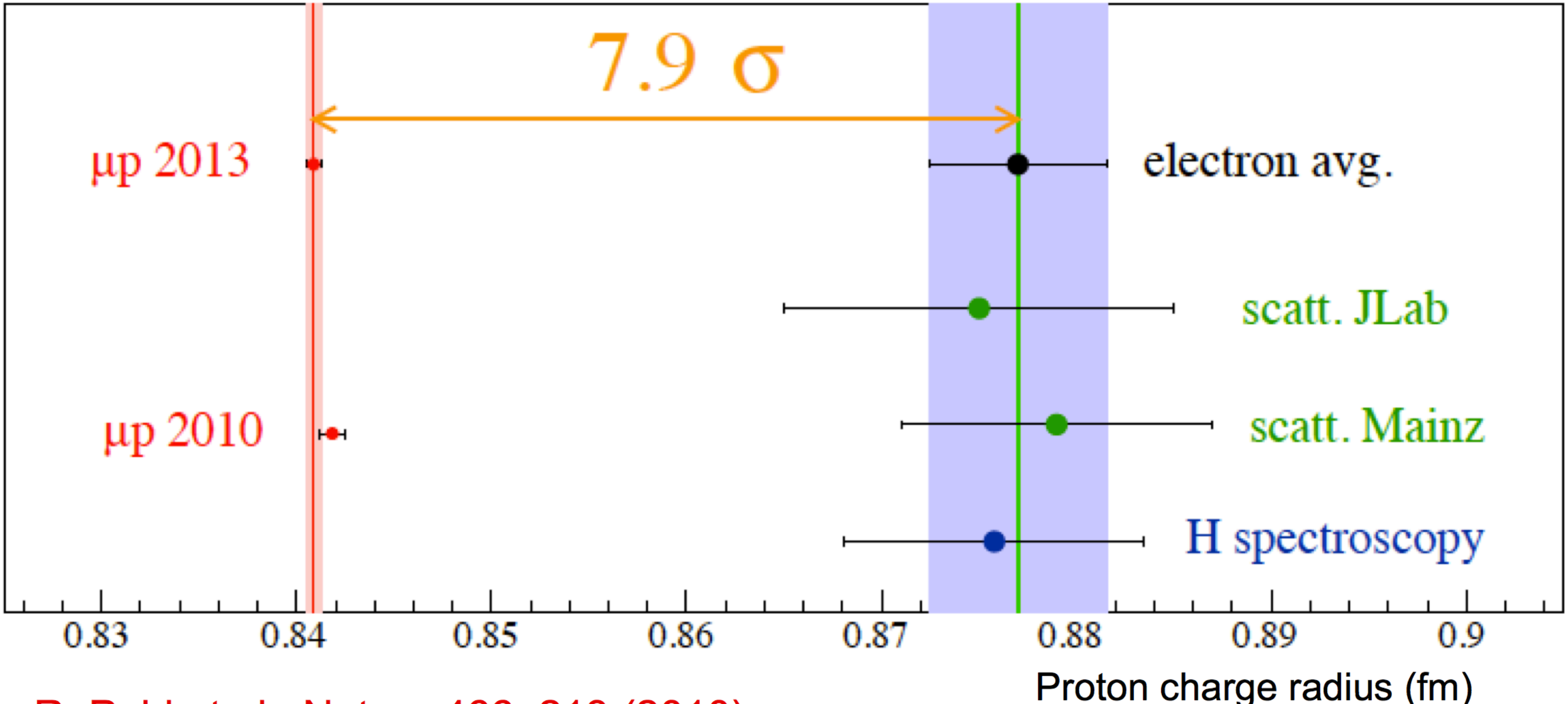
- ~ 8 σ discrepancy between the new muonic-hydrogen measurements and all previous results



New muonic-hydrogen result
R. Pohl et al., Nature 466, 213 (2010).

The Proton Radius Puzzle

The Proton Radius Puzzle (2013)



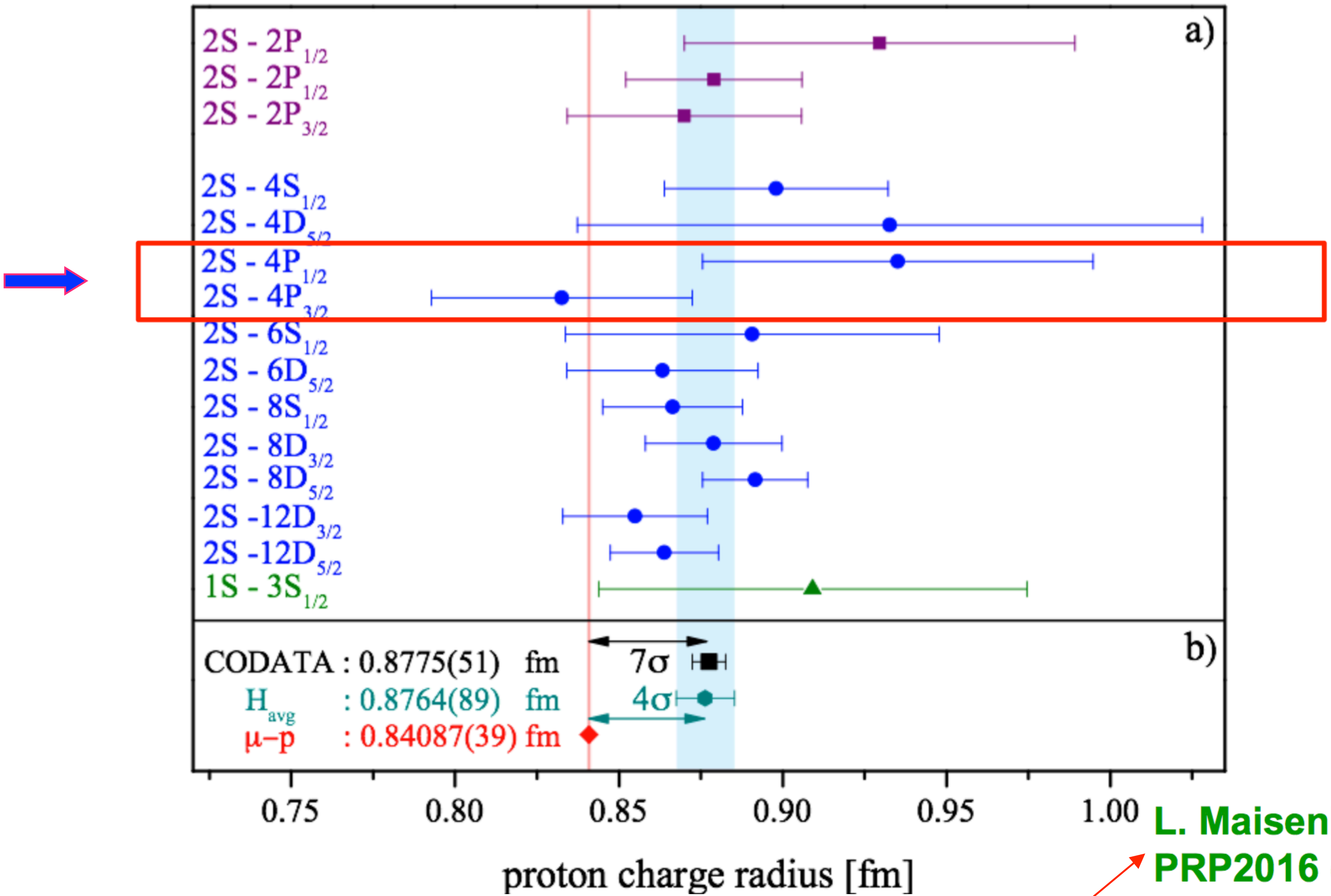
R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

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)



L. Maisenbacher, PRP2016 (Trento)

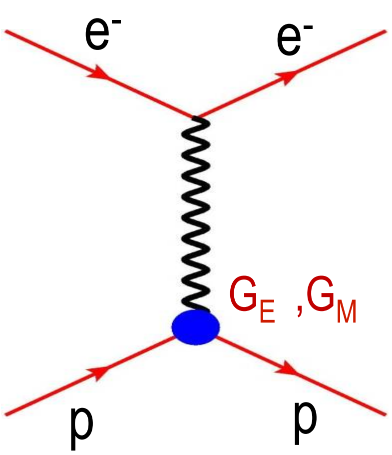
- New, preliminary value for R_p was reported in PRP-2016 Workshop (Trento, Italy) from ordinary hydrogen
- Consistent with the muonic-hydrogen result !
- Is the Puzzle solved? No, new measurements are needed (spectroscopy, ep-scattering)

Extraction of r_p from ep→ep Experiments

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

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

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



- Structureless proton:

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

- G_E and G_M 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:

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

✓ Extraction of the Proton Radius:
(r.m.s. charge radius given by the slope):

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

A New ep→ep Experiment?

- Practically all ep-experiments are done with magnetic spectrometers!

- Limitation on minimum Q^2: 10^{-3} GeV/C^2
  - ✓ limitation on min. scattering angle: $\theta_e \approx 5^0$
  - ✓ Typical beam energies: ~ 0.1 ÷1 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: ~ 2 ÷ 3%

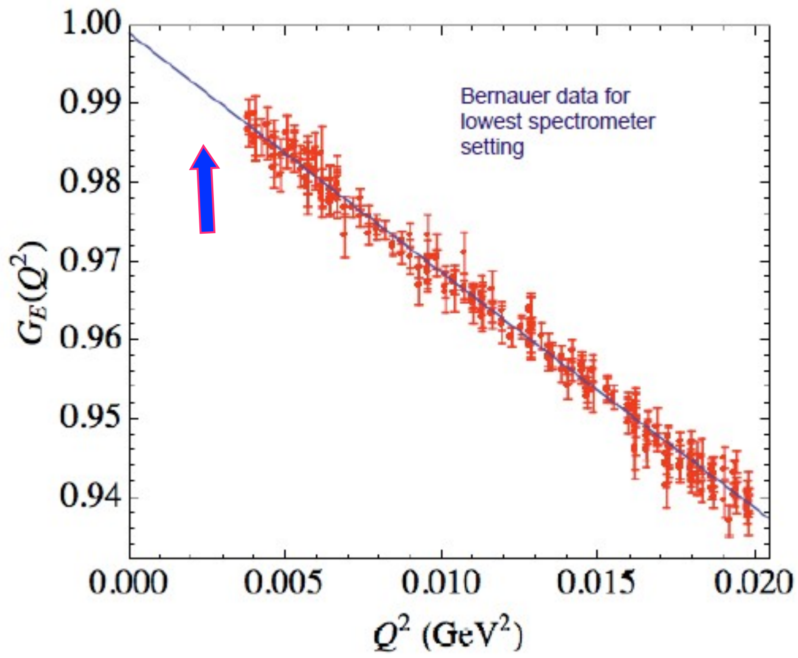
Three spectrometer facility of the A1 collaboration:

Mainz magnetic spectrometers

- A possible solution (the PRad approach):
  - ✓ Non-magnetic-spectrometer method
  - ✓ No target windows
  - ✓ Calibrate with other well-known QED processes

PRad Experiment

- Experimental goals:
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - 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: ($\Theta = 0.7^0 - 7.0^0$)
      ($Q^2 = 1\text{x}10^{-4} \div 6\text{x}10^{-2}$) GeV/c^2
      large Q^2 range in one experimental setting!
      essentially, model independent r_p extraction
  - ✓ Simultaneous detection of *ee* → *ee* Moller scattering
    - (best known control of systematics)
  - ✓ Use high density windowless H2 gas flow target:
    - beam background fully under control
    - minimize experimental background



Recent Mainz low Q^2 data set
from 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

