A High Precision Measurement of the Proton Charge Radius at JLab

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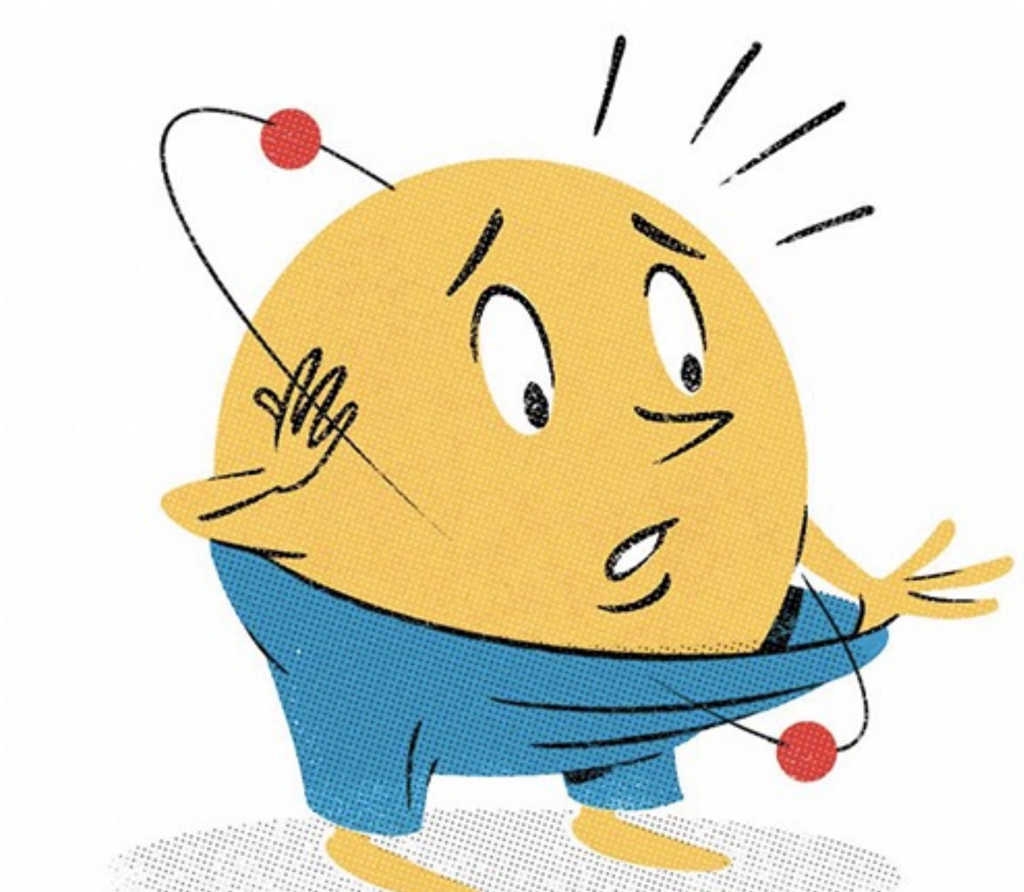
for the PRad Collaboration

APS GHP Meeting 2021
April 16^{th} 2021

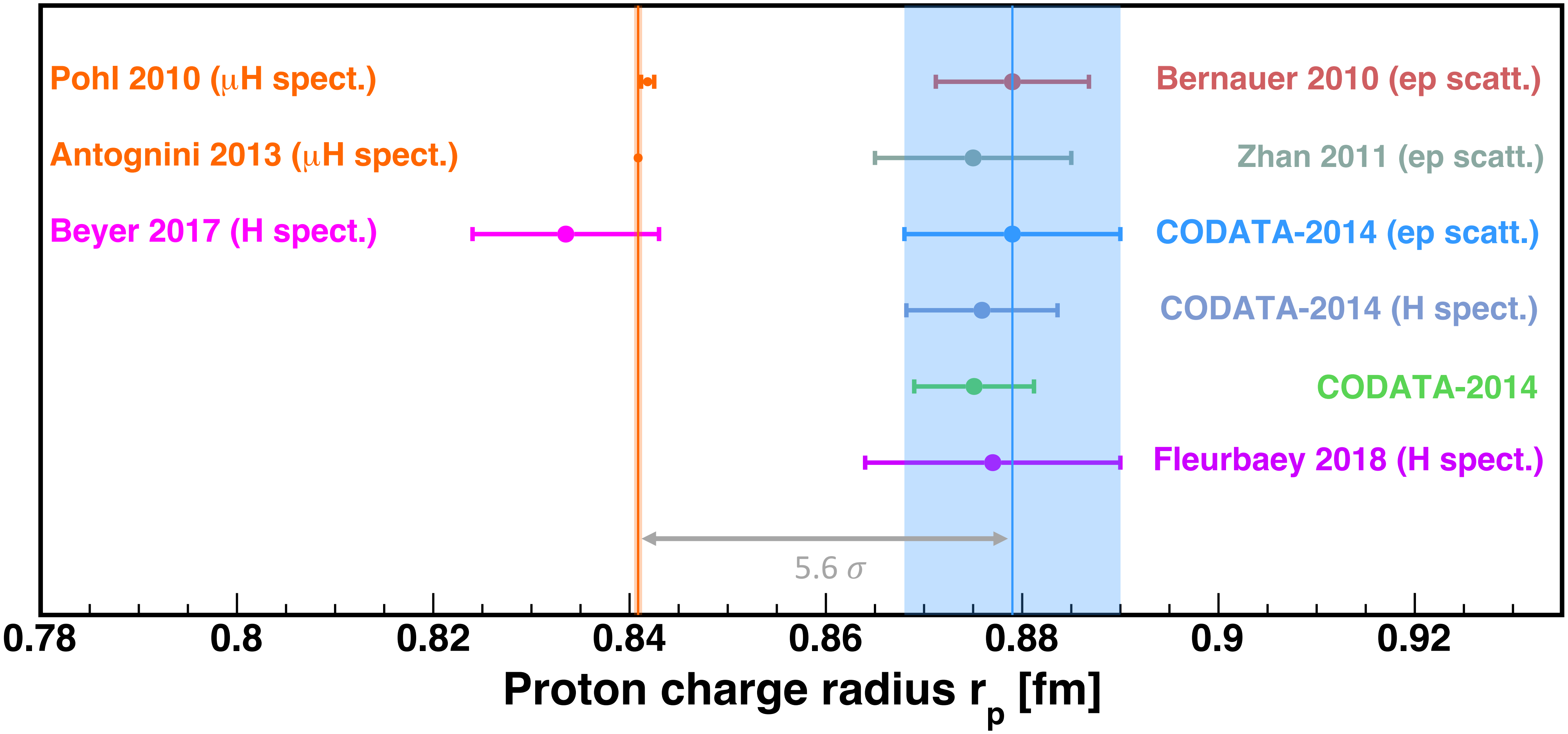
Outline

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



New York Times

Proton Charge Radius Puzzle in 2018



ep Elastic Scattering

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

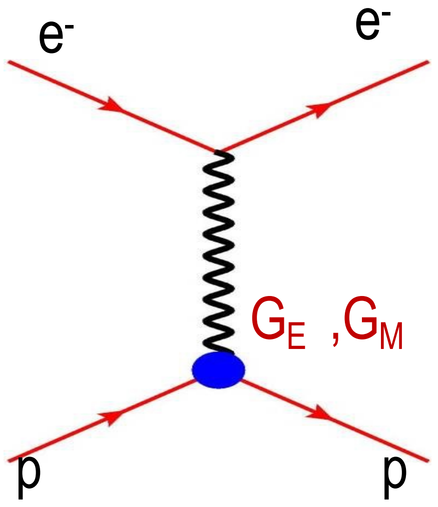
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

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

- Structure-less proton:

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

- 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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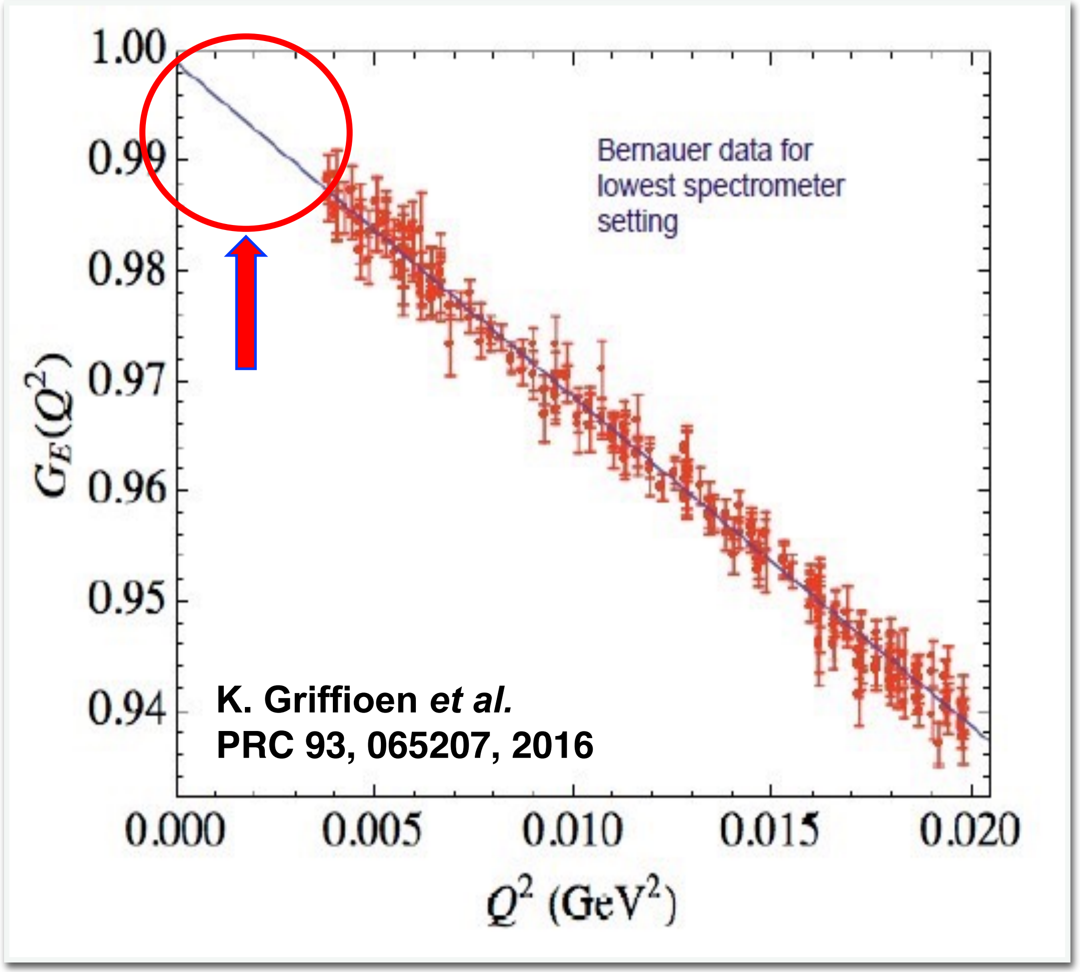
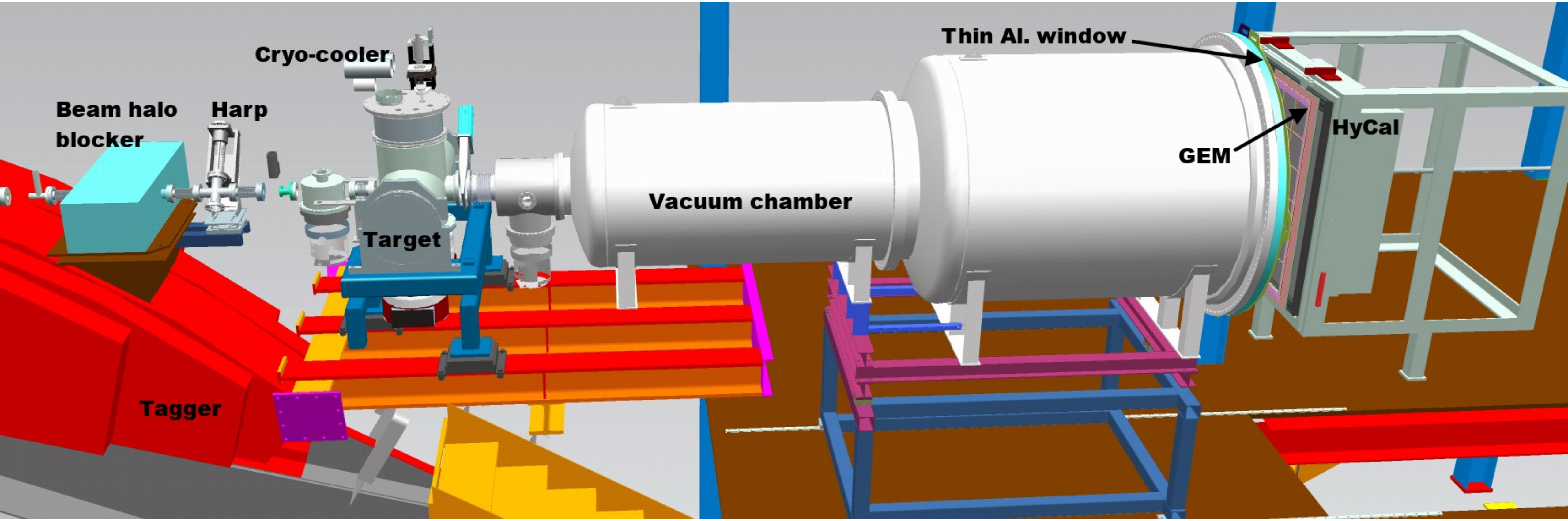


