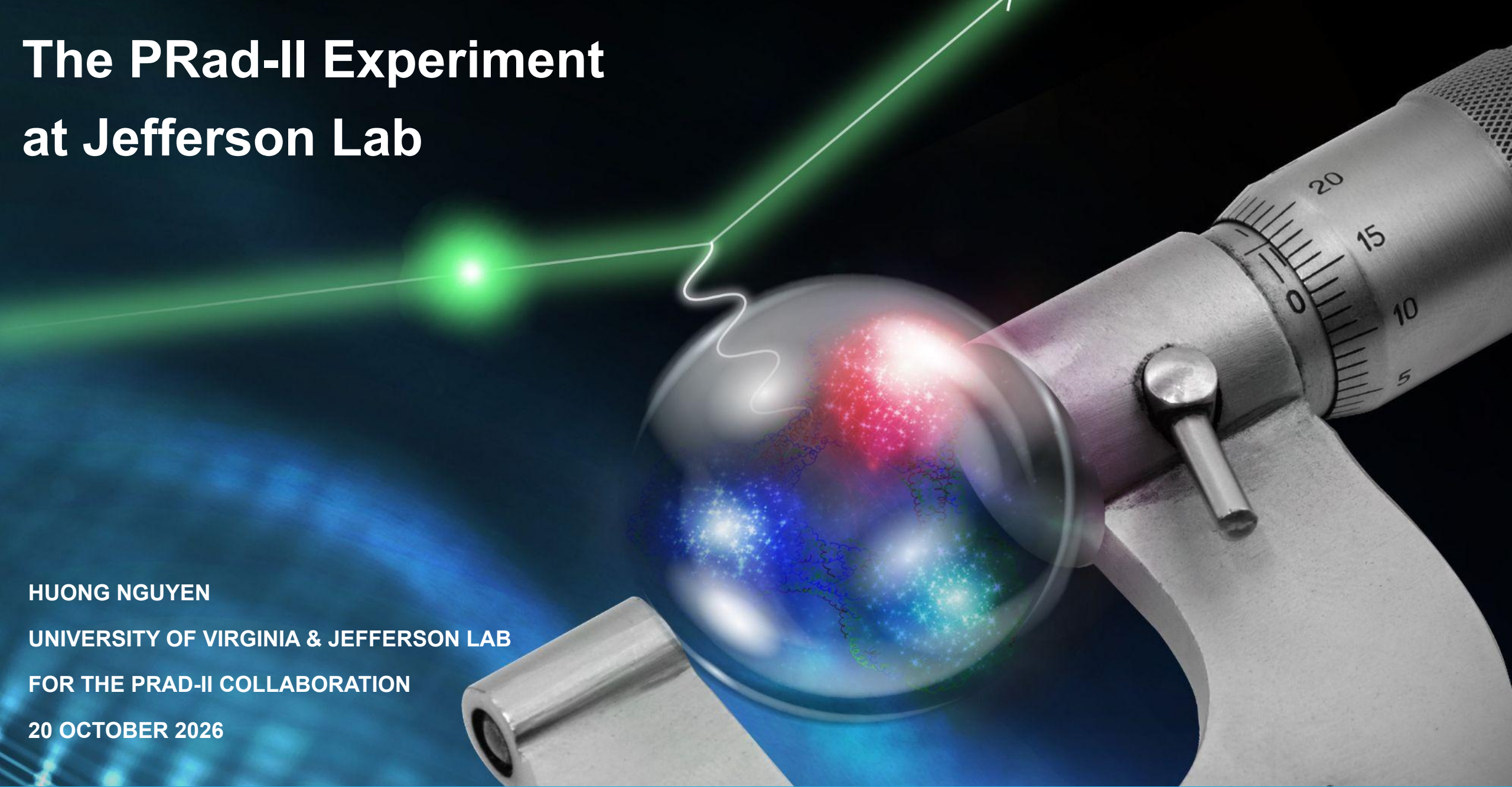


The PRad-II Experiment at Jefferson Lab



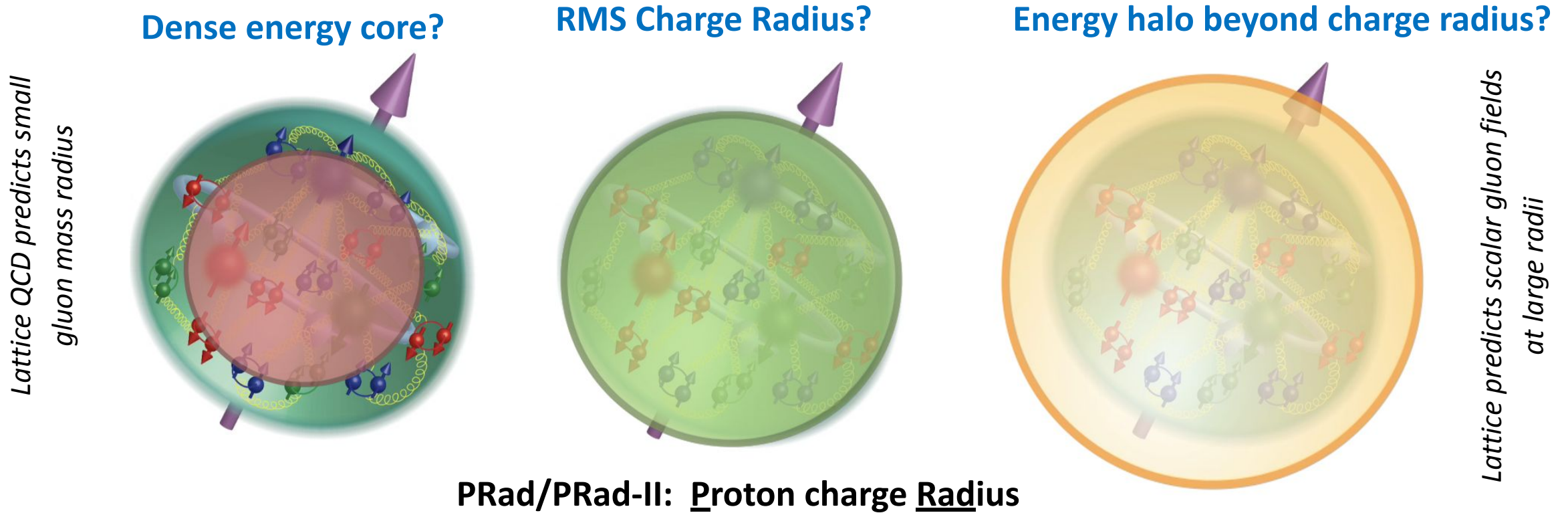
HUONG NGUYEN

UNIVERSITY OF VIRGINIA & JEFFERSON LAB

FOR THE PRAD-II COLLABORATION

20 OCTOBER 2026

What Is the Size of a Proton?



