Current Results of the PRad Experiment at JLab

Maxime Levillain

November 17, 2017

Outline

- The Proton Radius Puzzle
- PRad Setup
- Detectors Performances
- Analysis
- Summary

Outline

PRoton Radius

The Proton Radius Puzzle

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

PRad Setup

Detectors Performances

Analysis

Summary

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**

Accelerator based experiments at Mainz, SLAC, JLab, etc

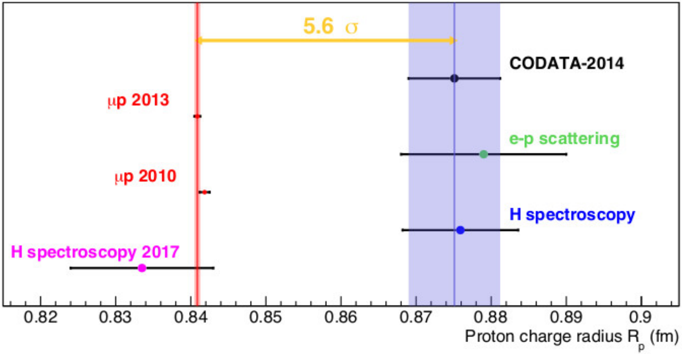
Muonic Hydrogen Spectroscopy

Lamb shift measurements by CREMA

μp Scattering

Future experiment PSI/MUSE

The Proton Radius Puzzle



elastic scattering $r_p(e^-) = 0.8751 \pm 0.0061 fm$

muonic spectroscopy $r_p(\mu^-) = 0.8409 \pm 0.0004 fm$

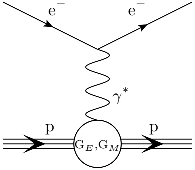
atomic spectroscopy $r_p(e^-) = 0.8335 \pm 0.0095 fm$

- Discrepancy between spectroscopy and atomic hydrogen scattering measurements

Elastic *ep* Scattering

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

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \frac{E'}{E} \cdot \frac{1}{1+\tau} \cdot (G_E^{n2}(Q^2) + \frac{\tau}{\epsilon} G_M^{n\,2}(Q^2))$$



with:

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

- Structureless proton:

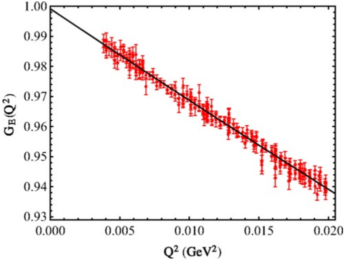
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2(1-\beta^2 sin^2\theta/2)}{4k^2 sin^4\theta/2}$$

- 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:

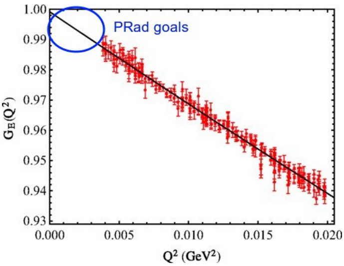
$$< r^2 >= -6 \cdot \frac{dG_E^p}{dQ^2}\Big|_{Q^2=0}$$



Phys. Rev. C 93, 065207

The PRad Experiment

- Previous measurements have large systematic uncertainties and a limited coverage at small Q^2
- Requirements for PRad Experiment:
  - large Q^2 range (two orders of magnitude)
  - extend to very low Q^2 ($2 \cdot 10^{-4}$ GeV^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



Phys. Rev. C 93, 065207

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

The Proton Radius Puzzle

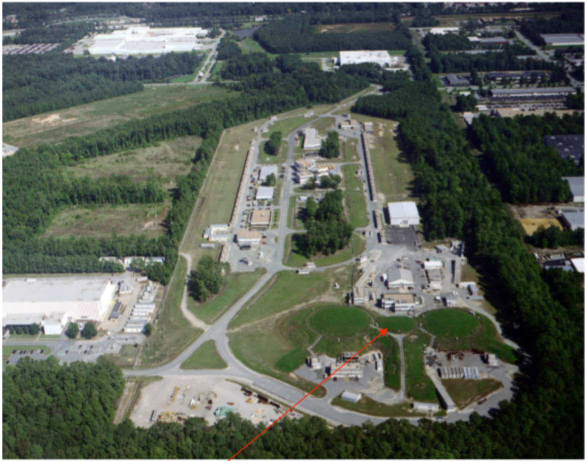
PRad Setup
- JLab Facility
- PRad Setup
- Windowless Gas Flow Target
- Hybrid Calorimeter
- GEM detectors

