The PRad Experiment

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Outline

The Proton Radius Puzzle

PRad Setup

Detectors Performance

Analysis

Summary

Outline

The Proton Radius Puzzle

- Different Methods of Measurement
- Elastic *ep* Scattering
- New Experiment Needed

PRad Setup

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Measurements of Form Factors

- First measurement at SLAC in 1961 through *ep* scattering
- 60 years of measurements, 4 possible different methods

Atomic Hydrogen Spectroscopy

Lamb shift measurements by MPQ and LKB

***ep* Scattering**

CODATA

Muonic Hydrogen Spectroscopy

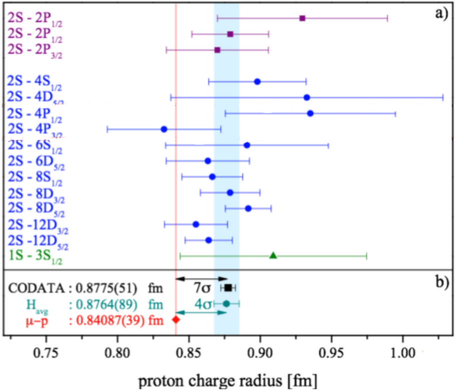
Lamb shift measurements by CREMA

μp Scattering

Future experiment MUSE

Spectroscopy Results

- Lamb shift measurements

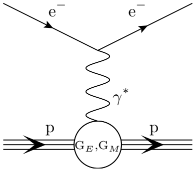


- atomic hydrogen spectroscopy results compatible with CODATA
- muonic hydrogen spectroscopy results at 0.84 fm

Elastic *ep* Scattering

- Elastic cross-section in the liit of the first Born approximation:

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



with:

$$Q^2 = 4EE' sin^2\theta/2 \quad \tau = \frac{Q^2}{4M_p^2} \quad \epsilon = 1/(1+2(1+\tau)tan^2\theta/2)$$

- Sructureless proton:

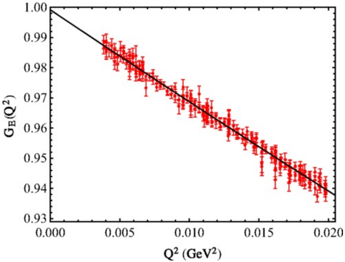
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2(1-\beta^2 sin^2\theta/2)}{4k^2 sin^4\theta/2}$$

- G_E can be expressed using a Taylor expansion at low Q^2:

$$G_E = 1 - \frac{Q^2}{6} < r^2 > + \frac{Q^4}{120} < r^4 > + ...$$

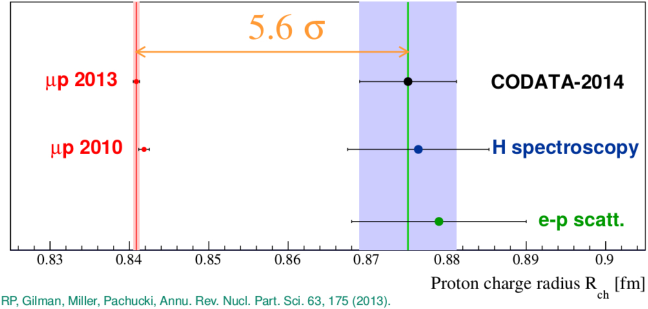
which gives:

$$< r^2 > = -6 \cdot \frac{dG_E^p}{dQ^2}\Big|_{Q^2=0}$$



Phys. Rev. C 93, 065207

The Proton Radius Puzzle



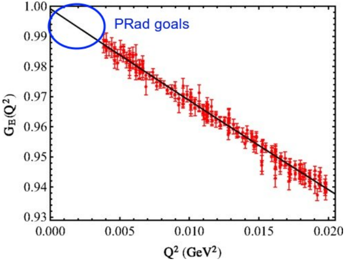
RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

$r_p(e^-) = 0.8770 \pm 0.0045 fm$ $\qquad$ $r_p(\mu^-) = 0.8409 \pm 0.0004 fm$

- Discrepancy between muonic hydrogen spectroscopy and atomic hydrogen (spectroscopy and scattering) measurements

The PRad Experiment

- Previous measurements have large systematic uncertainties and a limited coverage at small Q^2
- Requirements for PRad Experiment:
  - large Q^2 range
  - extend to very low Q^2
  - controlled systematics at sub-percent precision
- Choices:
  - Non magnetic spectrometer method
  - No target windows
  - high resolution high acceptance spectrometer
  - Normalization by Møller cross-section