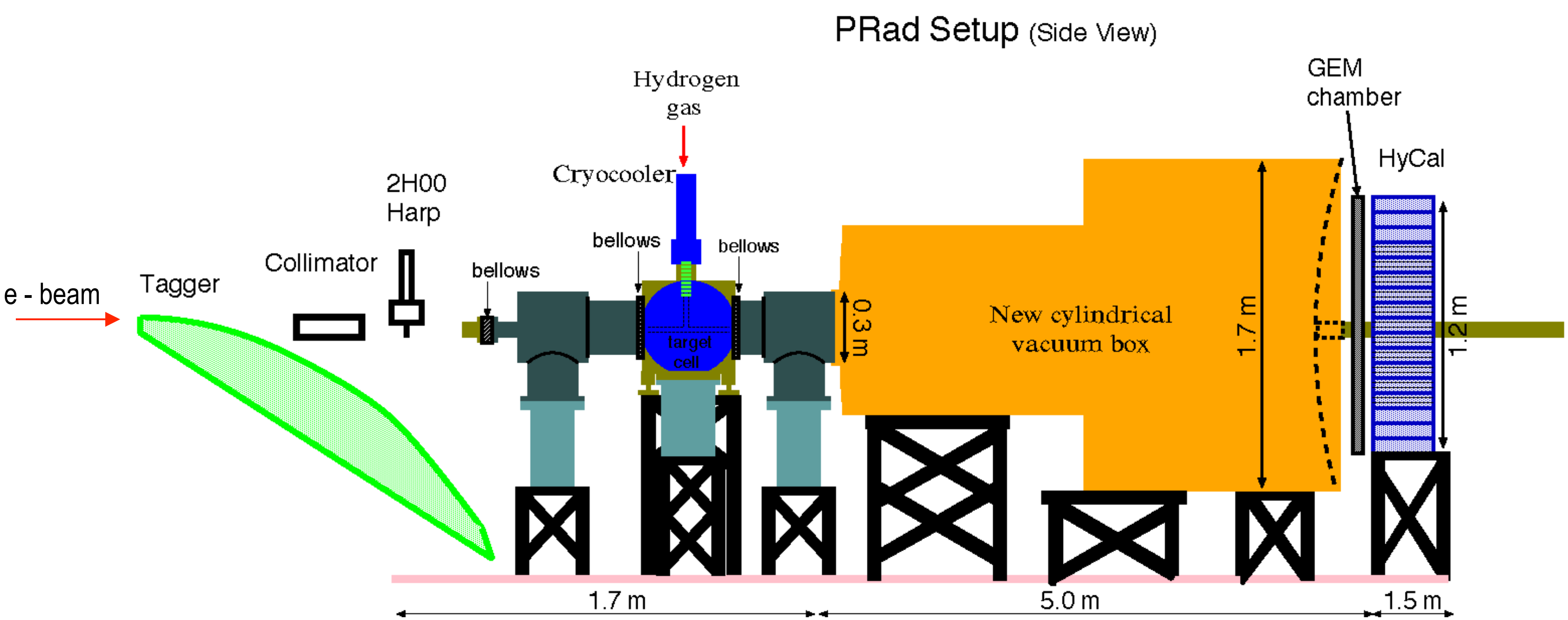
PRad Experiment Timeline

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

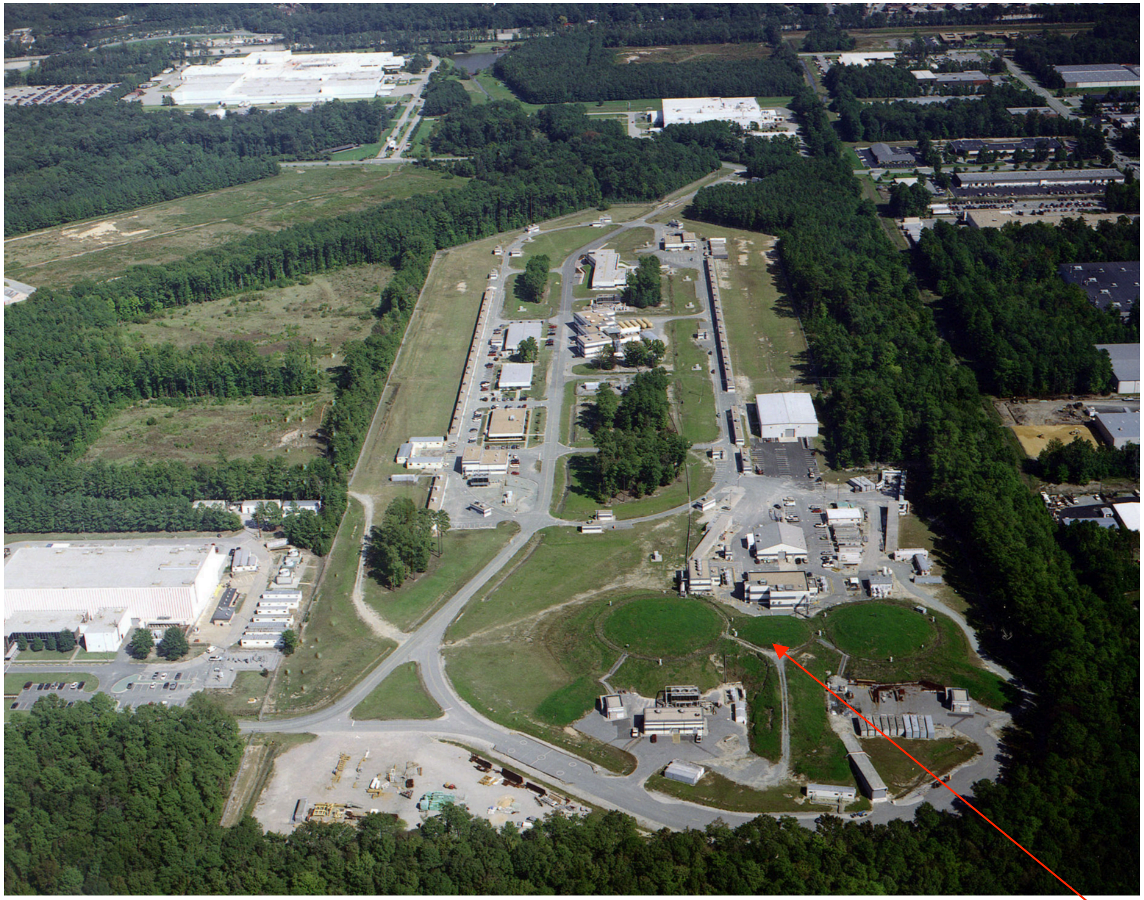
PRad Experimental Setup (schematics)

- Main detector elements:
  - windowless H_2 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



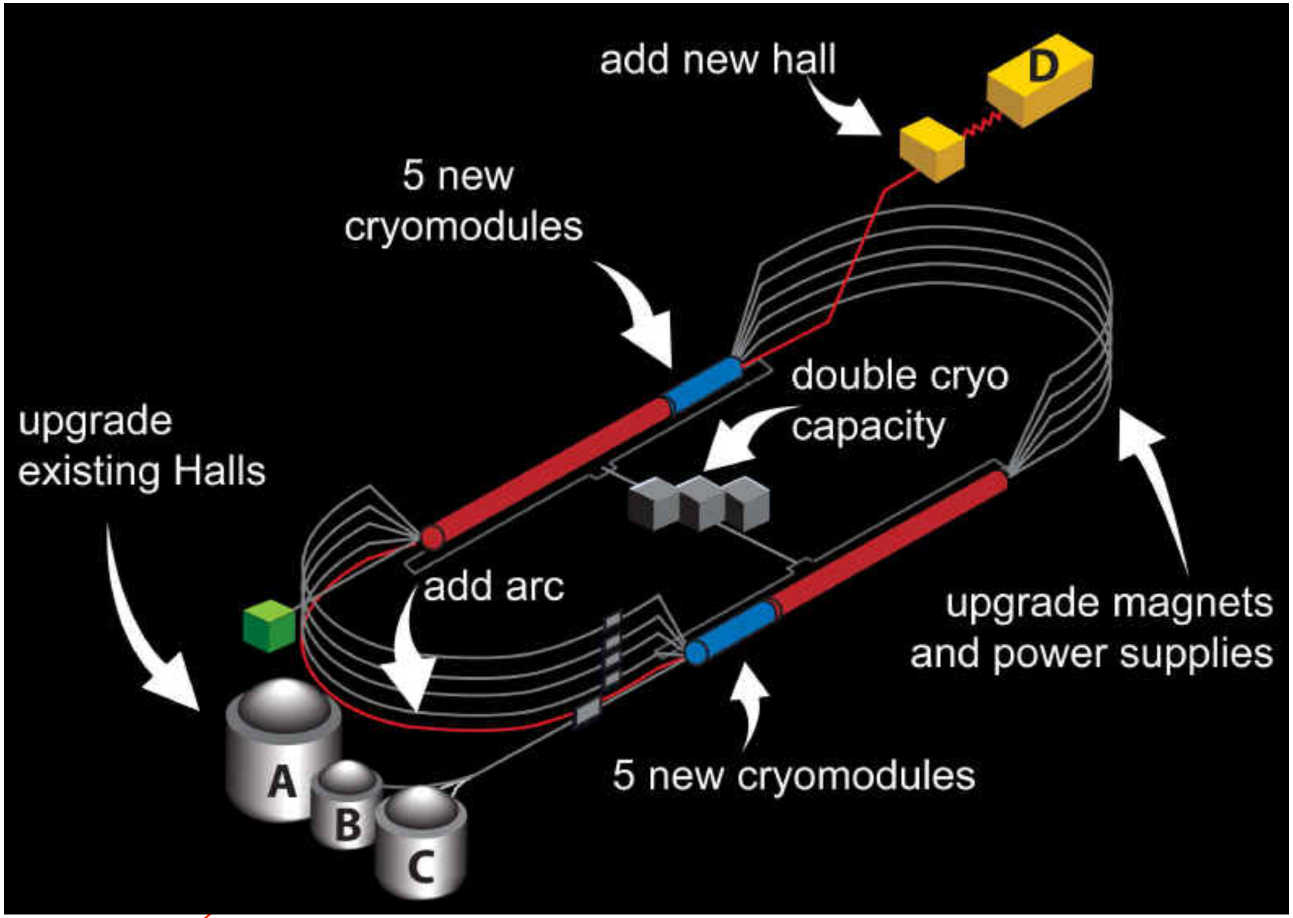
Jefferson Lab CEBAF accelerator Facility
(aerial view)



Newport News, VA USA

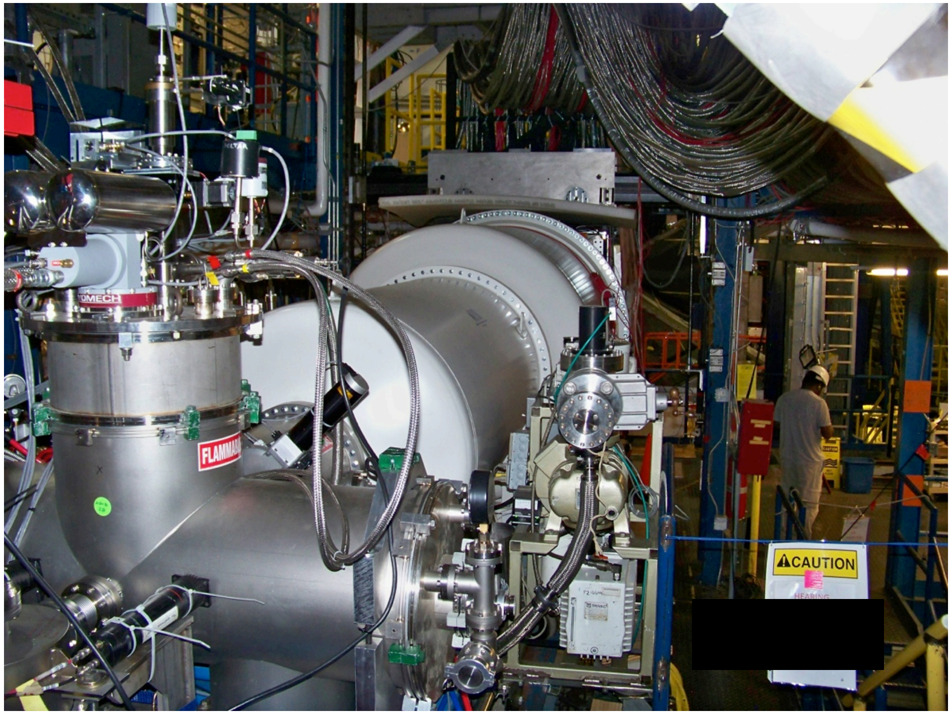
PRad was performed in Hall B

Jefferson Lab CEBAF accelerator Facility
(schematic view)