PRad Experimental Apparatus

Hall B



Major Steps in Analysis

1. Calibration
2. Event Selection
3. Background Subtraction
4. Getting *ep/ee* Ratio
5. Radiative Correction
6. Elastic *ep* cross section
7. Proton Electric Form Factor
8. Fitting for the Radius

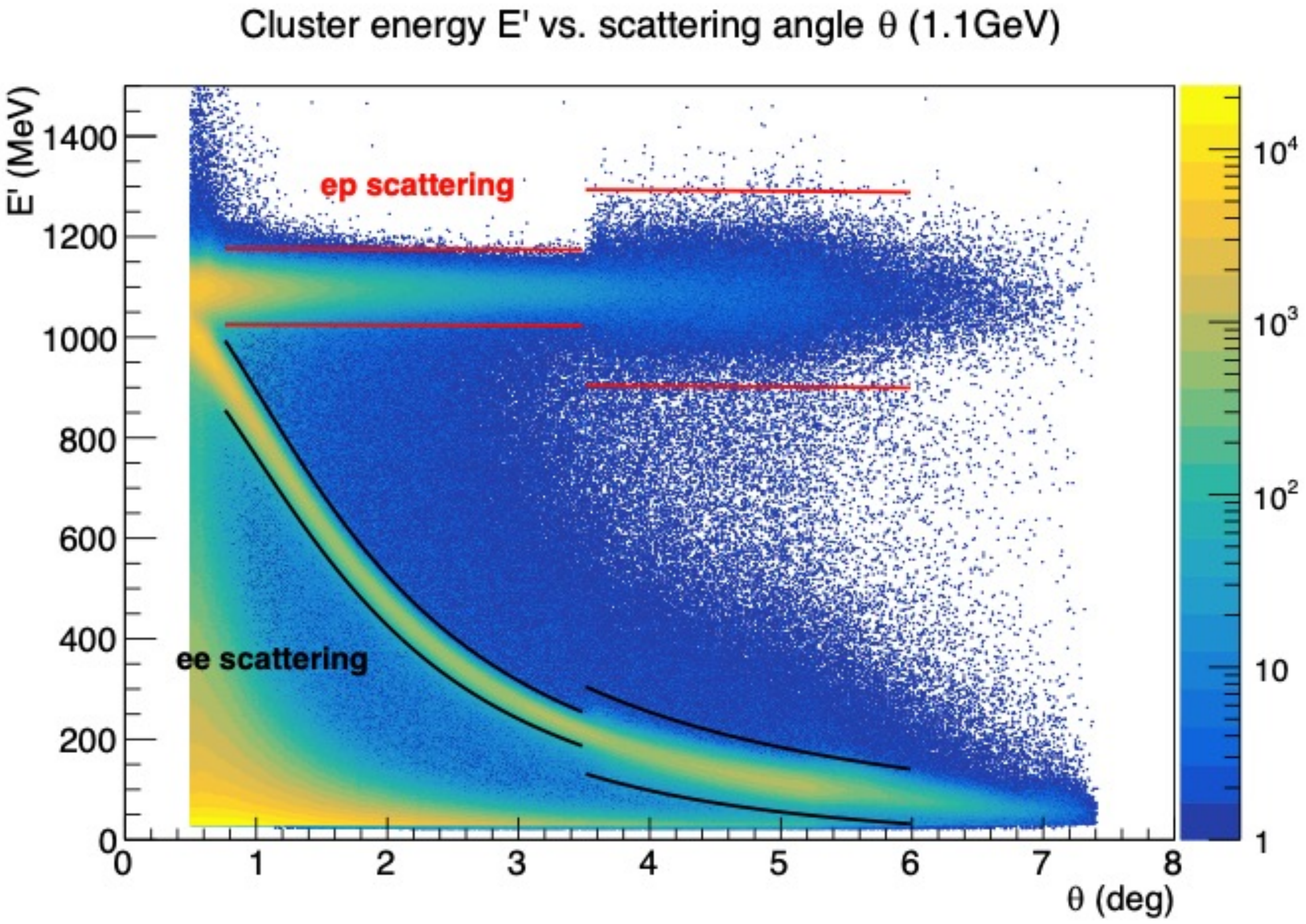
Analysis – Event Selection

Event selection method

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

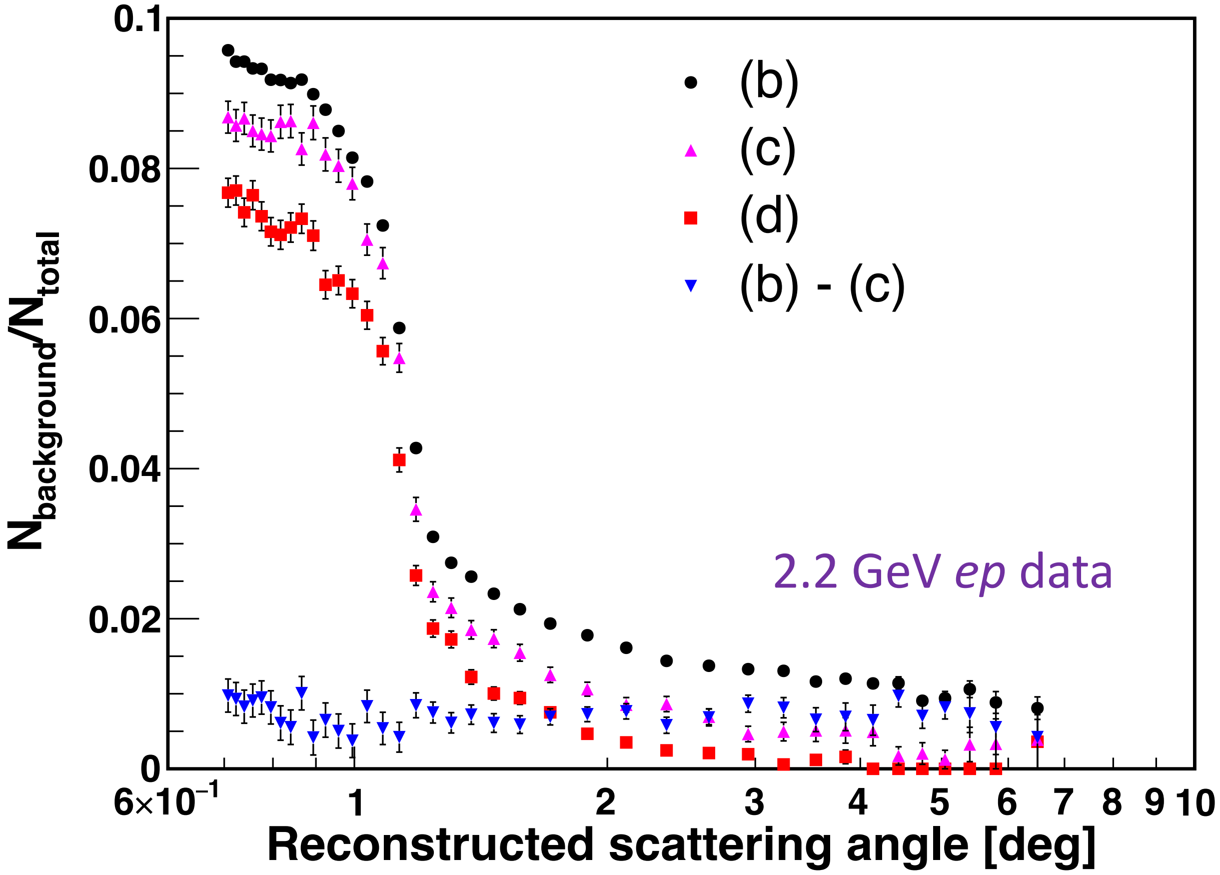
2. For *ep* and *ee* events, apply angle dependent energy cut based on kinematics
   1. Cut size depend on local detector resolution

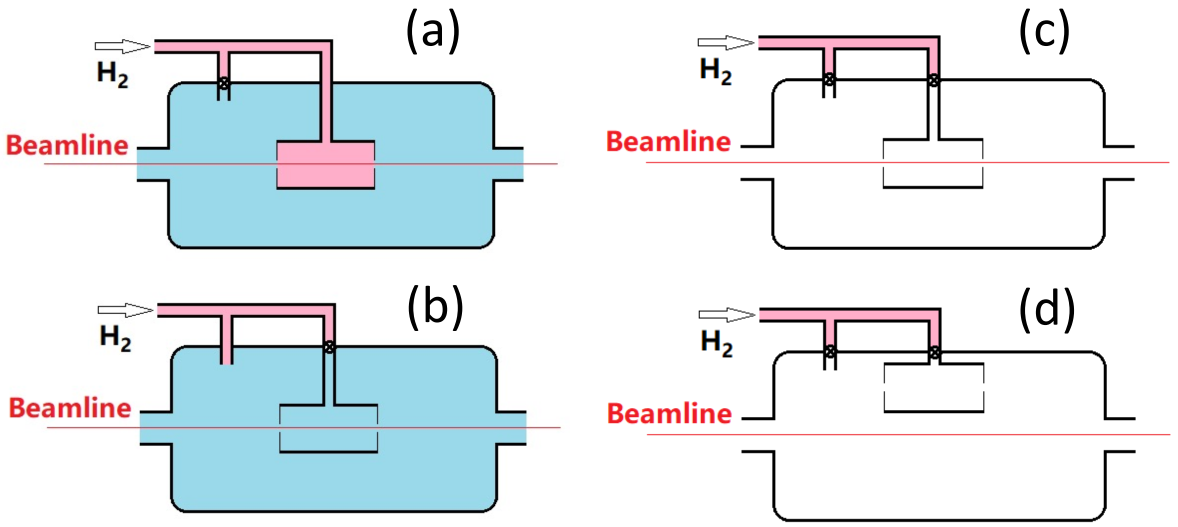
3. For *ee*, requiring double-arm events, apply additional cuts
   1. Elasticity
   2. Co-planarity
   3. Vertex z



Analysis – Background Subtraction (2.2 GeV)

