Proton Charge Radius (PRad) Experiment at Jefferson Lab

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For the PRad Collaboration

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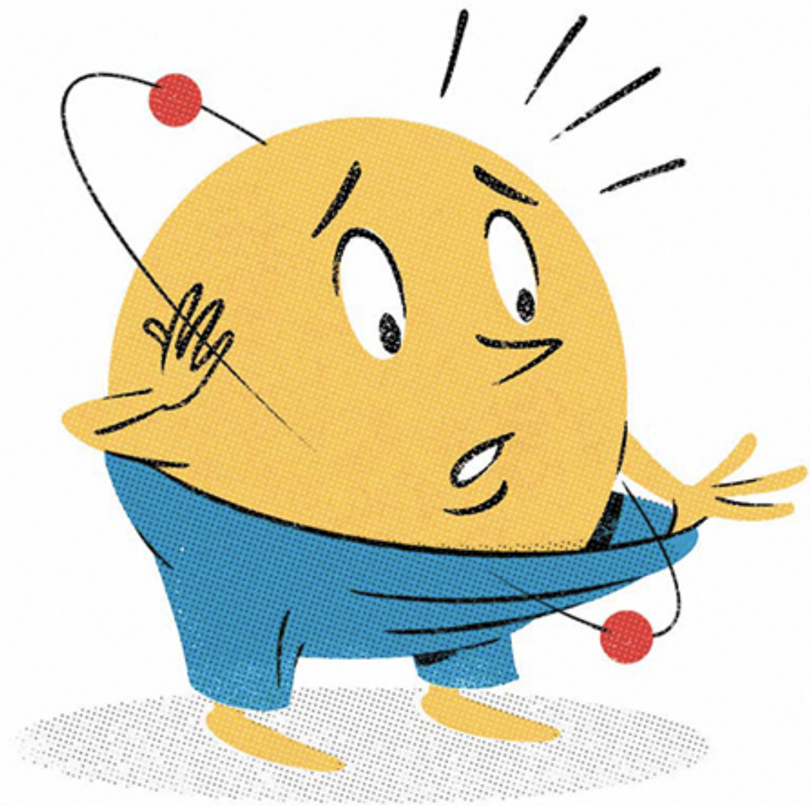
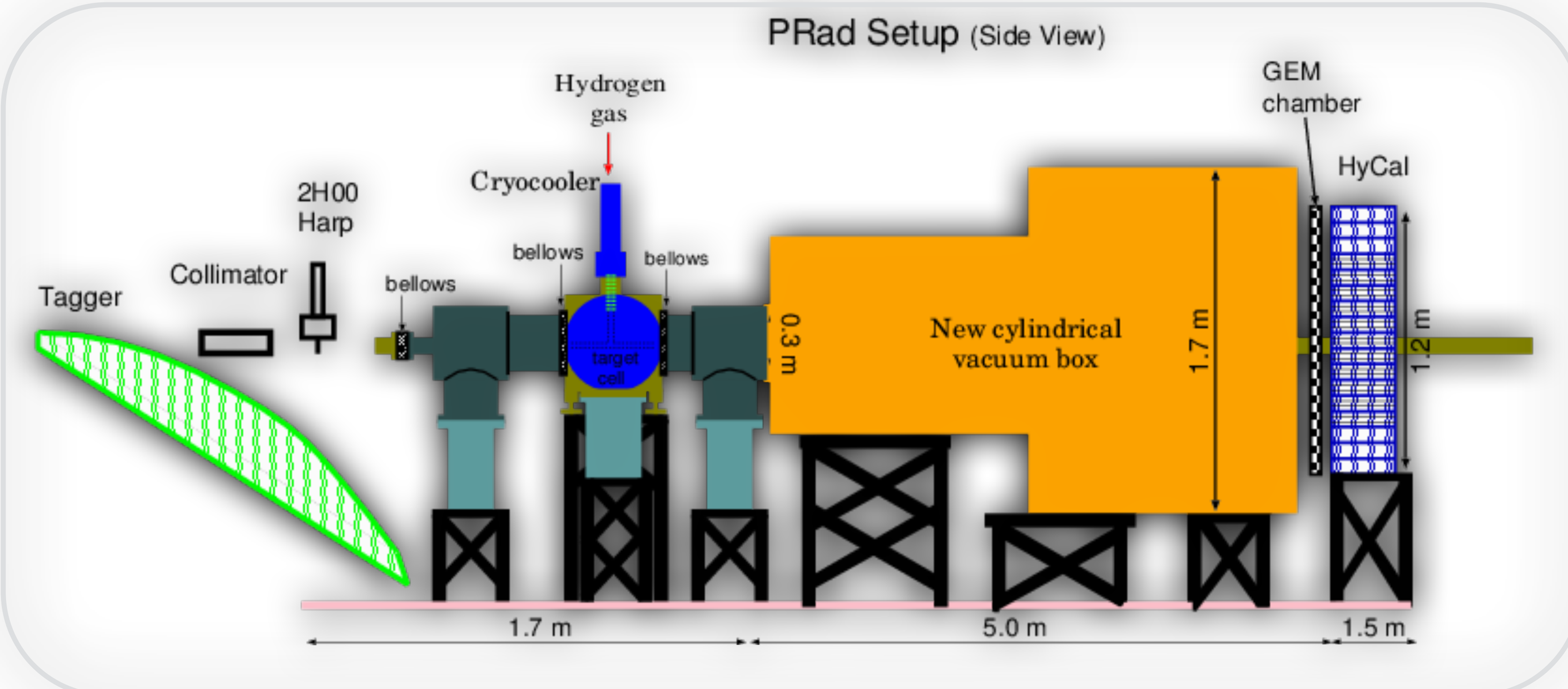
Outline

