Analysis and Preliminary Results of the PRad Experiment at JLab

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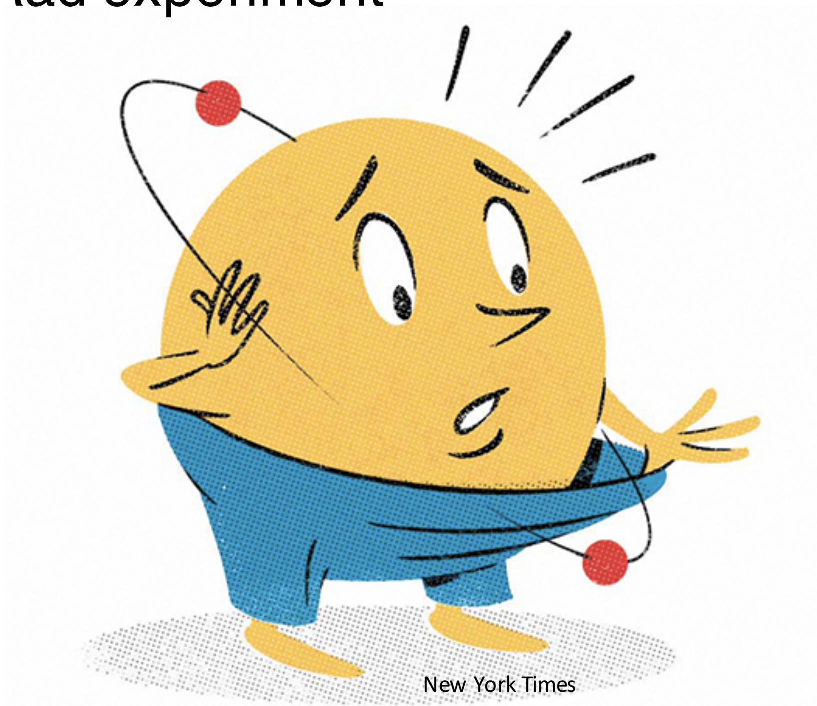
for the PRad Collaboration

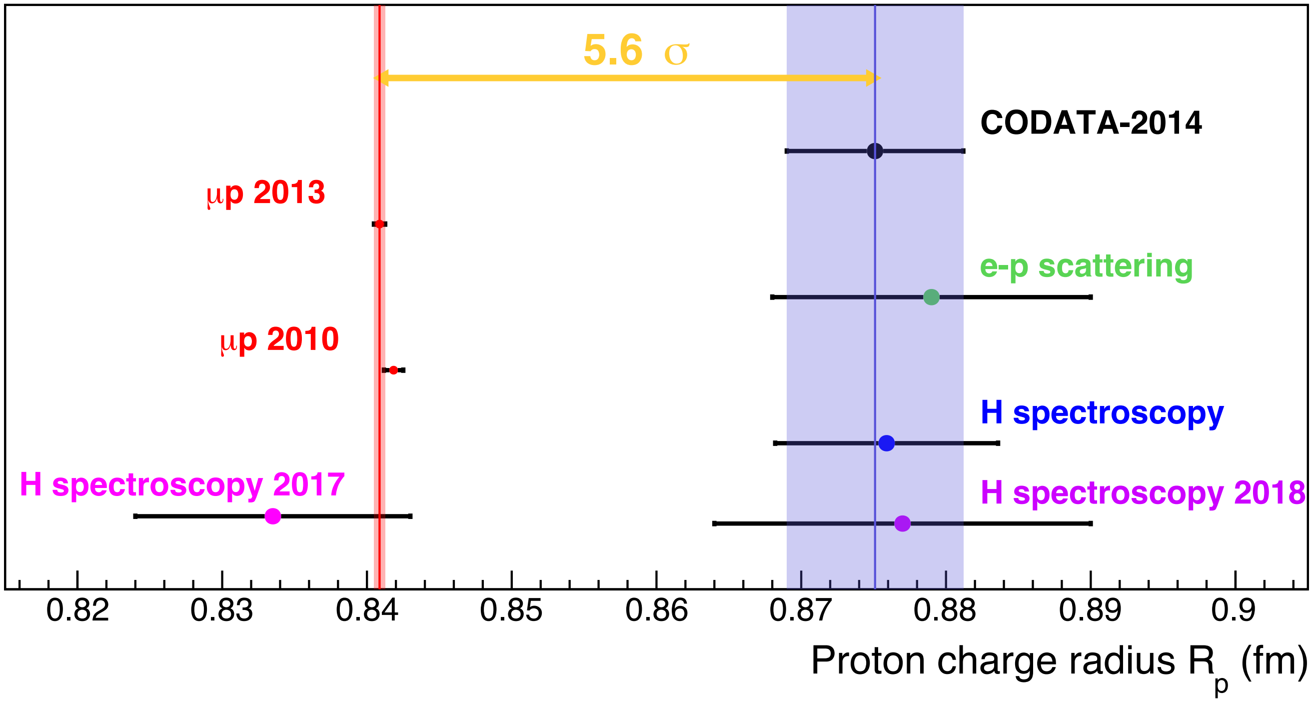
CIPANP Meeting 2018

Outline

- Proton charge radius puzzle and PRad experiment
- Experimental apparatus
- Analysis and preliminary results
- Summary



Proton Charge Radius Puzzle



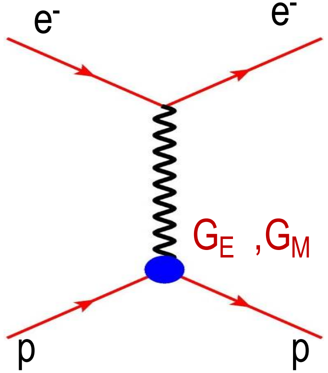
Electron scattering: 0.8751 ± 0.0061 fm (CODATA 2014)
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017): 0.8335 ± 0.0095 fm (A Beyer et al. Science 358 (6359). 2017)
H spectroscopy (2018): 0.877 ± 0.013 fm (H Fleurbaey et al. PRL.120.183001 (2018))

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 (~2×10^{-4} GeV^2)
  1. Fill in very low Q^2 region

