Current Results from the PRad Experiment

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for the PRad Collaboration

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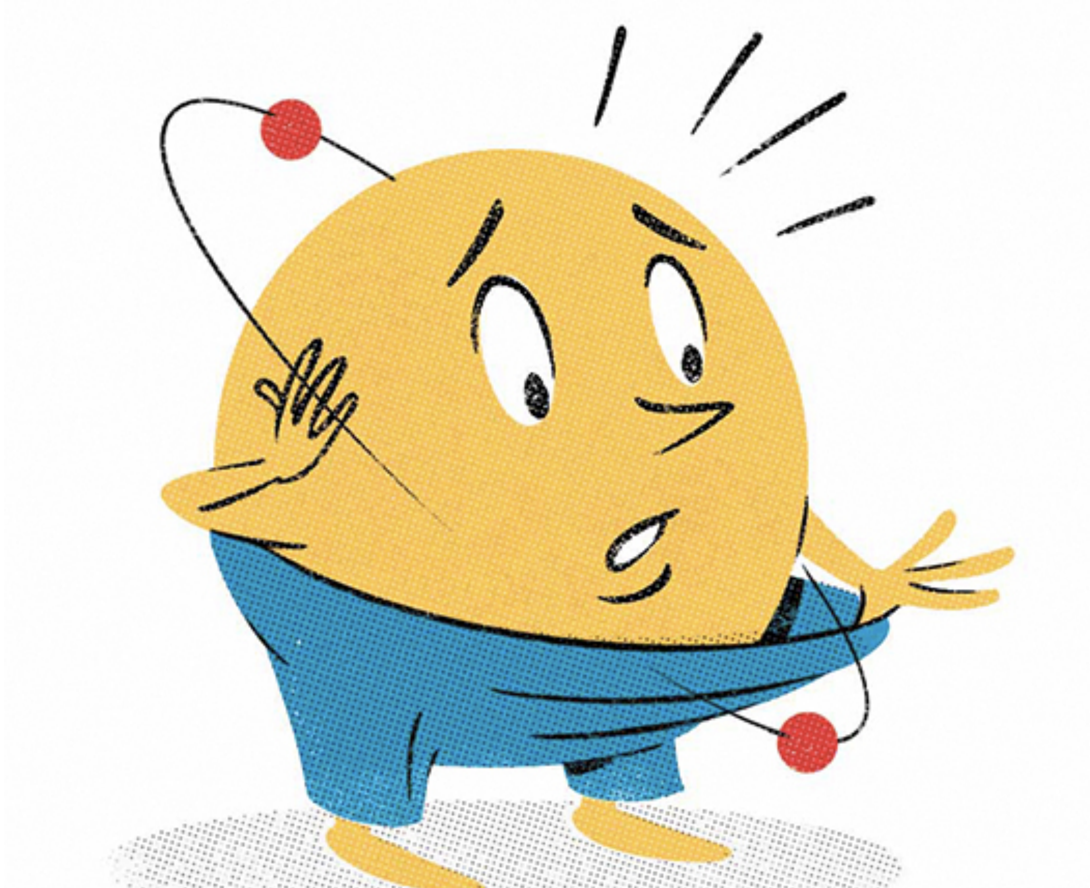
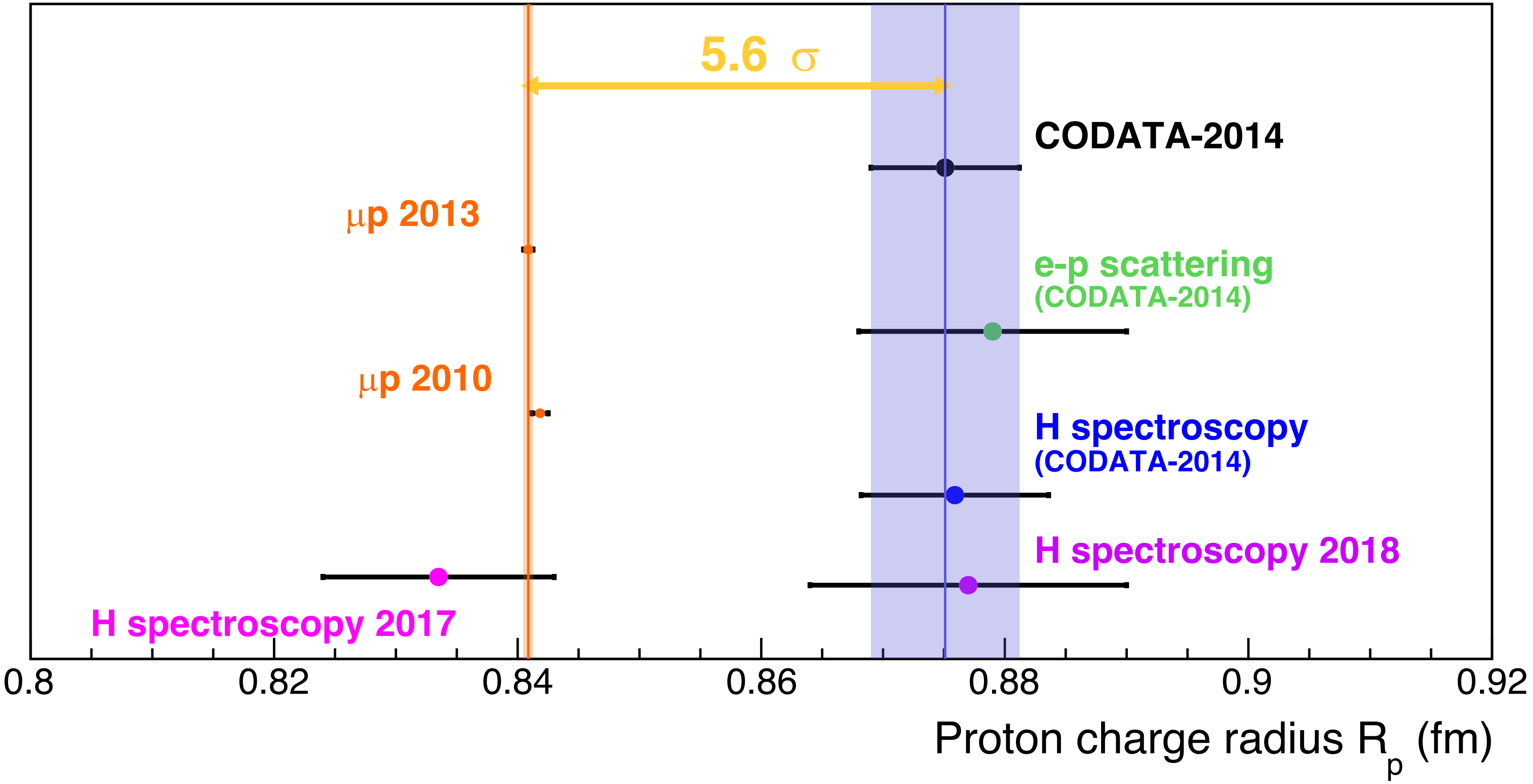
Outline

- Introduction and the proton charge radius puzzle
- PRad experiment and apparatus
- Analysis and current results
- Summary



New York Times

Proton Charge Radius Puzzle: Current Status



Electron scattering: 0.879 ± 0.011 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))

ep Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):

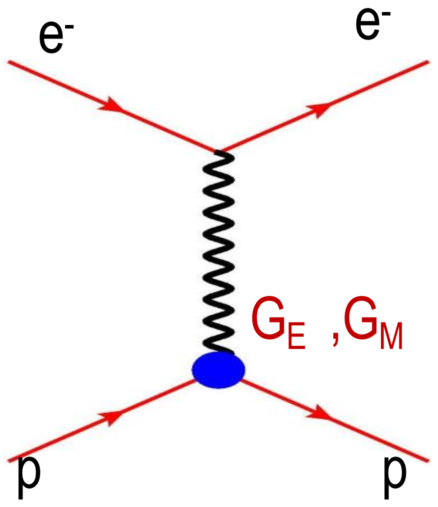
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