- *ep* background rate ~ 10% at forward angle (<1.1 deg, dominated by upstream beam halo blocker), less than 2% otherwise
- ee background rate ~ 0.8% at all angles





Residual hydrogen gas: hydrogen gas filled during background runs

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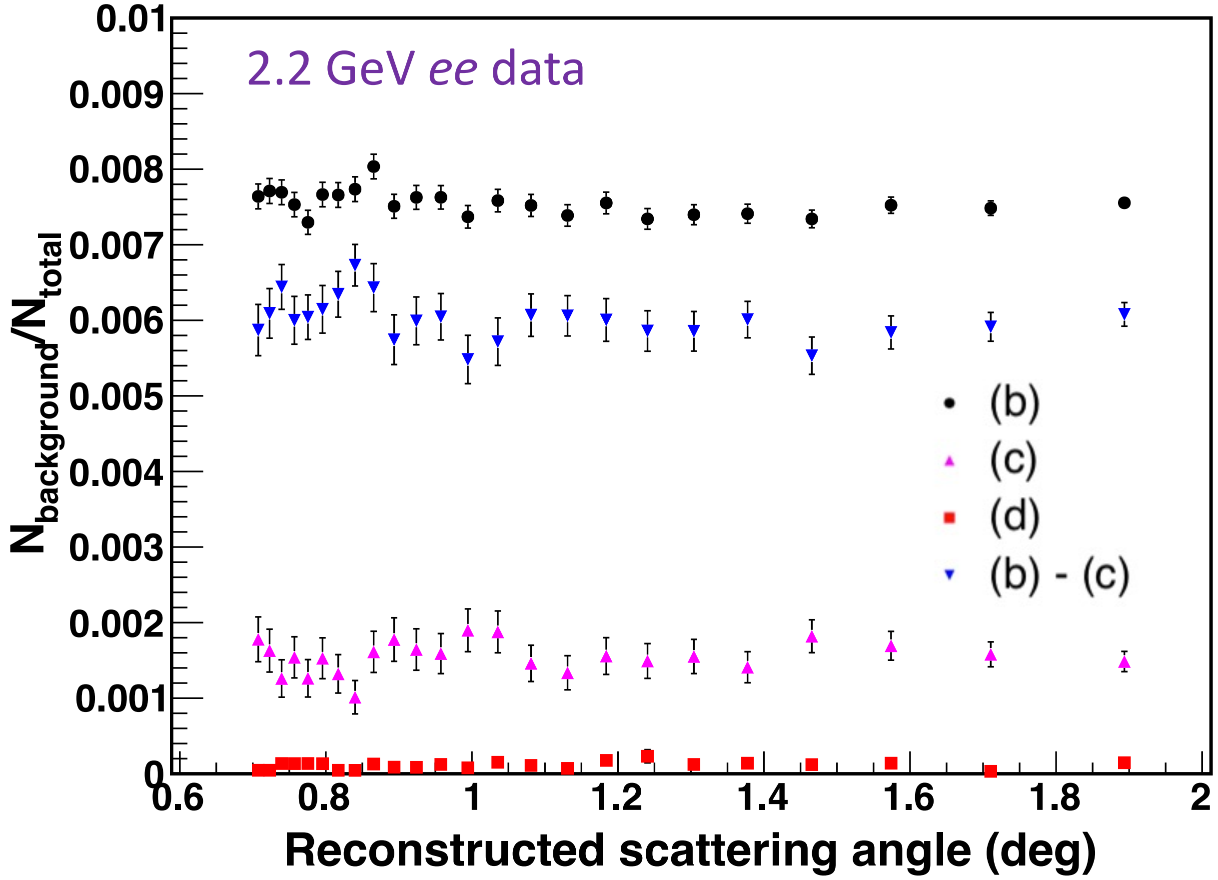
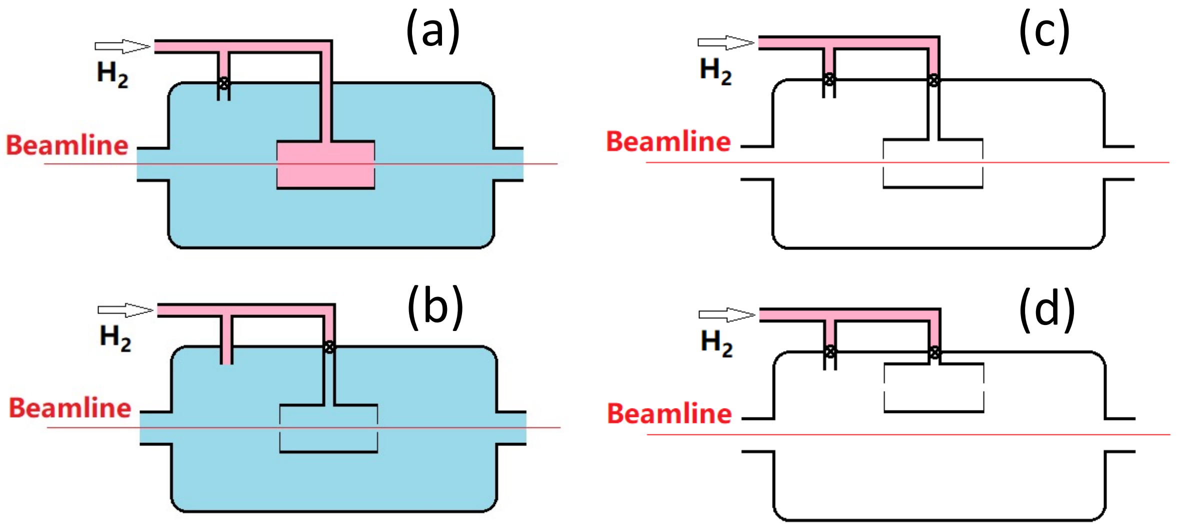
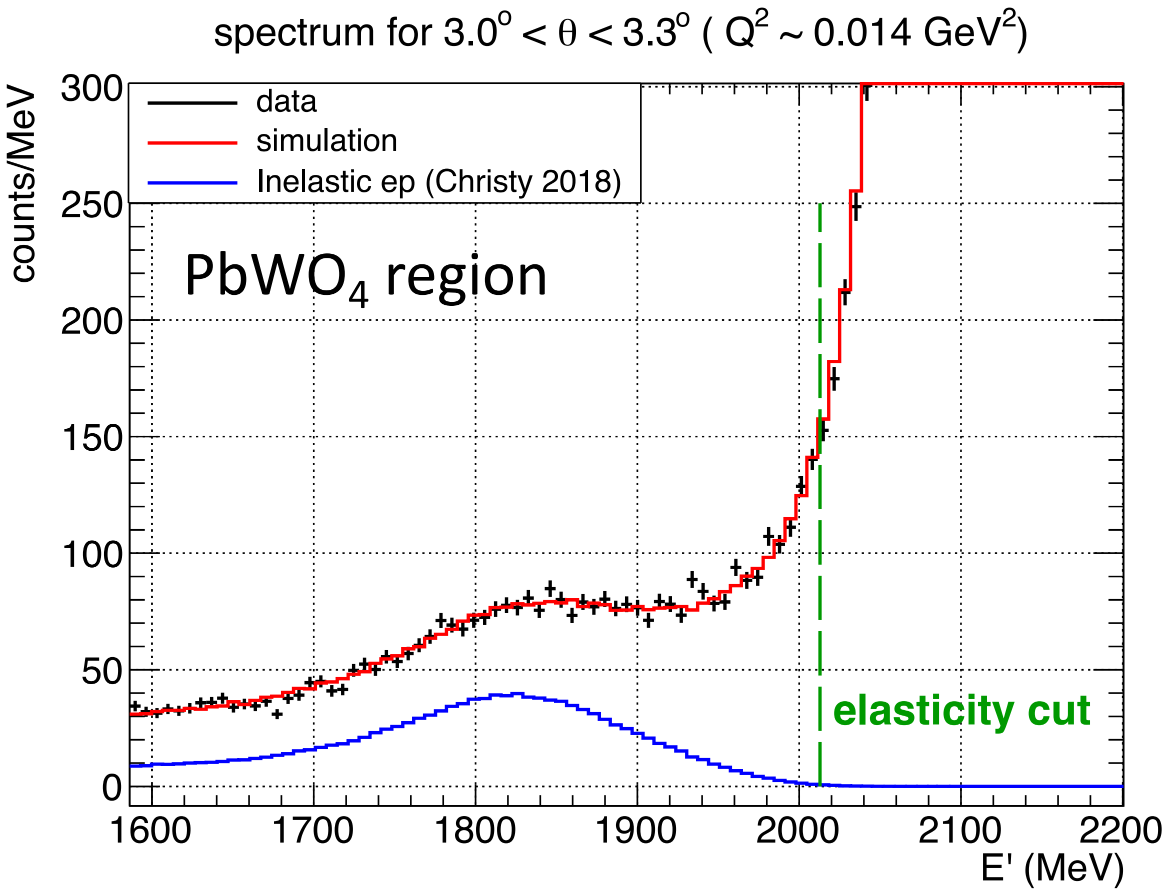


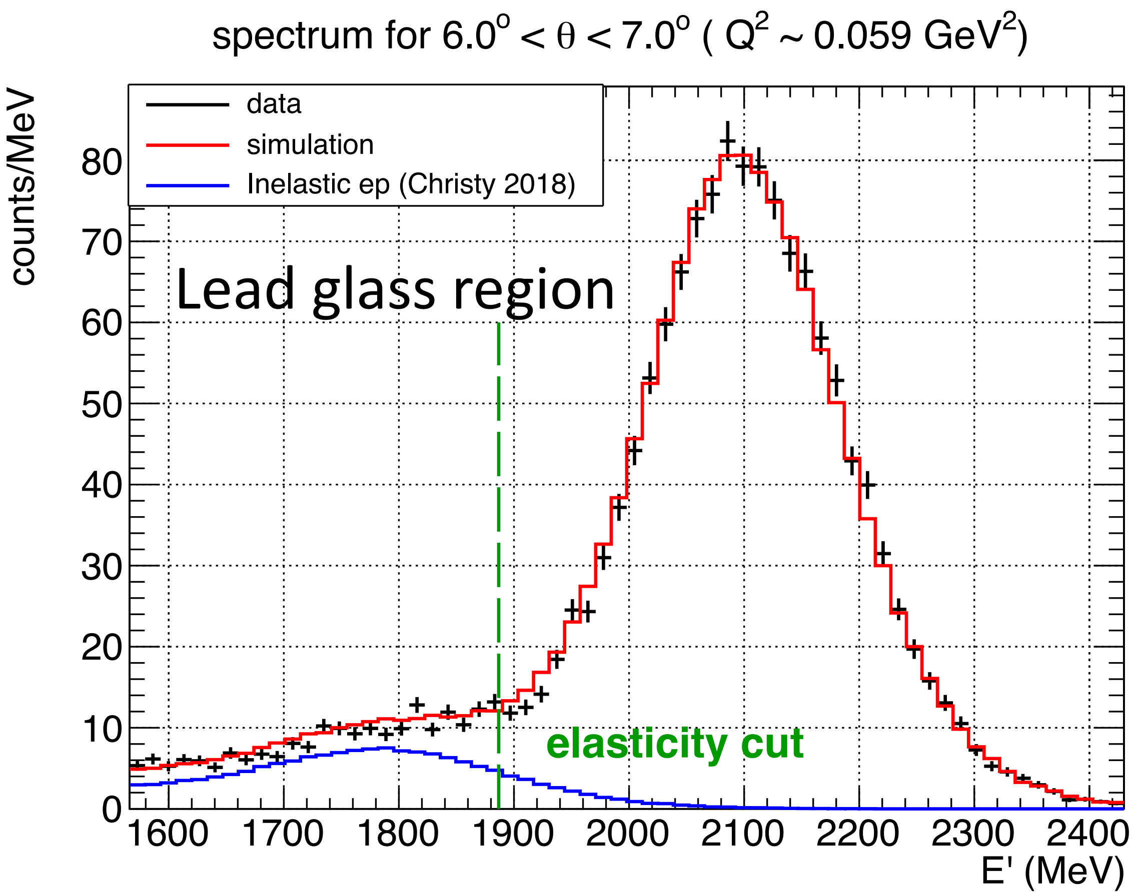


Residual hydrogen gas: hydrogen gas filled during background runs

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°), 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:

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

- 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

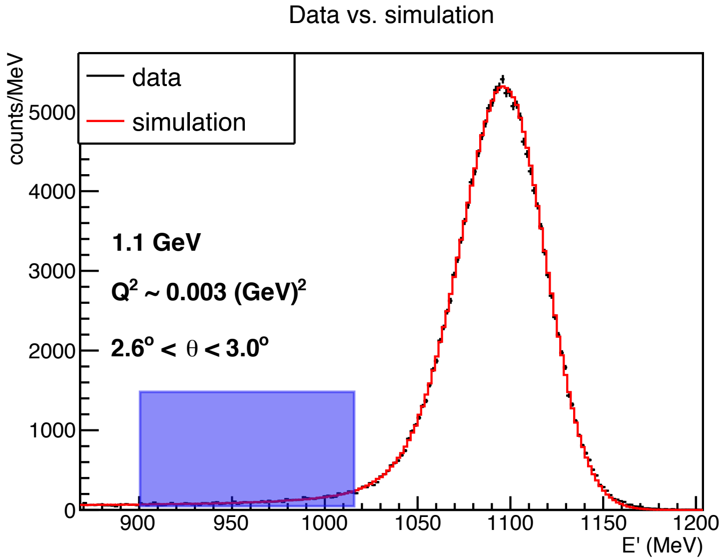
3. O. Tomalak, Few Body Syst. **59**, no. 5, 87 (2018)

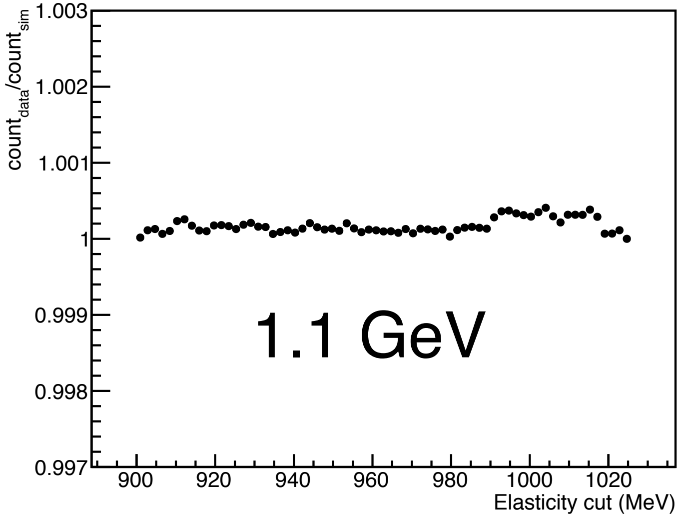
Systematic Uncertainties

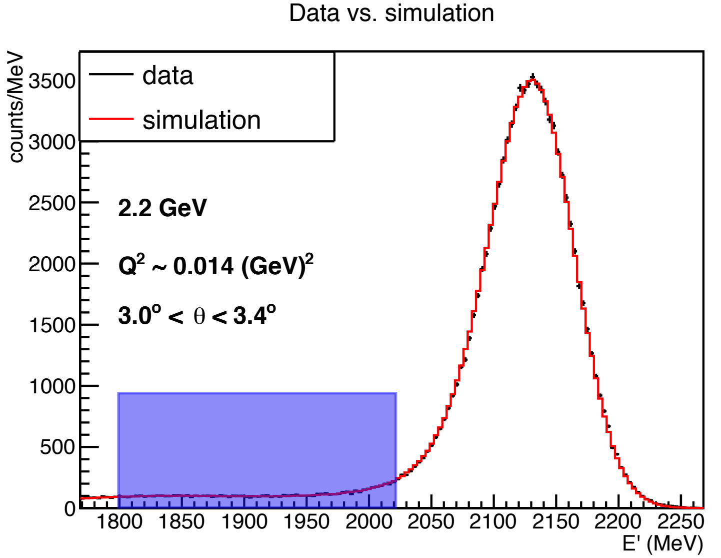
- For PRad, systematic uncertainties may come from:
  1. Event selection (elasticity cuts, co-planarity cuts…)
  2. Radiative correction
  3. Detector efficiencies (GEM and HyCal)
  4. Beam-line background (Halo hitting collimator, residual gas…)
  5. HyCal energy calibration
  6. Detector position
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

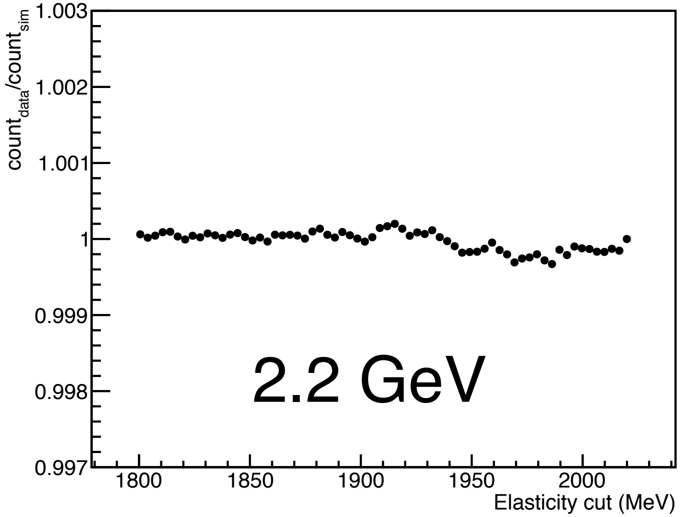
Systematic Uncertainties
(Example of Event Selection)