PRad was performed in Hall B

PRad Experimental Setup Installed in the Hall B Beam Line



Beam-down view

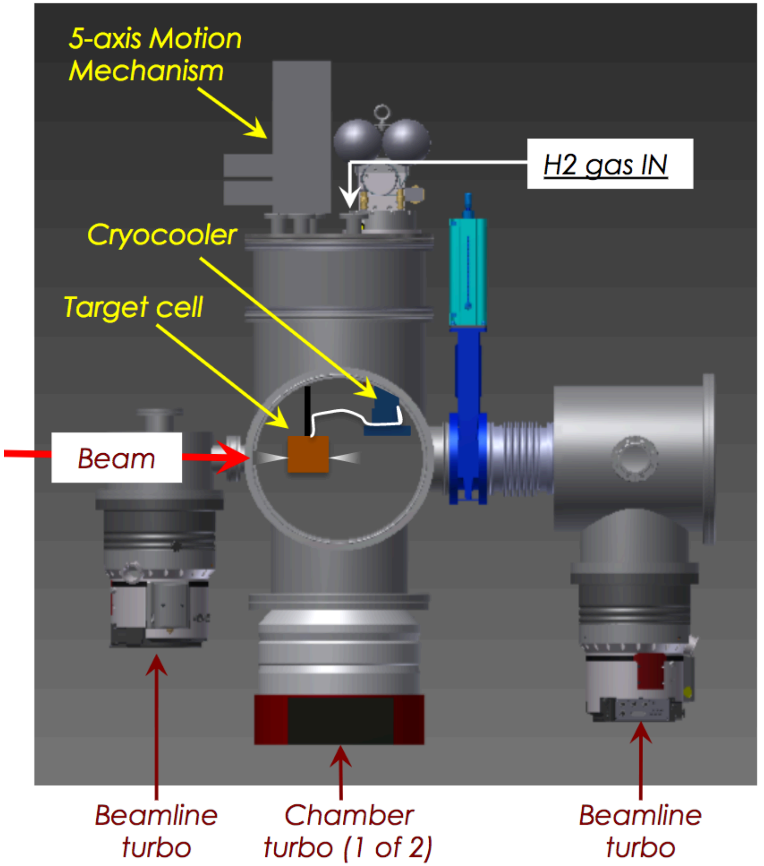
Beam-side view

- Beam line installation completed in May of 2016

Windowless H_2 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 μm 12C and Al*
  - H_2 input gas temp. 19.5 K

- Four-axis motion system to position the target cell with 10 μm accuracy



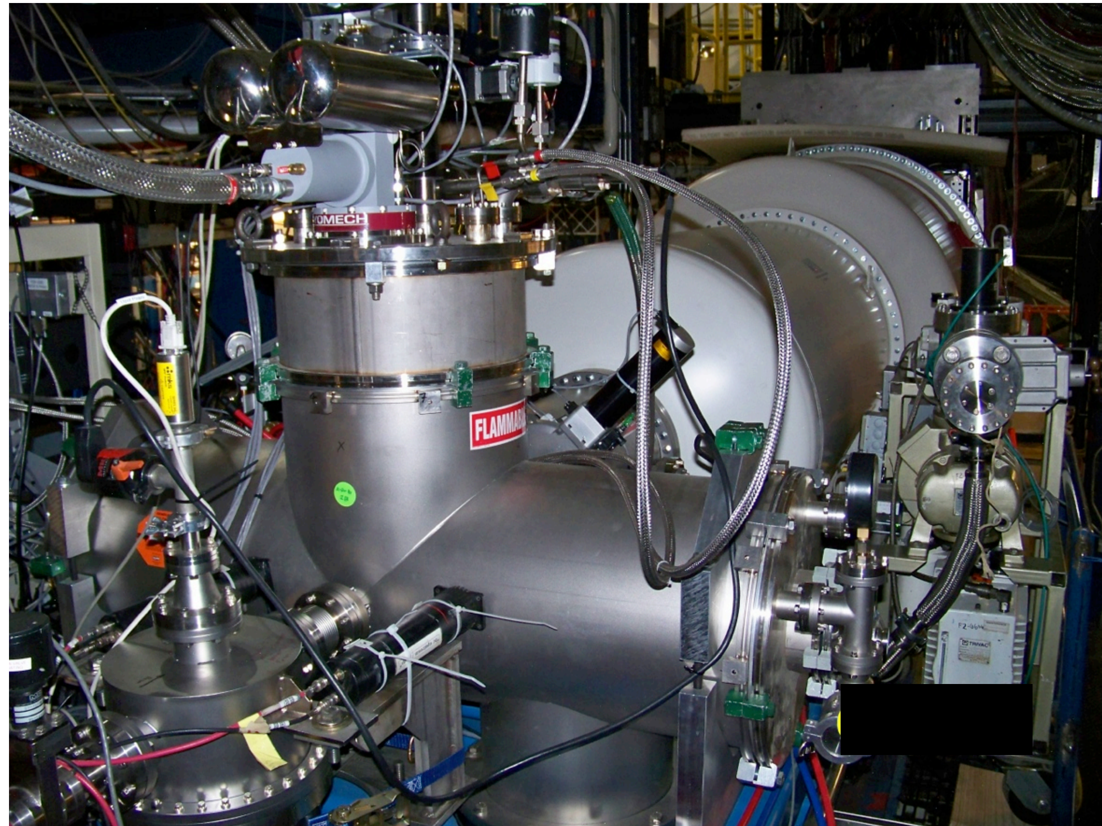
Windowless H_2 Gas Flow Target Installed in Hall B Beam Line

- ✓ Areal density: $1.8 \times 10^{+18}$ H atoms/cm^2

  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
  (471mtorr:0.3 mtorr);



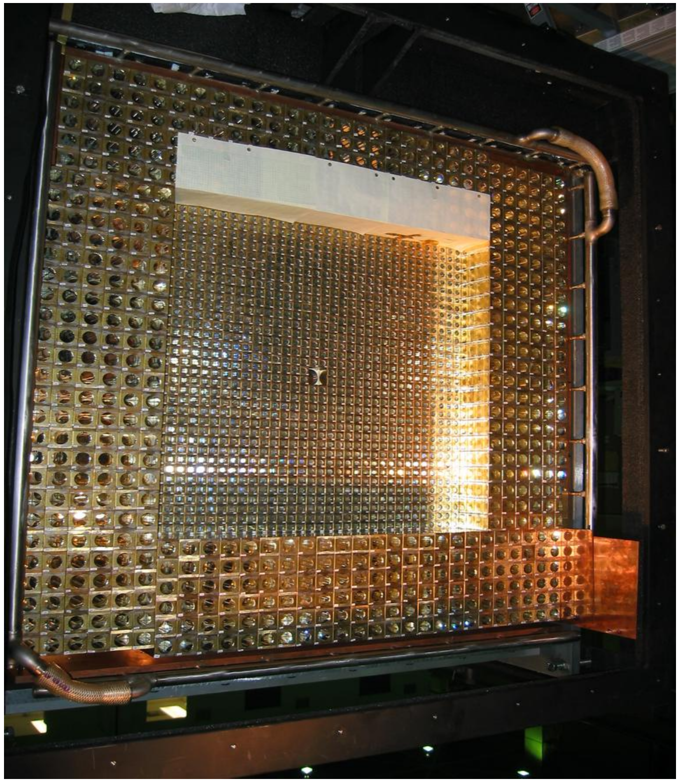
e - beam

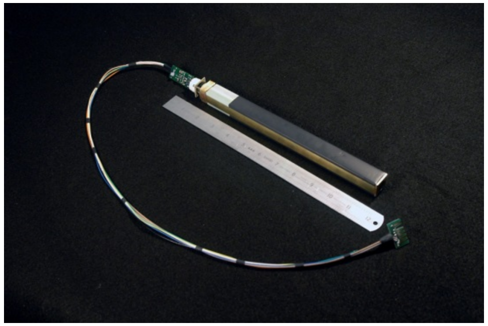
Target installed in Hall B beam line, May 2016

Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2)
  - 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors
  - 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
  - 2 x 2 $PbWO_4$ modules removed in middle for beam passage
  - 5.5 m from H_2 target (~0.5 sr acceptance)

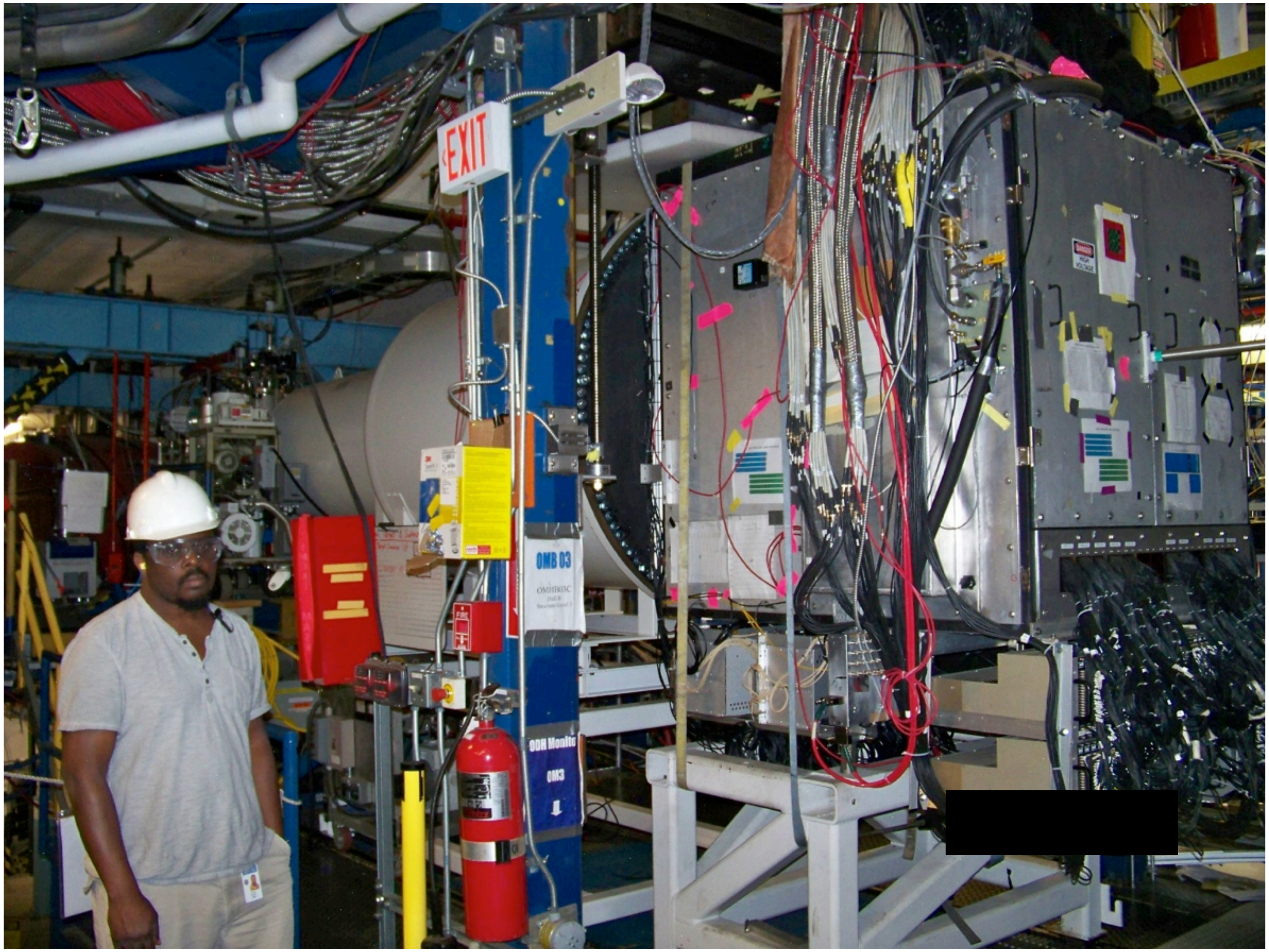
- Resolutions:
  - for $PbWO_4$ shower detectors:
    - ✓ energy: $\sigma/E = 2.6\ \%/\sqrt{E}$
    - ✓ position: $\sigma_{xy} = 2.5\ \text{mm}/\sqrt{E}$
  - for Pb-glass shower detectors factor of ~2.5 worse