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

- 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

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

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

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

- Windowless H_2 gas flow target removes major background source

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

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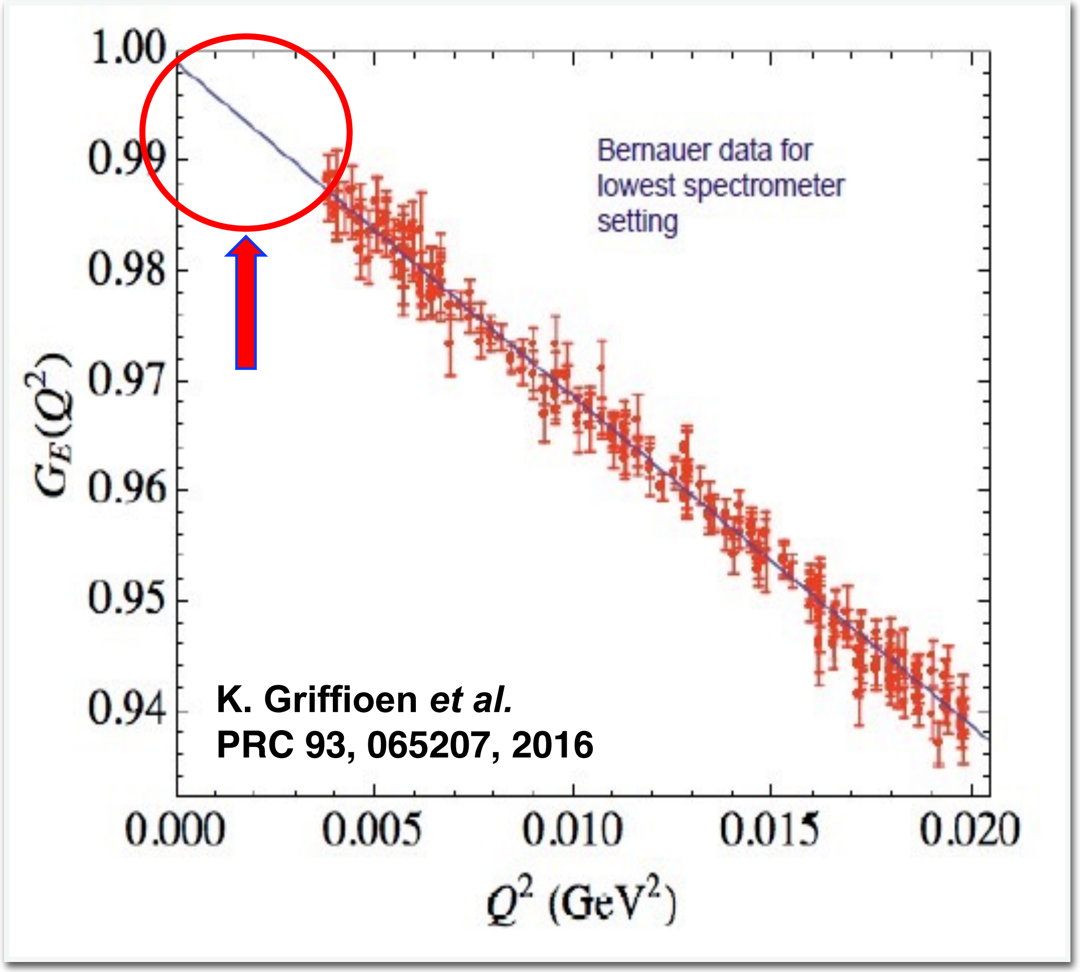
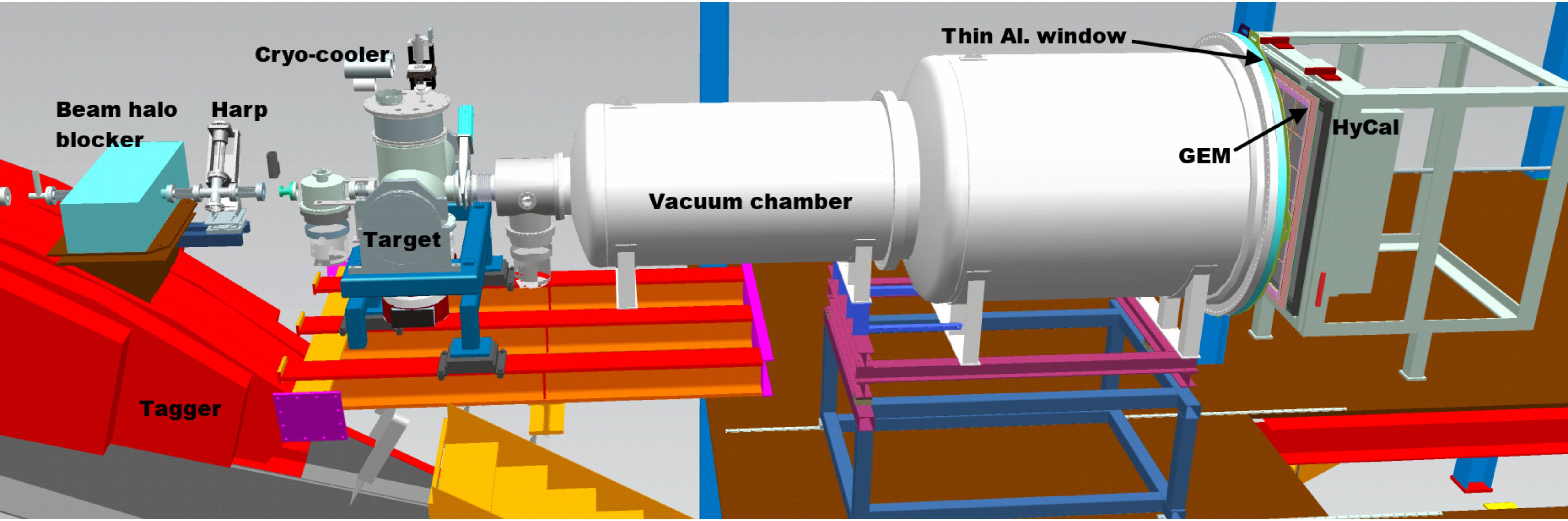