- PRad experiment
  - Determine proton charge radius with sub-percent precision
- PRad experimental apparatus
- Collected data
- Preliminary online analysis results

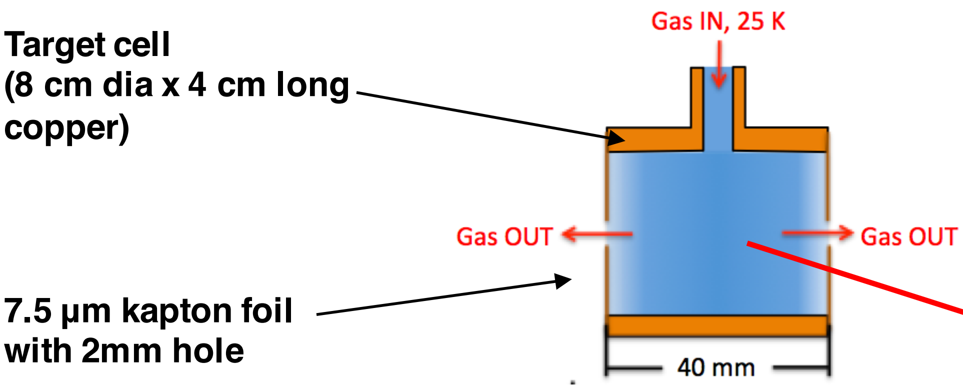


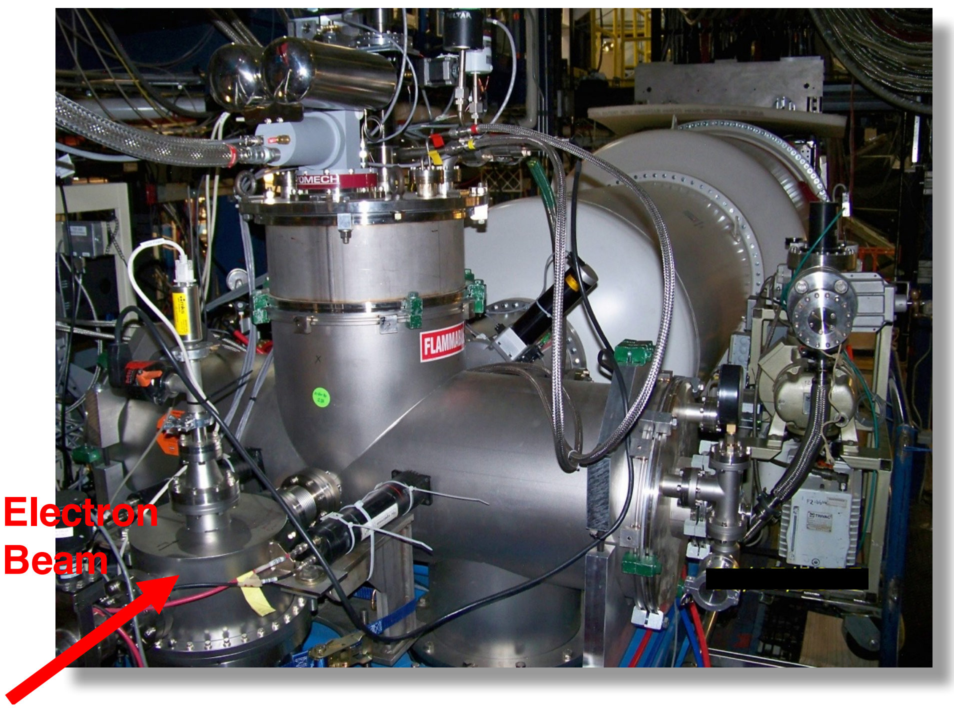
PRad Experimental Apparatus

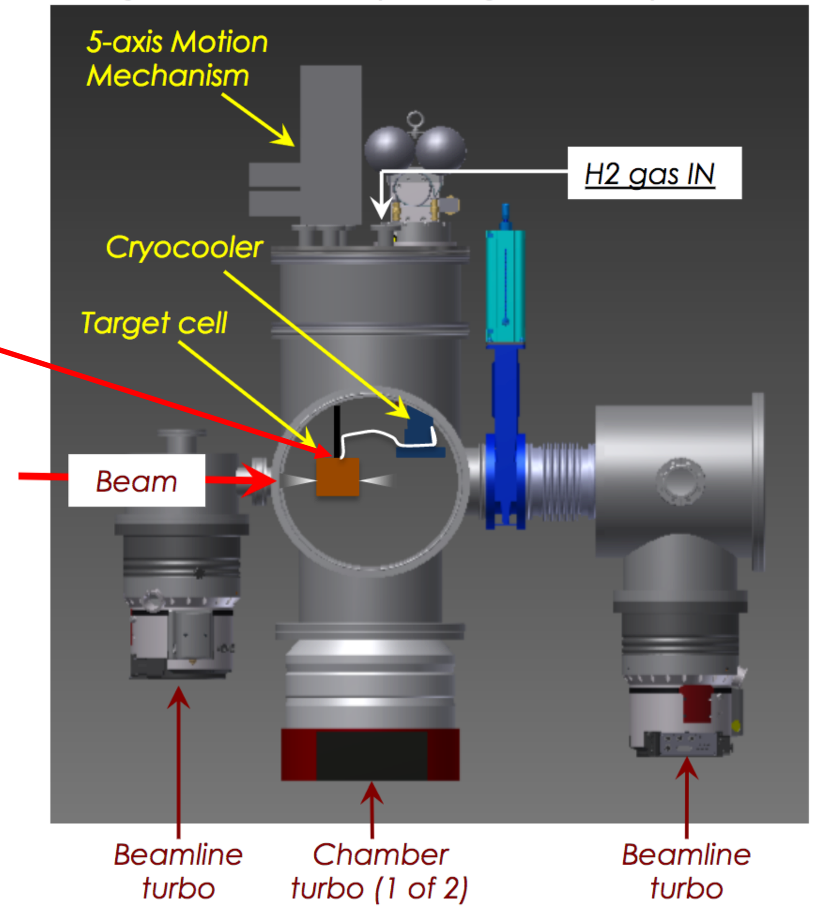


- Windowless, high density H_2 gas flow target (background control)
- Vacuum box, one thin window at downstream