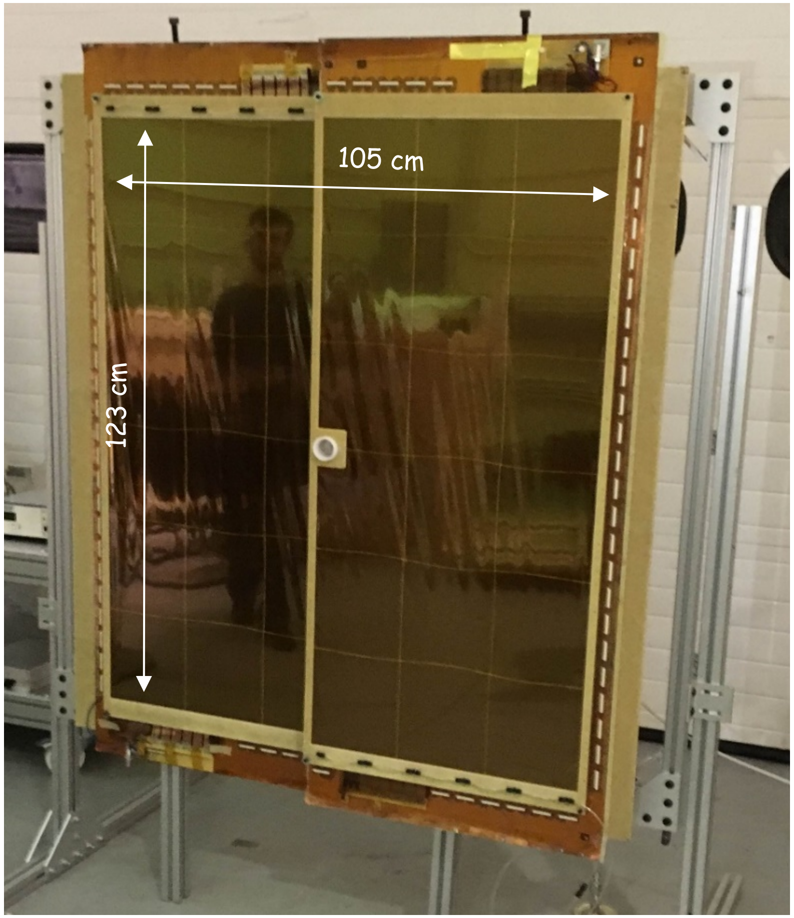
PbWO4 crystal cell

Electromagnetic Calorimeter in Hall B beam Line



GEM Coordinate Detectors

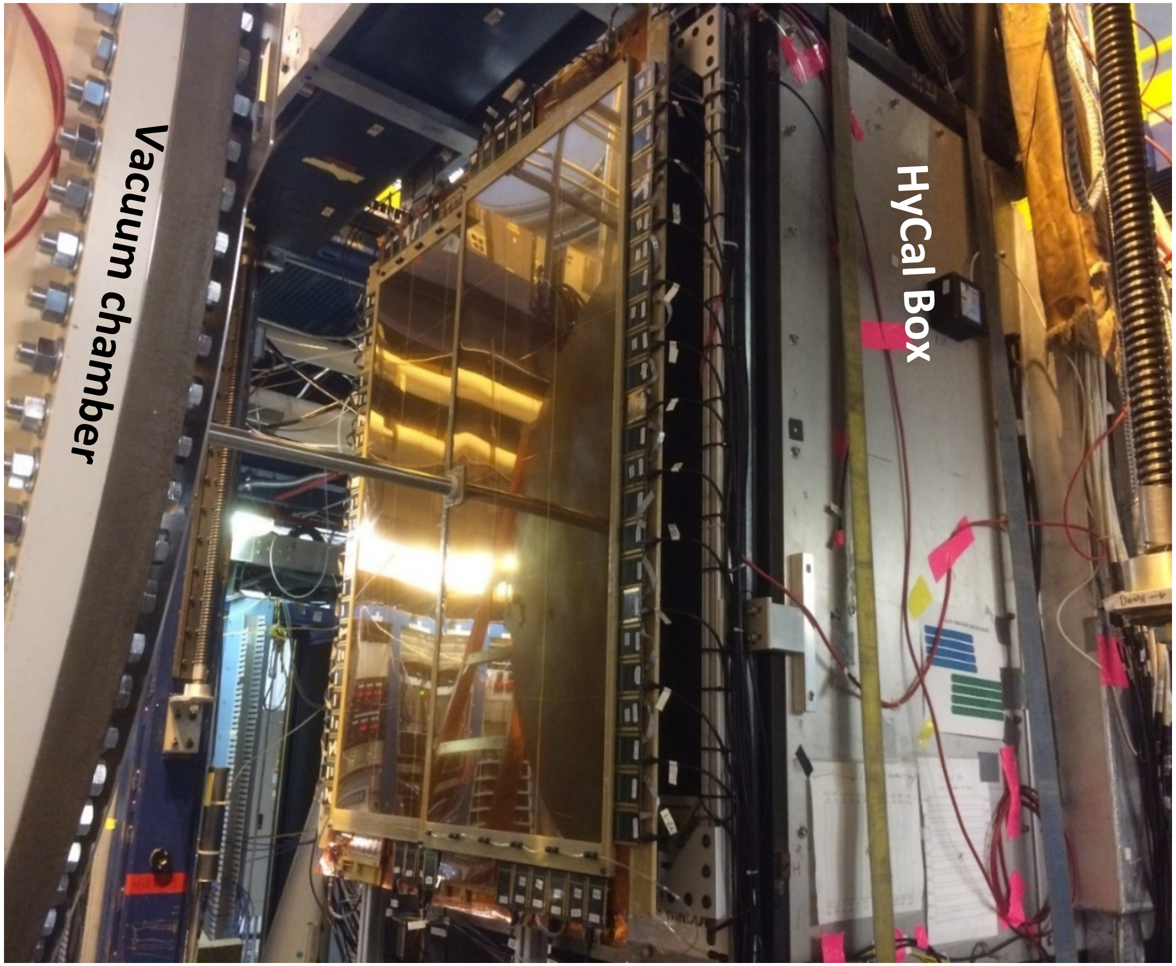
- Tasks for GEM:
  - factor of >20 improvements in coordinate resolutions
  - similar improvements in Q^2 resolution (very important)
  - unbiased coordinate reconstruction (including HyCal transition region)
  - increase Q^2 range by including HyCal Pb-glass part



- Designed and built at University of Virginia (UVa)

- Two large size GEM X and Y- coordinate detectors with 100 μm position resolution

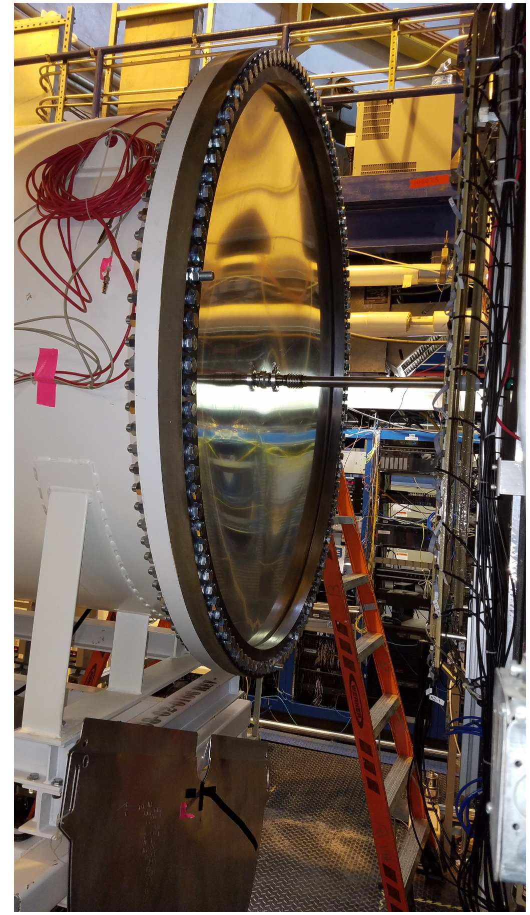
GEM Coordinate Detectors in Hall B Beam Line



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

Vacuum Box

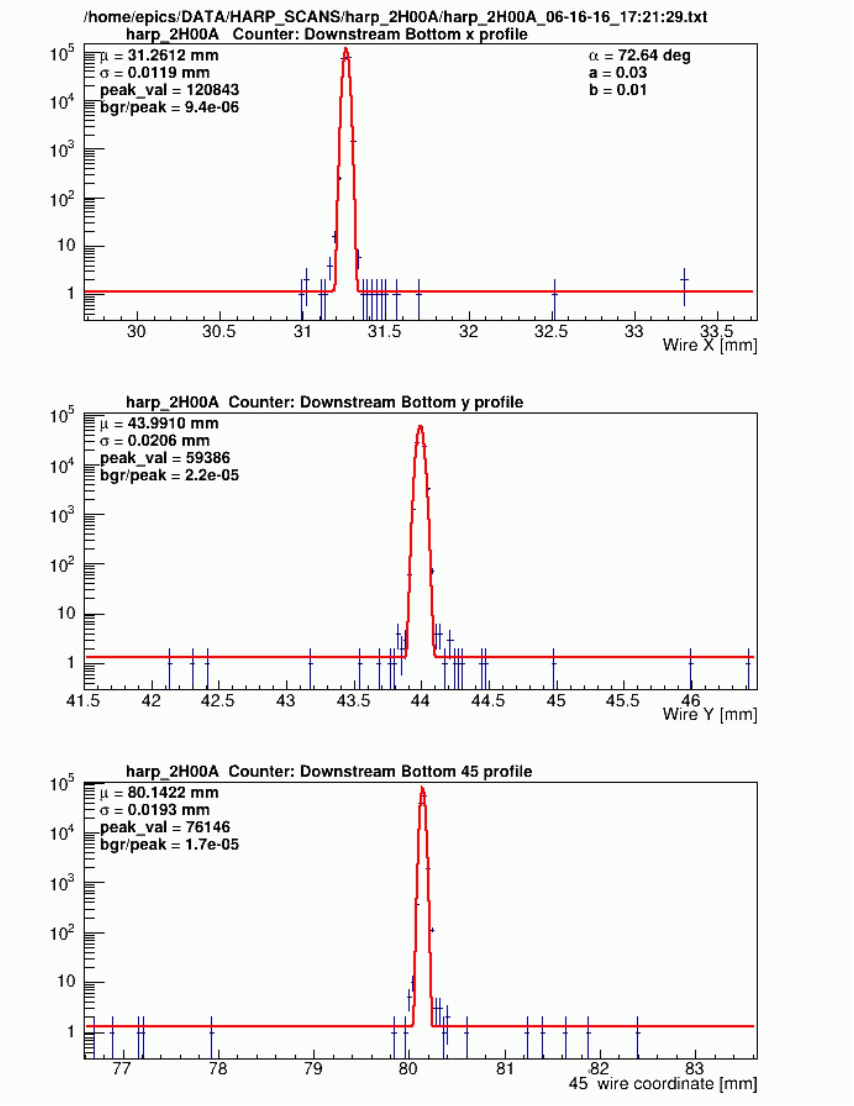
2-stage vacuum box in Hall B beam line



1.7 m diameter, 2 mm Al vacuum window

The CEBAF Electron Beam at JLab
(beam profile at the target)

- Done by "harp" scan before the target; typical size: 20 μm



Experimental Data Collected
(May/June 2016 Run)