PRad Experimental Apparatus

Hall B



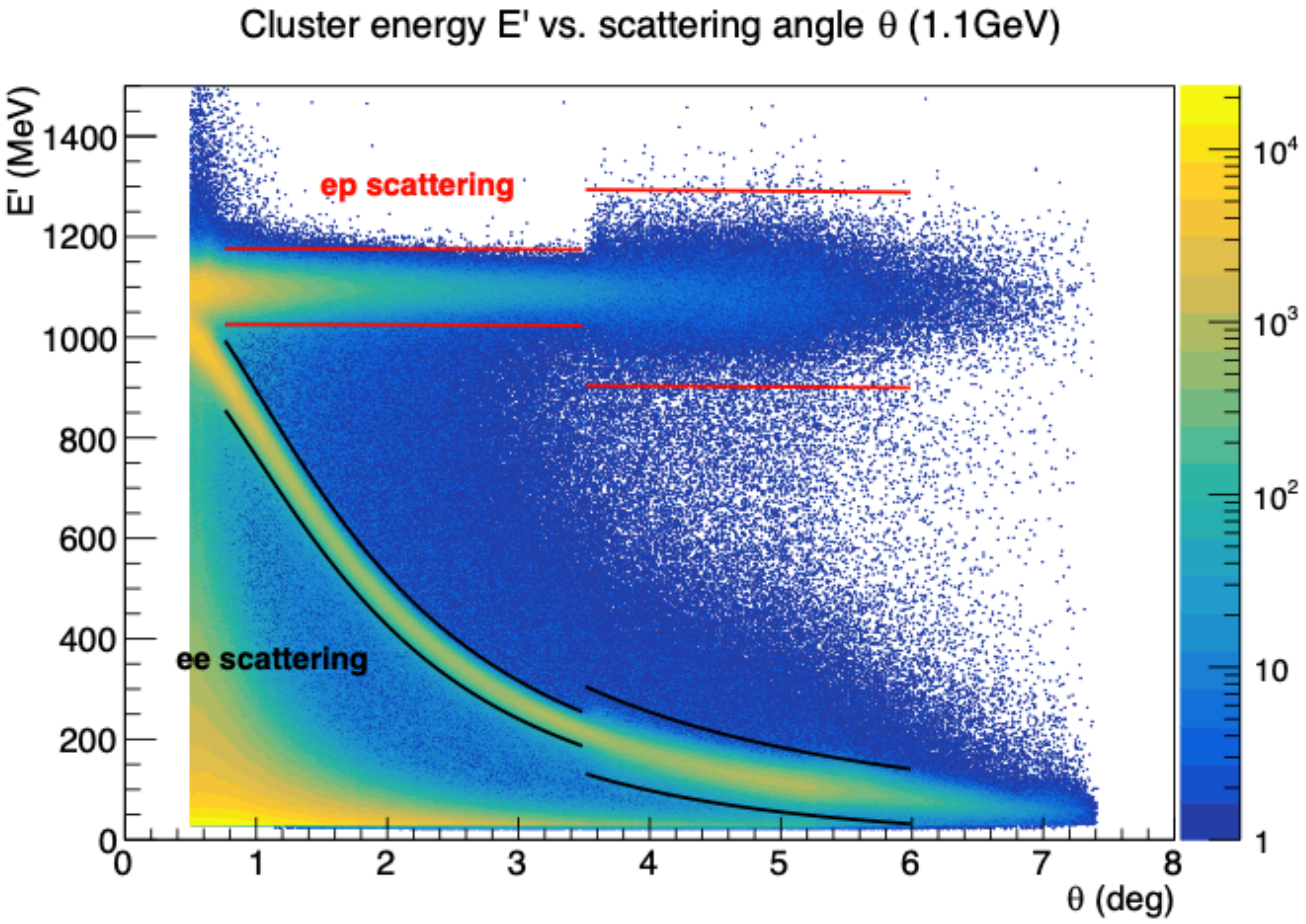
Analysis – Event Selection

Event selection method

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

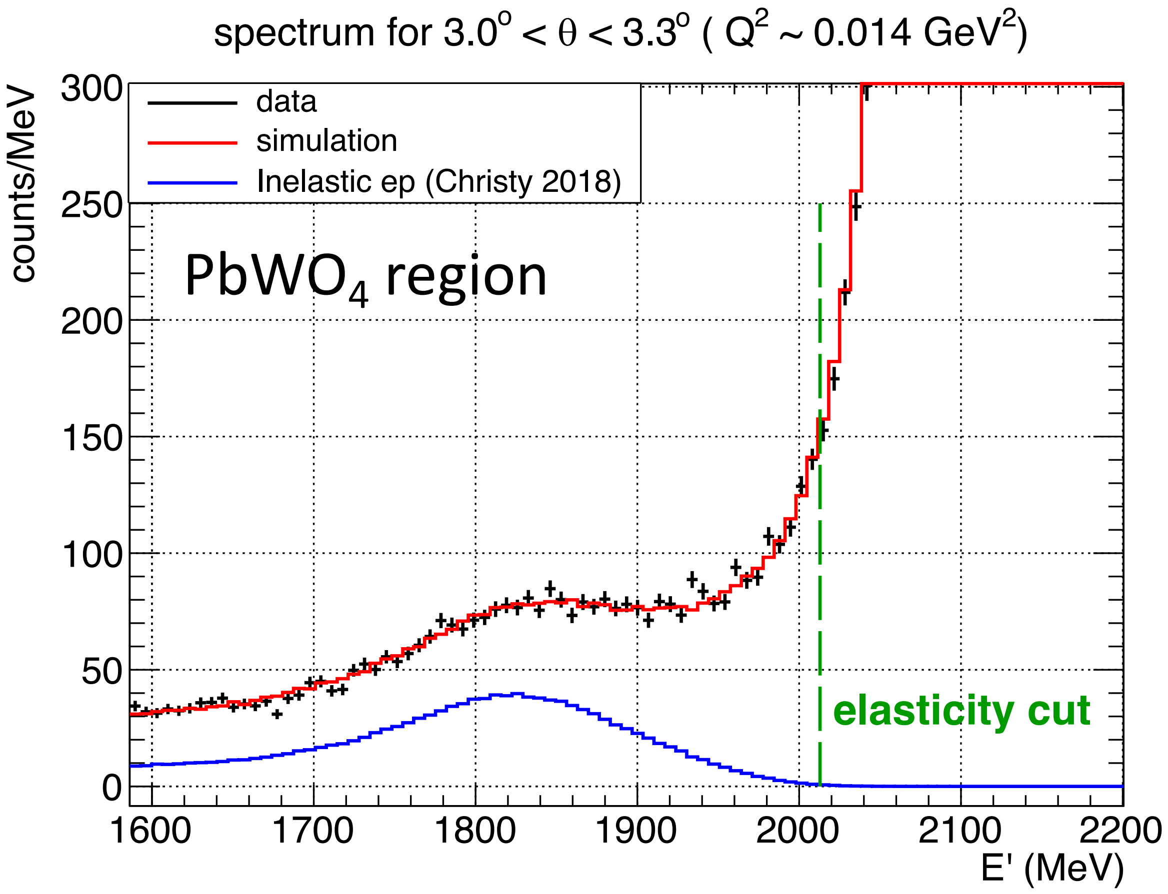
2. For *ep* and *ee* events, apply angle dependent energy cut based on kinematics
    1. Cut size depend on local detector resolution

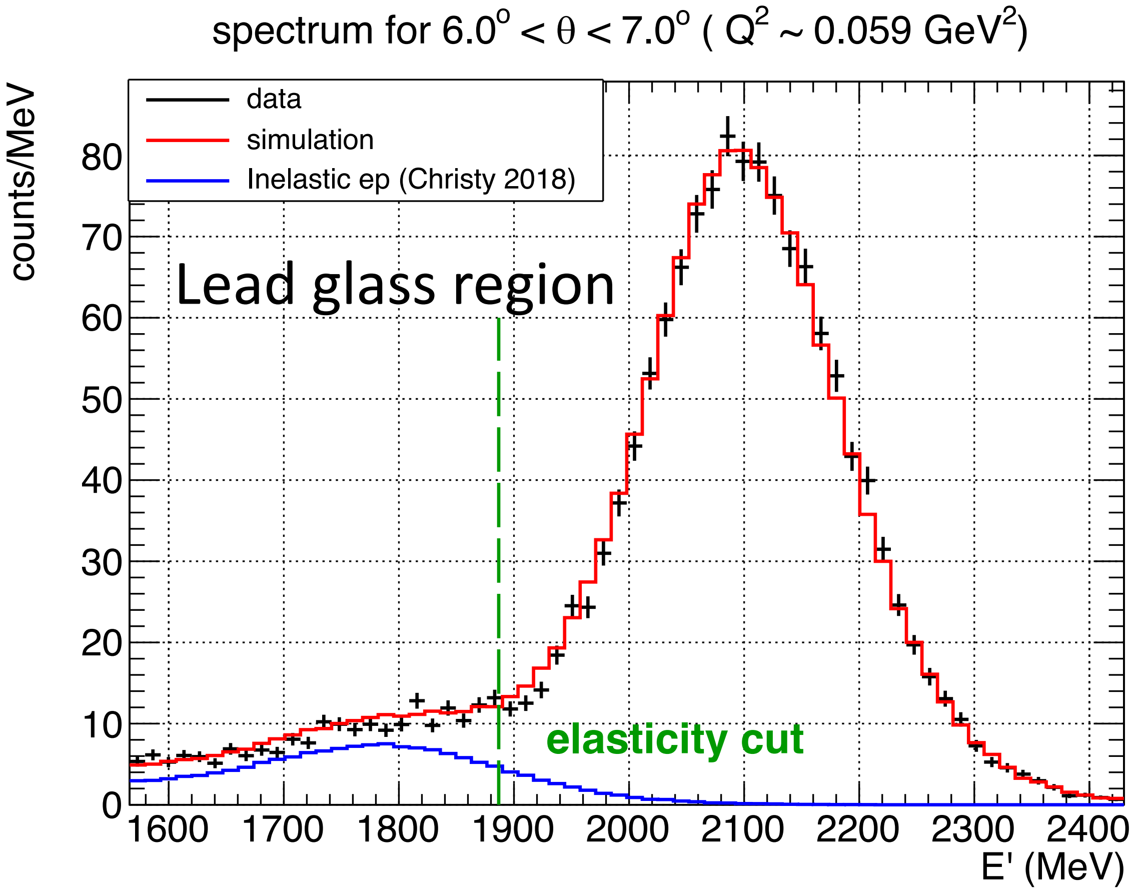
3. For *ee*, requiring double-arm events, apply additional cuts
    1. Elasticity
    2. Co-planarity
    3. Vertex z



Analysis – Inelastic ep Contribution

- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5^o), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region





M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)

Extraction of *ep* Elastic Scattering Cross Section

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

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

- Method 1: bin by bin method – taking *ep/ee* counts from the same angle bin
  - ➢ Cancellation of energy independent part of the efficiency and acceptance
  - ➢ Limited converge due to double arm Møller acceptance

- Method 2: integrated Moller method – integrate Møller in a fixed angle range and use it as common normalization for all angle bins

- Luminosity cancelled from both methods

Radiative Correction

- Radiative effects corrected by Monte-Carlo method:

  1. Geant4 simulation package with full geometry setup
  2. event generators with complete calculations of radiative corrections[1,2], include emission of radiative photons
  3. Consistent results between generators
  4. Include TPE effect[3], less than 0.2% for *ep* in PRad kinematic range
  5. Iterative procedure applied for radiative correction

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

1. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (fully beyond ultra relativistic approximation)
2. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001

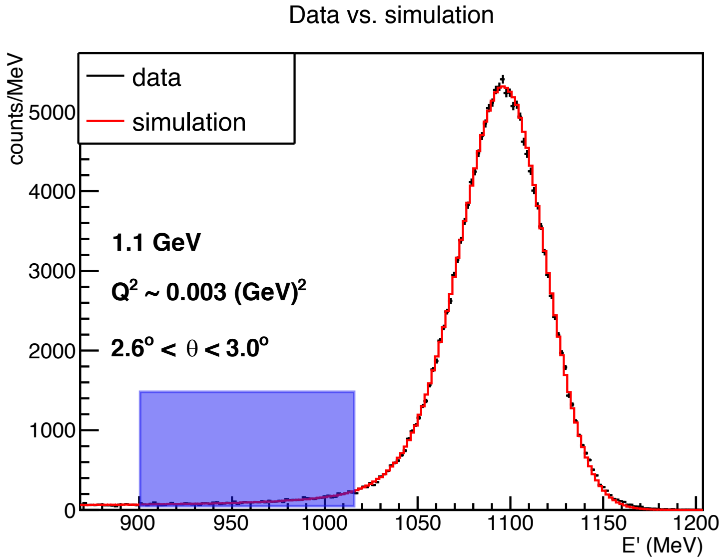
3. O. Tomalak, Few Body Syst. **59**, no. 5, 87 (2018)