- High resolution and high efficiency, Hybrid calorimeter (HyCal)
- Two large area Gas Electron Multipliers, improve position resolution

Windowless Gas Target



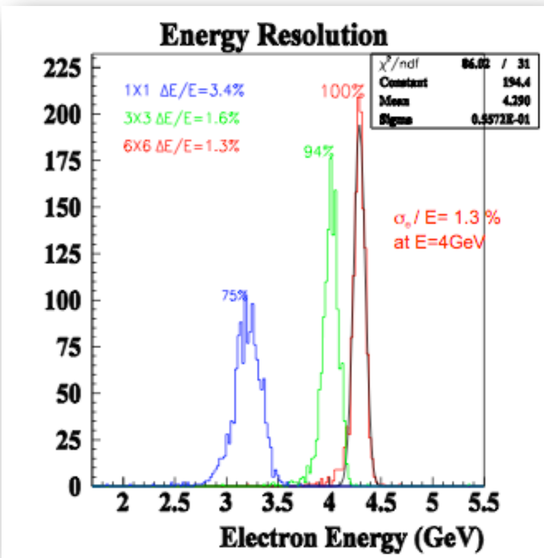


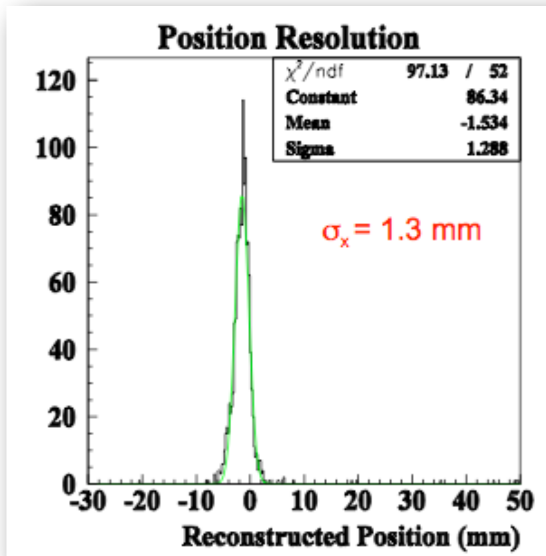


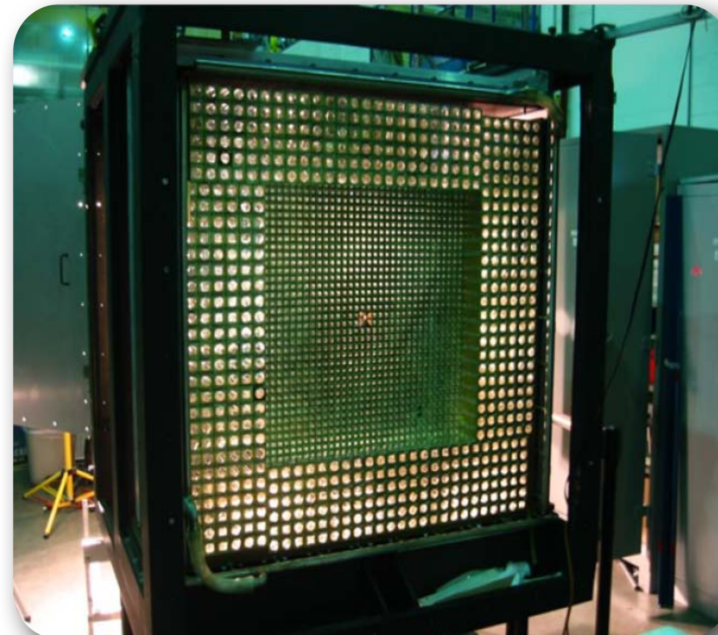
Areal density: ~2 x 10^{18} H atoms / cm^2
Cell / chamber / vacuum tank pressure:
470 mtorr / 2.3 mtorr / 0.3 mtorr