- Covers two orders of magnitude in low Q^2 with the same detector setting
  1. ~2×10^{-4} - 6×10^{-2} GeV^2

- Normalize to the simultaneously measured Møller scattering process
  1. best known control of systematics

- Extract the radius with precision from sub-percent cross section measurement

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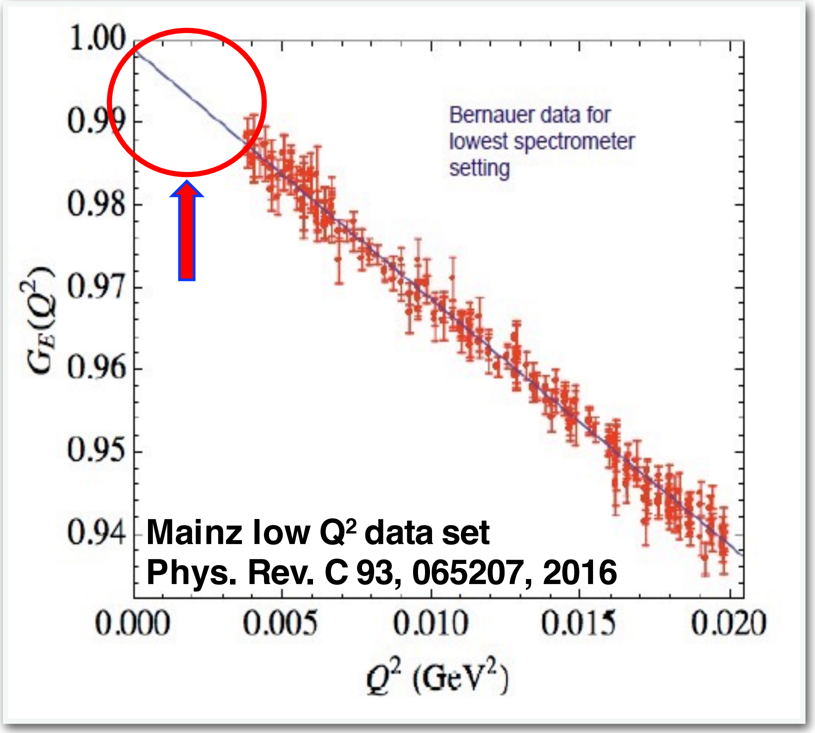
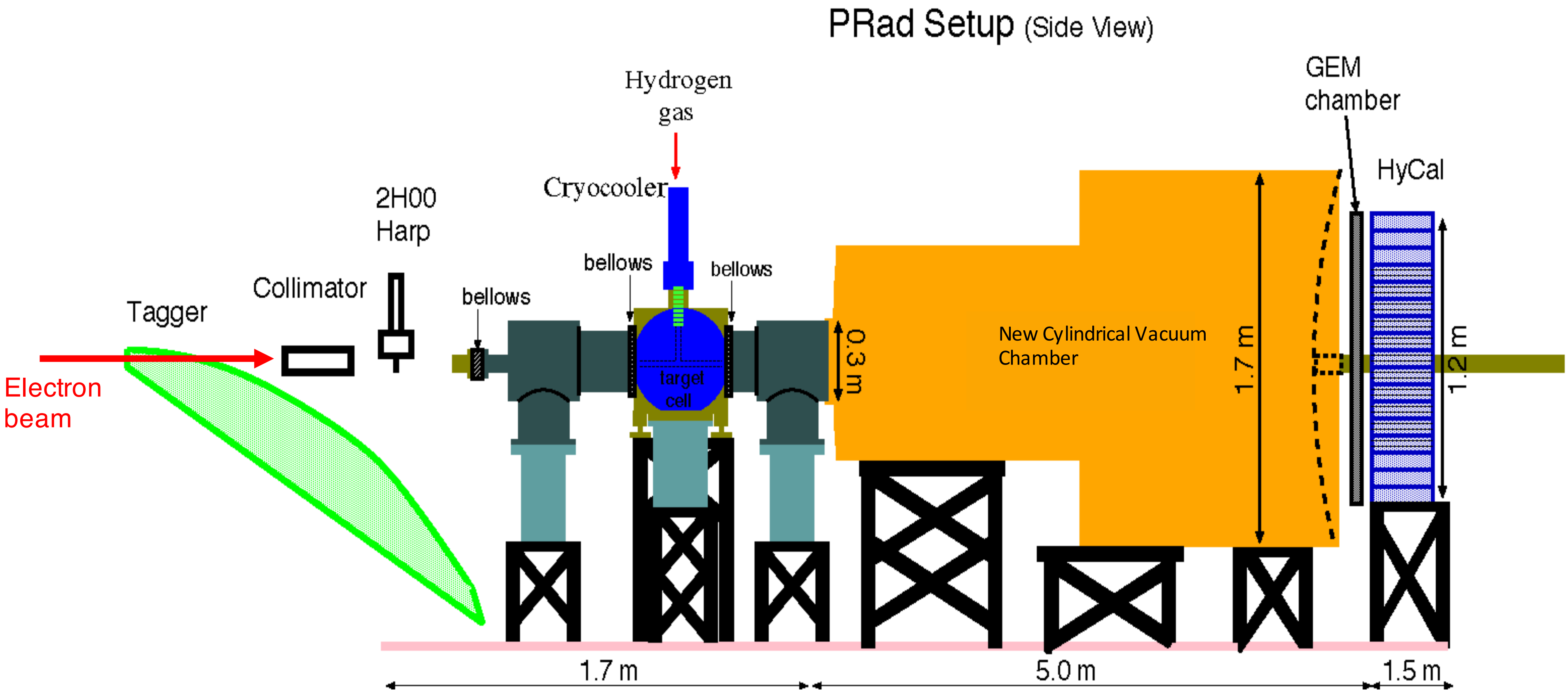