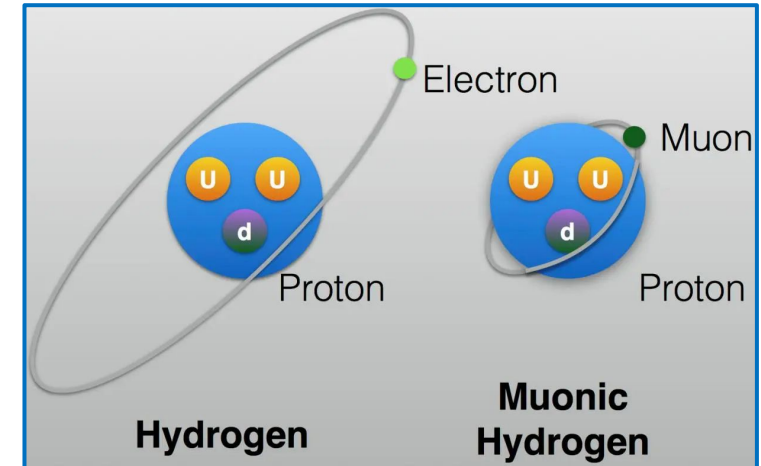
- The proton is an extended charged object with a well-defined mean-squared charge radius:

$$\langle r_p^2 \rangle = \int r^2 \rho_E(r) d^3r$$

Methods to Measure Proton Charge Radius r_p

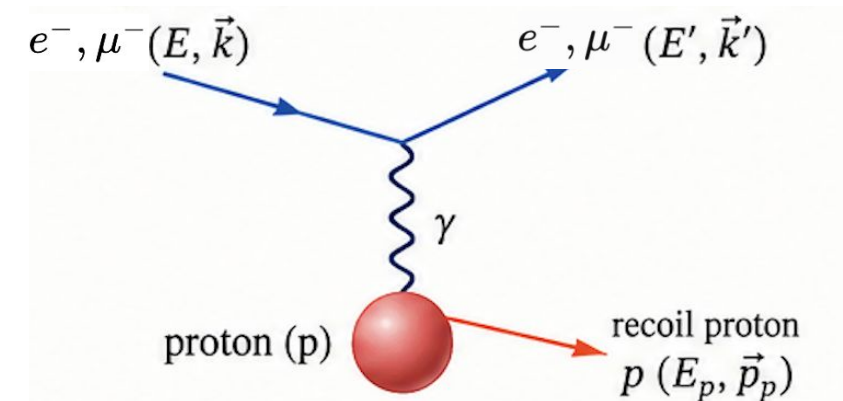
- **Hydrogen spectroscopy** (*atomic physics*)

- Ordinary-hydrogen
 - Determines r_p indirectly through its influence on electron energy levels
- Muonic-hydrogen
 - Smaller orbital radius makes muon energy levels more sensitive to proton's size



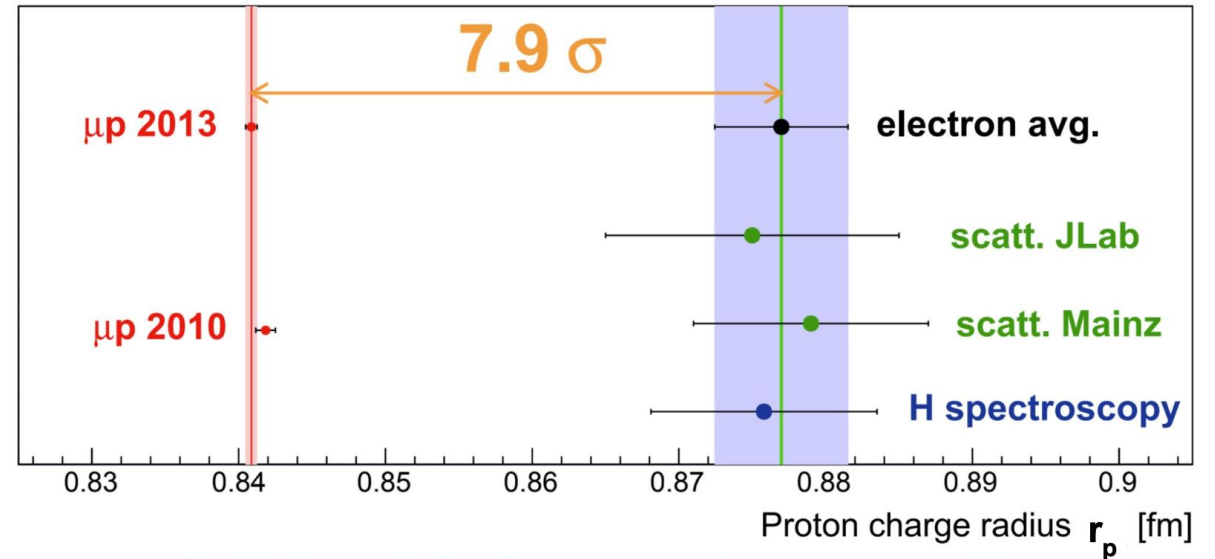
- **Lepton-proton elastic scattering** (*nuclear physics*)

- e-p elastic scattering (PRad/PRad-II)
- μ -p elastic scattering (MUSE, AMBER)