Detectors Performances

Analysis

Summary

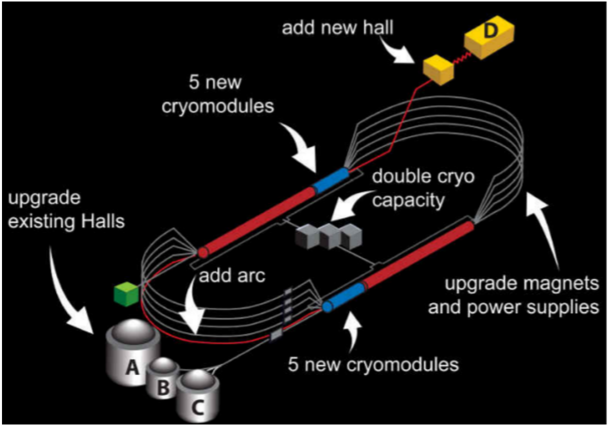
JLab Facility



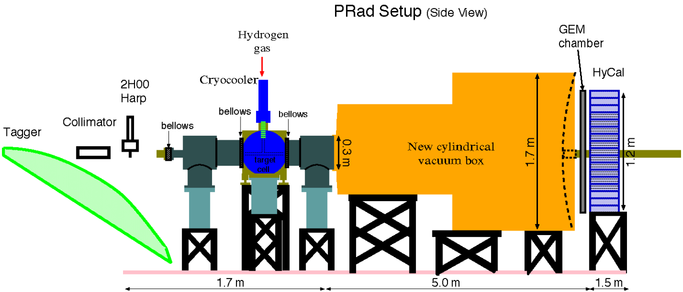
PRad was performed in Hall B at JLab

JLab 12GeV Upgrade

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



PRad Setup

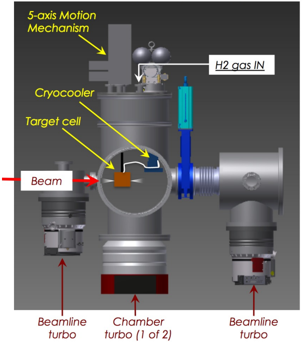


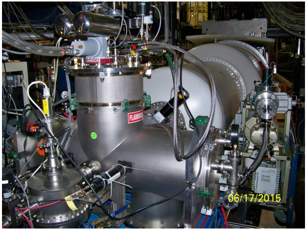
- Electron beam or tagged photon beam at ~ 1 GeV and ~ 2 GeV
- Windowless H_2 gas flow target
- Vacuum box
- GEM detectors
- Primex HyCal

Windowless H_2 Gas Flow Target

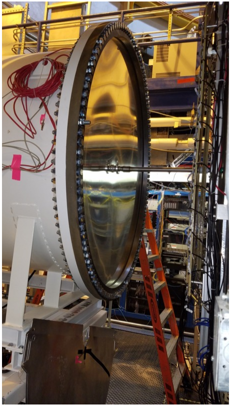
- gas target of cryogenically cooled hydrogen at 19.5 K
- beam opening: 2 mm, length: 4 cm
- cell density: $\sim 2 \cdot 10^{18}$ H atoms/cm^2
- pressures:
  - cell pressure: 471 mTorr
  - chamber pressure: 2.34 mTorr
  - vacuum chamber pressure: 0.3 mTorr

Developed and build by JLab target group





Vacuum Box



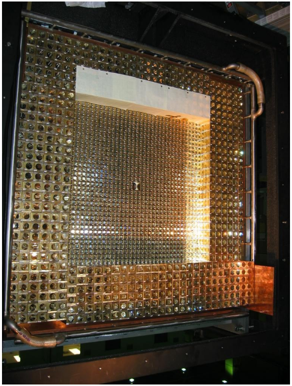
- 1.7 m diameter, 2 mm aluminum vacuum window

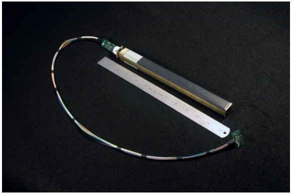
→ Limited background

Primex HyCal

Hybrid detector:

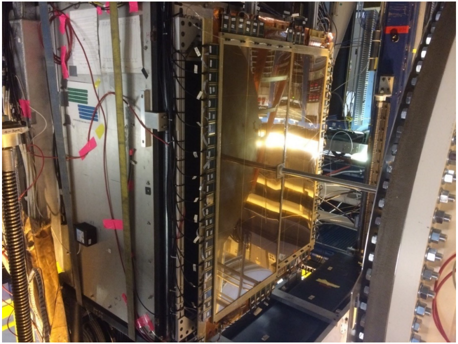
- Central part:
  - 34 x 34 matrix of $PbWO_4$ detectors
  - dimension of block: 2 x 2 x 18 cm^3
  - 2 x 2 blocks removed from the center for beam line to pass through
- Peripheral part:
  - 576 lead glass detectors
  - dimension of block: 4 x 4 x 45 cm^3
- 5.8m from the target
  $\rightarrow$ scattering angle coverage: $\sim 0.6°$ to $7.5°$
- Successfully used for Primex experiments

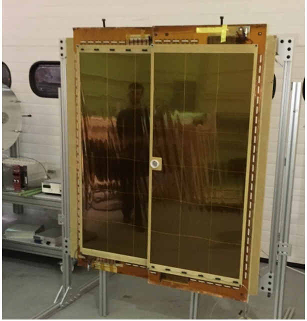




GEM Detectors

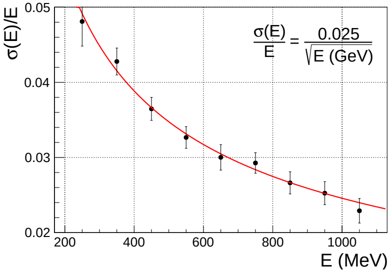
- Two large area GEM detectors: 55 cm x 123 cm
- Purpose:
  - improve spatial resolution by a factor 20 to 40 $\rightarrow$ $< 75\ \mu m$
  - $\rightarrow$ to reduce uncertainties on θ and Q^2
- Central overlap between the 2 planes and central hole for the beam line

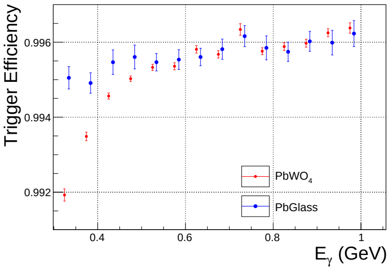




Developed and build by UVA

Outline

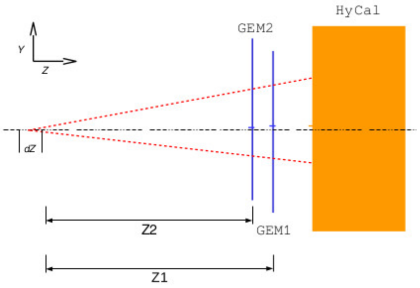


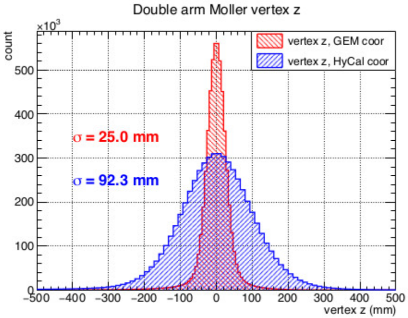


- Achieved expected energy resolution:
  - 2.5% at 1 GeV for $PbWO_4$
  - 6.1% at 1 GeV for Pbglass

- Plateau from 500 MeV with an efficiency 99.5%

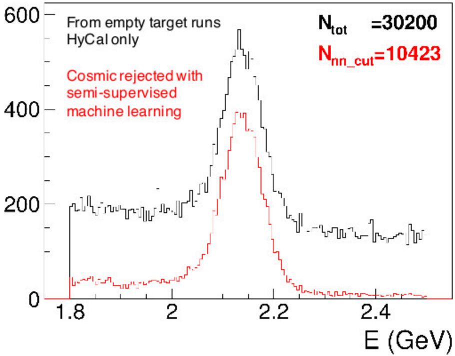
- Detector offsets and z position determined using double-arm Møller events
- Offset with $\sim 50\mu$m and z with 1 mm precision





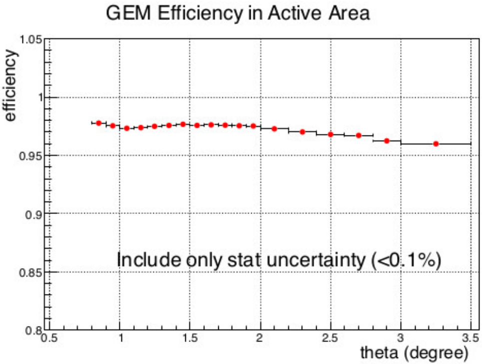
Cosmic Events

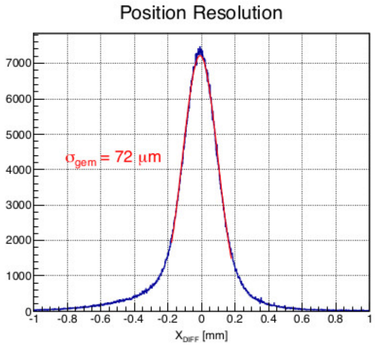
- Most cosmic events rejected from matching GEM and HyCal
- Negligible at small angle thanks to high event race
- Different algorithms to further reject cosmics:
  - Using empirical variables: cluster profile/size
  - Machine learning methods