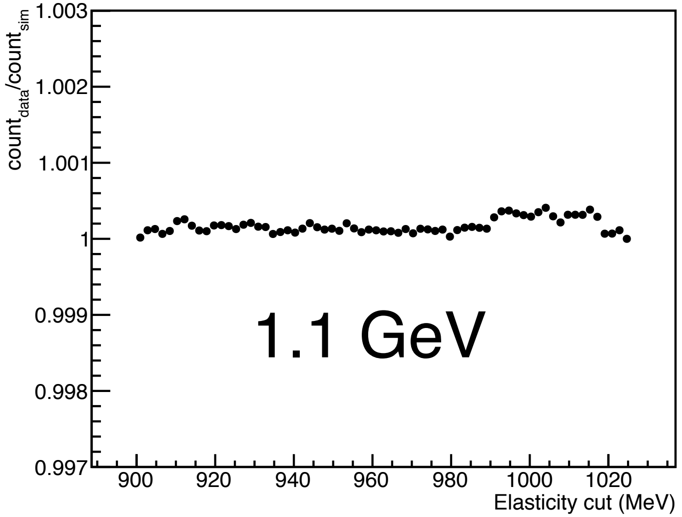
Systematic Uncertainties

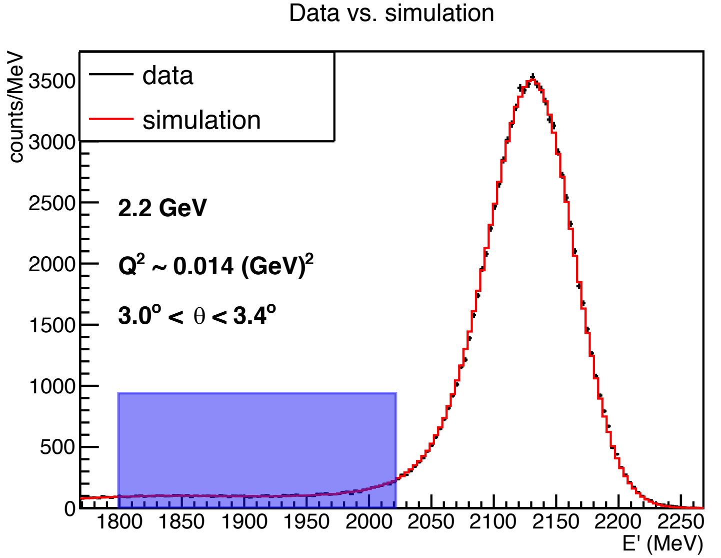
- For PRad, systematic uncertainties may come from:
  1. Event selection (elasticity cuts, co-planarity cuts…)
  2. Radiative correction
  3. Detector efficiencies (GEM and HyCal)
  4. Beam-line background (Halo hitting collimator, residual gas…)
  5. HyCal energy calibration
  6. Detector position
  7. Beam energy
  8. Inelastic *ep* contribution
  9. Assumed magnetic form factors during the G_E extraction
  10. …

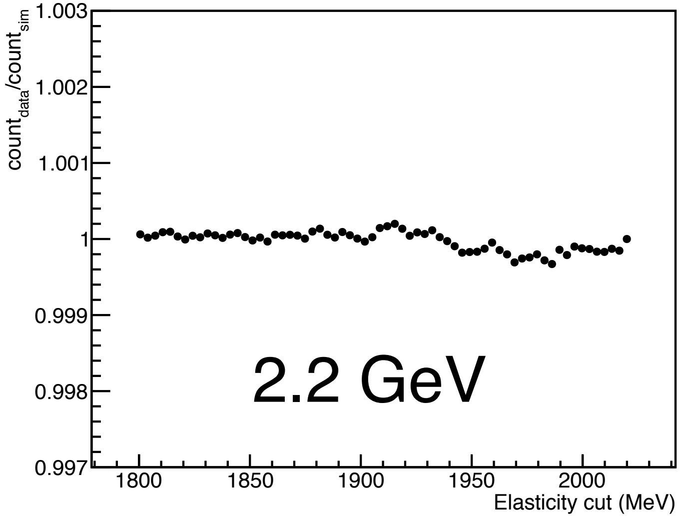
Systematic Uncertainties
(Example of Event Selection)

- Changing elasticity cut at the radiative tail and obtain different sets of cross section results
- Sensitivity on cross section: typically bounded by +/- 0.15%
- Mostly due to non-uniformity of HyCal modules