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PRad Timeline

- 2011 - 2012 Initial proposal
- 2012 Approved by JLab PAC39
- 2012 Funding proposal for windowless H_2 gas flow target
- 2012 - 2015 Development, construction of the target
- 2013 Funding proposals for the GEM detectors
- 2013 - 2015 Development, construction of the GEM detectors
- 2015, 2016 Experiment readiness reviews
- January/April 2016 Beam line installation
- May 2016 Beam commissioning
- May 24 - May 31 Detectors calibration
- June 4 - June 15 1.1 GeV data taking
- June 15 - June 22 2.2 GeV data taking

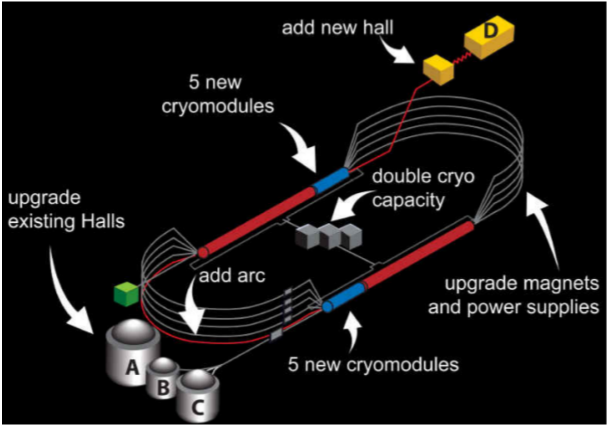
Outline

JLab Facility

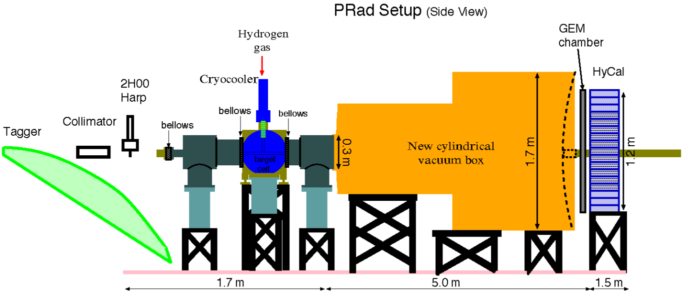
PRad was performed in Hall B at JLab

JLab 12GeV Upgrade

- First experiment finished using 12 GeV accelerator (not at full beam energy)



PRad Setup

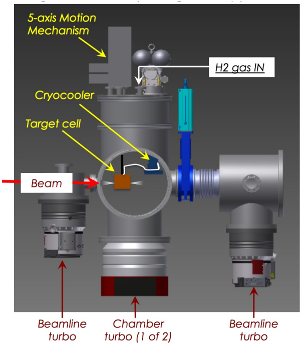


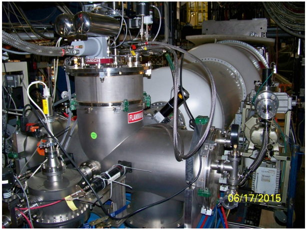
- Electron beam or tagged photon beam at ~ 1 GeV and ~ 2 GeV
- Windowless H_2 gas flow target
- Vacuum box
- GEM detectors
- Primex HyCal

Windowless H_2 Gas Flow Target

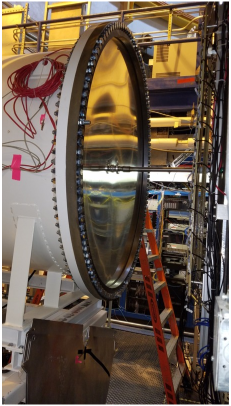
- gas target of cryogenically cooled hydrogen at 19.5 K
- beam opening: 2 mm, length: 4 cm
- cell density: $\sim 2 \cdot 10^{18}$ H atoms/cm^2
- pressures:
  - cell pressure: 471 mTorr
  - chamber pressure: 2.34 mTorr
  - vacuum chamber pressure: 0.3 mTorr

Developed and build by JLab target group





Vacuum Box



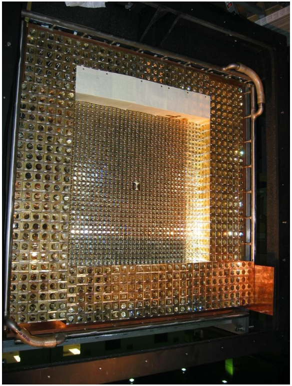
- 1.7 m diameter, 2 mm aluminum vacuum window

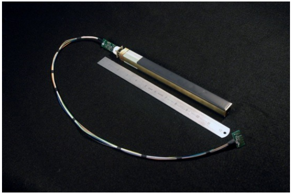
→ Limited background

Primex HyCal

Hybrid detector:

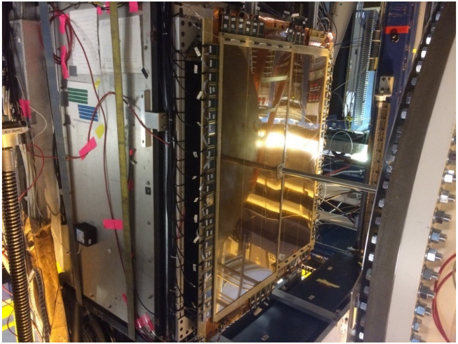
- Central part:
  - 34 x 34 matrix of $PbWO_4$ detectors
  - dimension of block: 2 x 2 x 18 cm^3
  - 2 x 2 blocks removed from the center for beam line to pass through
- Peripheral part:
  - 576 lead glass detectors
  - dimension of block: 4 x 4 x 45 cm^3
- Successfully used for Primex experiments

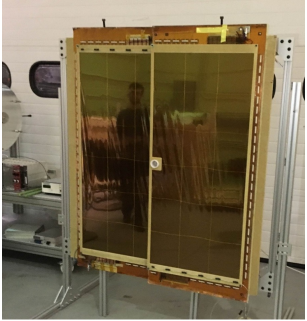




GEM Detectors

- Two large area GEM detectors: 55 cm x 123 cm
- Purpose:
  - improve spatial resolution by a factor 20 to 40 $\rightarrow$ 100 μm
  - $\rightarrow$ to reduce uncertainties on θ and Q^2
- Central overlap between the 2 planes and central hole for the beam line





Developed and build by UVA

Outline

The Proton Radius Puzzle

PRad Setup

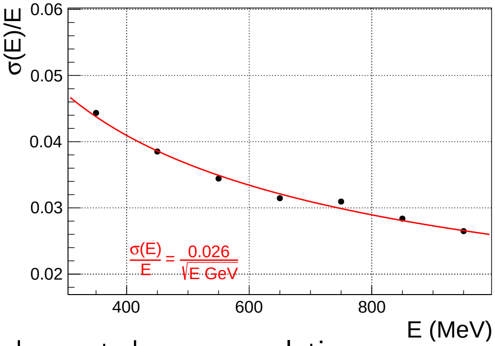
Detectors Performance
- HyCal Energy Resolution
- Trigger Efficiency
- GEM Matching Efficiency
- GEM Spatial Resolution

Analysis

Summary

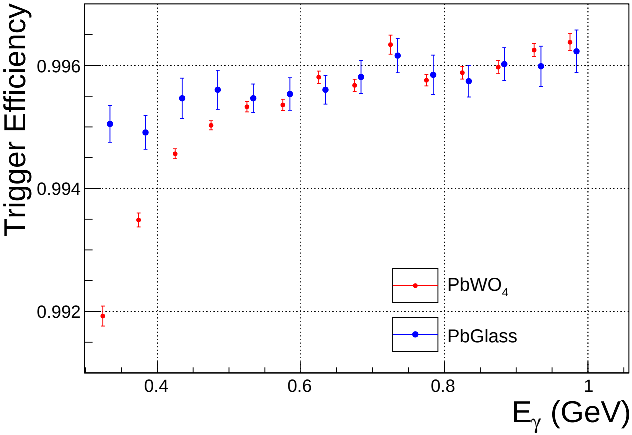
HyCal Energy Resolution

- Crystal energy resolution with statistical uncertainties



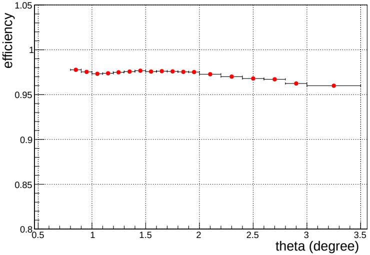
- Achieved expected energy resolution:
  - 2.5% at 1 GeV for crystal part
  - 6.1% at 1 GeV for lead glass part