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

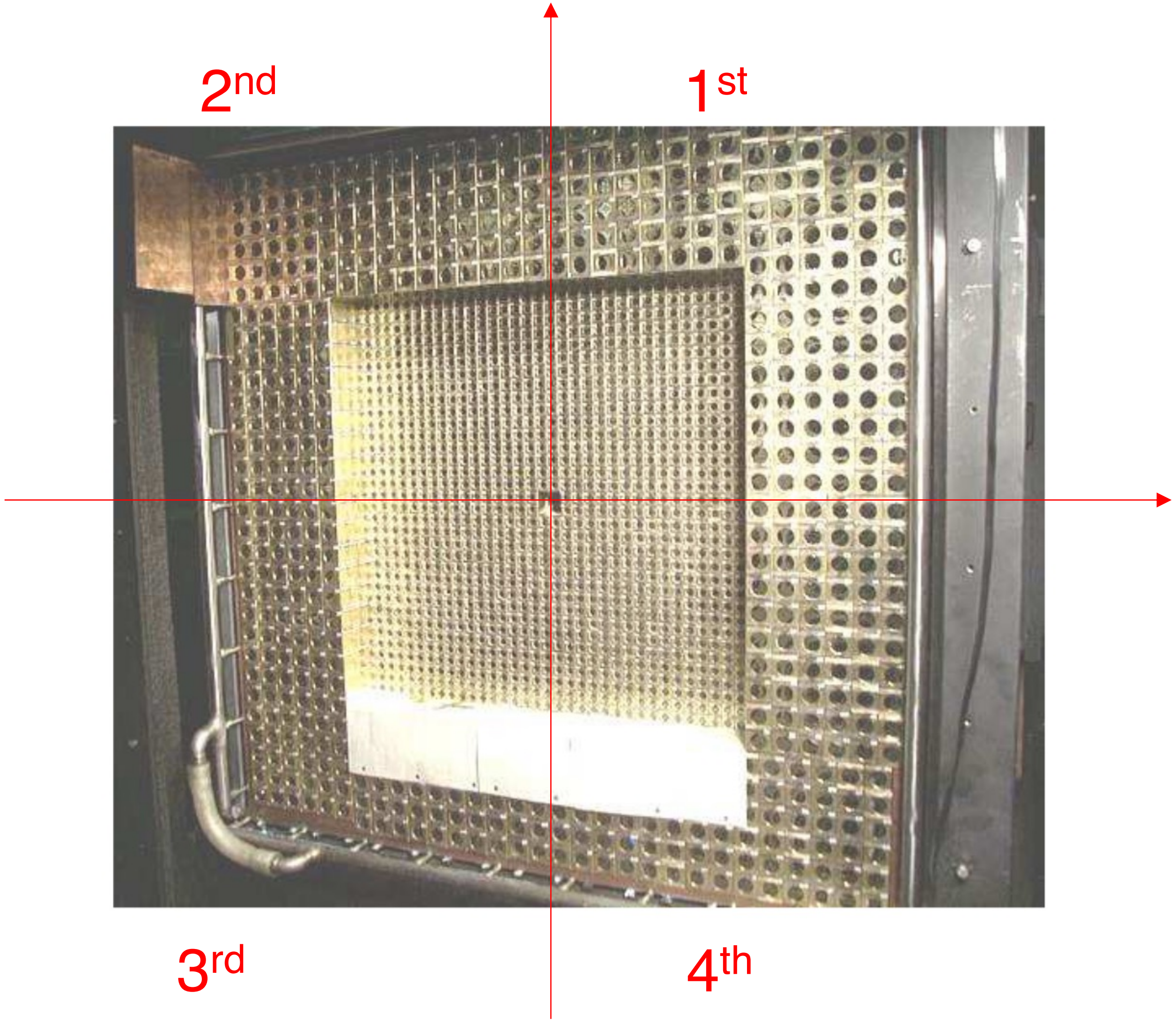


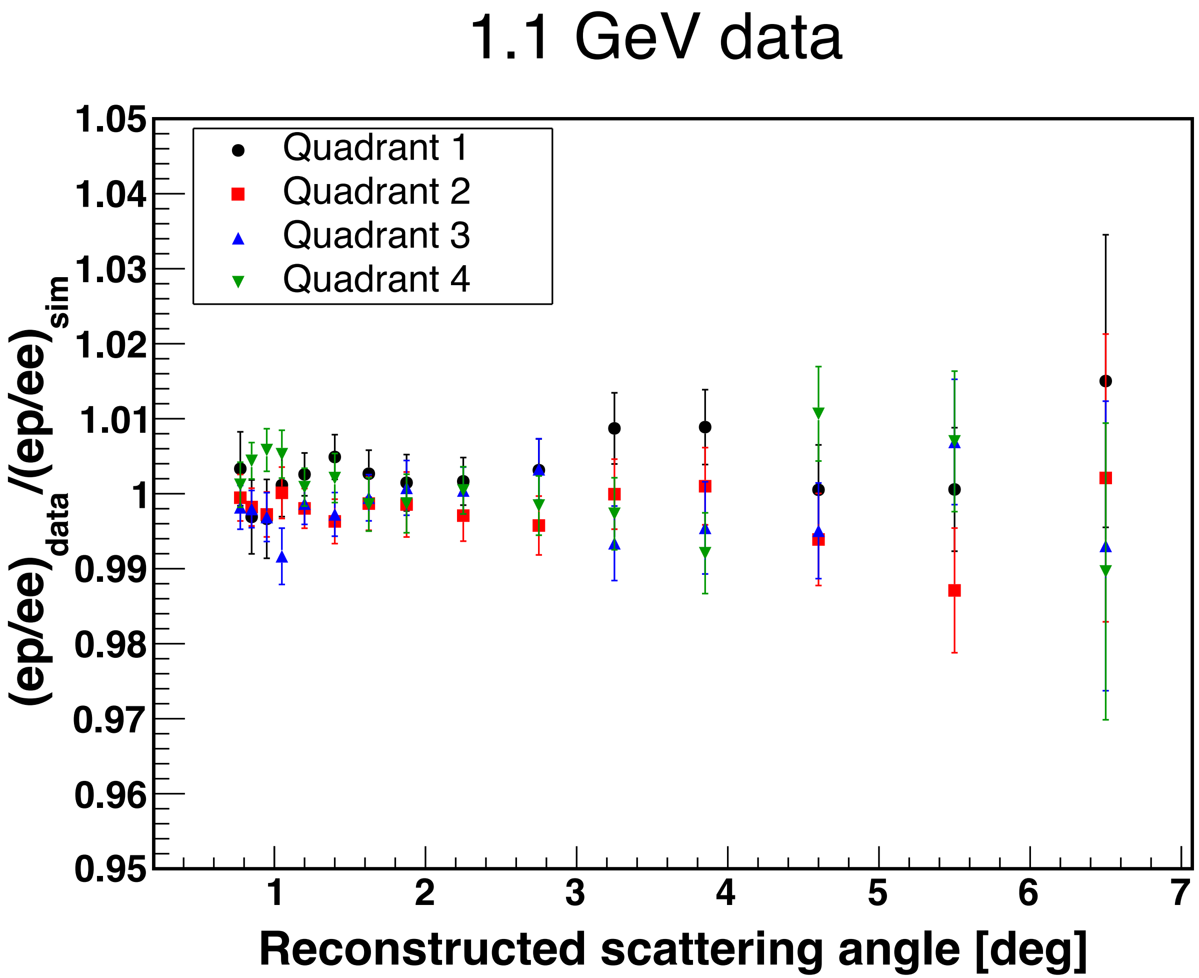






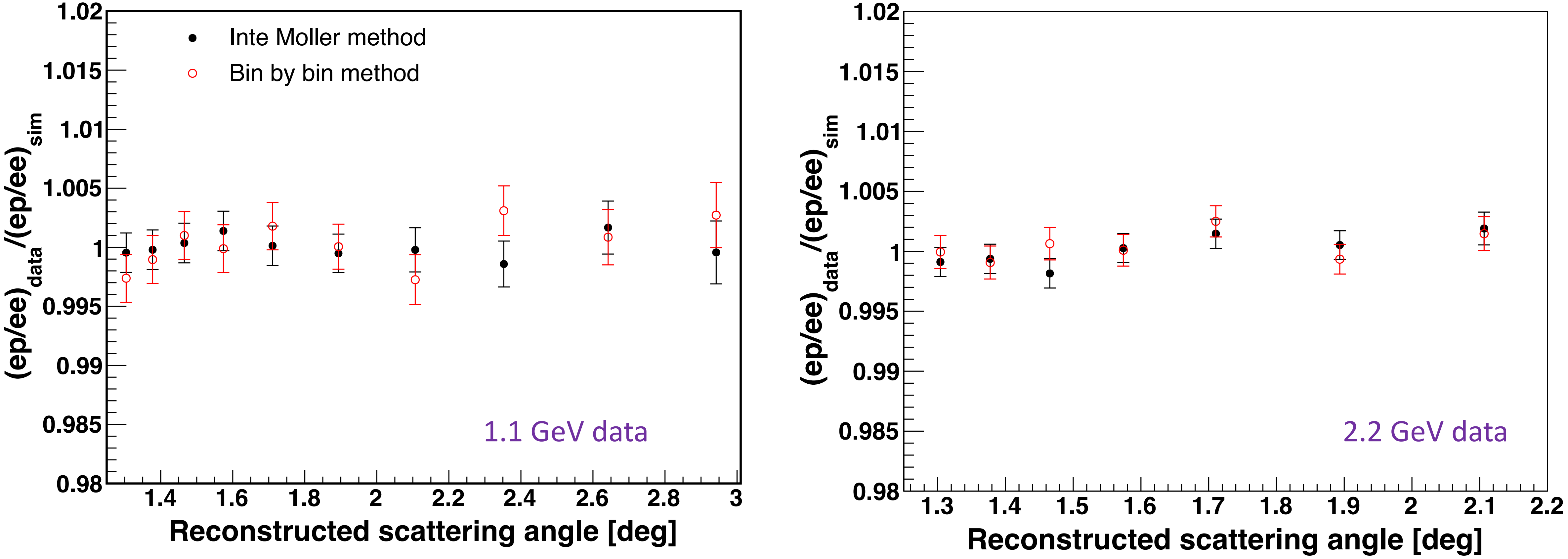
Checking Systematics – Azimuthal Symmetry





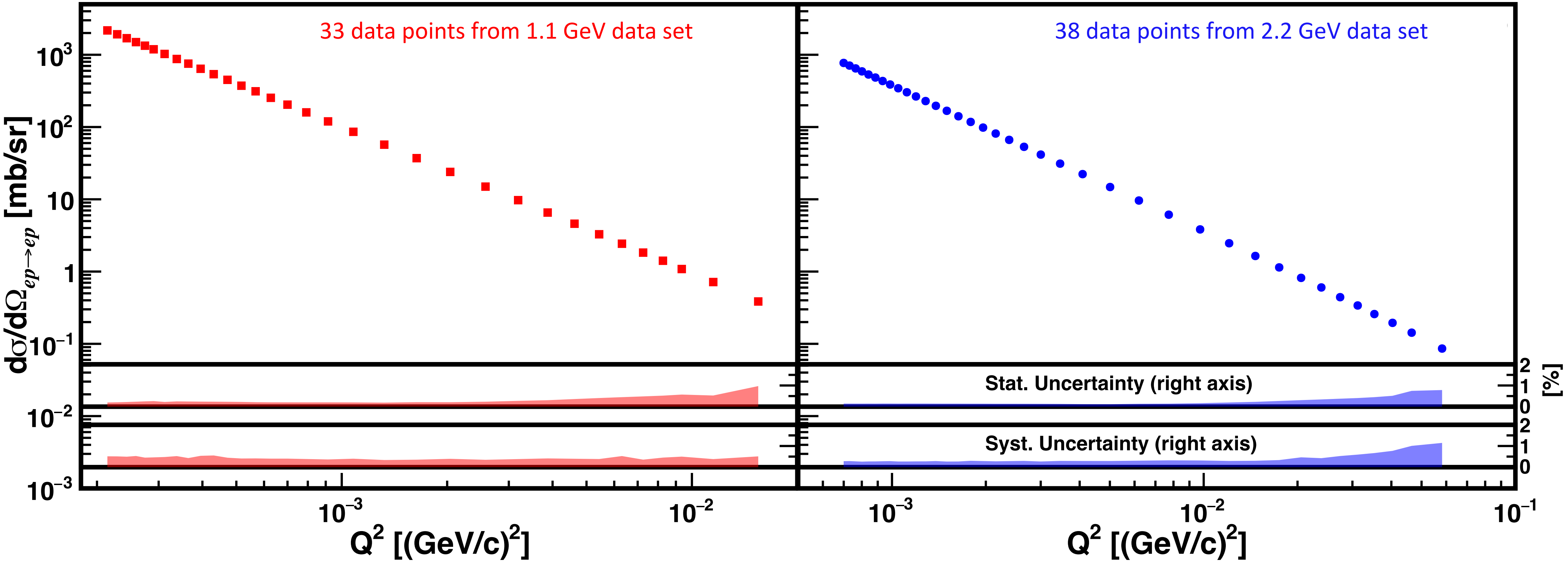
Checking Systematics – Different methods of Forming *ep/ee* ratio

- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angle bins
- Luminosity cancelled in both methods



Differential Cross Sections

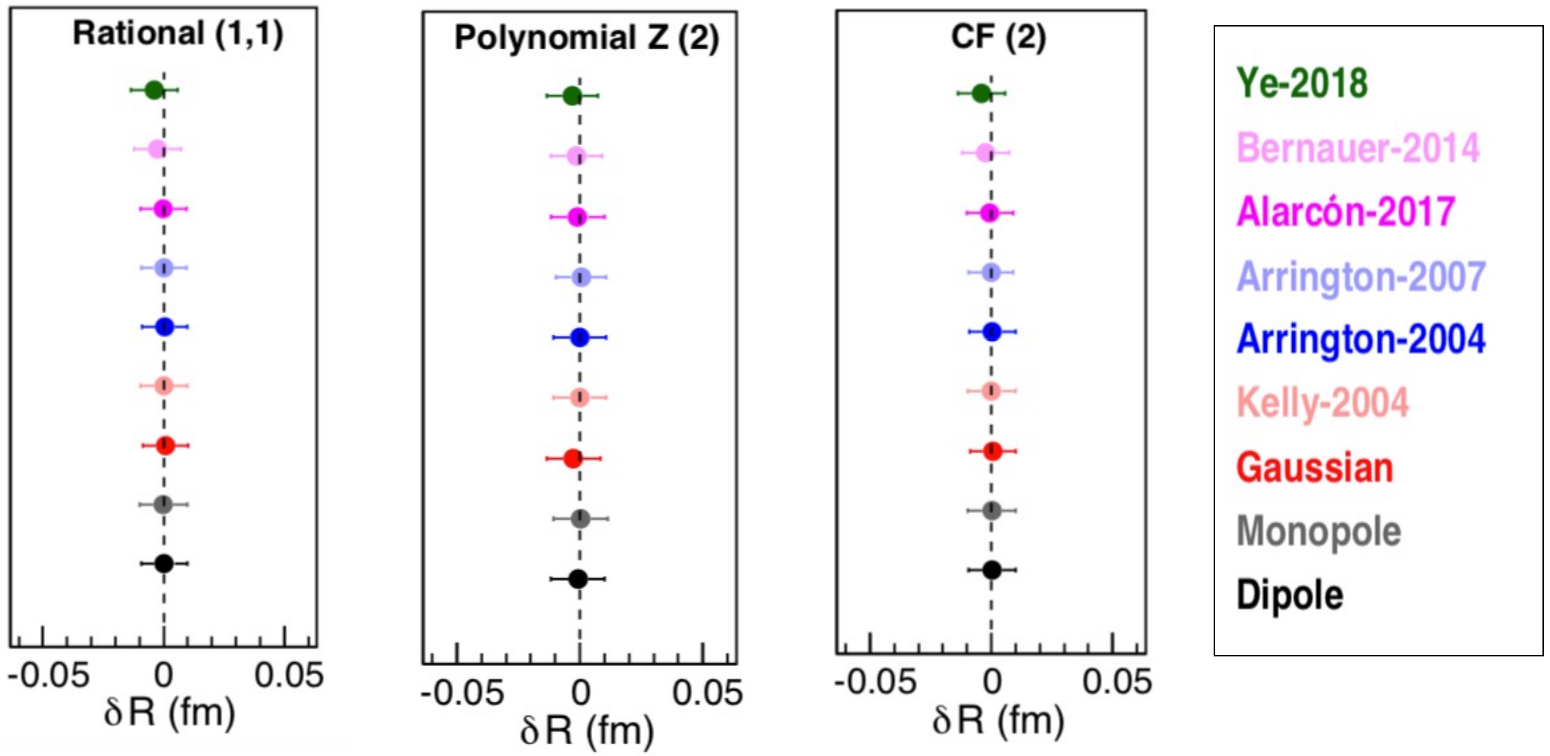
- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data
- Statistical uncertainties: ~0.15% for 2.2 GeV, ~0.2% for 1.1 GeV per point
- Systematic uncertainties: 0.3% ~ 1.1% for 2.2 GeV, 0.3% ~0.5% for 1.1 GeV



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
- Typically a floating parameter n is included to take care normalization uncertainties

$$f(Q^2) = n\, G_E^p(Q^2)$$



Rational (1,1)