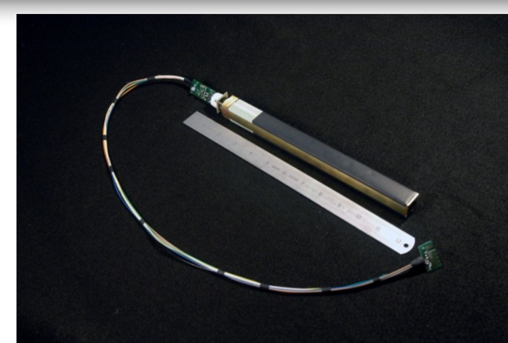
Hybrid Calorimeter (HyCal)

- Used in the PrimEx experiment
- $PbWO_4$ and Pb-glass calorimeter (118x118 cm^2)
- 576 Pb-glass modules (3.82x3.82 cm^2 x45 cm)
- 1152 $PbWO_4$ modules (2.05x2.05 cm^2 x18 cm)
- 5.8 m from the target
- Polar angle coverage: ~ 0.5˚ to 7.5˚
- Azimuthal angle coverage: 2π









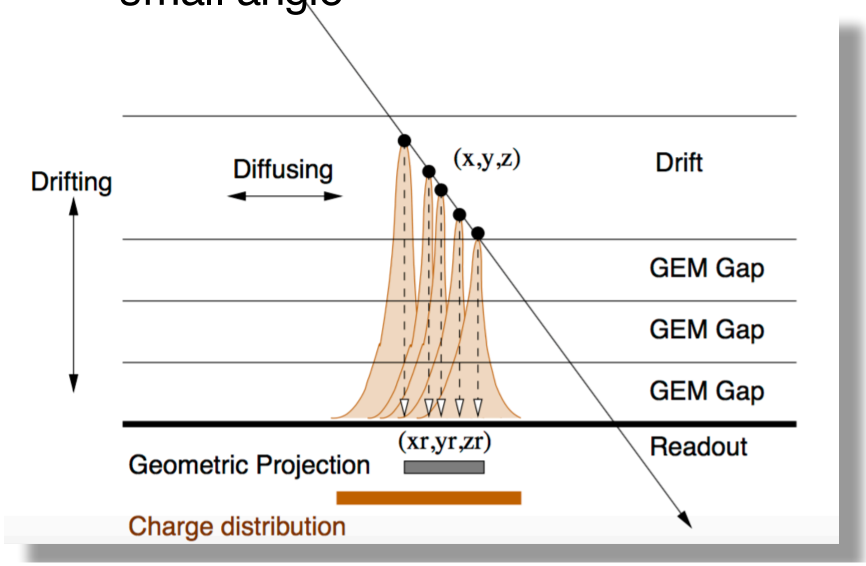
$PbWO_4$ resolution:
$\sigma_E/E = 2.6\%/\sqrt{E}$
$\sigma_{xy} = 2.6\ mm/\sqrt{E}$