Emergence of Proton Charge Radius Puzzle

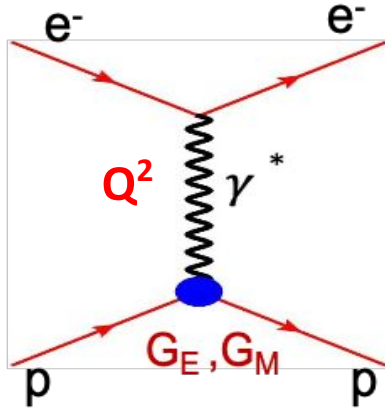
- **Before 2010:** Electron-based measurements yielded: $r_p \approx 0.88 \text{ fm}$
- **In 2010:** Muonic-hydrogen spectroscopy found a significantly smaller value: $r_p \approx 0.84 \text{ fm}$



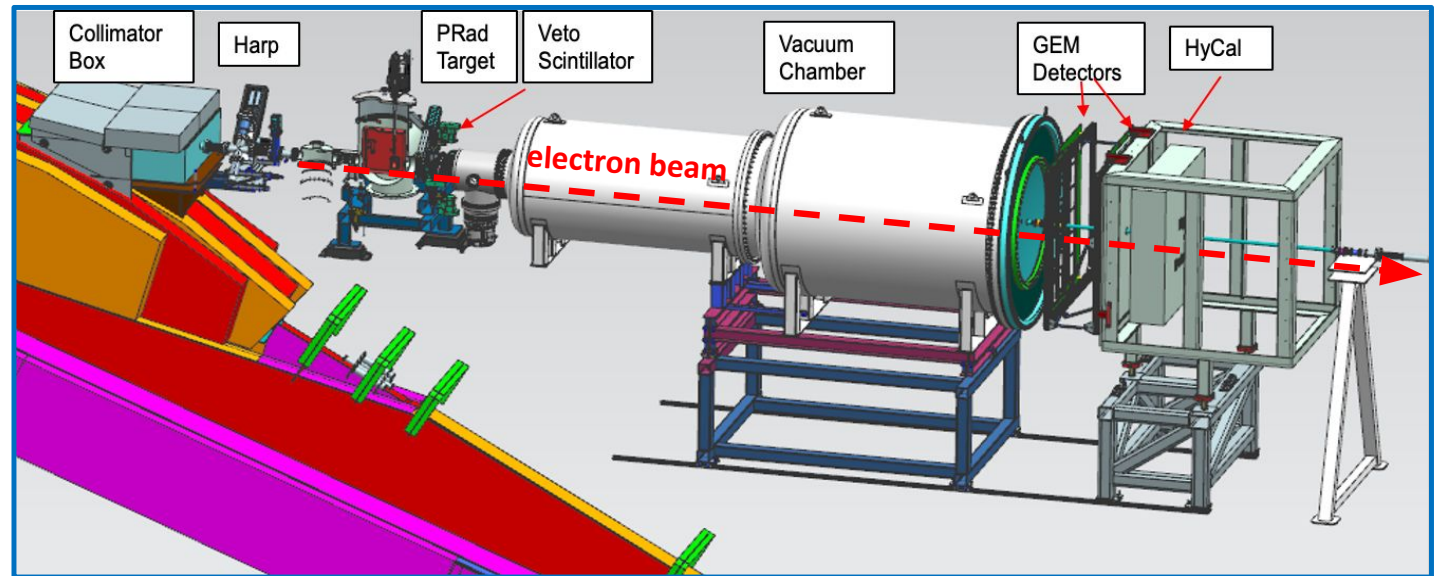
- The difference was much larger than experimental uncertainties:
 - Gave rise to the **Proton Charge Radius Puzzle**
 - Triggered an international program to determine whether the discrepancy came from:
 - Experimental error, theory corrections, analysis methods, or possible new physics?

PRad and PRad-II at Jefferson Lab

Precision determination of r_p using e-p elastic scattering



- Clean pointlike probe of proton structure
- Well-known electron vertex from QED



- Optimize the spectrometer, target, beamline, beam energy and analysis to minimize measurement uncertainties
- [PRad ran in 2016](#)
- [PRad-II: An upgrade of Prad, Ran in 2026](#)

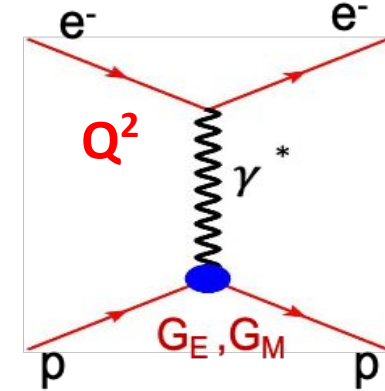
PRad and PRad-II: Measure r_p with ep Elastic Scattering

- The elastic ep cross section in one-photon exchange approximation:

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

With: $\tau = \frac{Q^2}{4M_p^2}, \quad \epsilon = \frac{1}{1 + 2(1 + \tau) \tan^2(\theta/2)}$

- $(d\sigma/d\Omega)_{\text{Mott}}$ is cross section for scattering from a pointlike relativistic spin- $\frac{1}{2}$ charge.
- G_E and G_M are electric and magnetic form factors of proton



- At extremely low Q^2 , the cross section is dominated by G_E : $G_E(Q^2) \approx \sqrt{\frac{(d\sigma/d\Omega)_{\text{measured}}}{(d\sigma/d\Omega)_{\text{Mott}}}}$
- Taylor expansion of G_E near $Q^2 = 0$: $G_E^p(Q^2) = 1 - \frac{Q^2}{6} \langle r^2 \rangle + \frac{Q^4}{120} \langle r^4 \rangle + \dots$
- Extracting proton charge radius from slope of $G_E(Q^2)$ at $Q^2 \rightarrow 0$: $\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$

Experimental Approach for Prad and PRad-II

Nonmagnetic Large Angular Acceptance Spectrometer

- **Forward large-acceptance PbWO_4 calorimeter & GEM tracking system:**

- Energy resolution of calorimeter: $\frac{\sigma_E}{E} = \frac{2.6\%}{\sqrt{E}}$
- Spatial resolution of tracker: $70\ \mu\text{m}$