- with E_e = 1.1 GeV beam:

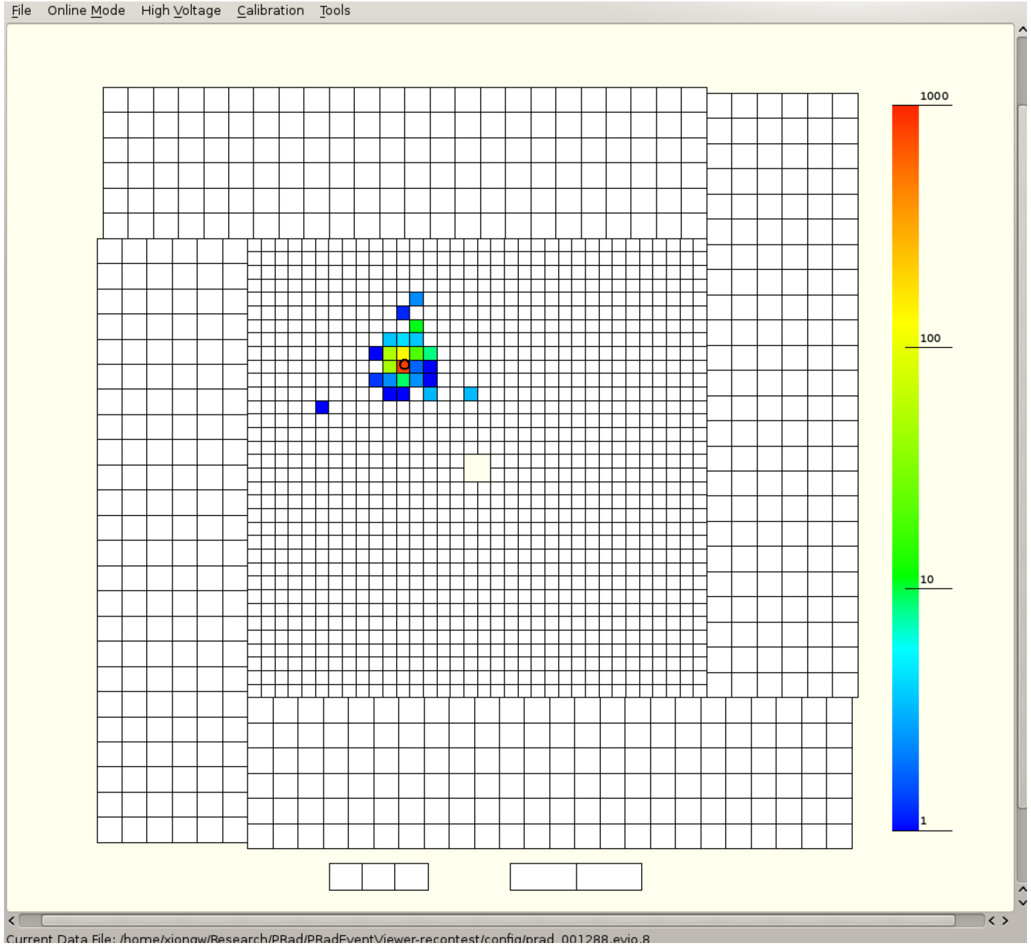
  - ✓ 4.2 mC (target areal density: $2x10^{+18}$ H atoms/cm^2)
  - ✓ 604 M events with target;
  - ✓ 53 M events with “empty” target;
  - ✓ 25 M events with ^{12}C target for calibration.

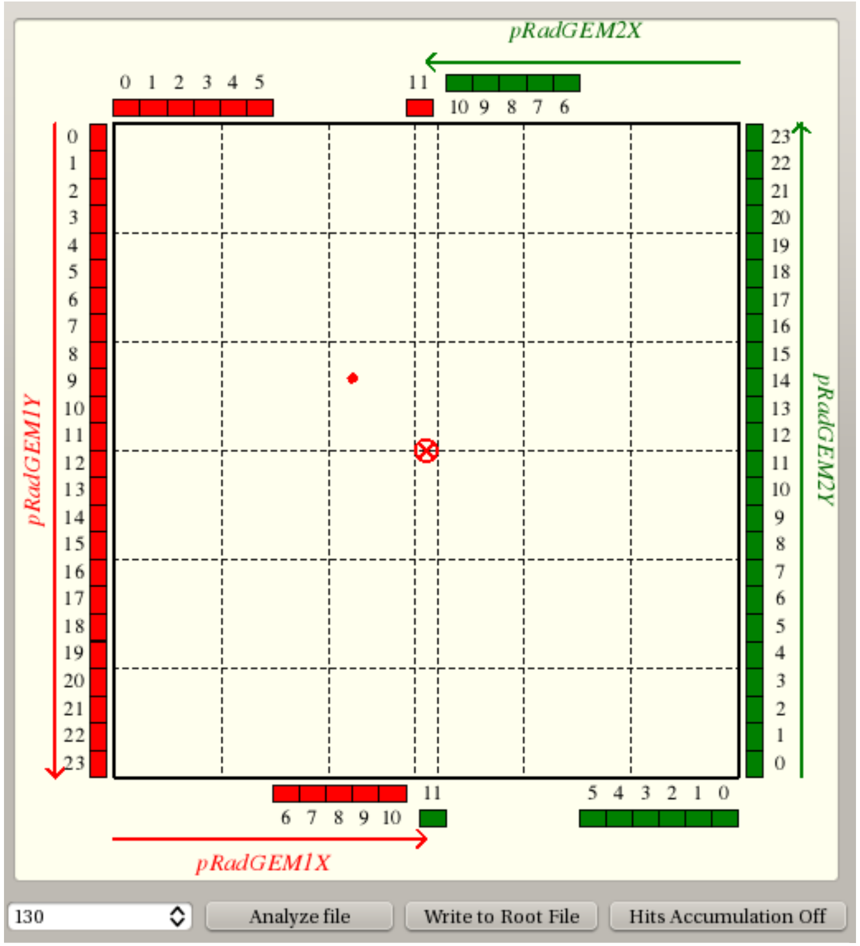
- with E_e = 2.2 GeV beam:

  - ✓ 14.3 mC (target areal density: $2x10^{+18}$ H atoms/cm^2)
  - ✓ 756 M events with target;
  - ✓ 38 M events with “empty” target;
  - ✓ 10.5 M events with ^{12}C target for calibration.

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

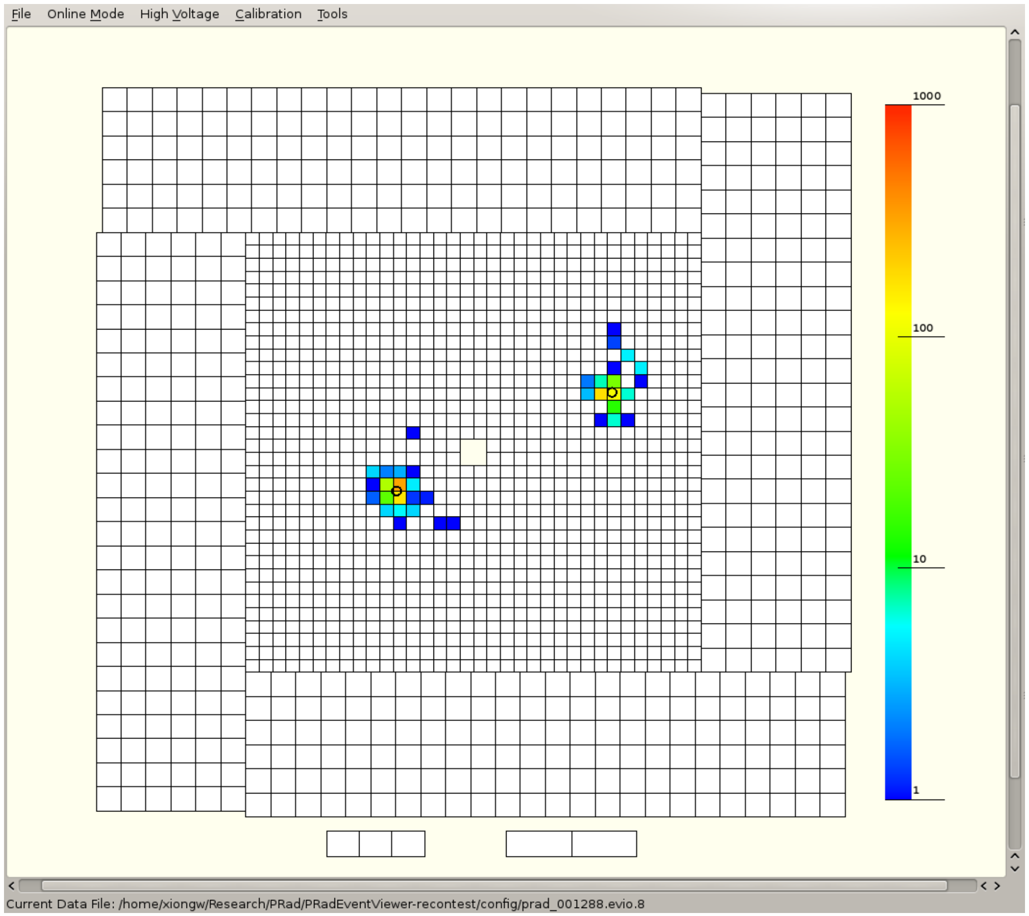
- $ep \longrightarrow ep$ event candidate