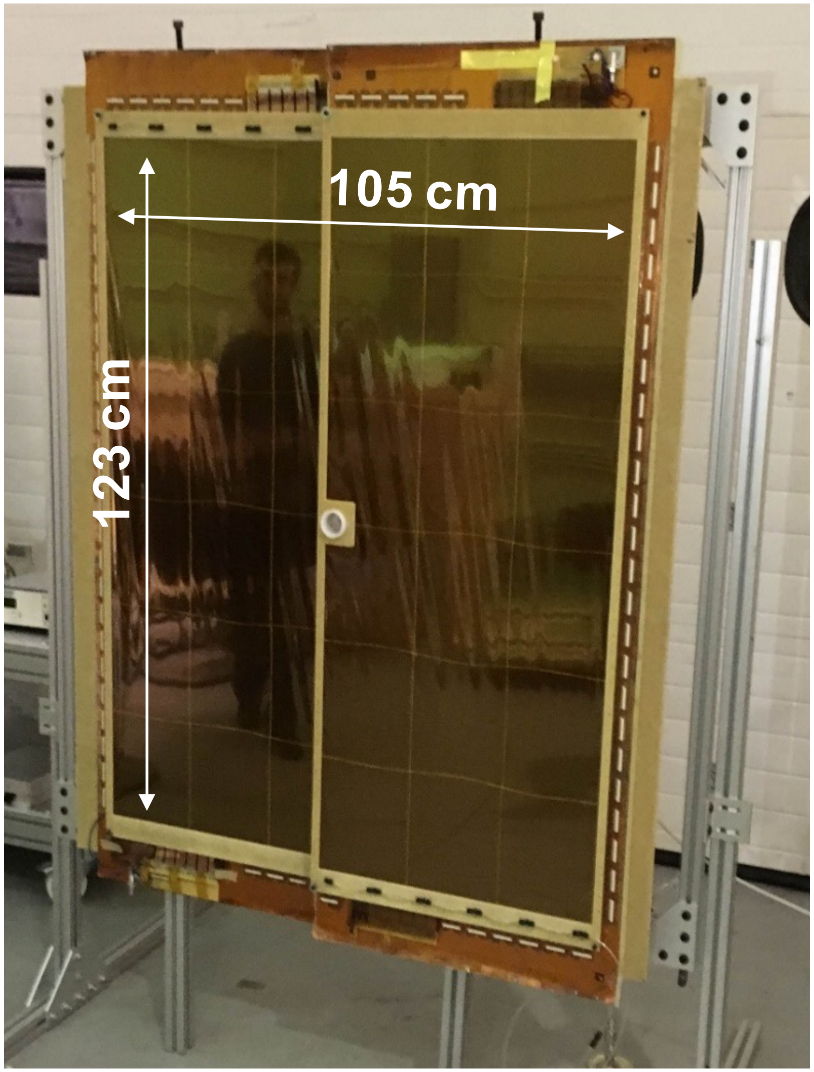
Pb-glass:
2.5 times worse

Gas Electron Multipliers (GEM)

- Two large area GEM detectors with 2D Cartesian readout planes
- ~100 μm 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

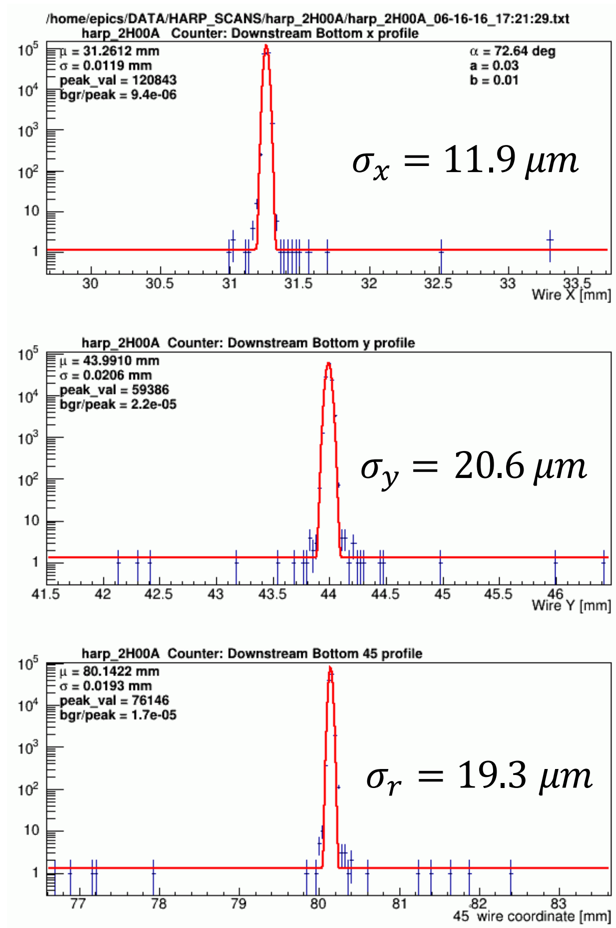
Experimental Data Collected

- Experiment ran in May - June 2016
- Large amount of data taken with high quality and stable electron beam from CEBAF
  - Beam position stability: ~250 µm
  - Beam width: ~ 25 µm