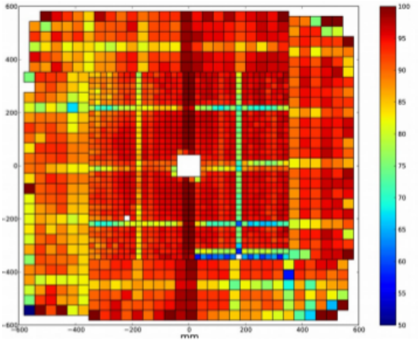
Trigger Efficiency



- Plateau from 500 MeV with an efficiency of 0.995
- Good uniformity

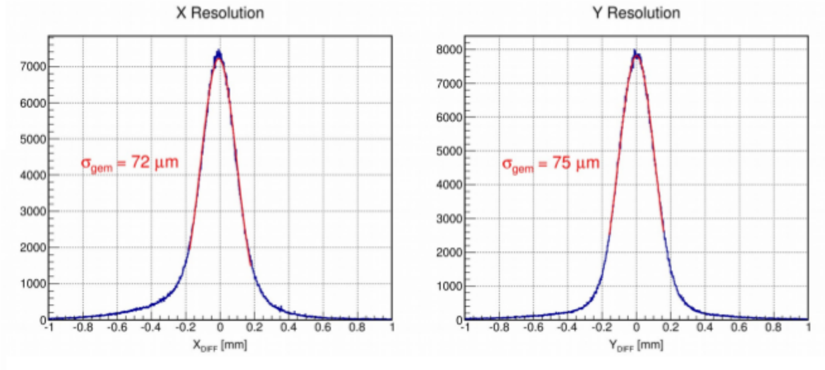
GEM Matching Efficiency





- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (ep and ee)
- Almost flat efficiency $> 97\%$ after removal of spacers and dead zones

GEM Spatial Resolution



- Really good spatial resolution $\sim 74\ \mu m$
- 20 to 40 times better than HyCal spatial resolution

Outline

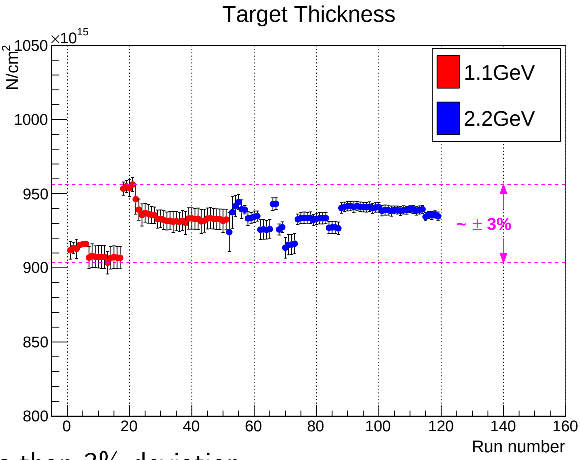
Data Collected

PRoton Radius

- Calibration with tagged photon beam
  - Every calorimeter module moved into the beam
  - Allows study of resolution, linearity, trigger efficiency
- 1.1 GeV electron beam
  - 4.2 mC
  - 604 M events with target
  - 53 M events with “empty target”
  - 25 M events with ^{12}C target for calibration
- 2.2 GeV electron beam
  - 14.3 mC
  - 756 M events with target
  - 38 M events with “empty target”
  - 10.5 M events with ^{12}C target for calibration

Target Stability

- Control of target properties (pressure, temperature, position) via EPICS

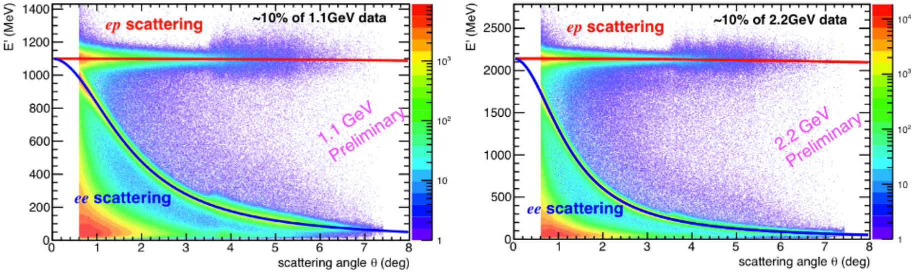


→ Less than 3% deviation

Weizhi Xiong

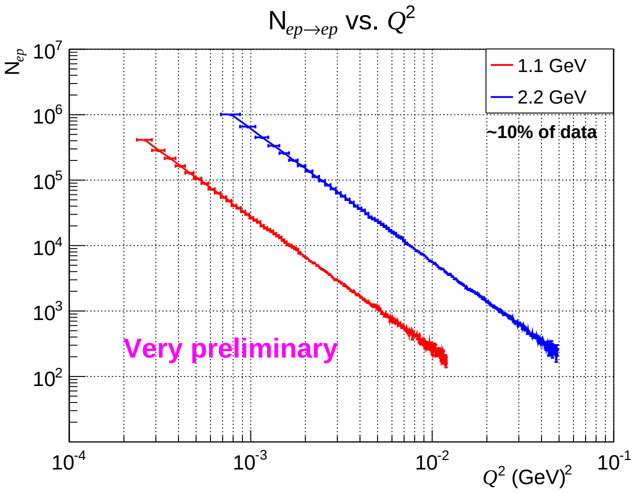
Phase Space

- Phase space after background subtraction



- Separation of *ep* and Møller phase space (for $\theta > 0.85 deg$ for 1 GeV)