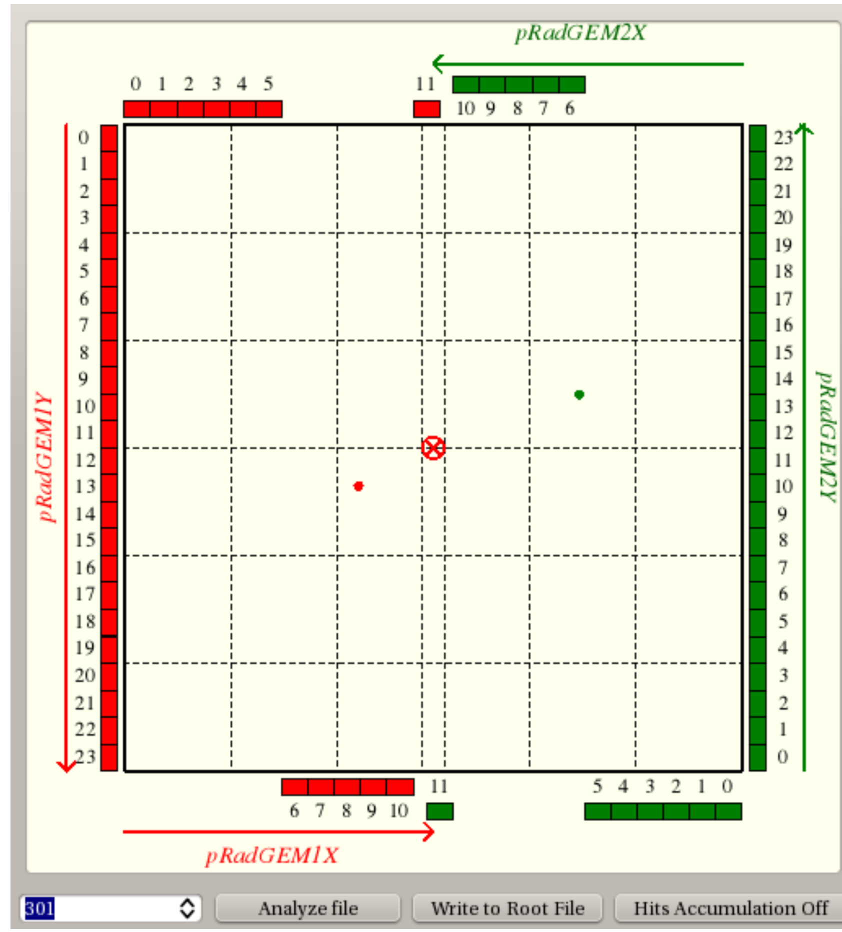




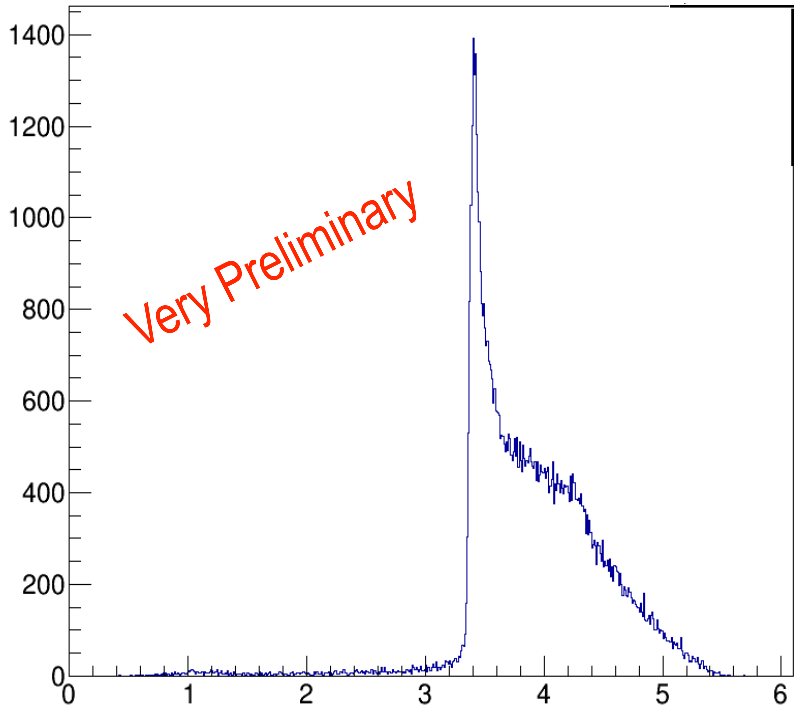
Fresh Results from On-Line Analysis
(HyCal-GEM double-cluster event matching)

- $ee \longrightarrow ee$ event candidate

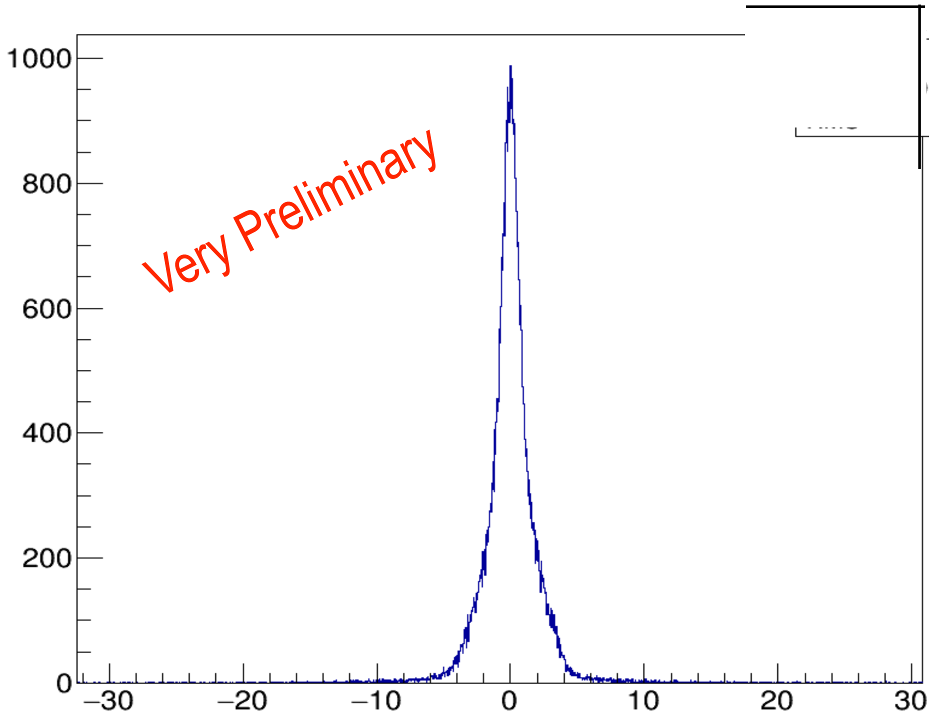




Fresh Results from On-Line Analysis
(clear signature of Moller events)



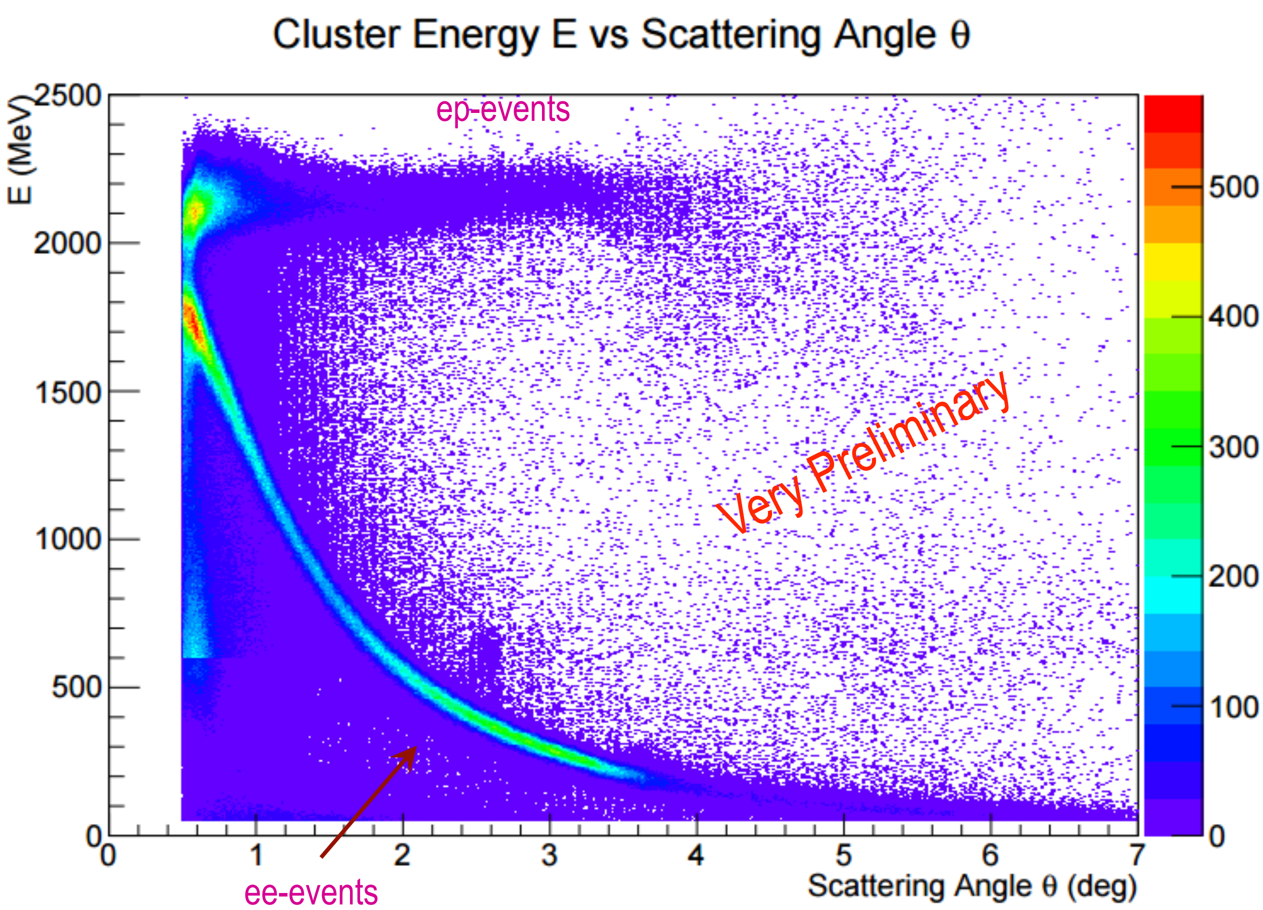
Møller opening angle (deg)



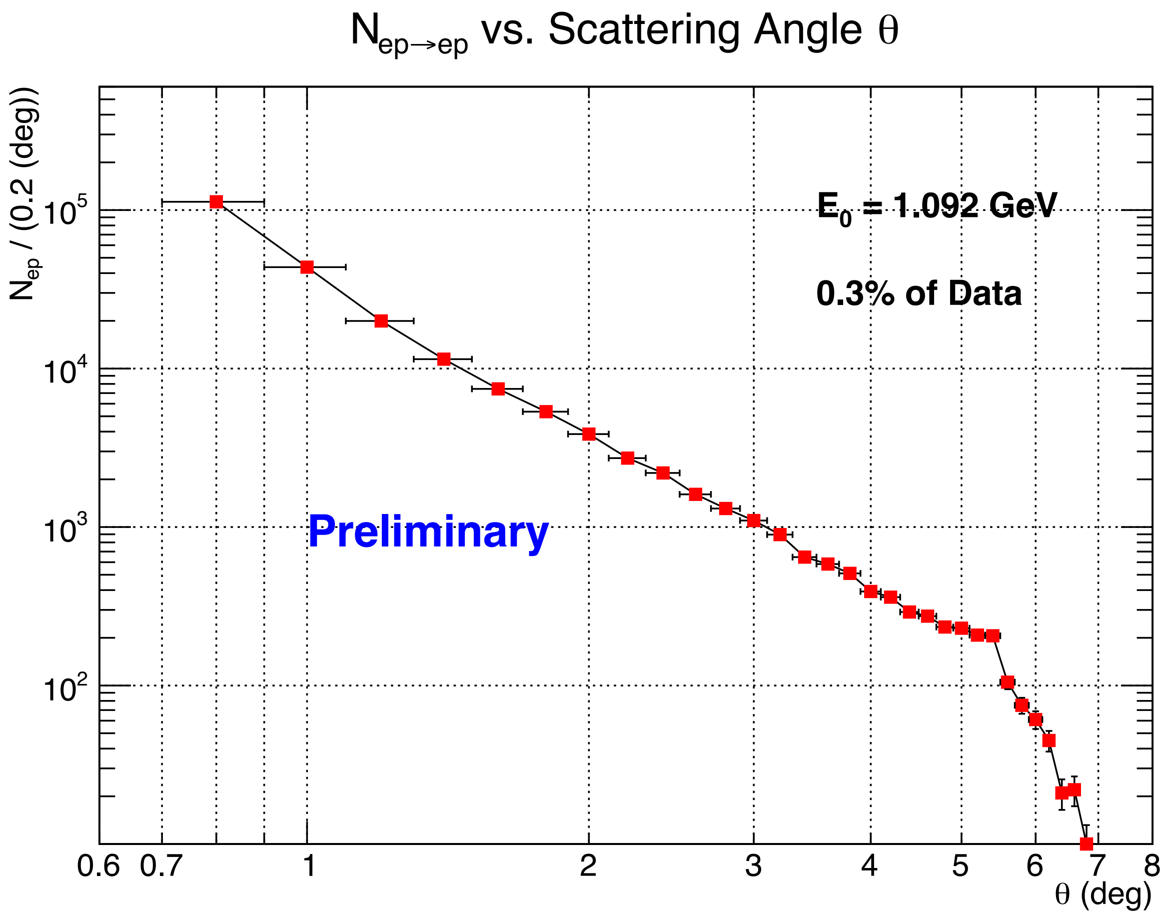
Møller Δφ (deg)

Fresh Results from On-Line Analysis
(2D distribution of cluster energy vs. scattering angle)