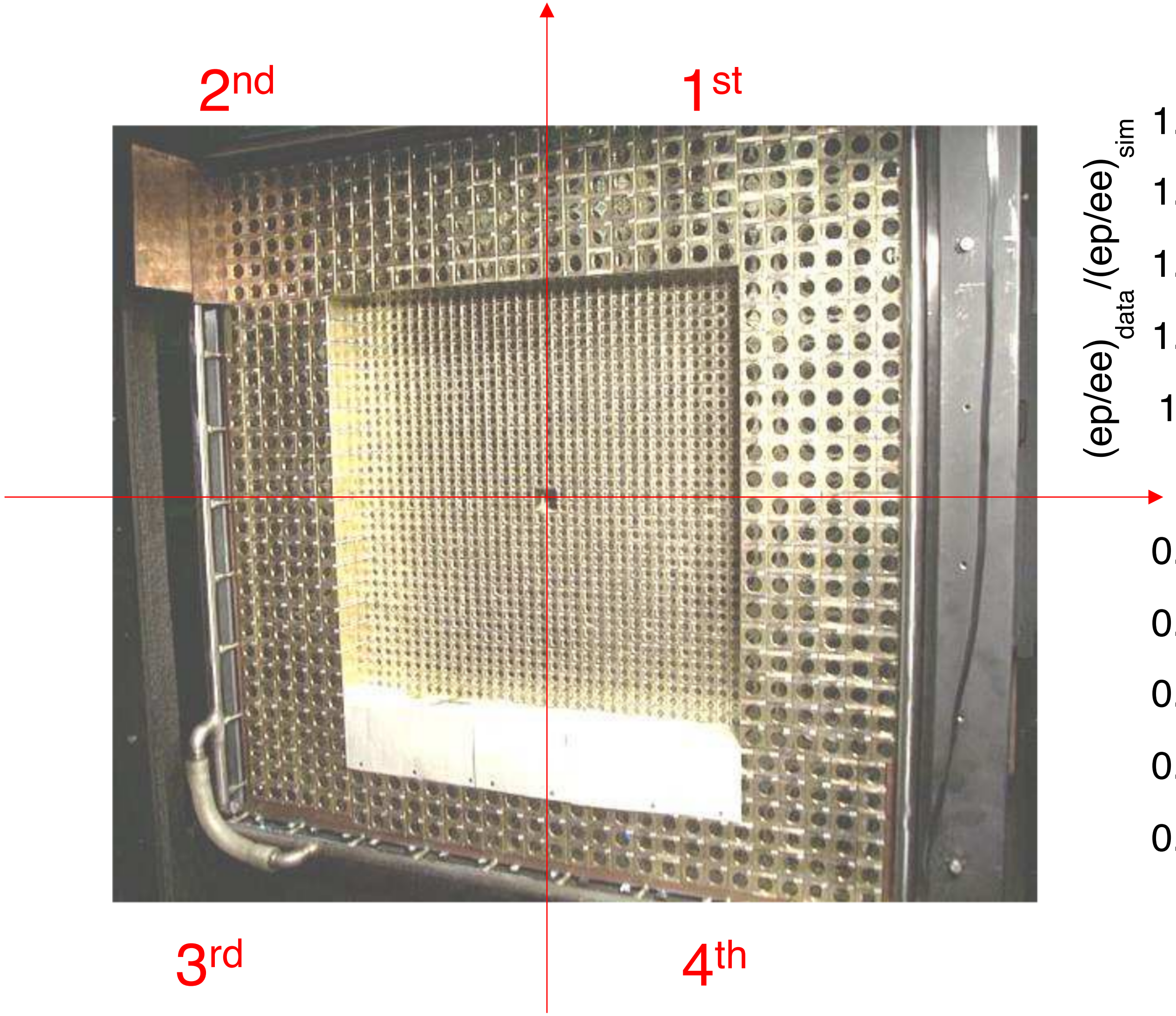


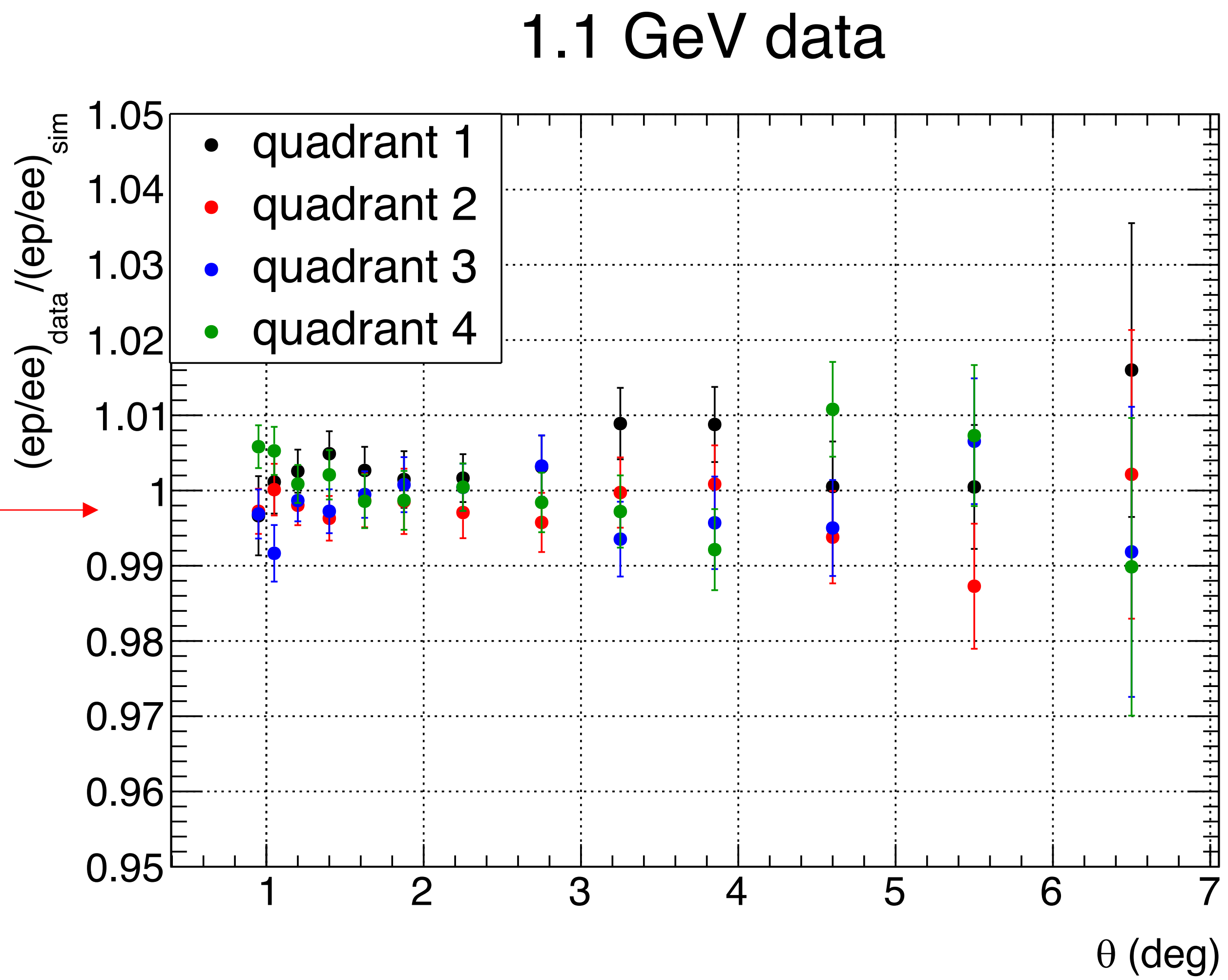






Checking Systematics – Sector Dependence





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