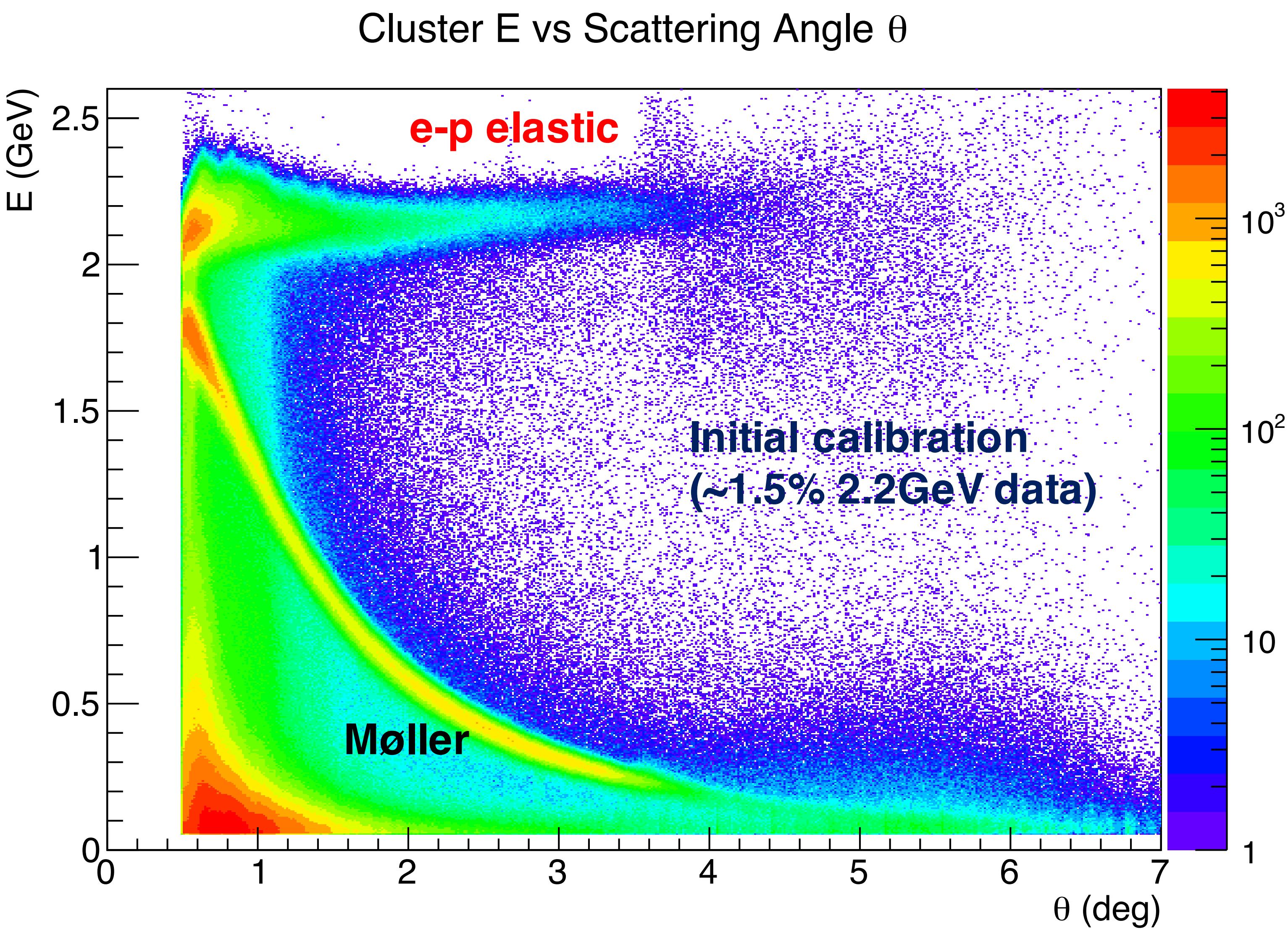
- Data taking with 1.1 GeV beam:
  - 604 M events with H_2 in cell
  - 53 M events without H_2 in cell
  - 25 M events with 1µm carbon foil target
  - Collected 4.2 mC on target (2x10^{18} H atoms/cm^2)

- 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 1µm carbon foil target
  - Collected 14.3 mC on target (2x10^{18} H atoms/cm^2)

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



Preliminary Online Analysis Results



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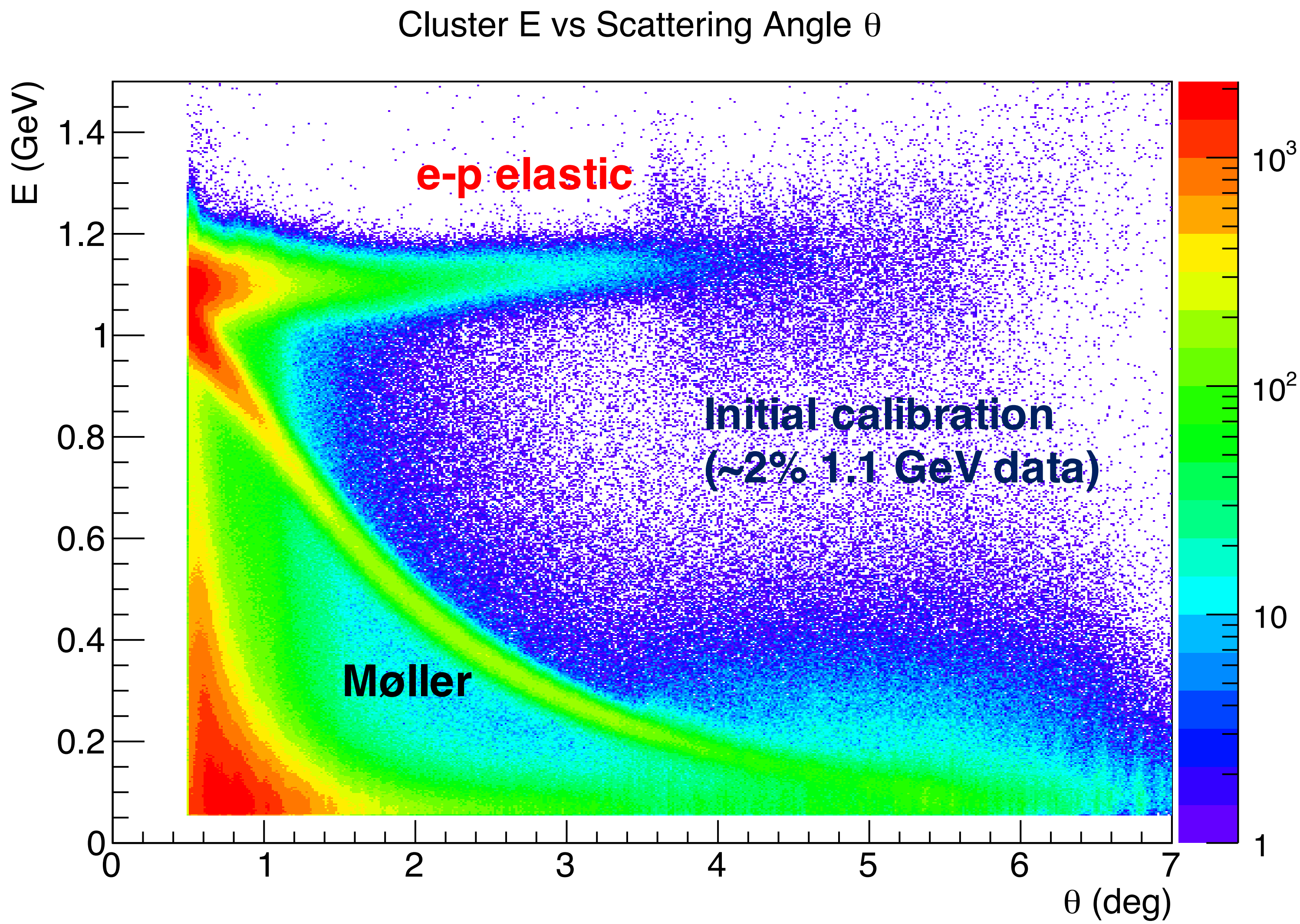