PRad Experimental Apparatus



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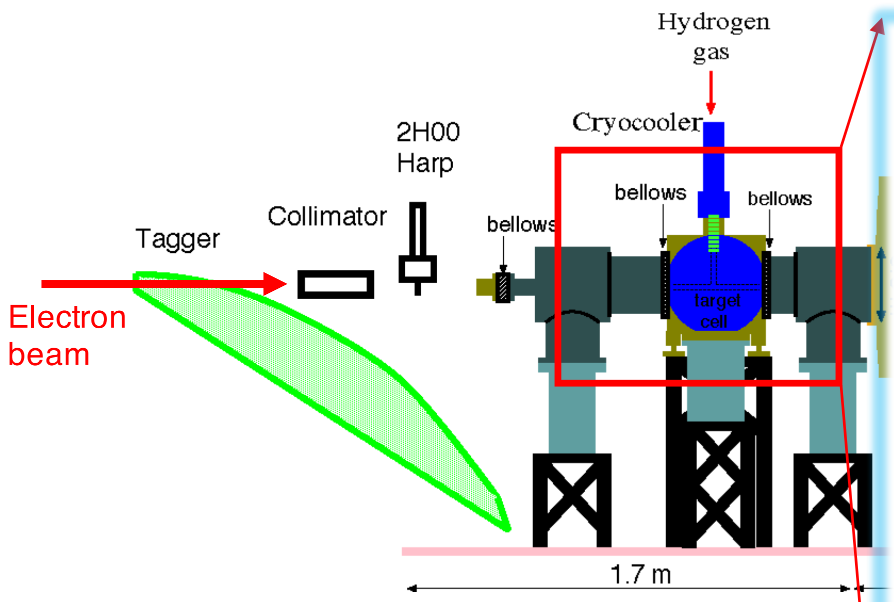
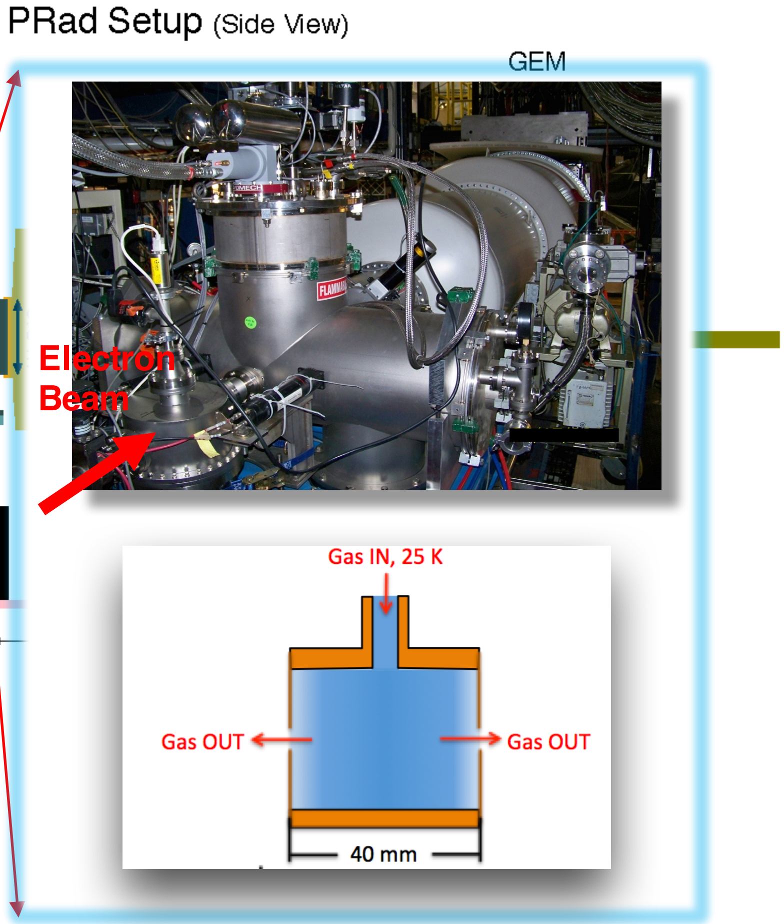
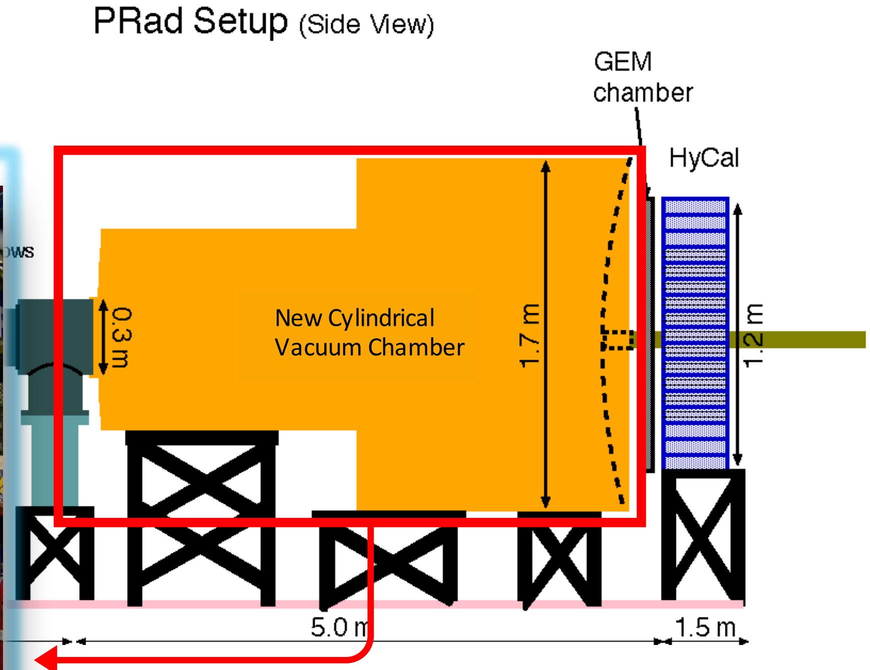




- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2

PRad Experimental Apparatus

Hydrogen gas



- 5 m long two stage vacuum chamber, further remove possible background source
- vacuum chamber pressure: 0.3 mTorr