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

2nd order z transformation

$$1 + p_1 z + p_2 z^2,$$

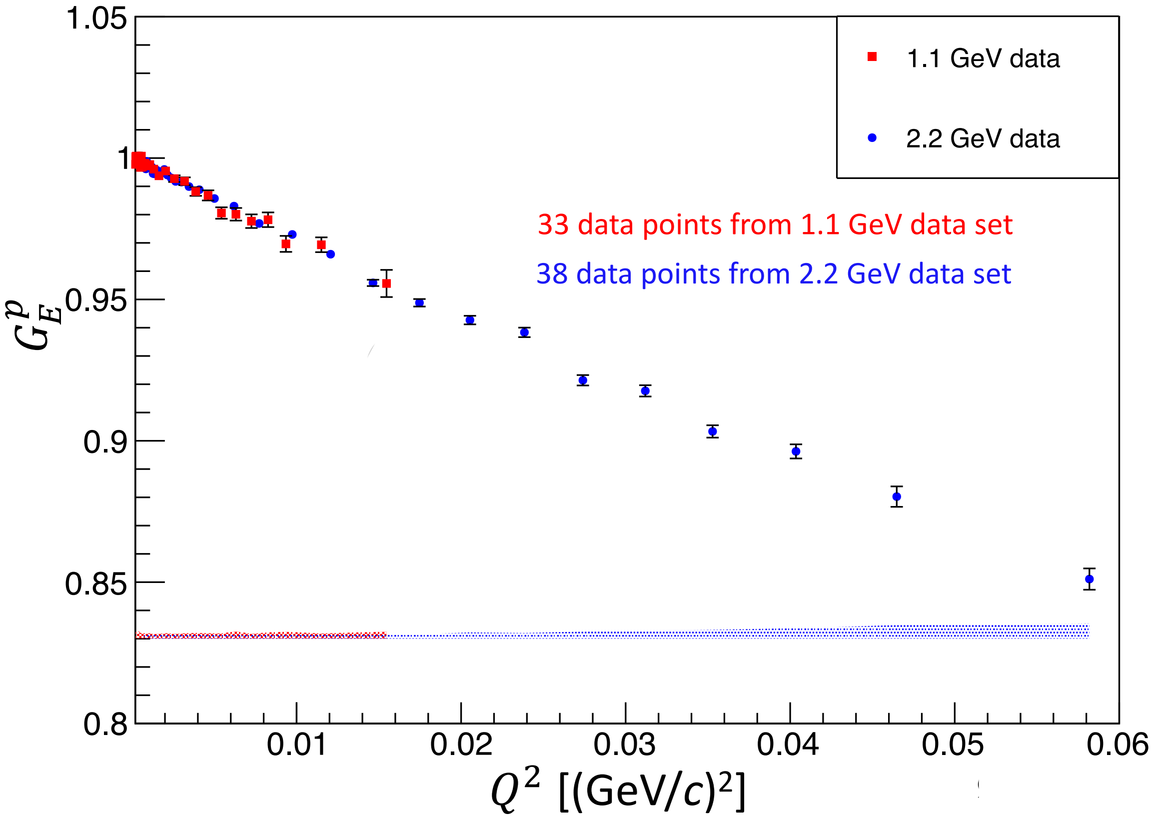
$$z = \frac{\sqrt{T_c + Q^2} - \sqrt{T_c - T_0}}{\sqrt{T_c + Q^2} + \sqrt{T_c - T_0}}$$

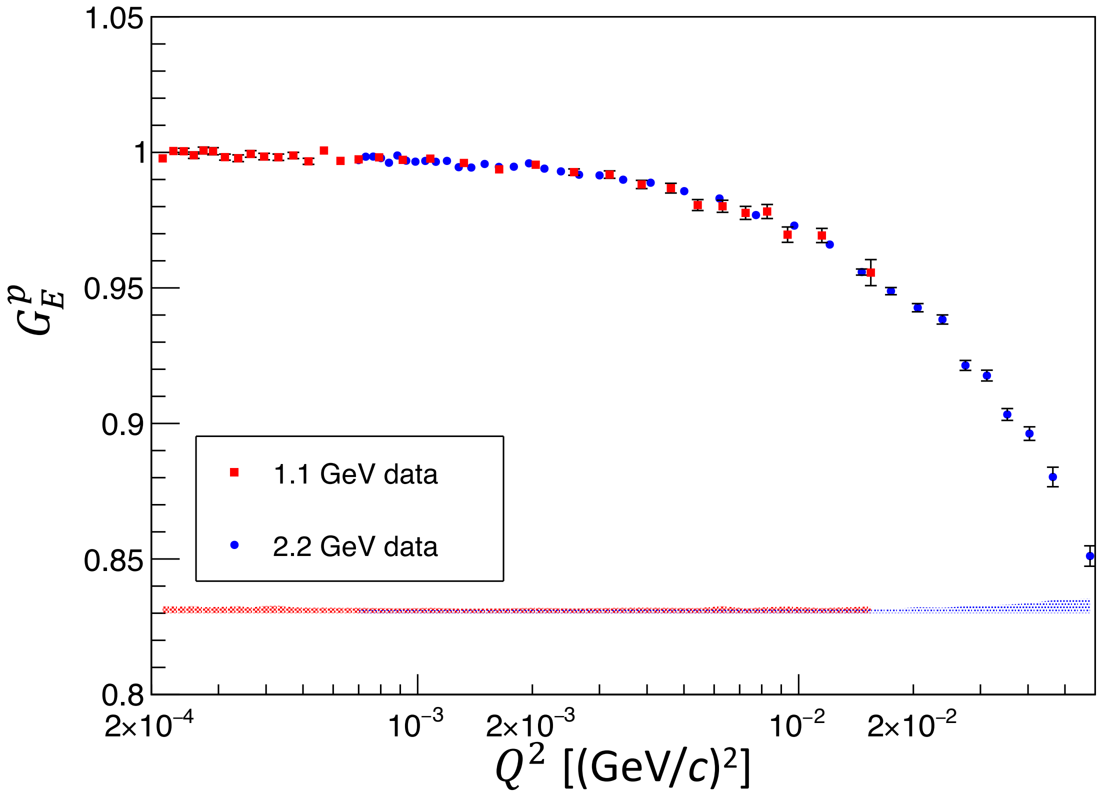
2nd order continuous fraction

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

Proton Electric Form Factor G_E^p

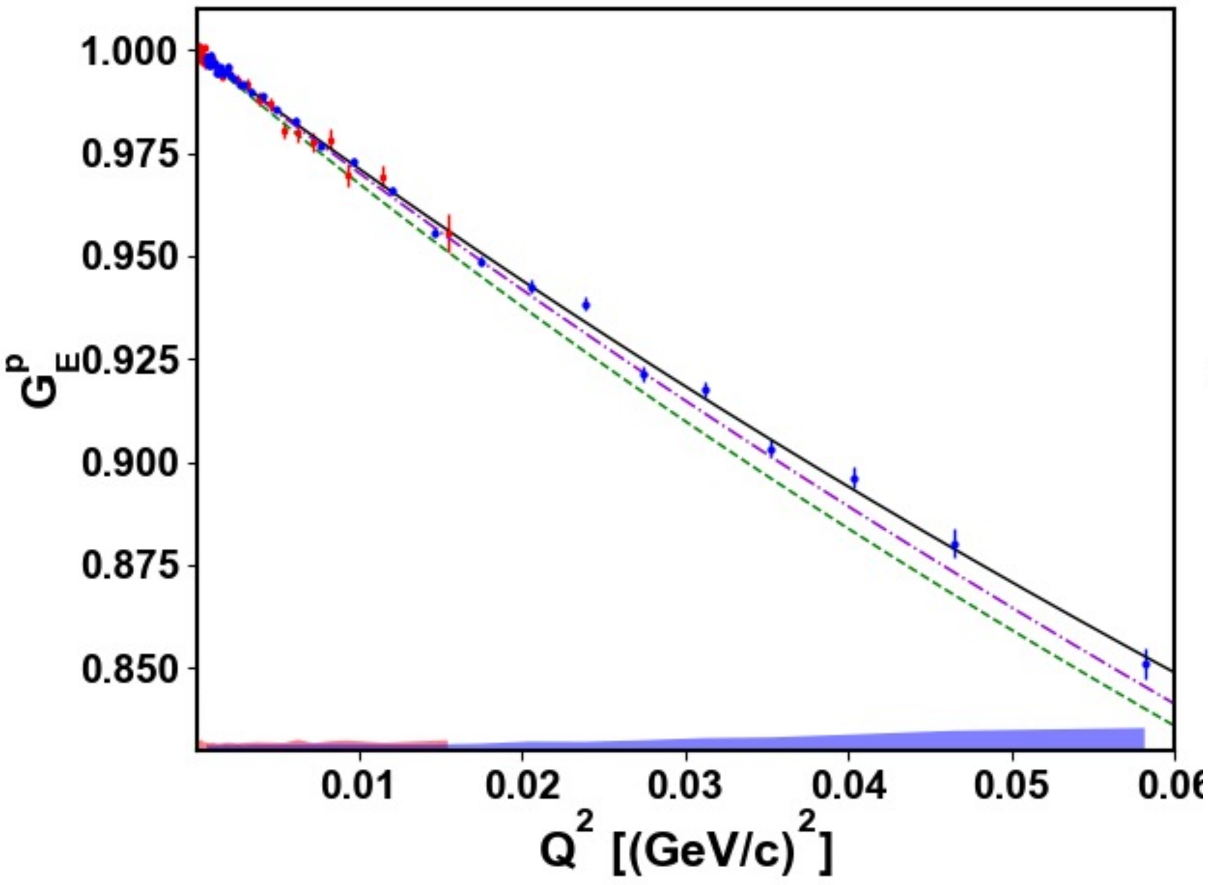
- n_1 and n_2 obtained by fitting PRad electric form factors to $f(Q^2) = \begin{cases} n_1 G_E^p(Q^2), & \text{for 1.1 GeV data} \\ n_2 G_E^p(Q^2), & \text{for 2.2 GeV data} \end{cases}$
- G_E^p as normalized electric form factor: $\begin{cases} f(Q^2)/n_1, & \text{for 1.1 GeV data} \\ f(Q^2)/n_2, & \text{for 2.2 GeV data} \end{cases}$
- $G_E^p(Q^2) = \frac{1+p_1Q^2}{1+p_2Q^2}$, the rational (1,1), a robust fitter based on X. Yan *et al.* Phys. Rev. C98, 025204 (2018)