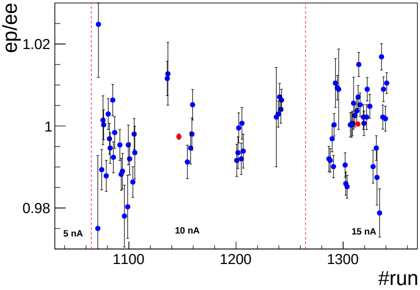
ep Yields

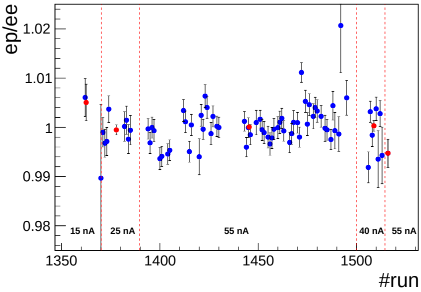


- 1.1 GeV data set: $Q^2 \in [2 \cdot 10^{-4}, 1.3 \cdot 10^{-2}]$ GeV^2
- 2.2 GeV data set: $Q^2 \in [8 \cdot 10^{-4}, 6 \cdot 10^{-2}]$ GeV^2

Yields Stability

- Stability of ratio *ep*/*ee* after background subtraction for different beam intensity





- Good stability for the 2GeV period

Extraction of Cross-section

PRoton Radius

- Normalization of *ep* cross-section by Møller cross-section:

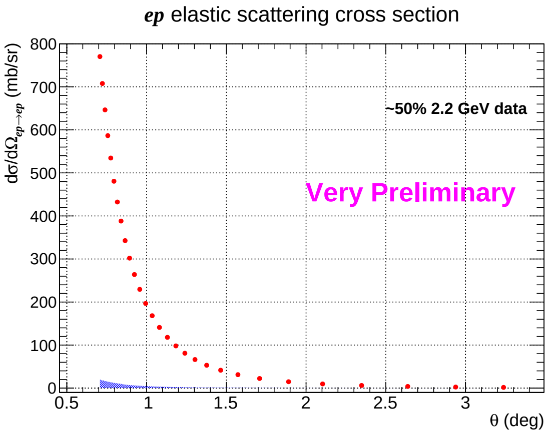
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \to ep \, in \, \theta_i \pm \Delta\theta)}{N_{exp}(ee \to ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

- Several event generators have been developped for *ep* and Møller scattering taking into account complete calculations of radiative corrections beyond ultra relativistic approximations
  - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
- Geant4 is used to take into account all external radiative effects

$$\sigma^{Born}_{ep} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \sigma^{Born}_{ee}$$

Preliminary *ep* Cross-section

- Preliminary *ep* cross-section for the 2.2 GeV data set
- Statistical uncertainties at ∼ 0.2% per point
- Conservative systematic uncertainties at ∼ 2% per point



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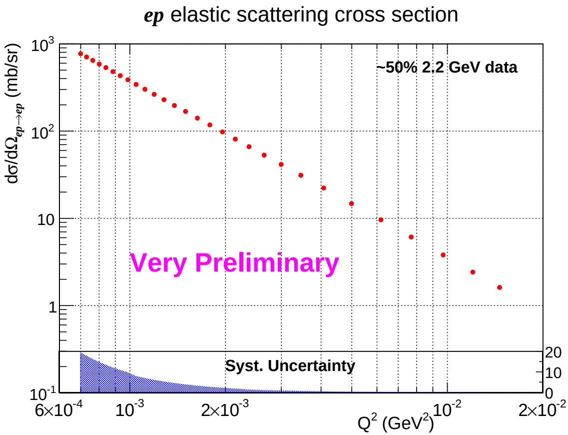

Summary

- The PRad experiment was uniquely designed to address the *Proton Radius Puzzle*
- The experiment was successfully performed in May-June 2016
- Wide range of Q^2 without normalization on more than two orders of magnitude ($2 \cdot 10^{-4}$ GeV^2 to $6 \cdot 10^{-2}$ GeV^2)
- Lowest Q^2 data set of ep elastic scattering ($2 \cdot 10^{-4}$ GeV^2)
- First preliminary extraction of the proton radius expected at the end of October

Thanks to JLab, Hall B, Accelerator Division and Target Group

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