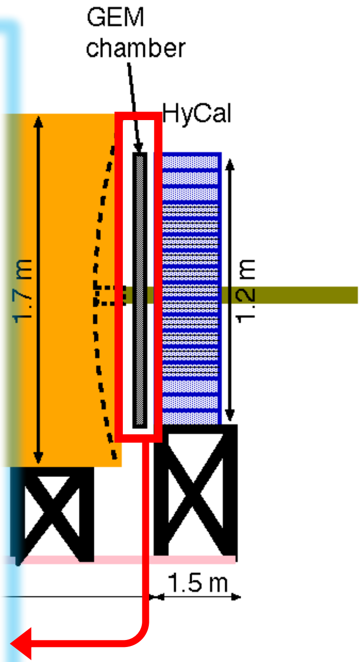
PRad Experimental Apparatus

PRad Setup (Side View)

Hydrogen

Ele
bea

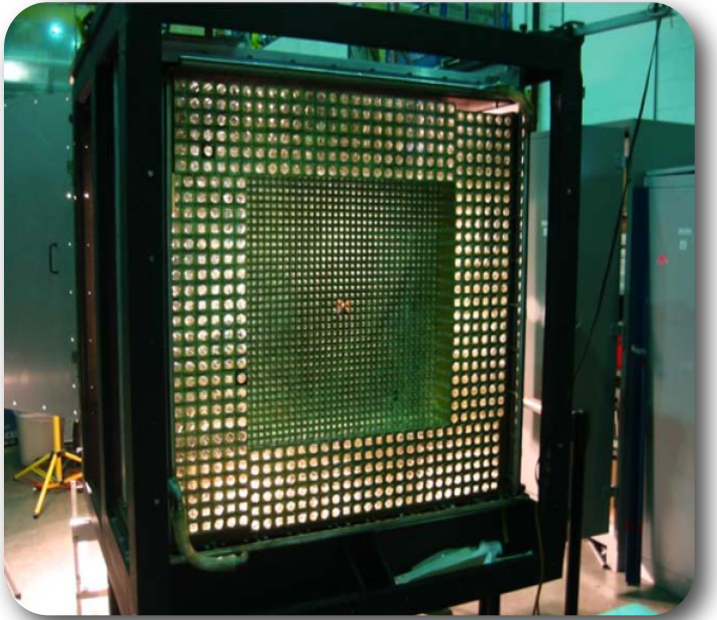
- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Large improvement for Q^2 determination



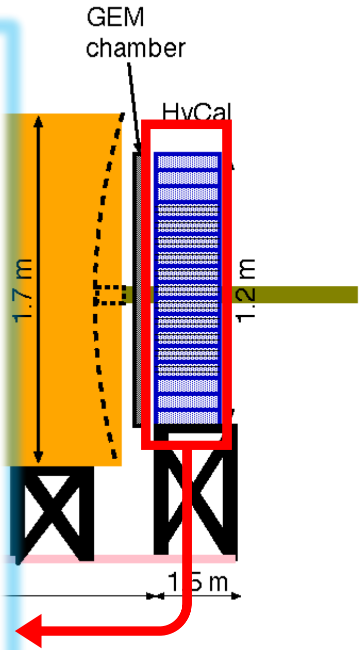
PRad Experimental Apparatus

PRad Setup (Side View)

Hydrogen

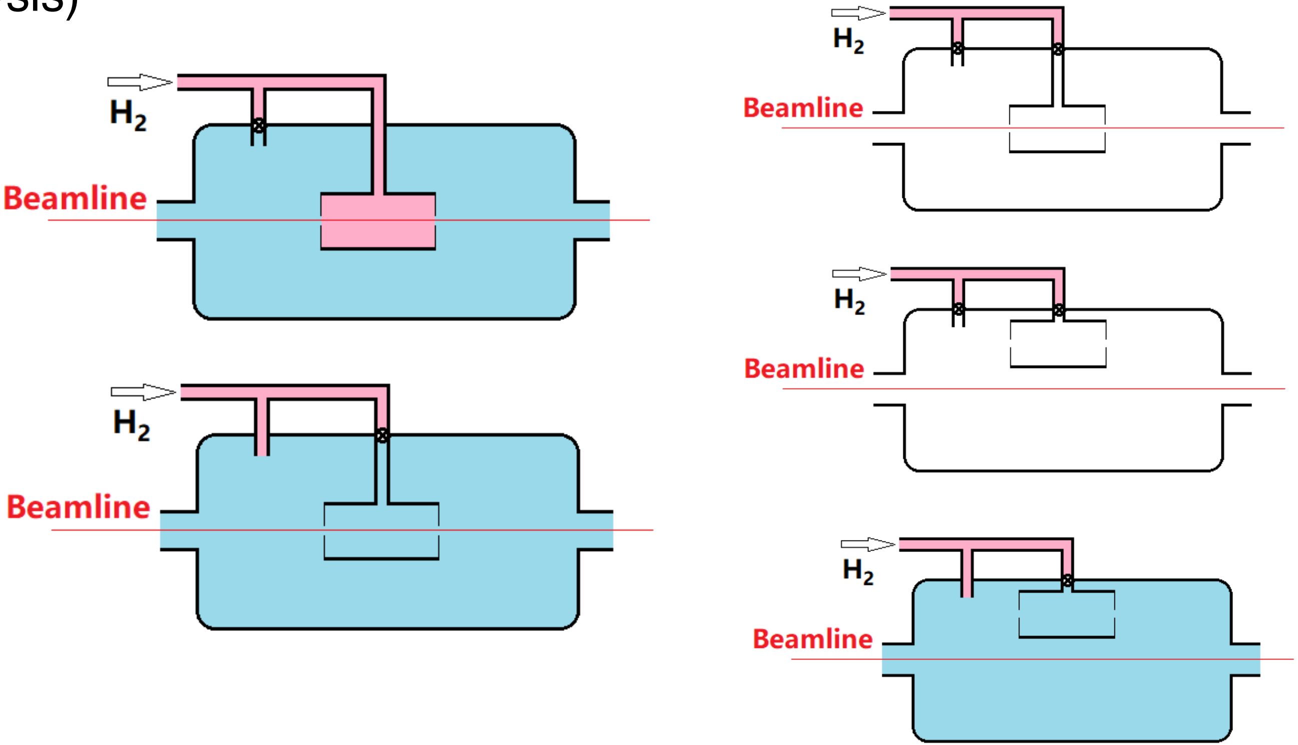


- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO_4 modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~ 0.6° to 7.5°
- Full azimuthal angle coverage
- High resolution and efficiency