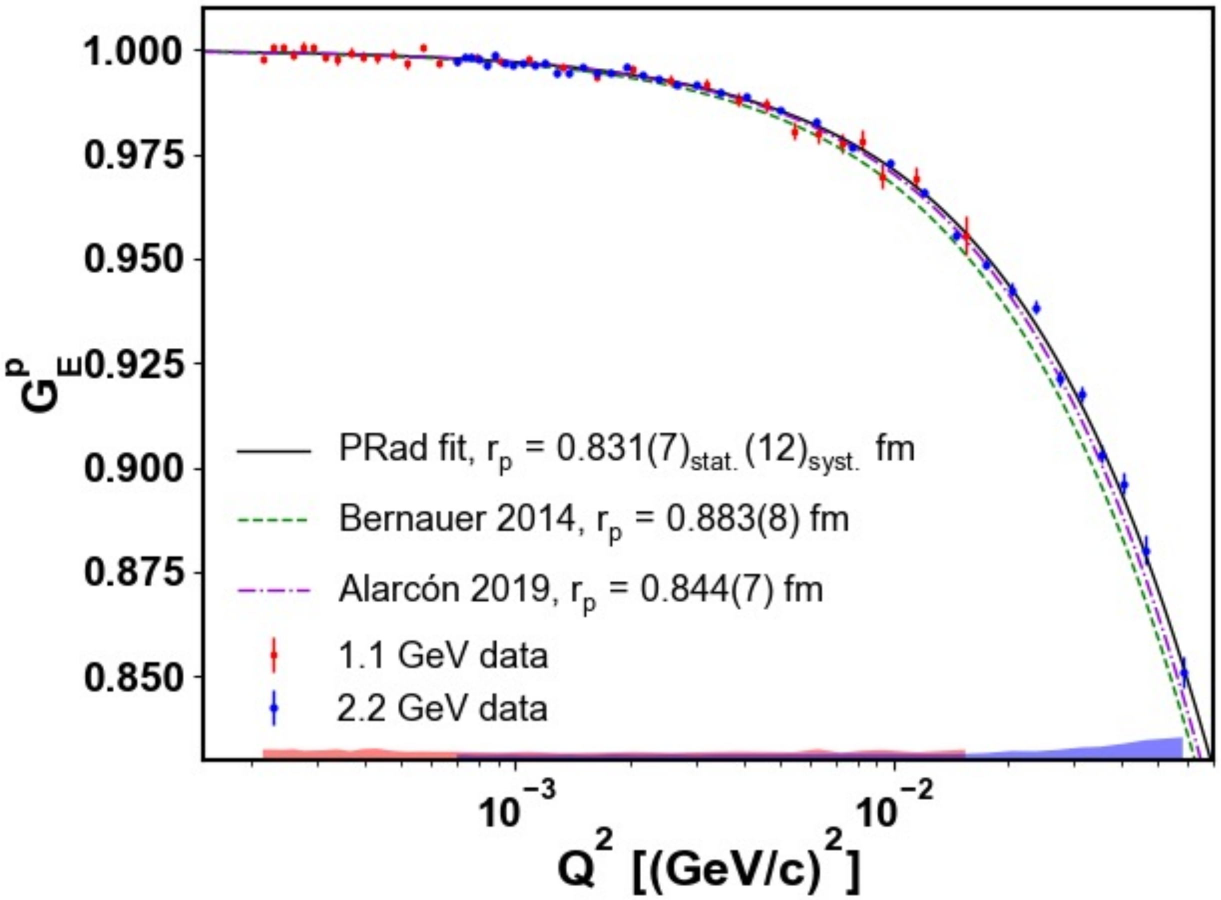




Proton Electric Form Factor G_E^p

r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm





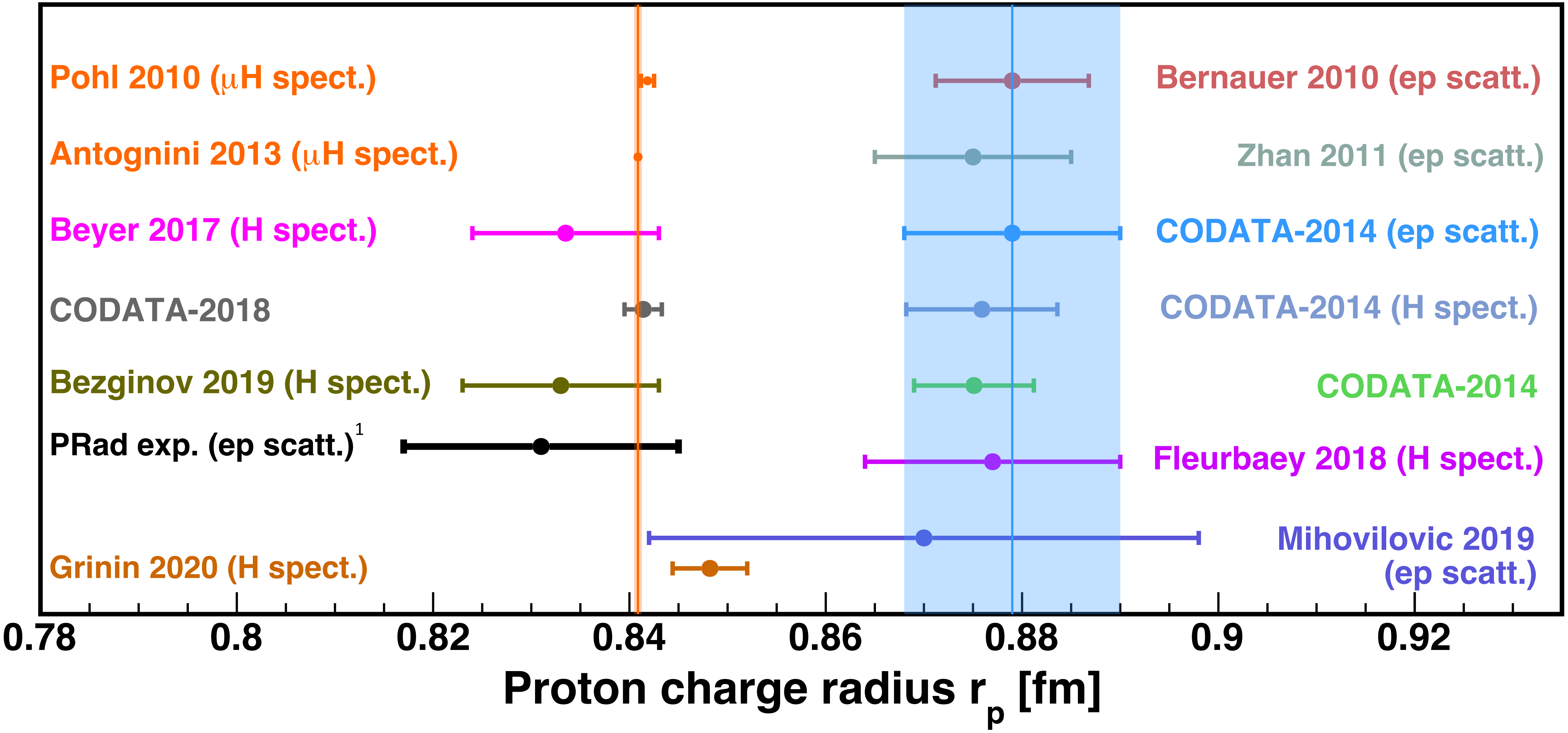
n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.), n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

Systematic Uncertainties

Item	r_p uncertainty [fm]	n_1 uncertainty	n_2 uncertainty
Event selection	0.0070	0.0002	0.0006
Radiative correction	0.0069	0.0010	0.0011
Detector efficiency	0.0042	0.0000	0.0001
Beam background	0.0039	0.0017	0.0003
HyCal response	0.0029	0.0001	0.0001
Acceptance	0.0026	0.0001	0.0001
Beam energy	0.0022	0.0001	0.0002
Inelastic *ep*	0.0009	0.0000	0.0000
G_M^p parameterization	0.0006	0.0000	0.0000
Total	0.0115	0.0020	0.0013

PRad Proton Charge Radius

PRad result: r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

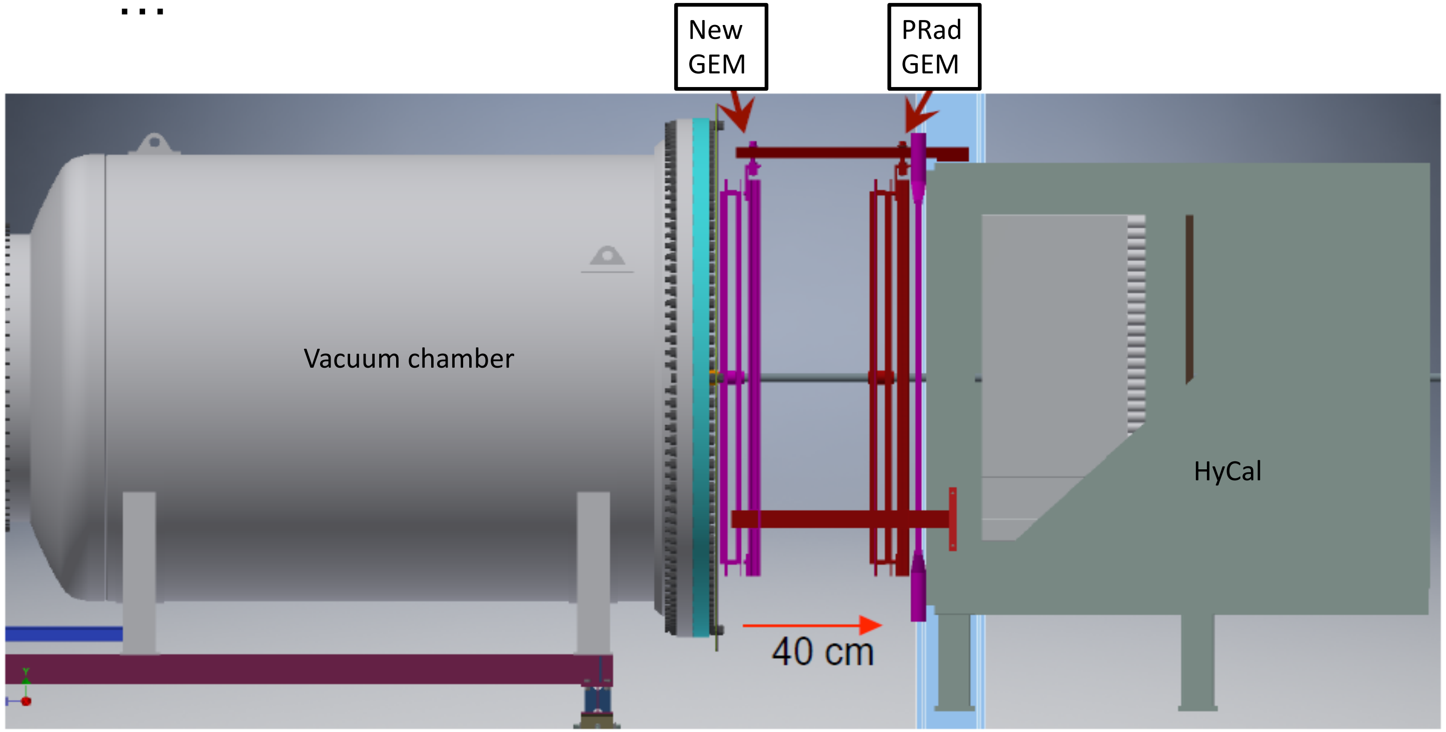


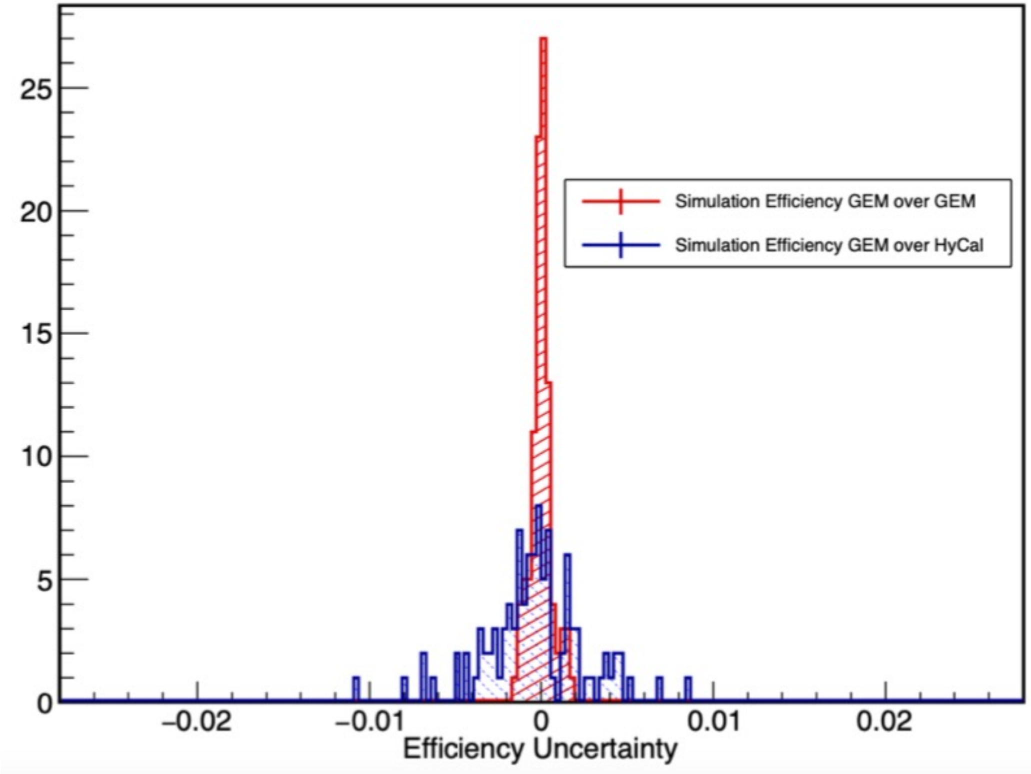
1: W. Xiong et al. Nature **575**, no. 7781, 147 (2019)