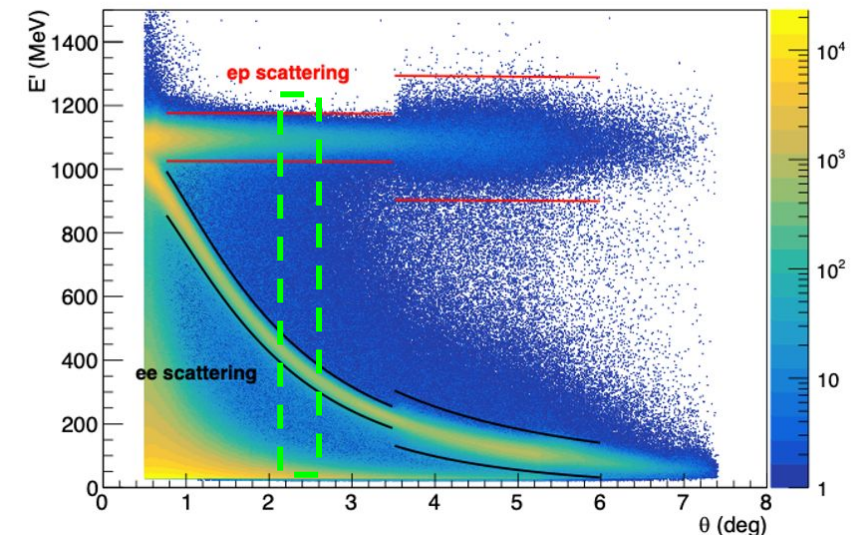
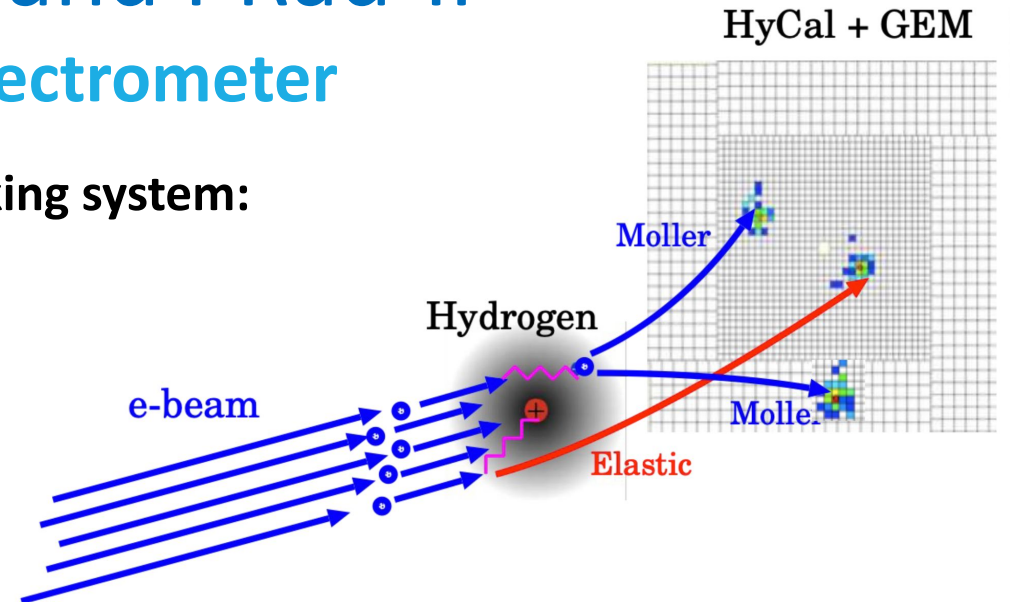
- Allows access to **extreme forward-angles**

- Allows large angular and momentum coverage in a **single experimental setting:**

- Prad-I: $\theta_e = 0.7^\circ - 7.0^\circ$; $Q^2 = 2 \times 10^{-4} - 6 \times 10^{-2} (\text{GeV}/c)^2$
- **Prad-II: $\theta_e = 0.5^\circ - 4.0^\circ$; $Q^2 = 4 \times 10^{-5} - 6 \times 10^{-2} (\text{GeV}/c)^2$**

- Provides **azimuthal symmetry acceptance**, enabling:

- Simultaneous detection of $ee \rightarrow ee$ Møller events
- Robust calibration of elastic ($e-p$) cross sections to control systematic uncertainties



Experimental Approach for PRad and PRad-II

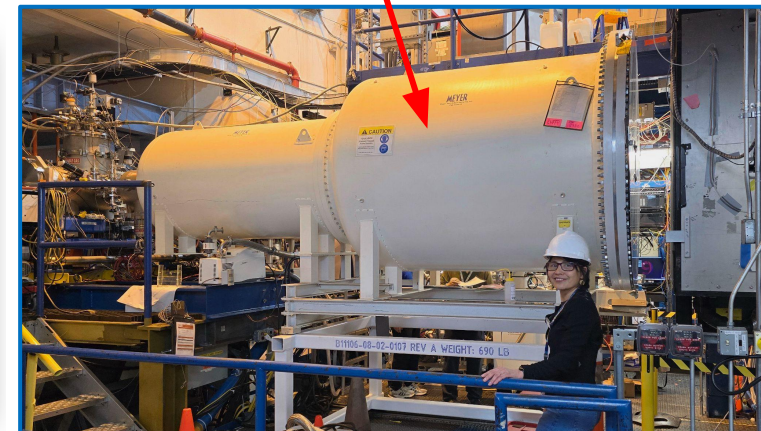
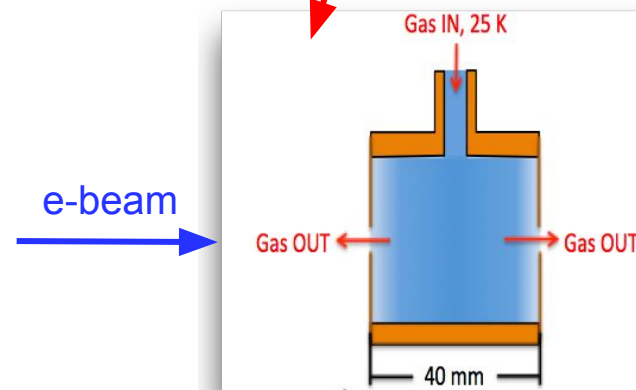
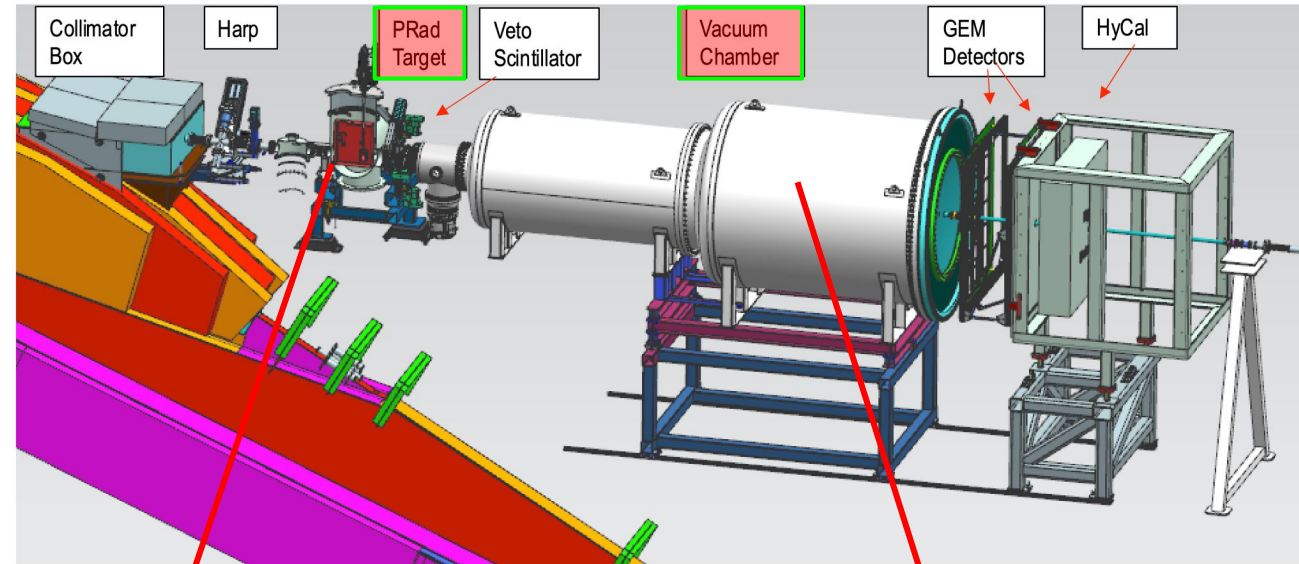
Suppress backgrounds and minimize multiple scattering