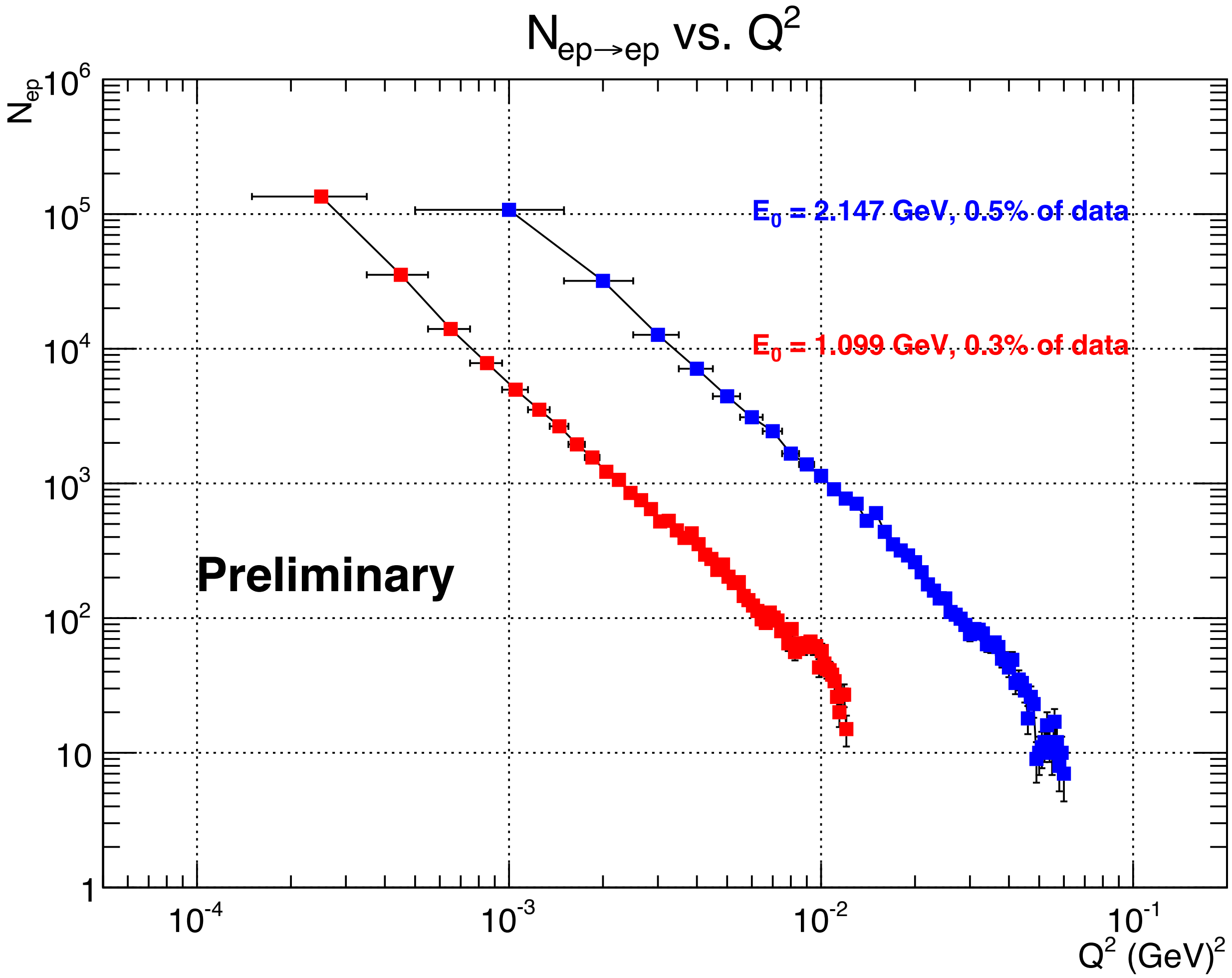
$E_0 = 2.2$ GeV



Fresh Results from On-Line Analysis



Fresh Results from On-Line Analysis



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

Summary

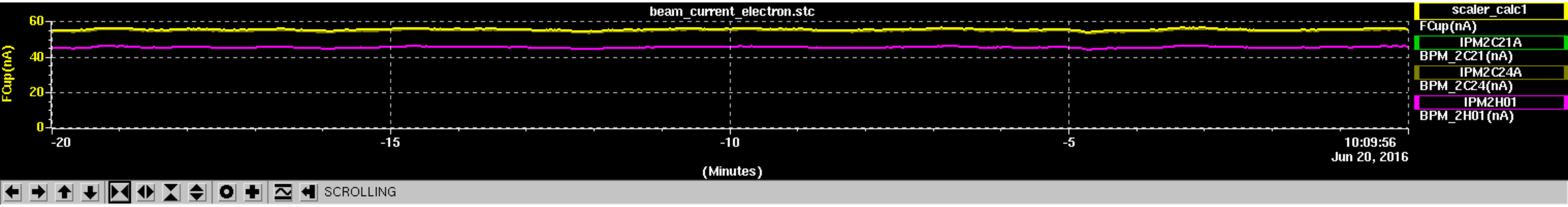
- PRad was uniquely designed to address the "*Proton Radius Puzzle*"
- Experiment had been performed in May/June of 2016
- Large statistics, high quality, rich data have been collected:
  - ✓ Lowest Q^2 data set ($\sim 10^{-4}$ GeV/C^2) has been collected for the first time in ep-scattering experiments;
  - ✓ Simultaneous measurement of Moller and Mott scattering processes has been demonstrated to control systematic uncertainties.
- 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

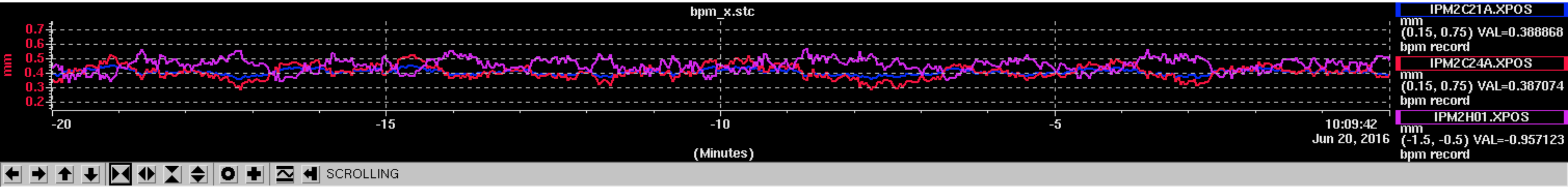
The End

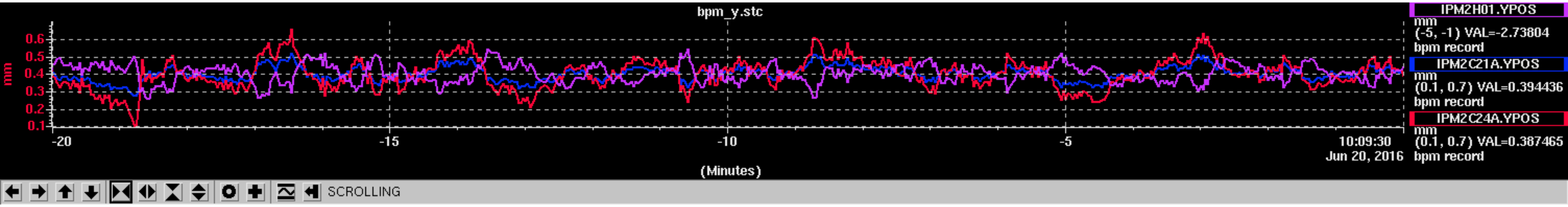
The CEBAF Electron Beam at JLab

- Beam current monitoring (55 nA)



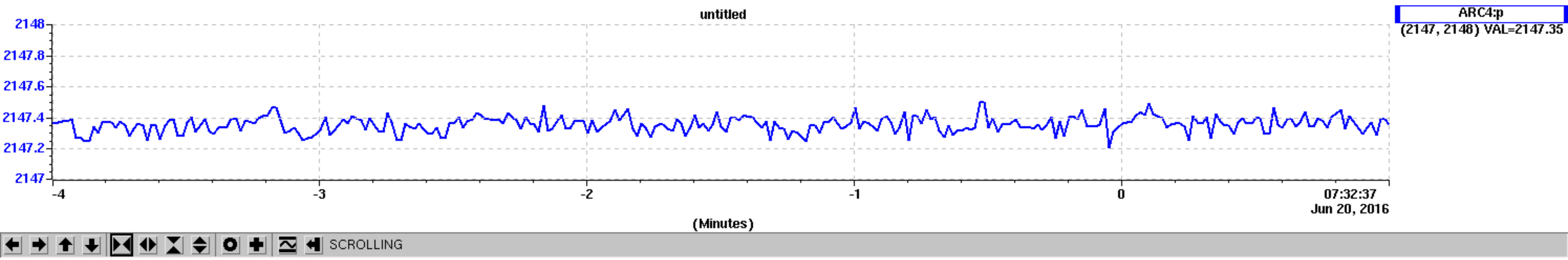
- X and Y position stability (± 0.1 mm)





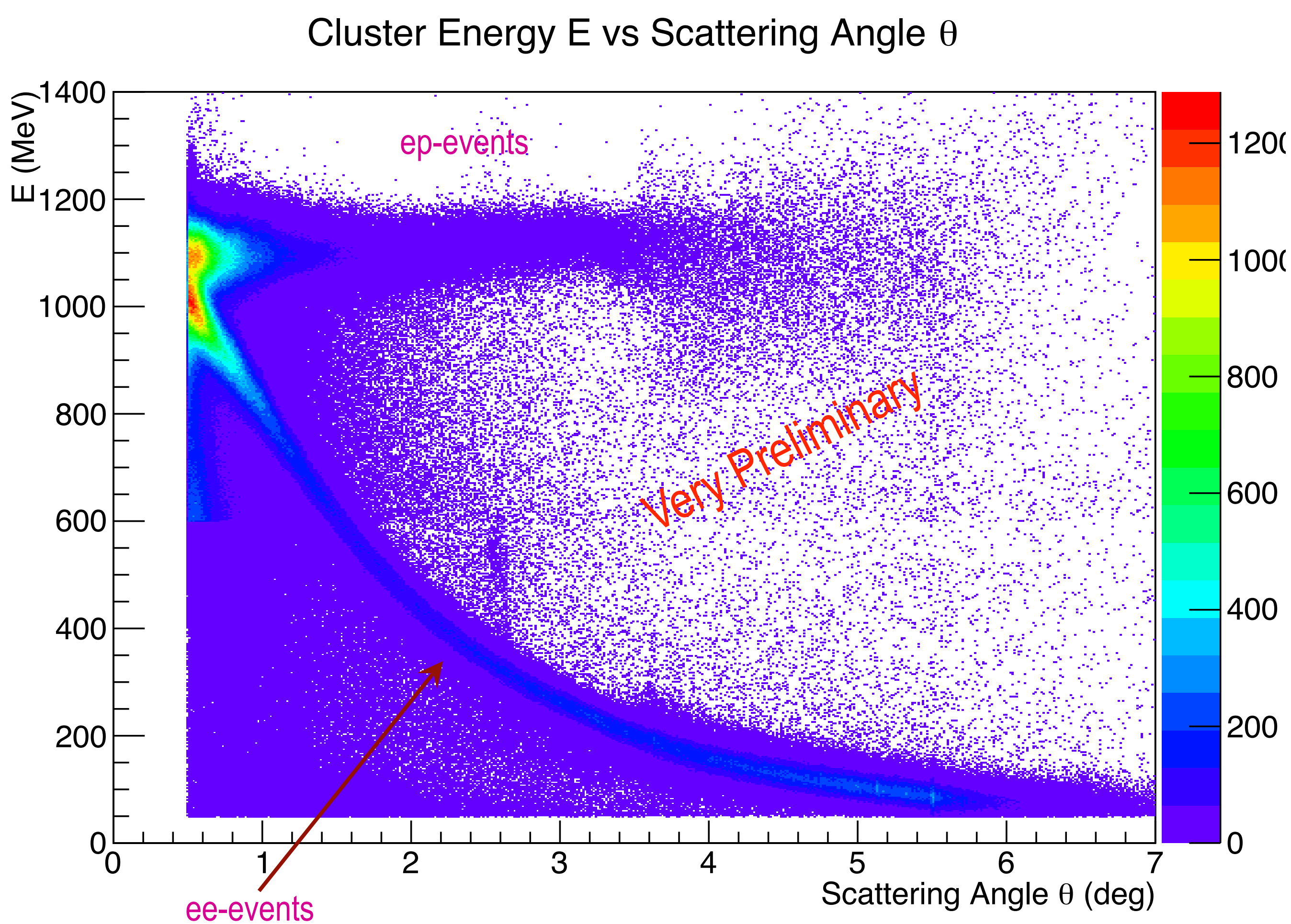
The CEBAF Electron Beam at JLab
(energy stability)