GEM Performances

PRoton Radius





- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (ep and ee)
- GEM resolution measured using overlap region ($< 75\mu$m)

Outline

The Proton Radius Puzzle

PRad Setup

Detectors Performances

Analysis

- Stability
- Background Study
- Event Selection
- Cross-sections

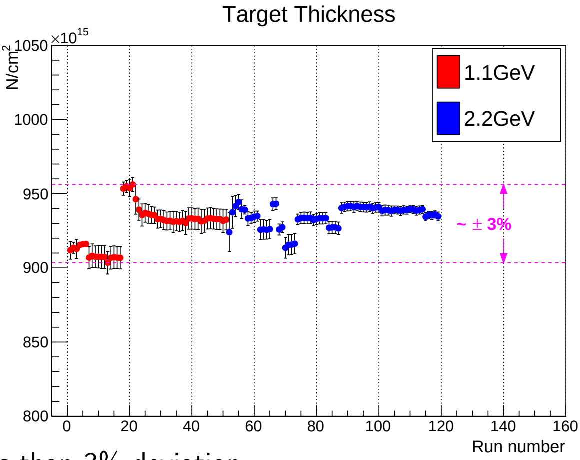
Summary

Data Collected

- 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

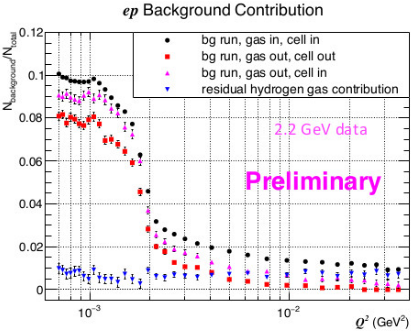
- Control of target properties (pressure, temperature, position) via EPICS

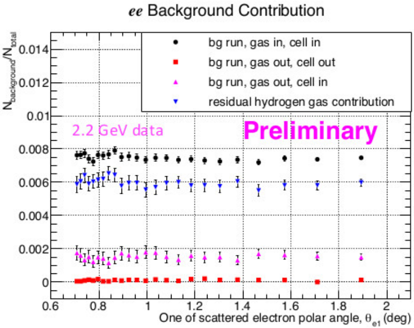


→ Less than 3% deviation

Weizhi Xiong

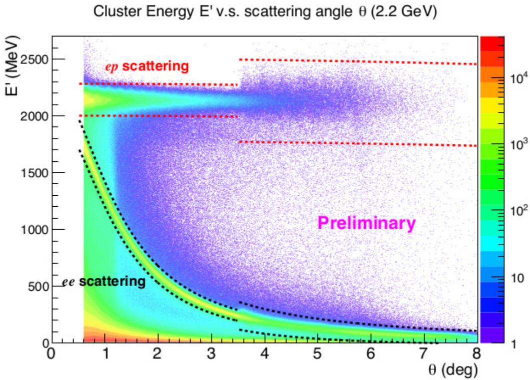
Background Subtraction





- *ep* background $\sim$ 10% at forward angle and $<$ 2% otherwise
- *ee* background $\sim$ 0.8%

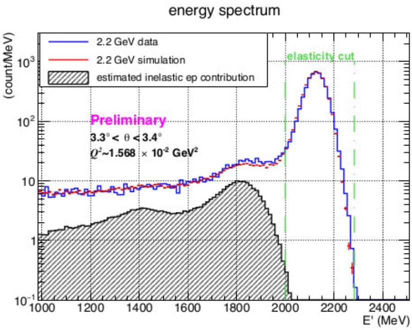
Event Selection

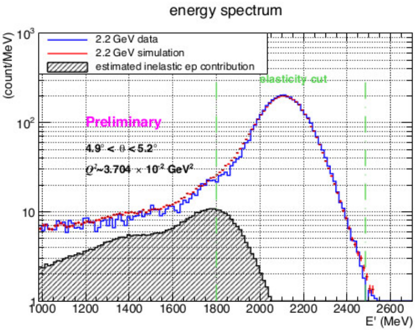


- Matching hits between HyCal and GEMs
- For *ep* and *ee* events, angle dependent energy cut (resolution depending on HyCal region)
- For *ee* events, double-arm selection with additional cuts:
  - Elasticity
  - Co-plnarity
  - Vertex z