PRad-II Experiment

- JLab PAC 48 approved PRad-II (PR12-20-004) with the highest scientific rating "A"
- Goal: reach ultra-high precision (~4 times smaller total uncertainty), resolve tension with modern *e-p* scattering results
- The new proposal includes:
    1. Adding tracking capacity (second GEM plane)

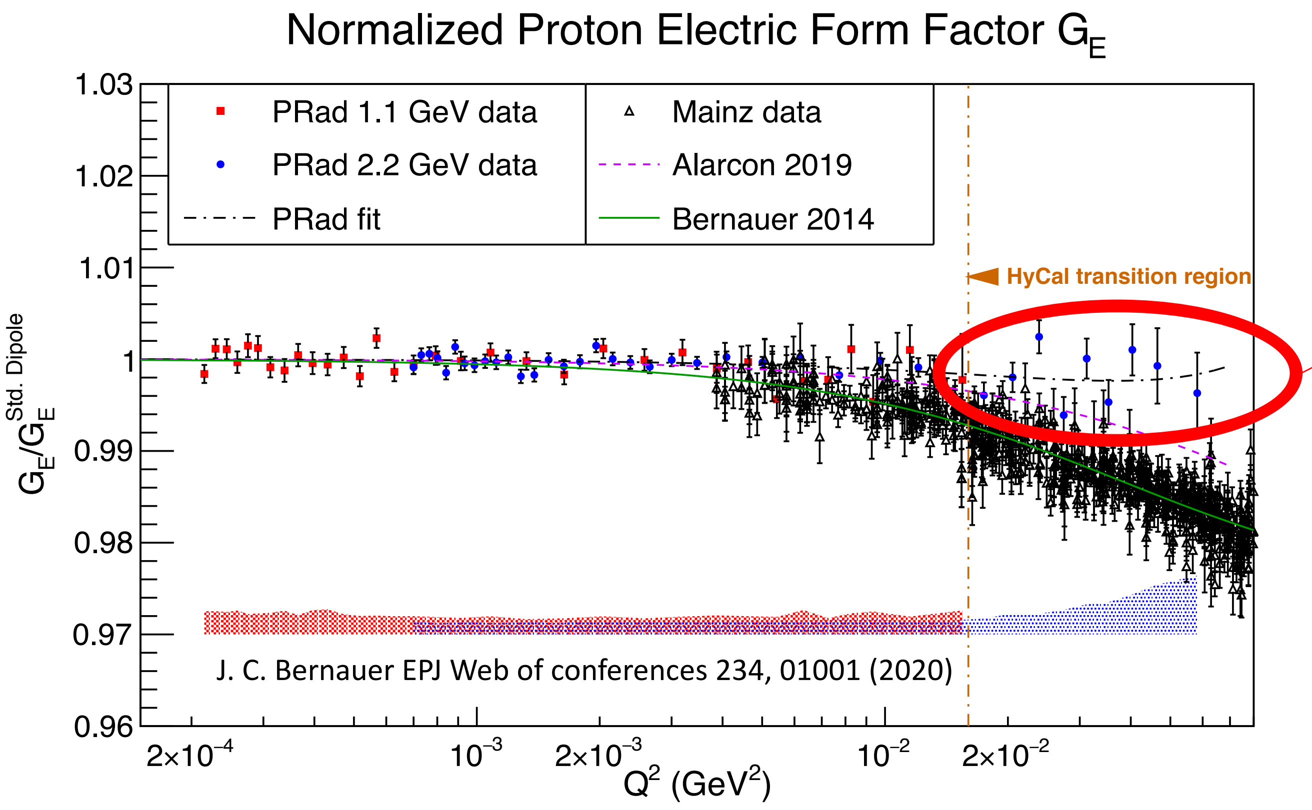
    …

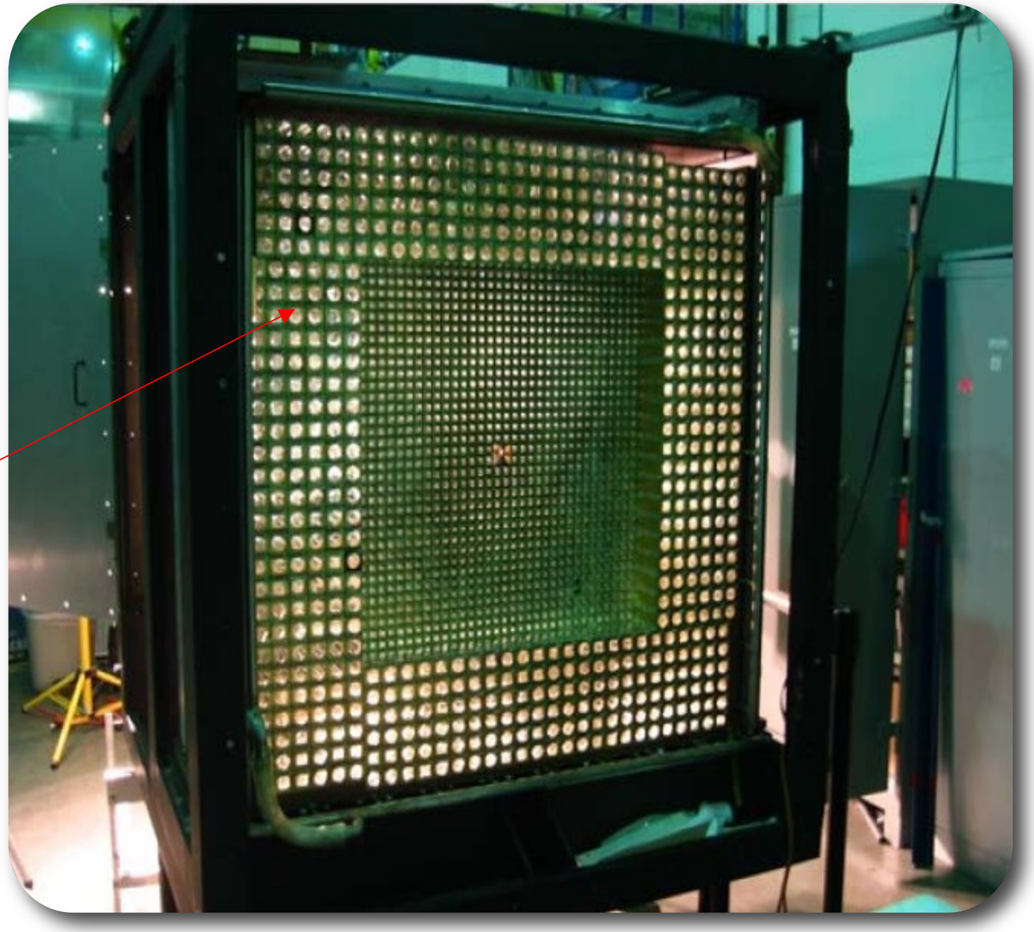




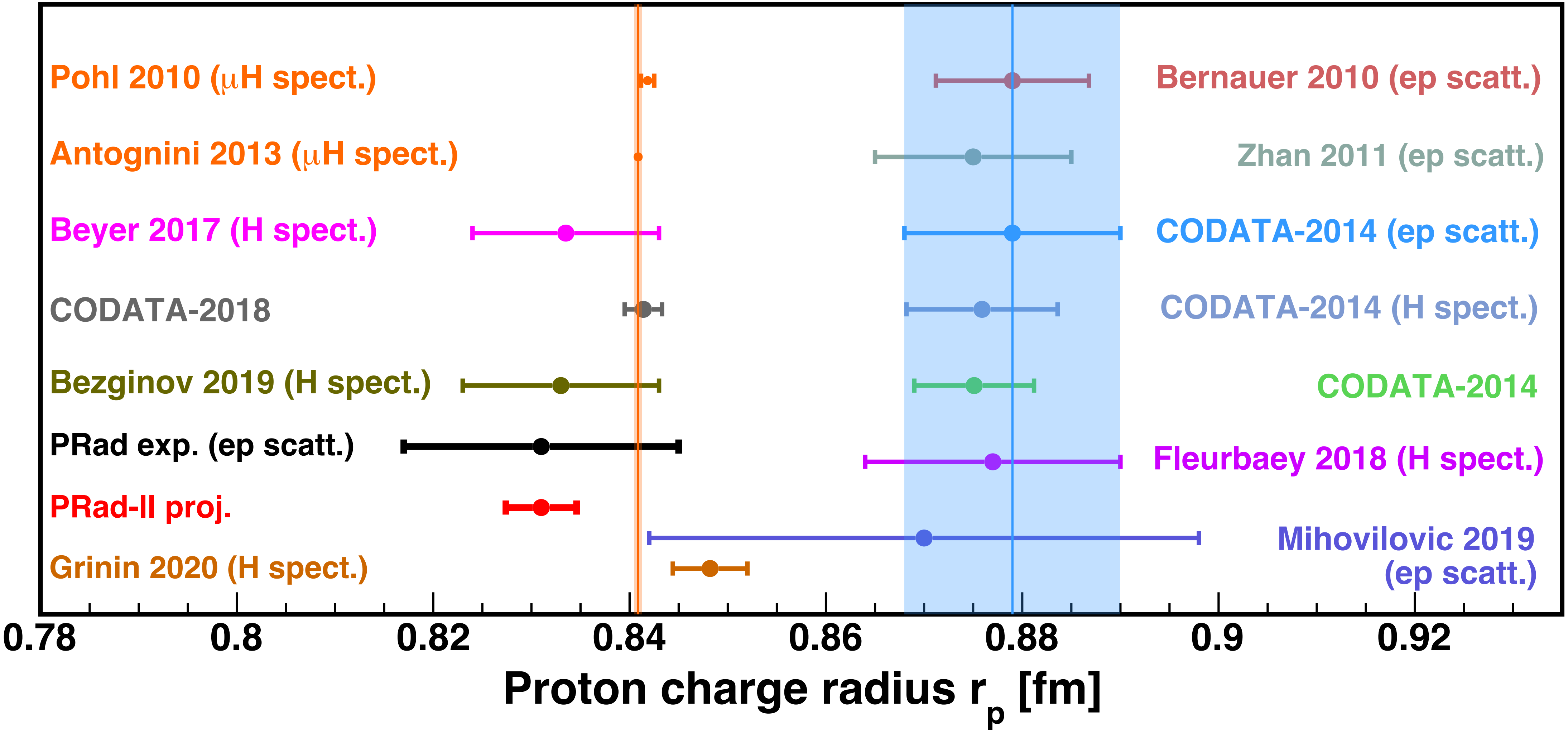
PRad-II Experiment – Cont.

- The new proposal includes:
  1. Adding tracking capacity (second GEM plane)
  2. Upgraded HyCal with all high resolution $PbWO_4$ modules
  3. Convert to FADC based readout for HyCal
  4. Four times smaller stat. uncertainty
  5. Better RC calculating including NNLO diagrams





PRad-II Experiment – Projected Result



Expected total uncertainty: 0.0036 fm

Projected result with full detector upgrades

Summary

- The PRad collaboration carried out the 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. Novel use of a window-less cryogenically cooled hydrogen gas target
  4. Simultaneous measurements of *ep* and *ee* scattering to reduce systematics

- The PRad result: r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm
- Planning on follow-up experiment, aim for ~4 times of improvement on total r_p uncertainty

This work was supported in part by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-03ER41231