- **Windowless Hydrogen Gas Flow Target**

- **Windowless:** beam enters and exits via 2 mm orifices in kapton foils
- 7.5 cm diam. x 4 cm , 2.6×10^{31} atom/cm²
- Suppresses background and controls systematics at forward angles & low Q^2

- **Vacuum chamber**

- 5 m long x 1.7 m diameter
- Located between target and trackers
- Maintained at pressure < 0.5 mTorr
- Minimize experimental background

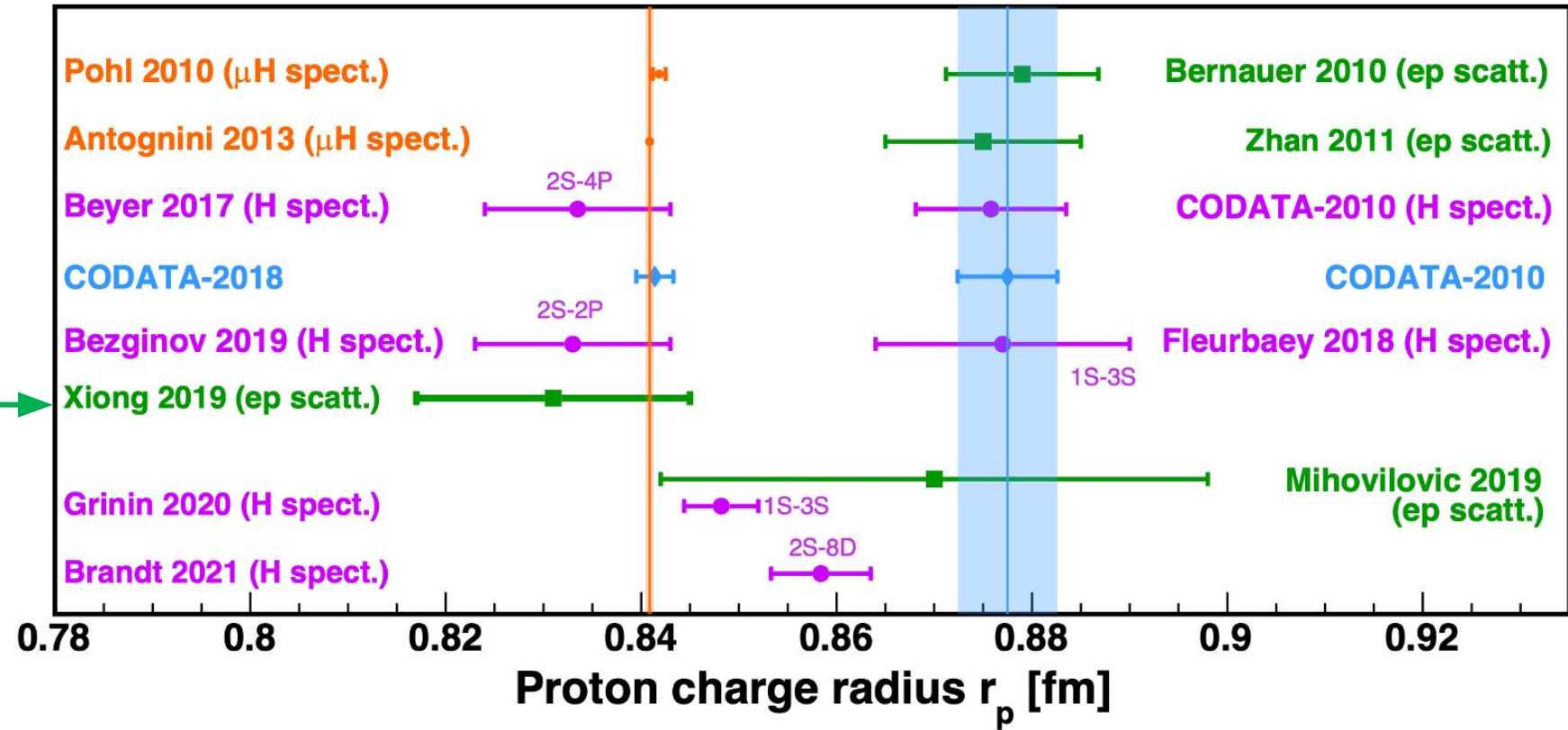


PRad Result in 2019

- PRad is in agreement with the smaller r_p values from μH spectroscopy:

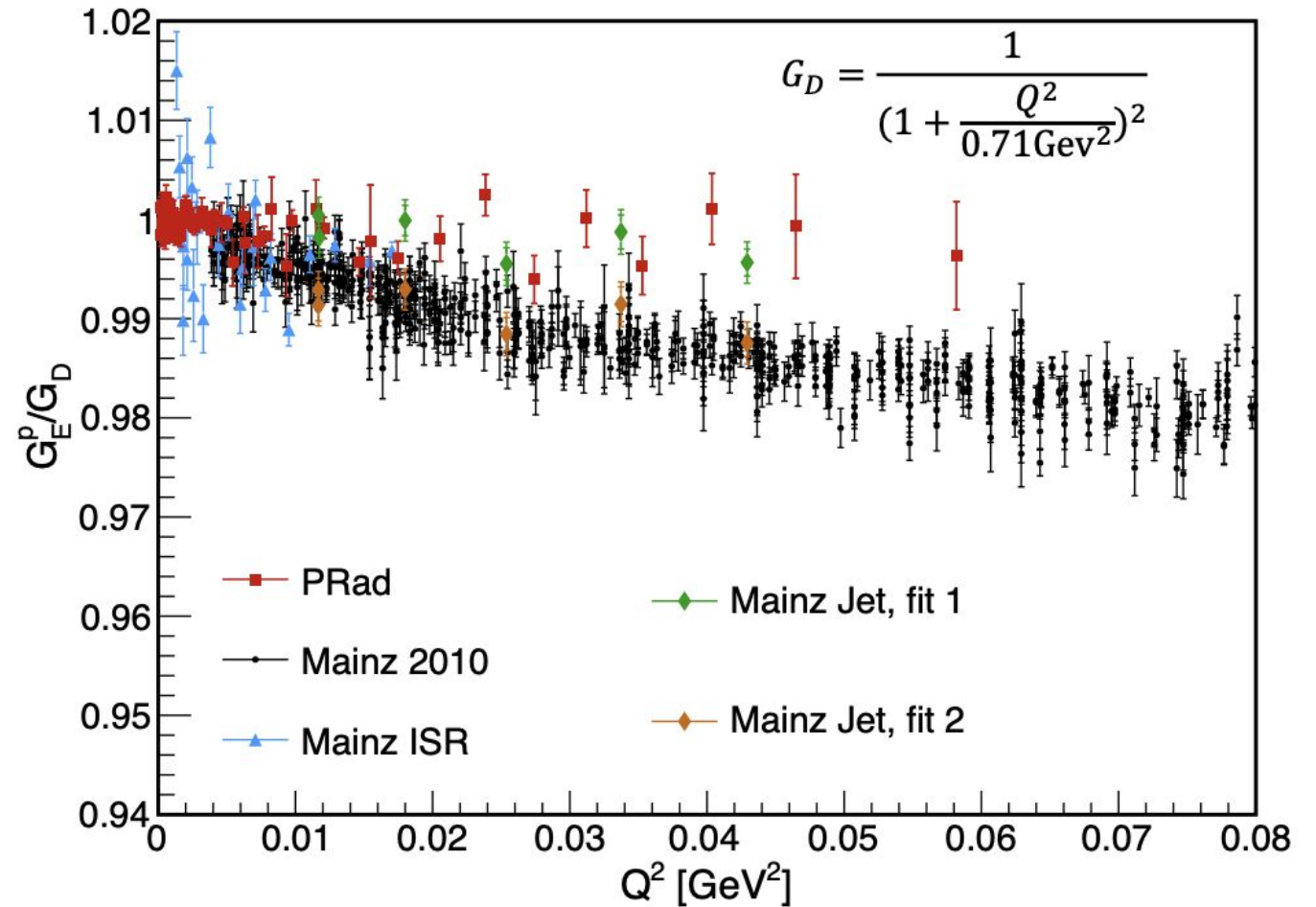
$$r_p = 0.831 \pm 0.0127 \text{ fm}$$

Xiong et al., Nature 575, 147–150 (2019)



PRad vs Mainz A1: Form Factor Discrepancy

- The G_E values extracted from PRad differ systematically from those reported by Mainz A1 by more than 1% in the higher- Q^2 overlap region
- Possible causes:
 - Radiative corrections?
 - Unknown systematic uncertainties?
- PRad-II with higher precision will address these differences



The Main Objectives of PRad-II

- Remeasure the proton electric form factor with high accuracy at very low Q^2 range
- Investigate discrepancies between PRad and other modern (ep)-scattering experiments
- Reach extreme forward angles and unprecedentedly low momentum transfer:
 - $\theta_e \sim 0.5^\circ$; $Q^2 \sim 4 \times 10^{-5} (\text{GeV}/c)^2$
- Extract the proton charge radius with **three times higher precision** than achieved by PRad