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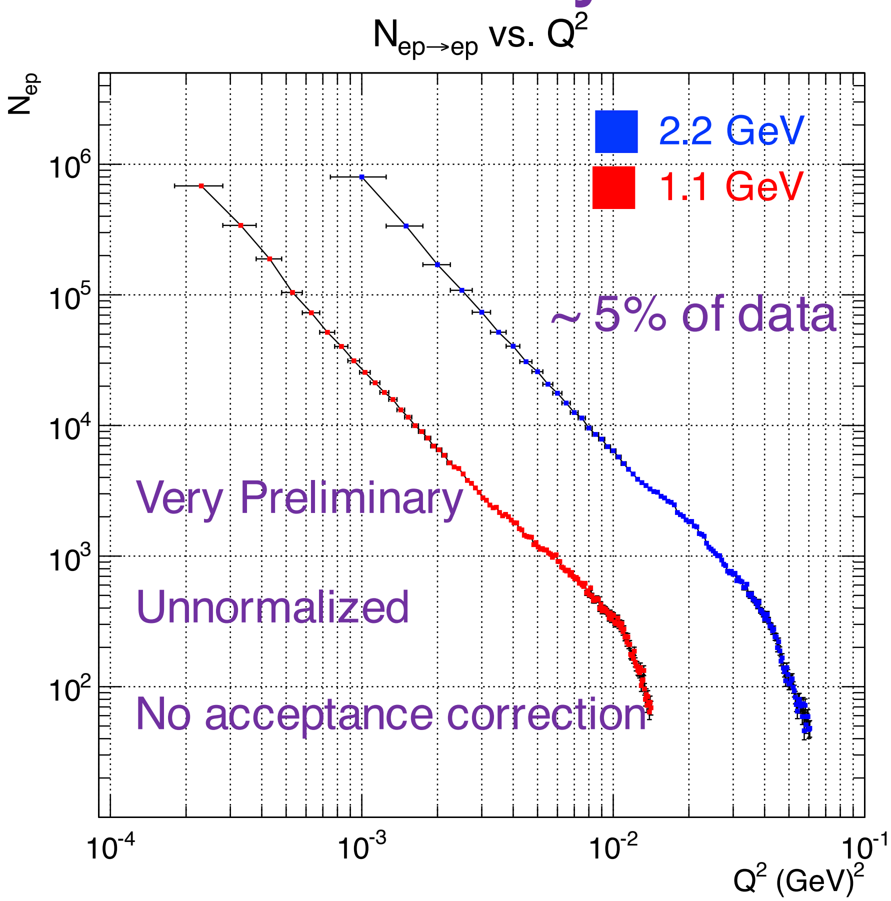