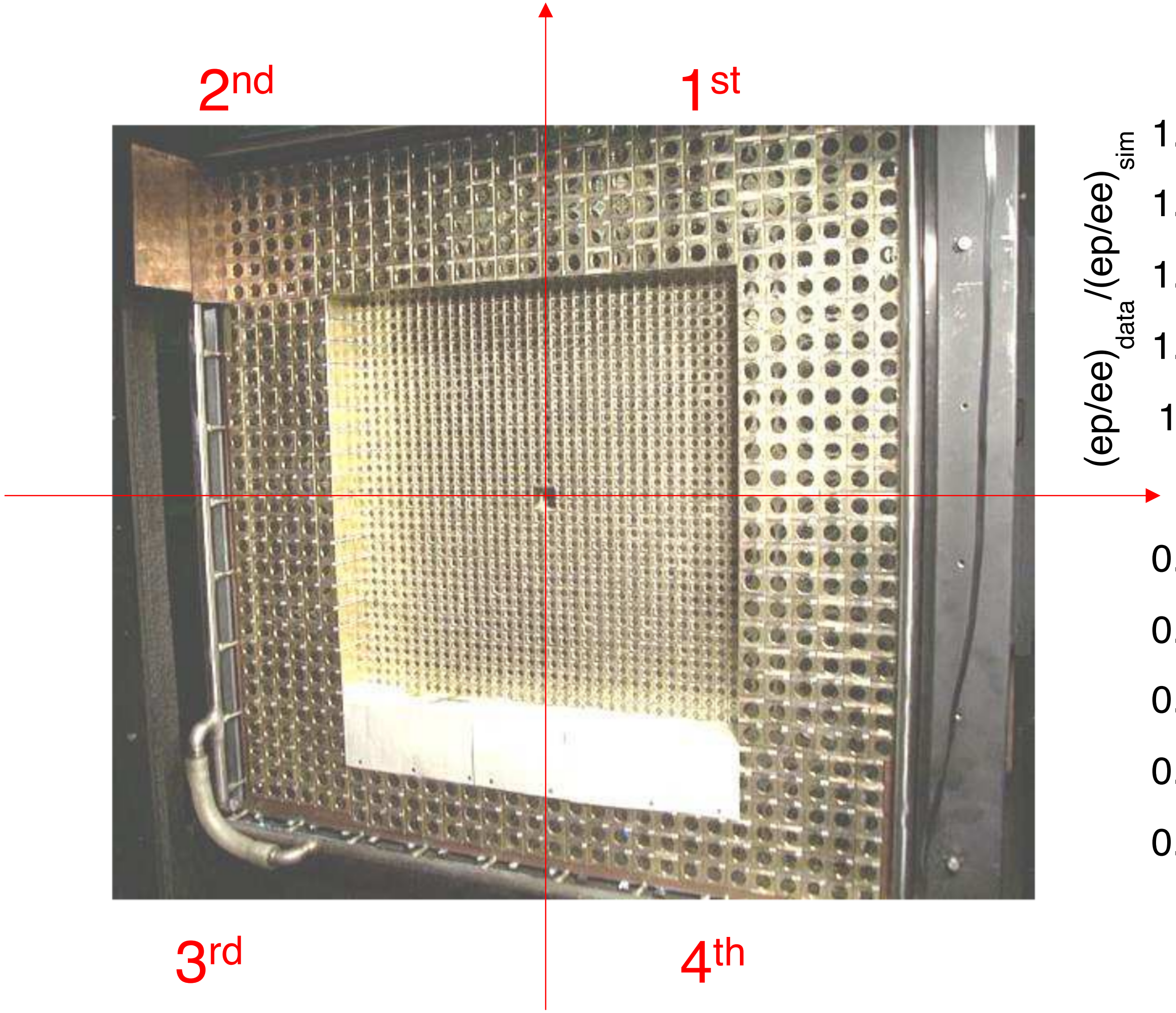
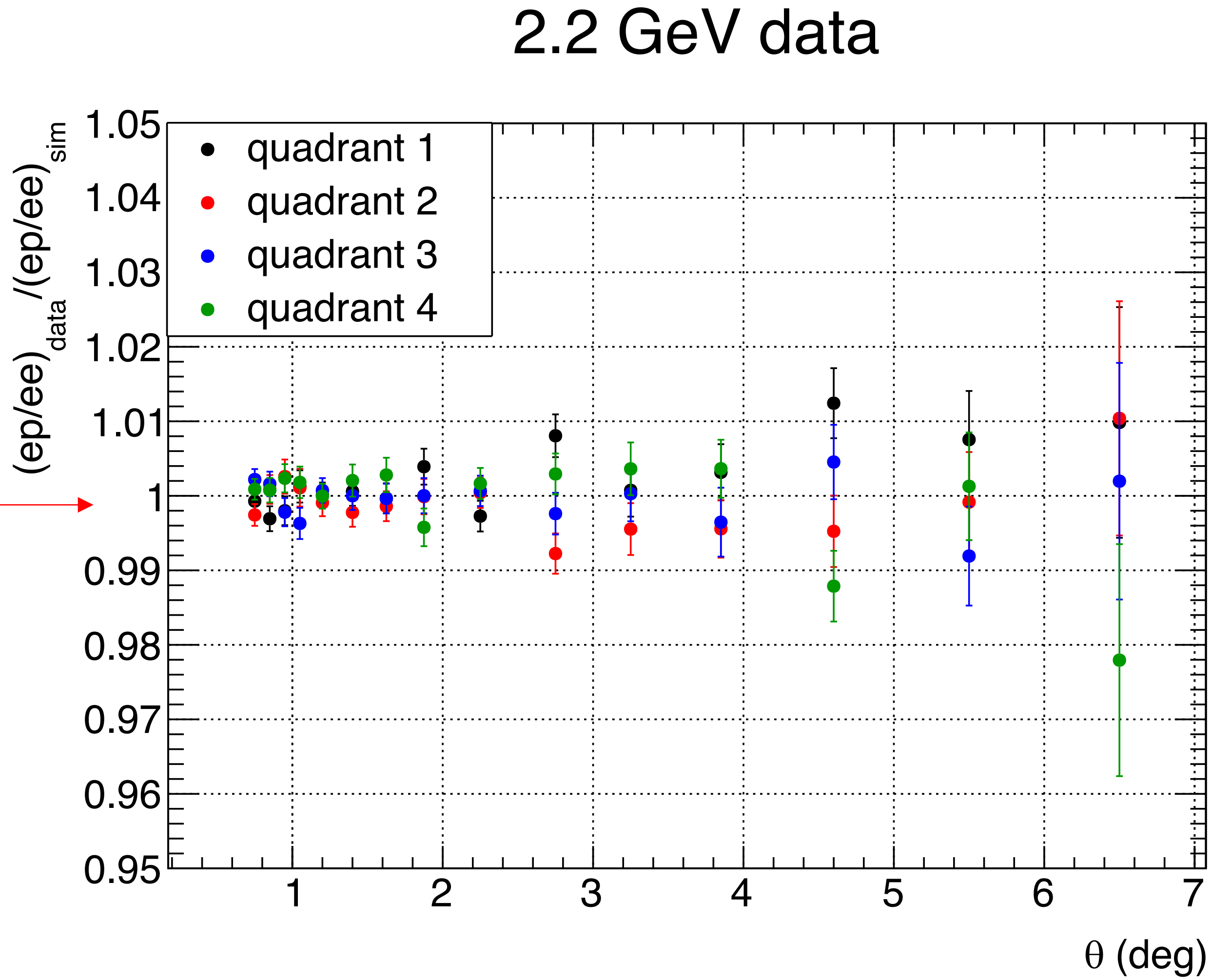
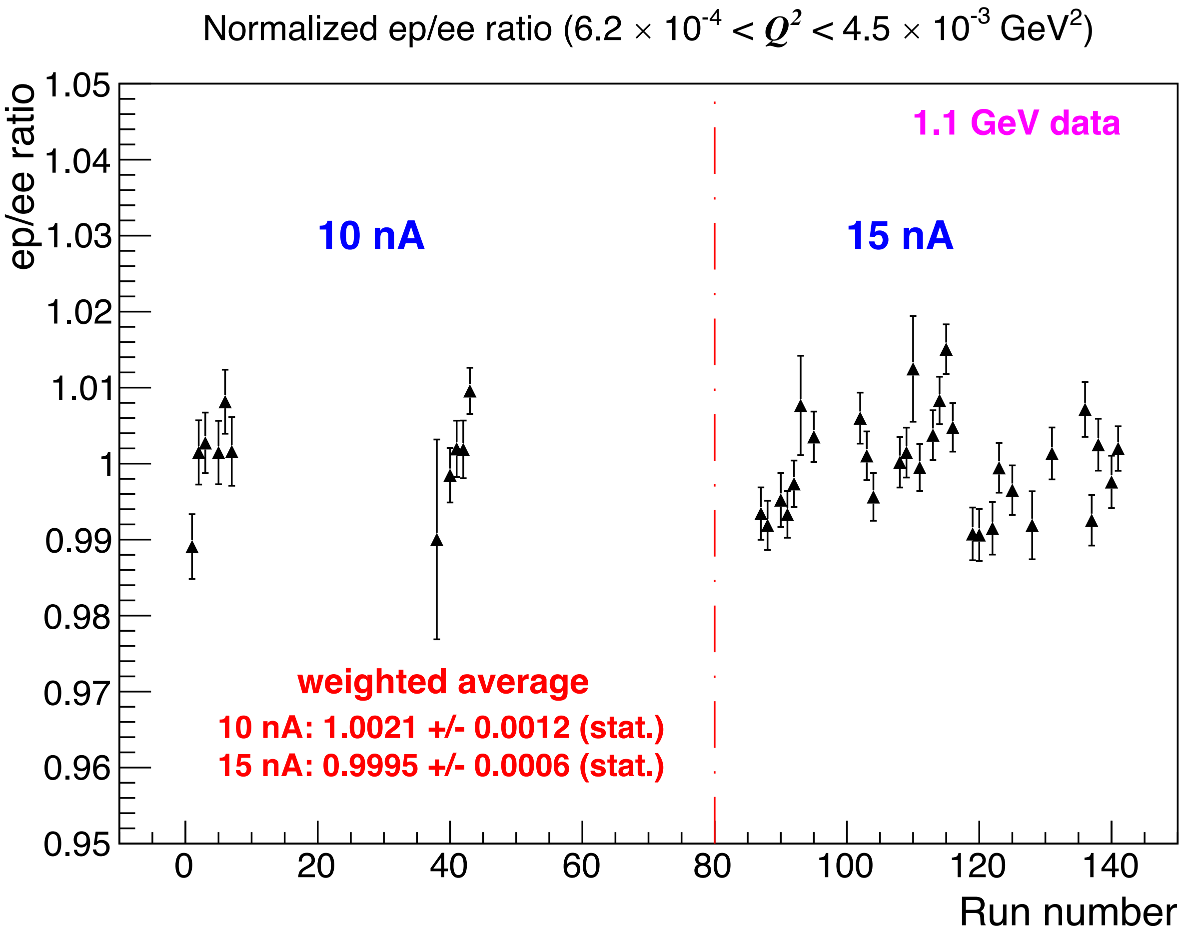
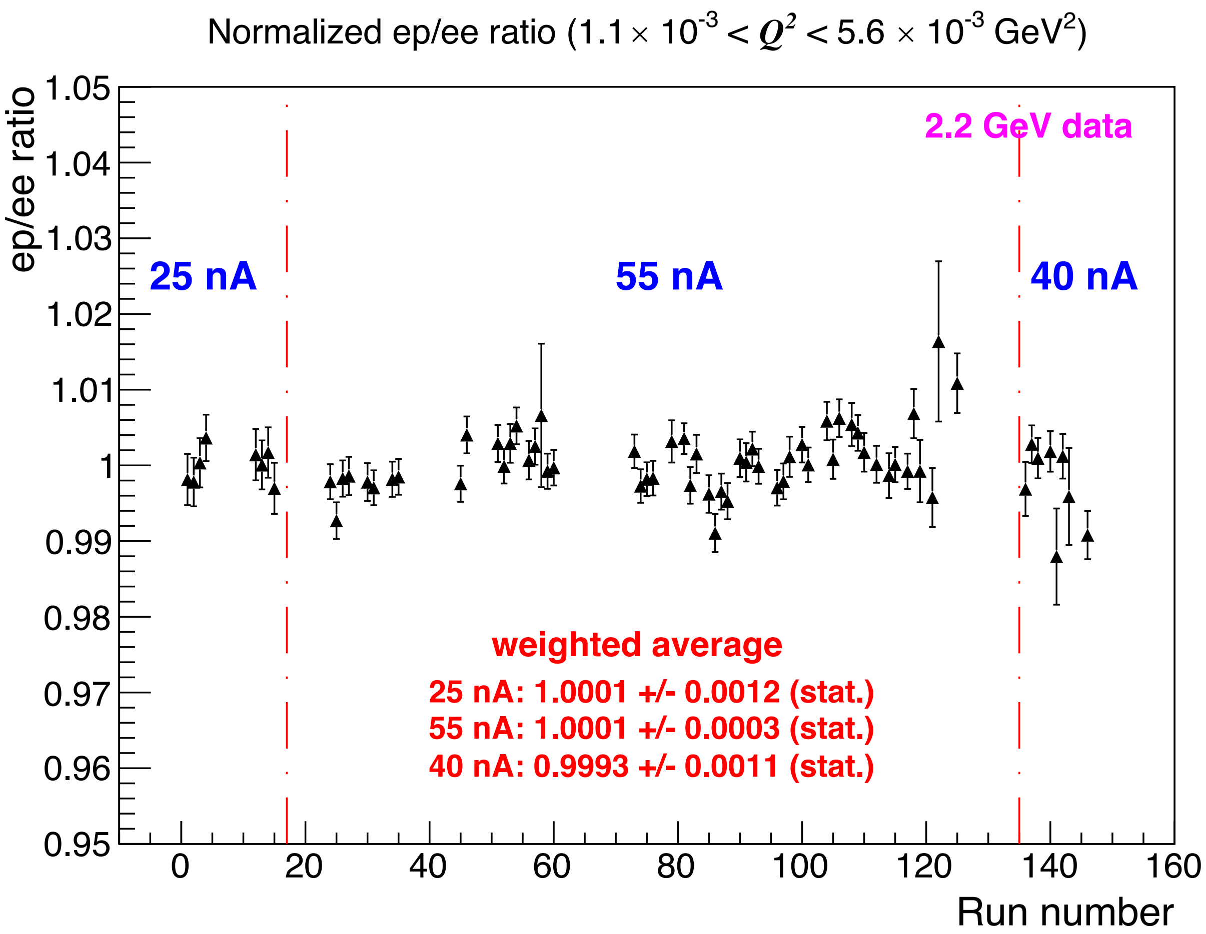