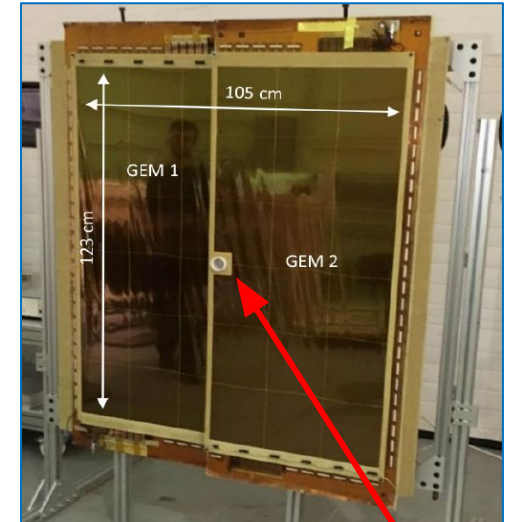
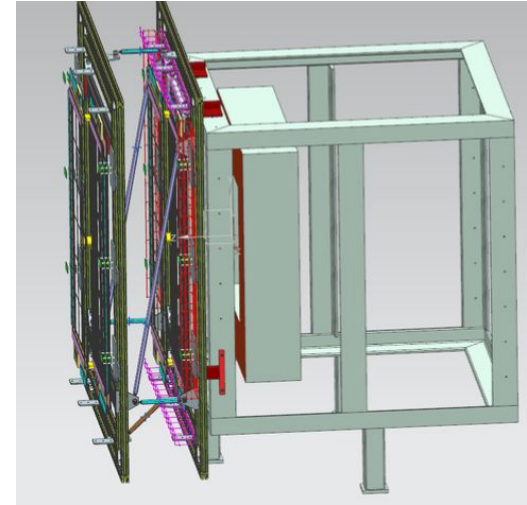
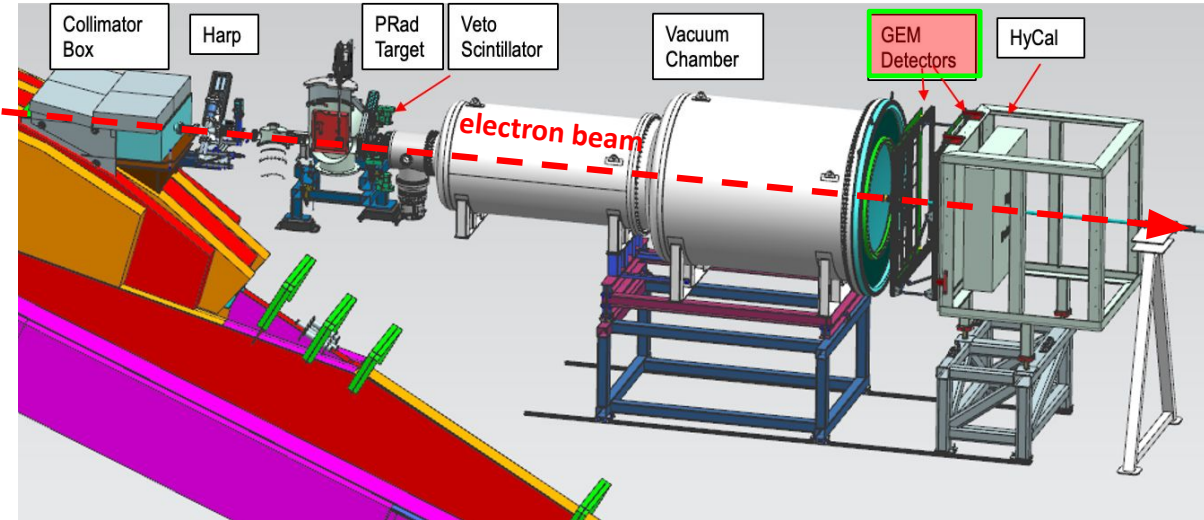
Experiment Setup to Achieve PRad-II's Goals

Improvements with Respect to PRad

- Add a second plane of GEM tracking detectors:
 - Improve tracking capability, spatial resolution & background rejection
 - Add new scintillating detectors
 - Improve separation of Møller electrons from (ep) electrons near the lowest Q^2
($Q^2 \sim 10^{-5} (\text{GeV}/c)^2$)
 - Improve radiative correction calculations
- Upgrade the DAQ and readout systems
 - Enable data taking at rates 5 times higher than PRad
 - Support more sophisticated triggering algorithms
 - Improve vacuum system and beamline
 - Suppress beamline backgrounds
 - Collect more statistics

The Upgraded PRad-II Spectrometer

Adding a Second GEM Plane to the Tracking System



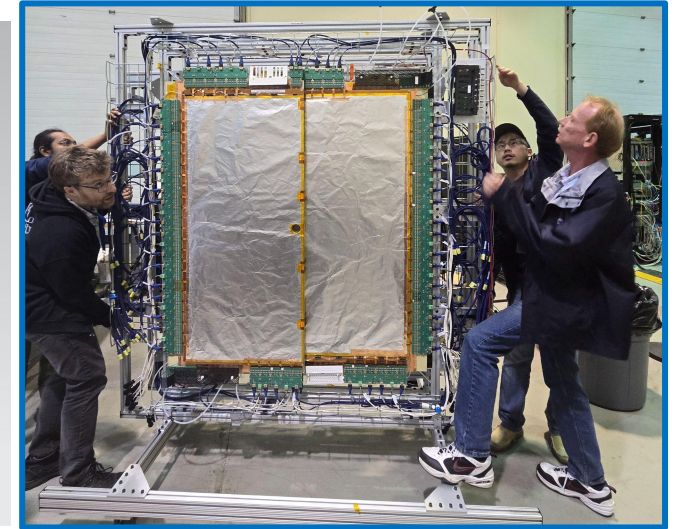
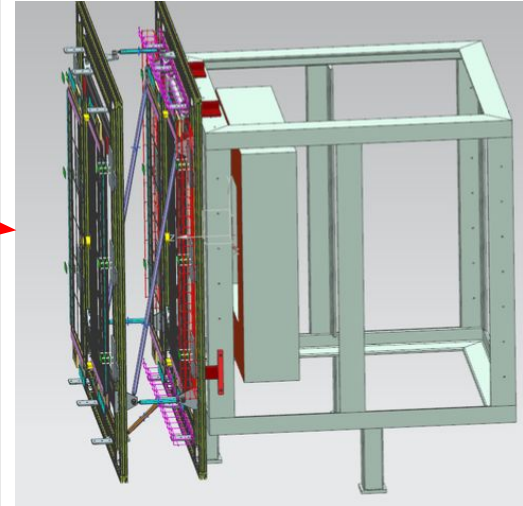
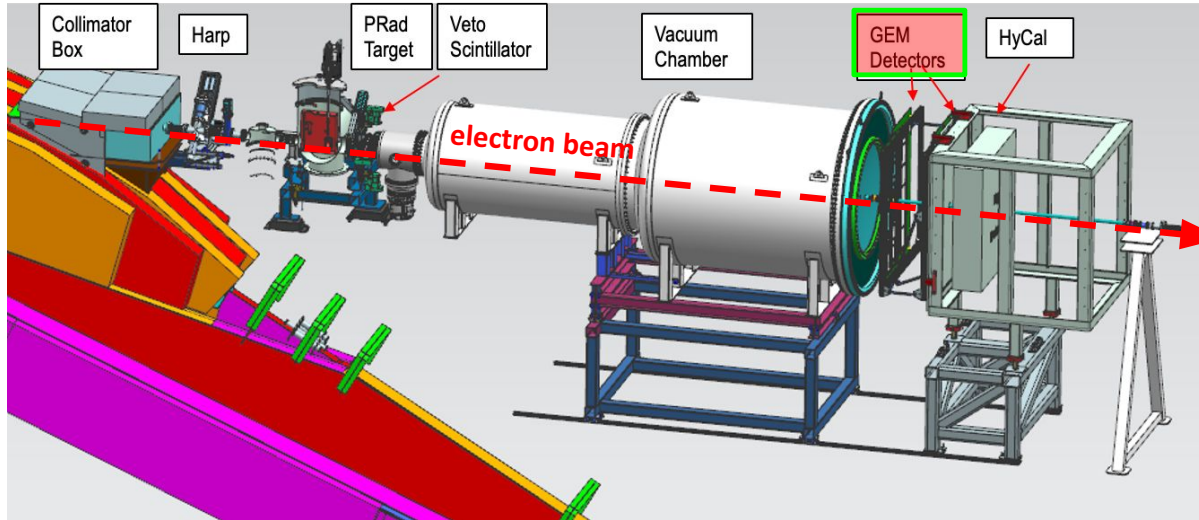
- **Capability of tracking system with TWO GEM planes:**