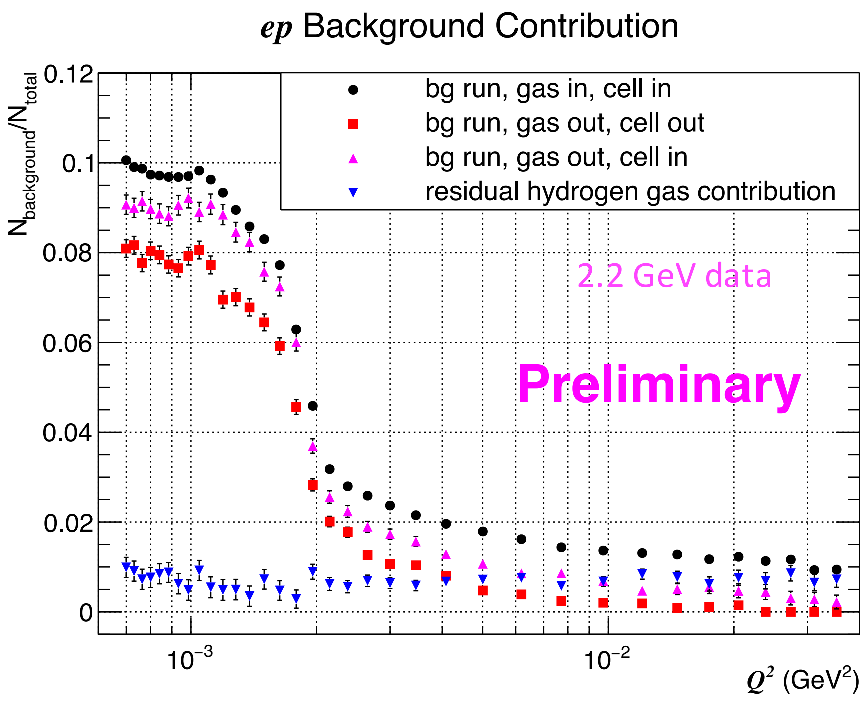
Analysis – Background Subtraction

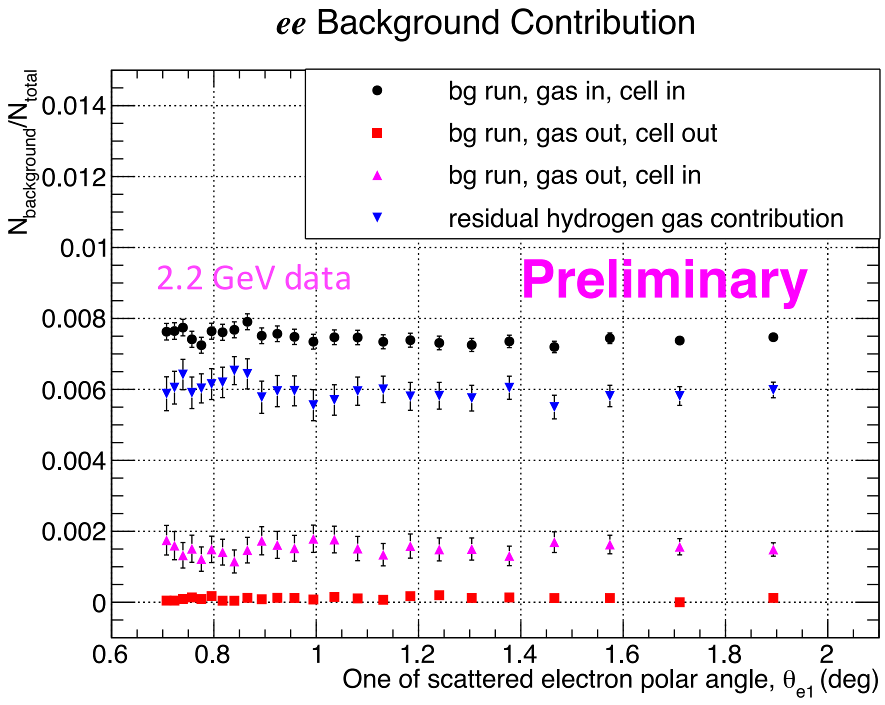
- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)



Analysis – Background Subtraction (2.2 GeV)

- *ep* background rate ~ 10% at forward angle (<1.3 deg, dominated by upstream collimator), less than 2% otherwise
- ee background rate ~ 0.8% at all angles