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

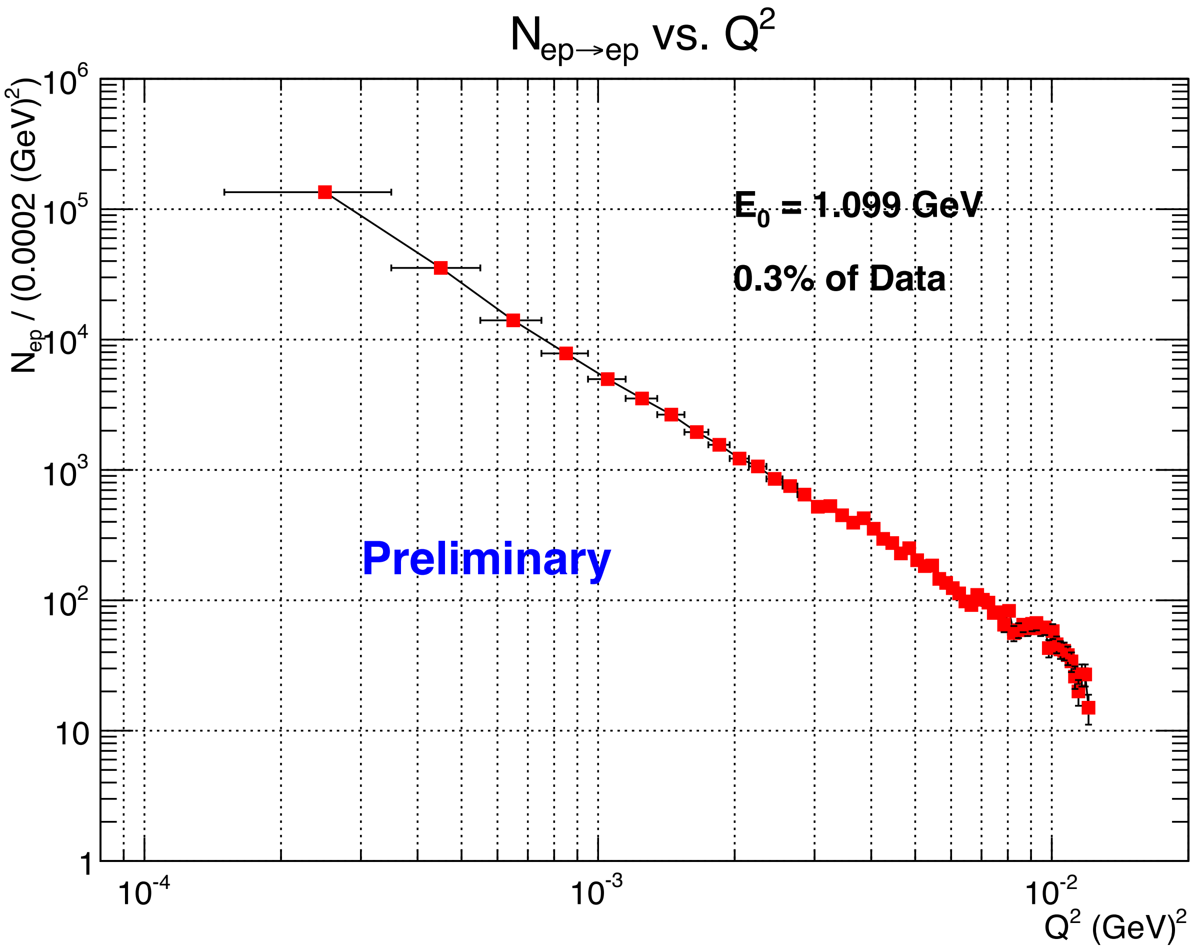


Fresh Results from On-Line Analysis
(2D distribution of cluster energy vs. scattering angle)

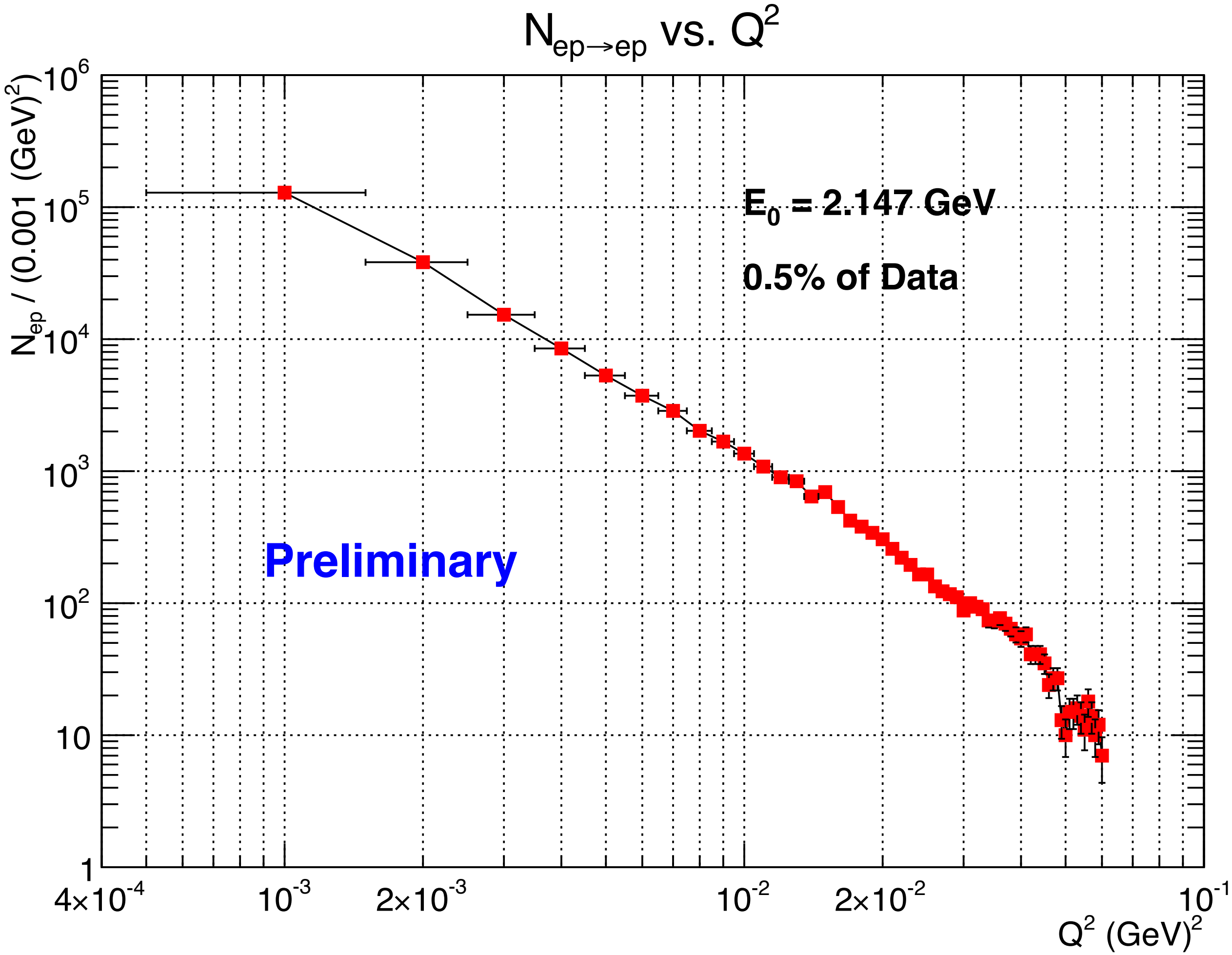
E_0 = 1.1 GeV



Fresh Results from On-Line Analysis



Fresh Results from On-Line Analysis

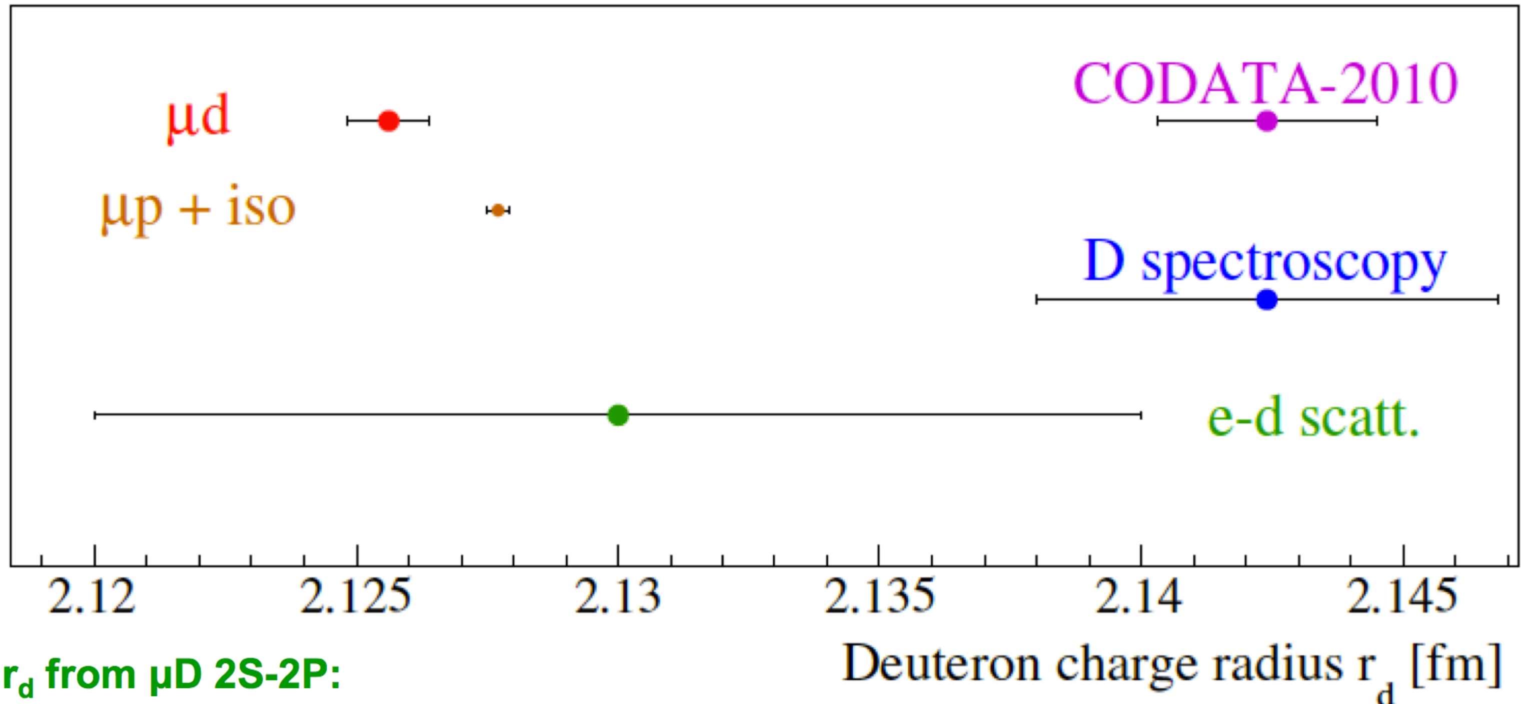


Estimated Uncertainties

Contributions	Estimated Error (%)
Statistical error	0.2
Acceptance (including Q^2 determination)	0.4
Detection efficiency	0.1
Radiative corrections	0.3
Background and PID	0.1
Fitting error	0.2
Total Error	0.6%

- Estimated error budget (added quadratically)

Muonic Deuterium



r_d from μD 2S-2P:
J. Krauth, PSAS2016
+ PRP2016 (Trento), submitted

Theory: J. Krauth et al., Ann. of Phys. 366, 168 (2016)
arXiv:1506.01298v2 [physics.atom-ph]

There is a deuteron radius puzzle:
7.5 σ between r_d (μD) and CODATA-2010