Inelastic *ep* Contribution

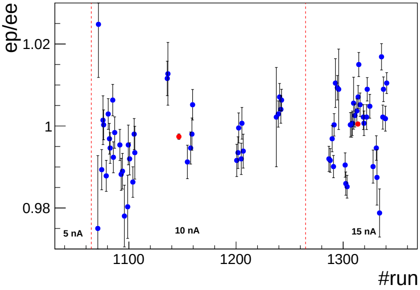
- Two different generators (one inclusive and one for exclusive pions)
- Expected contribution $< 0.1\%$ in $PbWO_4$, $\sim 3.5\%$ for PbGlass 2.2 GeV and $< 1\%$ for PbGlass 1.1 GeV

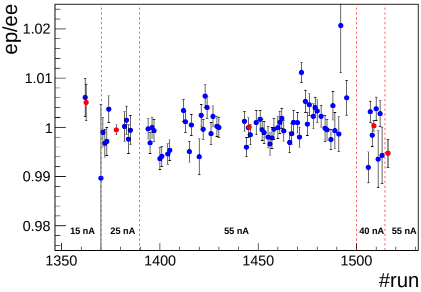




Yields Stability

- 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:

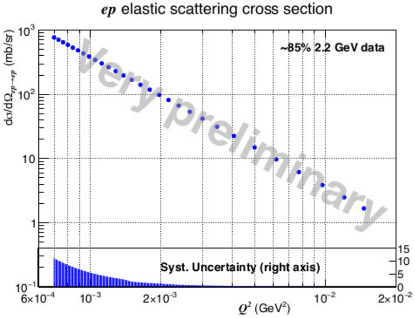
$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \to ep \, in \, \theta_i \pm \Delta\theta)}{N_{exp}(ee \to ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

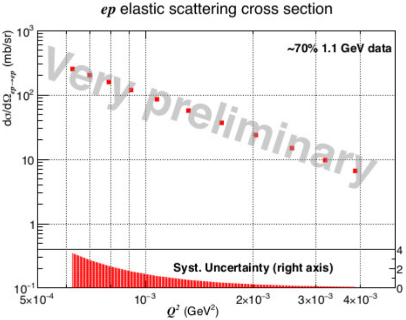
- Several event generators have been developped for *ep* and Møller scattering taking into account complete calculations of radiative corrections beyond ultra relativistic approximations
  - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
- 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 (1.1) GeV data set
- Statistical uncertainties at $\sim 0.18\%$ ($\sim 0.3\%$) per point
- Conservative point-to-point systematic uncertainties at $\sim 1.3\%$

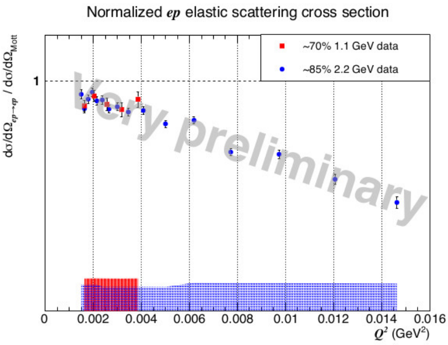


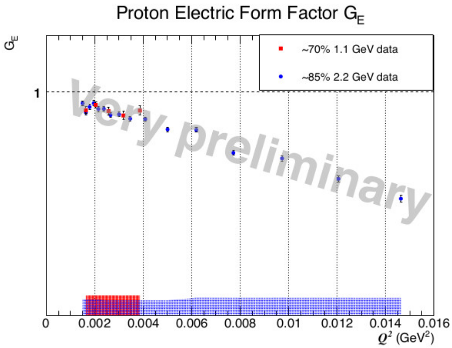


Preliminary Electric Form Factors

- Differential cross-section normalized to Mott cross-section

- Proton electric form factor G_E





Summary

- The *Proton Radius Puzzle* is still unresolved
  - New converging spectroscopy results needs some confirmation from other experiment
  - Further experiments preparing for μp scattering (MUSE, COMPASS)
- The PRad experiment was uniquely designed to address this puzzle
  - 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)
- Very preliminary cross-section, covering $Q^2 \in [6 \cdot 10^{-4}, 1.5 \cdot 10^{-2}]$ GeV^2

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

PRad is supported in part by NSF MRI award PHY-1229153, as well as DOE awards for GEM; my research work is supported by NSF awards: PHY-1506388 and PHY-0855543