Residual hydrogen gas: hydrogen gas filled during background runs

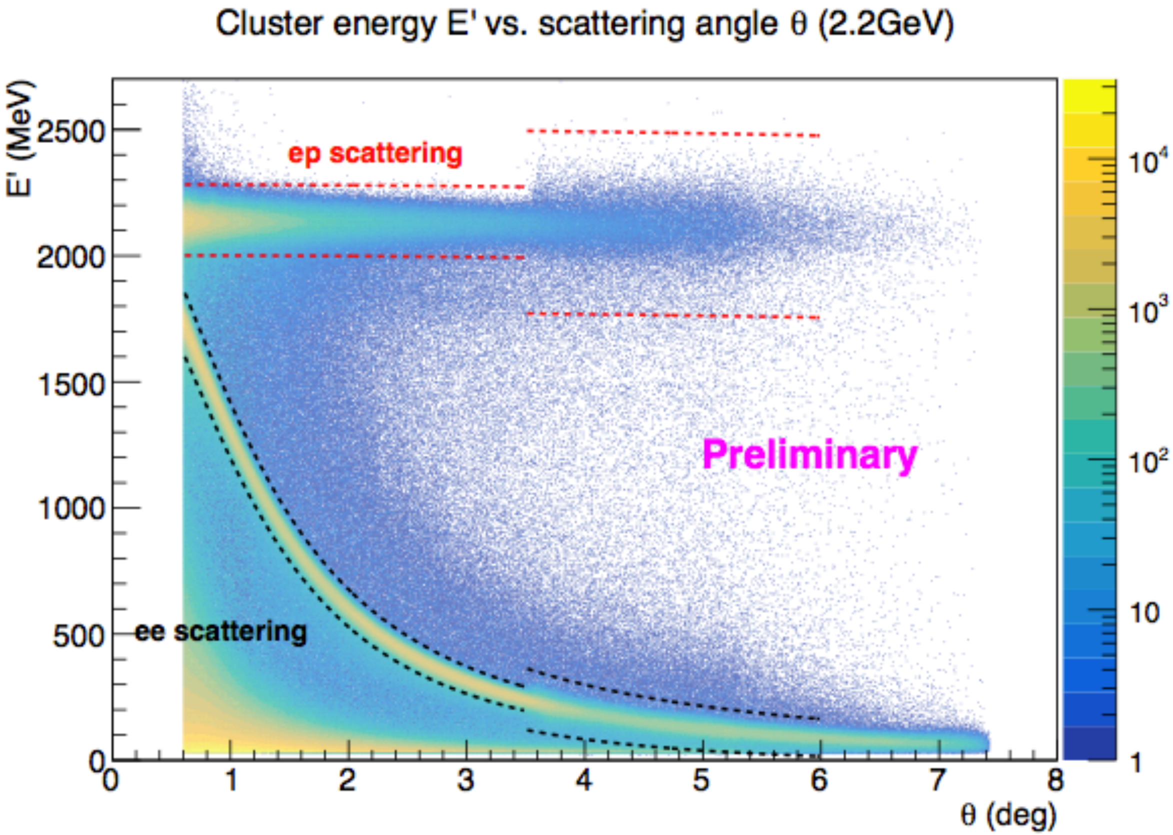
Analysis – Event Selection

Event selection method

1. For all events, require hit matching between GEMs and HyCal

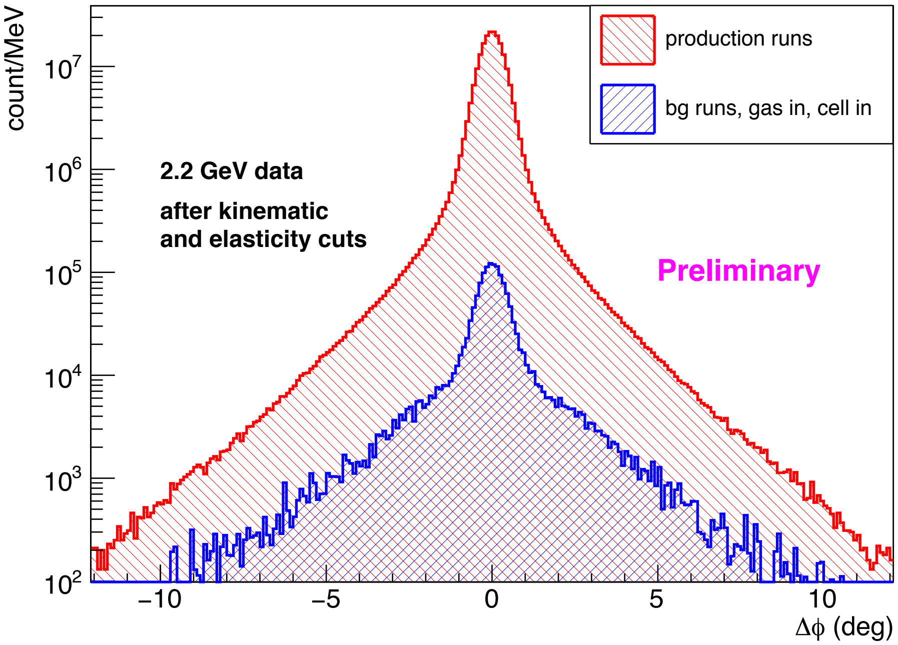
2. For *ep* and *ee* events, apply angle dependent energy cut based on kinematics
    1. Cut size depend on local detector resolution

3. For *ee*, if requiring double-arm events, apply additional cuts
    1. Elasticity
    2. Co-planarity
    3. Vertex z

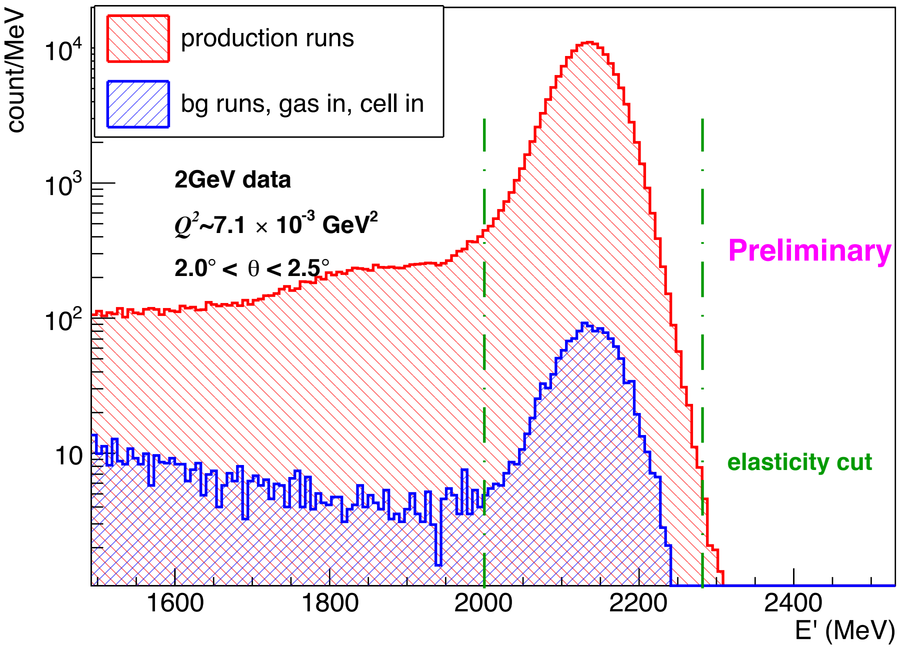


Analysis – Event Selection

Co-planarity for ee scattering



elasticity cut for ep scattering



Extraction of *ep* Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the ep cross section is normalized to the Møller cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \left[\frac{N_{\exp}(ep \to ep \text{ in } \theta_i \pm \Delta\theta_i)}{N_{\exp}(ee \to ee)} \cdot \frac{\varepsilon^{ee}_{\text{geom}}}{\varepsilon^{ep}_{\text{geom}}} \cdot \frac{\varepsilon^{ee}_{\text{det}}}{\varepsilon^{ep}_{\text{det}}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections
  1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  2. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (fully beyond ultra relativistic approximation)