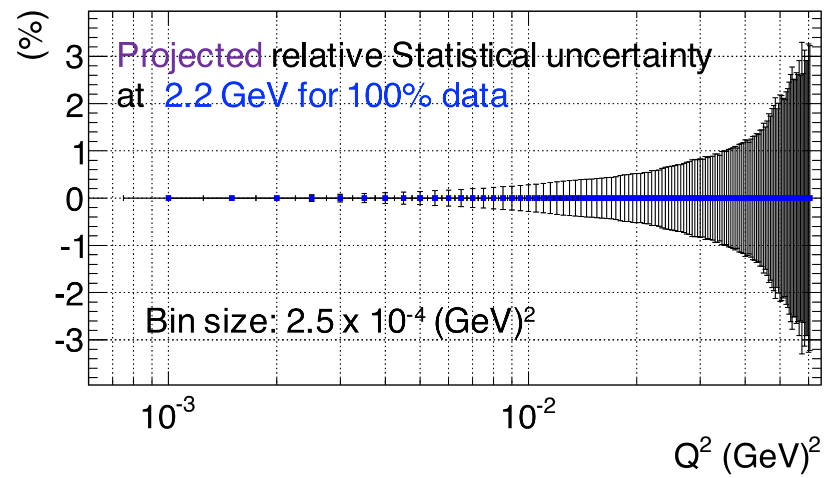

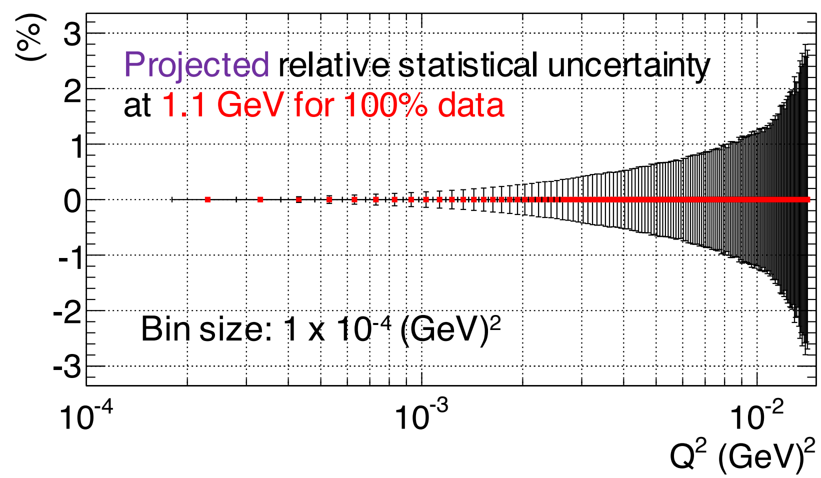

- Good Q^2 resolution and large statistics at low Q^2 will allow finer binning

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 (~2×10^{-4} GeV^2) has been collected for the first time in ep elastic scattering experiment
  - Data in a large Q^2 range (~2×10^{-4} – 6×10^{-2} GeV^2) 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

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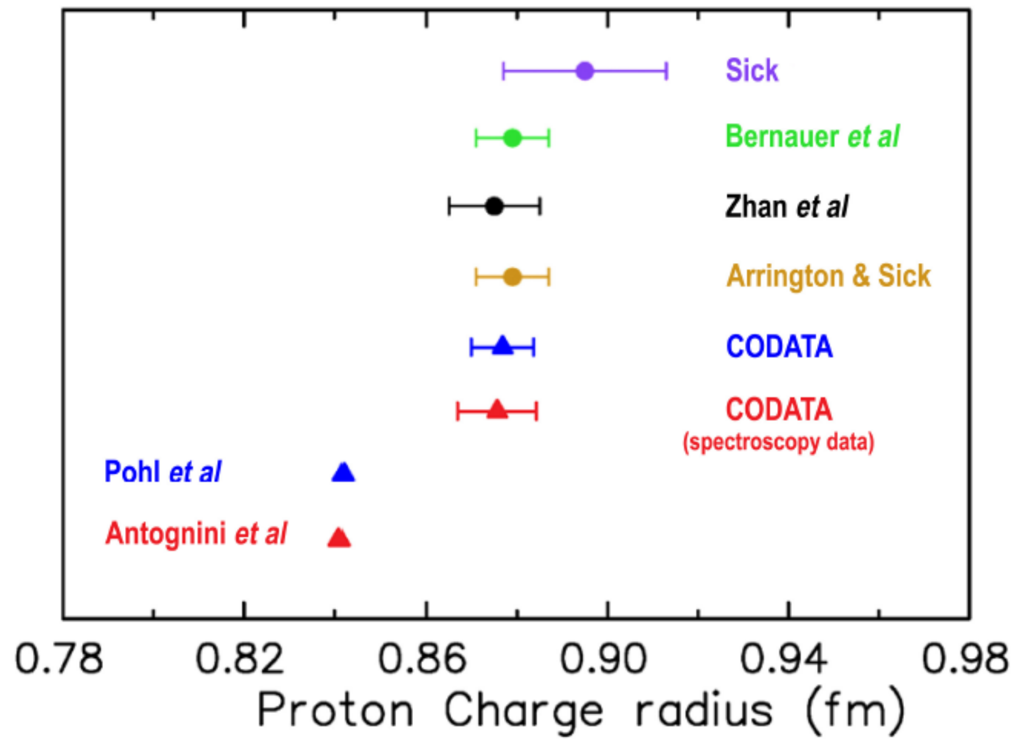
Backup

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):

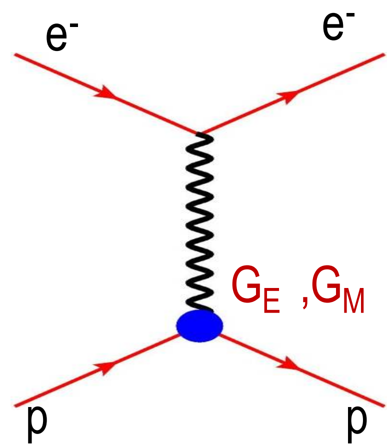
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2) \right)$$

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

- Structure-less 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 can be extracted using Rosenbluth separation
- For PRad, cross section dominated by G_E



Taylor expansion of G_E at low Q^2

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

Derivative at low Q^2 limit

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

PRad Experiment Overview

- PRad goal: Measuring proton charge radius using ep elastic scattering

- Unprecedented low Q^2 (~$2x10^{-4}$ GeV^2)
  - Fill in very low Q^2 region
- Large Q^2 range in a single setting
  - ~$2x10^{-4}$ - $6x10^{-2}$ 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