Checking Systematics – Stability vs. Run



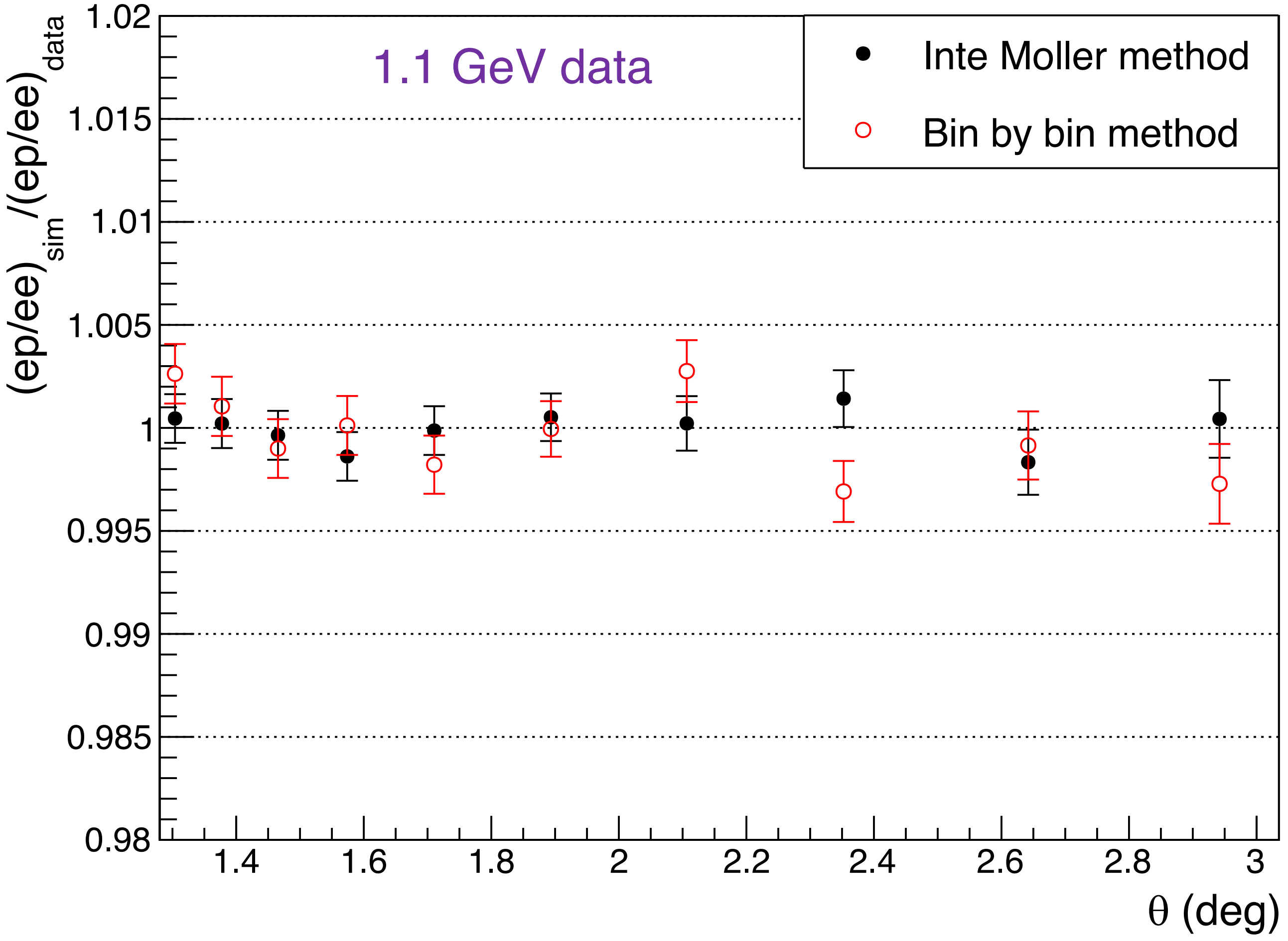


Checking Systematics – Different methods of Forming *ep/ee* ratio

- Method 1: bin by bin method – taking ep/ee counts from the same angle bin
  - ➢ Cancellation of GEM efficiency
  - ➢ May introduce Q^2 dependent uncertainty from Moller
  - ➢ Limited converge due to double arm Moller acceptance

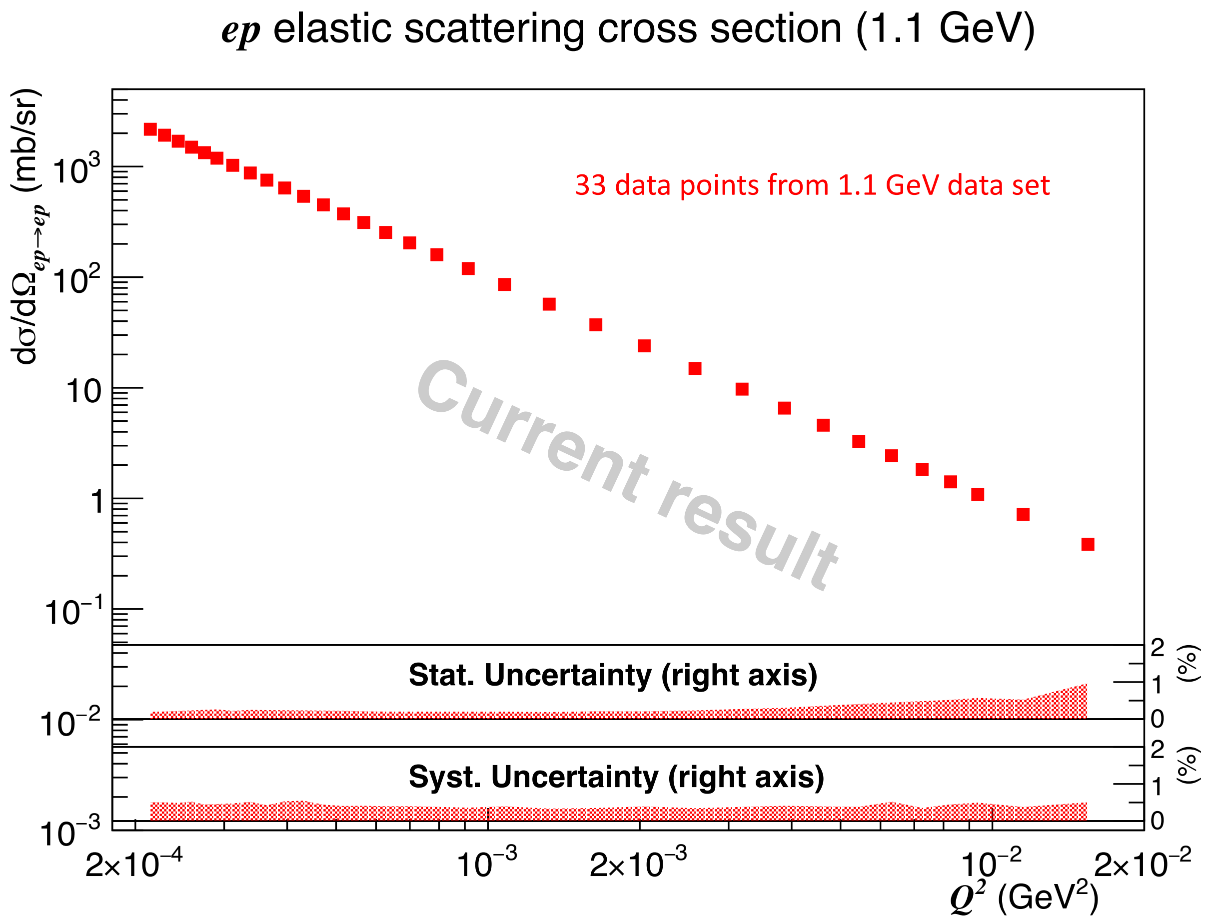
- Method 2: integrated Moller method – integrate Moller in a fixed angle range and use it as common normalization for all angle bins
  - ➢ Moller uncertainty only affects normalization
  - ➢ Need to correct for GEM efficiency