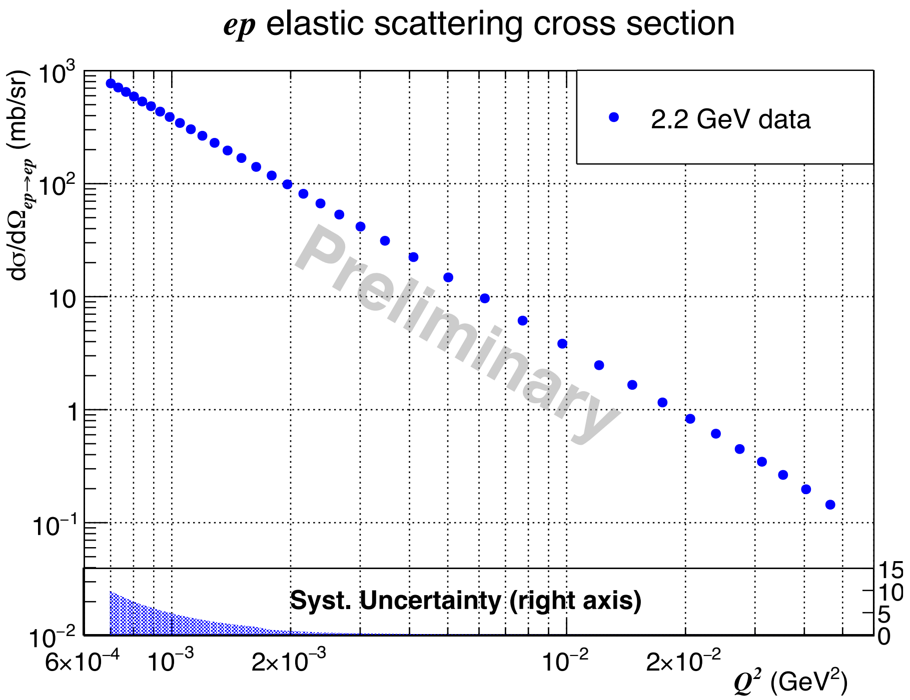
- A Geant4 simulation package is used to study the radiative effects:

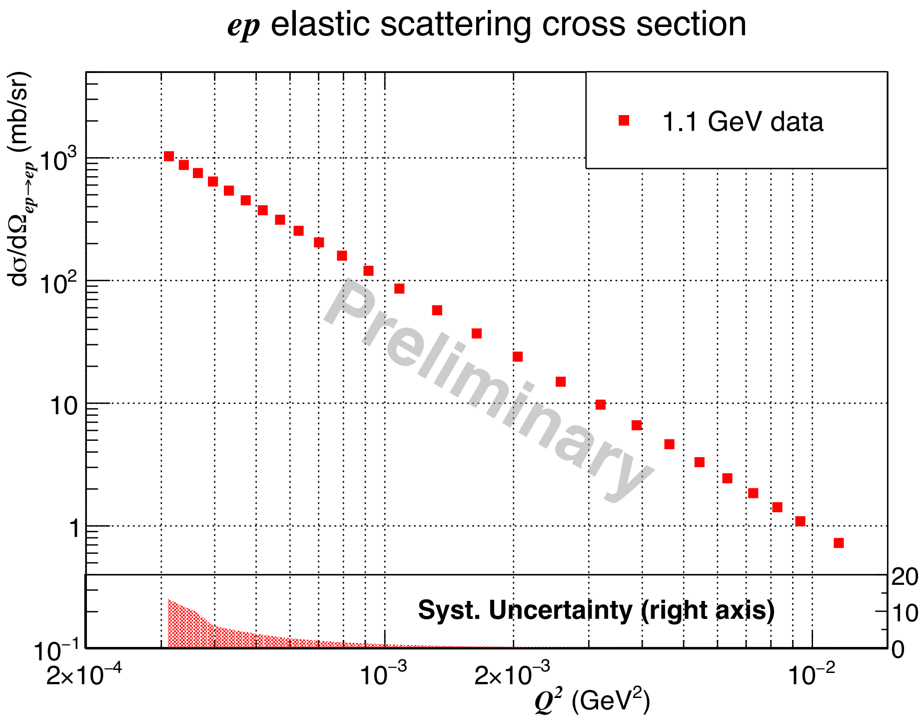
$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

- Iterative procedure applied for radiative correction

Differential Cross Sections (Preliminary)

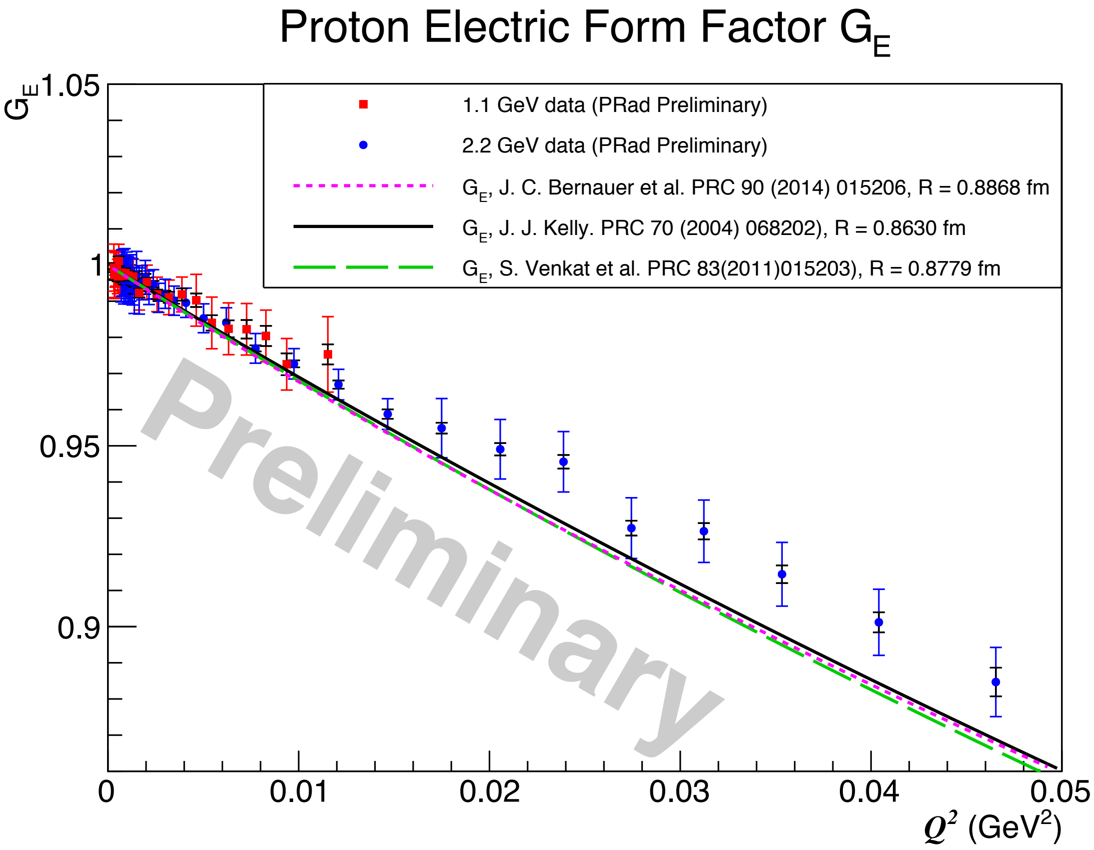
- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Statistical uncertainties at current stage: ~0.18% for 2GeV, ~0.3% for 1GeV per point
- Systematic uncertainties at current stage: 0.8% ~ 2.0% for 2GeV, 0.9% ~2.0% for 1GeV (shown as shadow area)





Form Factor G_E (Preliminary)

- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slope seems to favor smaller radius



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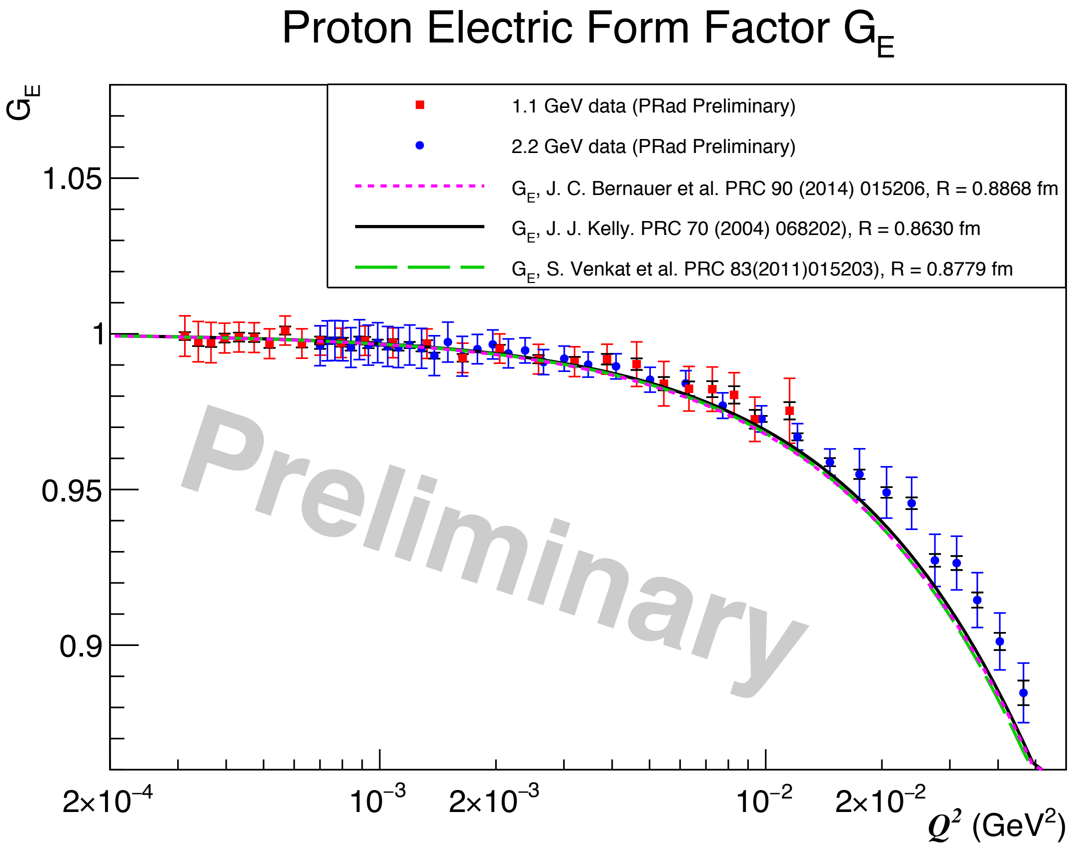

Analysis Plan

- Finalize cross sections for both energy runs (summer 2018)
- Preliminary extraction of radius (summer 2018)
- Final extraction of proton charge radius (end of 2018)

- We are currently still working on a number of corrections and systematic uncertainties
  1. Background subtraction and pile-up effects at small angle (θ<1.1°)
  2. Radiative correction
  3. Inelastic ep contribution
  4. Trigger efficiency
  5. Bremsstrahlung photon from target
  6. ...
- Radius fitting study is ongoing: https://arxiv.org/abs/1803.01629

Summary

- PRad experiment is uniquely designed to address the *Proton Radius Puzzle*
  1. Discrepancy between electron scattering and muon spectroscopy results
  2. Unprecedented low Q^2 data set (~2×10^{-4} GeV^2) has been collected in *e-p* elastic scattering experiment
  3. Data with two orders of magnitude in low Q^2 range (~2×10^{-4} – 6×10^{-2} GeV^2) in one experimental setting

- Preliminary cross section and G_E extracted, covering Q^2 from 3×10^{-4} to 5×10^{-2} GeV^2
- Preliminary G_E slope seems to favor smaller radius

- Ongoing work:
  1. Finalizing systematic uncertainties
  2. Utilizing the full Q^2 data range
  3. Fitting study based on https://arxiv.org/abs/1803.01629

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