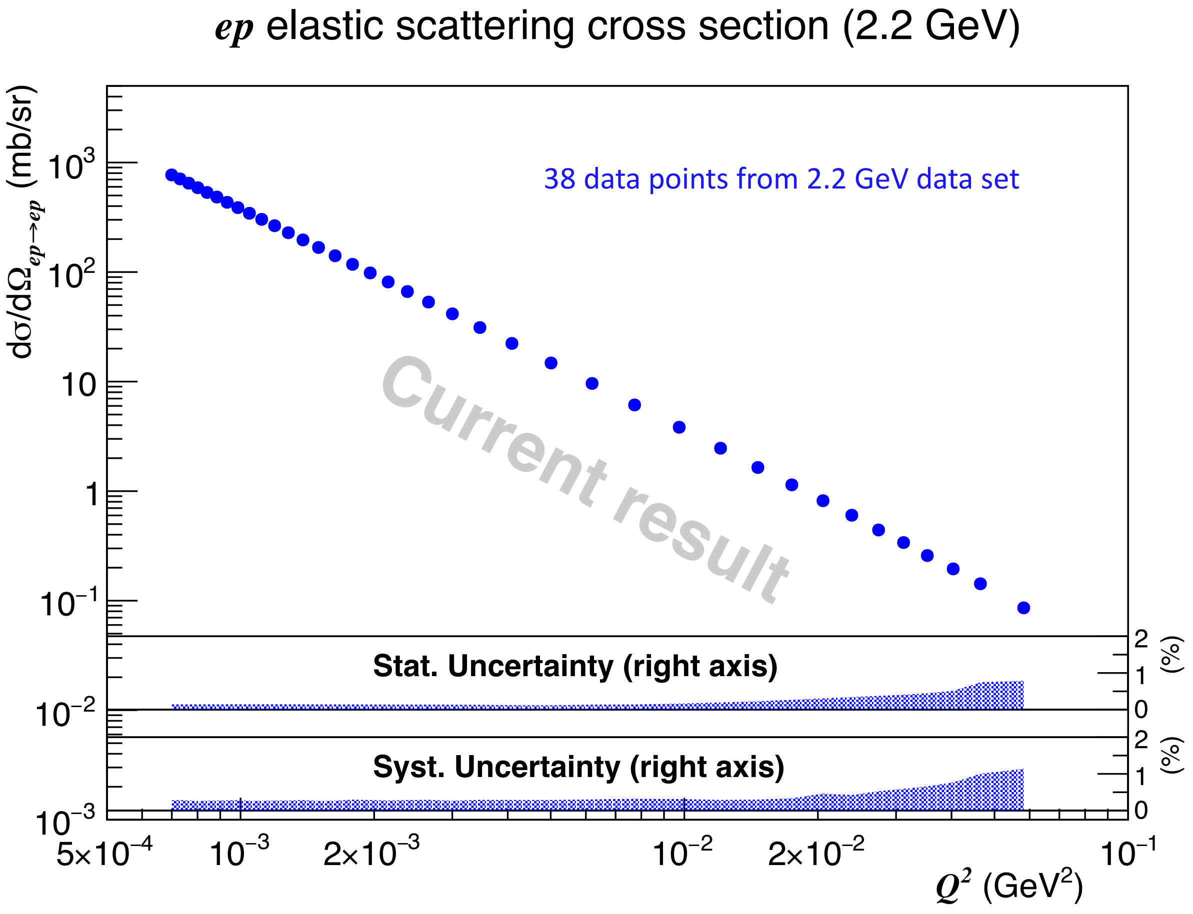
- Luminosity cancelled in both methods



Extracted Differential Cross Sections (Current)

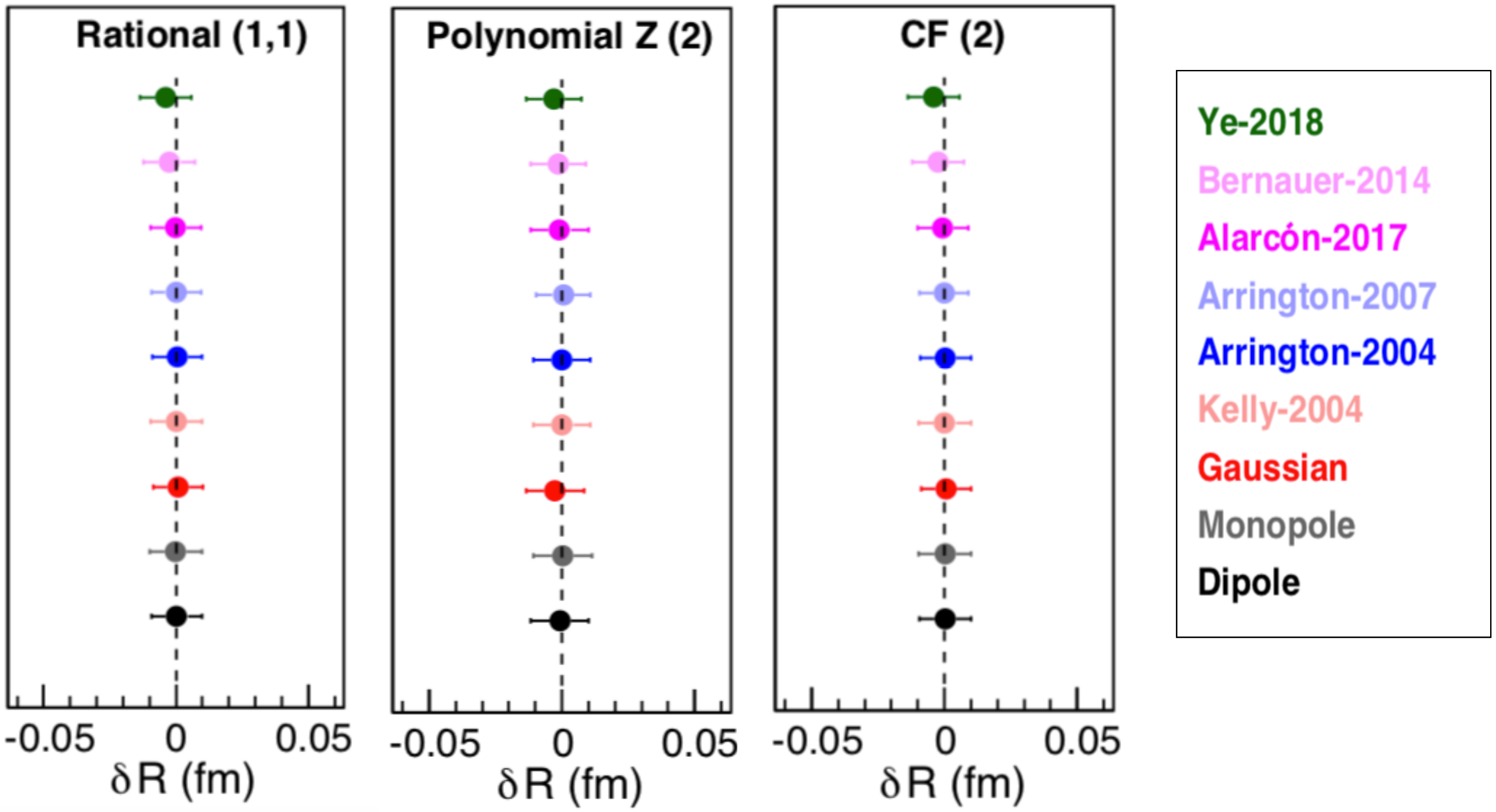
- Extracted differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data (current)
- Statistical uncertainties at current stage: ~0.15% for 2GeV, ~0.2% for 1GeV per point
- Systematic uncertainties at current stage: 0.3% ~ 1.1% for 2GeV, 0.3% ~0.5% for 1GeV





Searching the Robust fitters

- Various fitters tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties:
  - X. Yan *et al.* Phys. Rev. C98, 025204 (2018)
- Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties



Rational (1,1)

$$p_0 \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

2nd order z transformation

$$p_0(1 + p_1 z + p_2 z^2)$$

$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

2nd order continuous faction

$$p_0 \frac{1}{1 + \frac{p_1 Q^2}{1 + p_2 Q^2}}$$

PRad Collaboration Institutional List

- Currently 17 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 , Russia
MIT

- Graduate students:

Chao Peng (Duke)
Weizhi Xiong (Duke)
Li Ye (MSU)
Xinzhan Bai (UVa)
Abhisek Karki (MSU)

- Postdocs:

Chao Gu (Duke)
Xuefei Yan (Duke)
Mehdi Meziane (Duke)
Zhihong Ye (Duke)
Maxime Lavilain (NC A&T)
Krishna Adhikari (MSU)
Rupesh Silwal (MIT)

Summary

- After almost 10 years, the proton radius puzzle still unresolved
- The PRad collaboration carried out a first electron scattering experiment using a non-magnetic spectrometer approach – calorimeter and GEMs
  1. Covers two orders of magnitude in low Q^2 with the same detector setting
  2. Unprecedented low Q^2 data set (~2×10^{-4} GeV^2) has been collected in *e-p* elastic scattering experiment
  3. Simultaneous measurements of *ep* and *ee* scattering to reduce systematics
  4. Novel use of a window-less cryogenically cooled hydrogen gas target

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