- Provides better track reconstruction and spectrometer spatial resolution
- Improves precision on GEM detection efficiency
- Maintains low material budget: minimizes multiple scattering
- Large active area ($105 \times 125 \text{ cm}^2$) with built-in hole:
Provide fully azimuthal coverage for forward angles $\theta = [0.47^\circ - 3.78^\circ]$

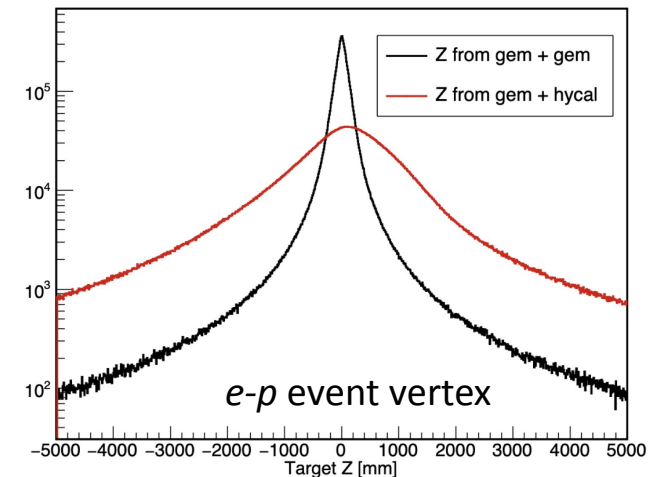
A built-in hole of 4 cm radius at the center of GEM layers for beam passage

The Upgraded PRad-II Spectrometer

Adding a Second GEM plane to the Tracking System

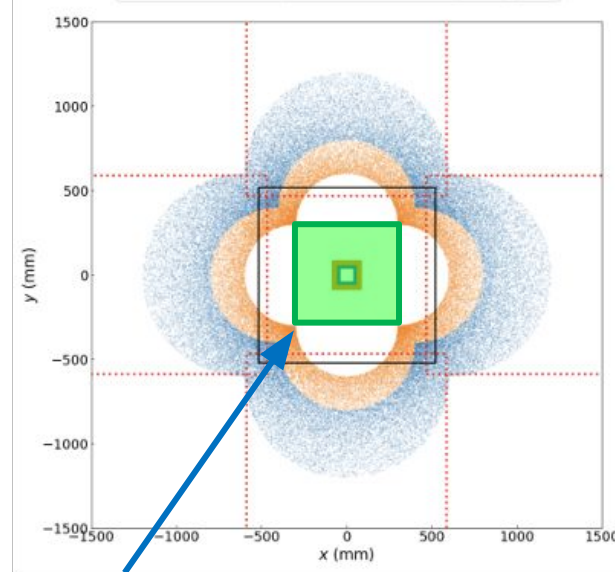
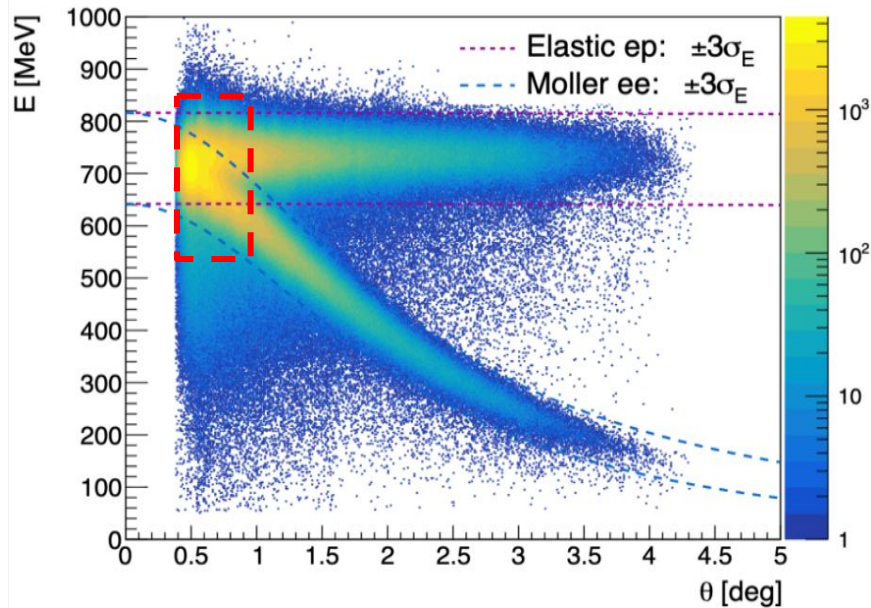


- **Tracking system with TWO GEM planes enables:**
 - Improved vertex reconstruction
 - Suppression of accidental backgrounds and non-target events
 - Increase Q^2 resolution, reduce systematic uncertainties

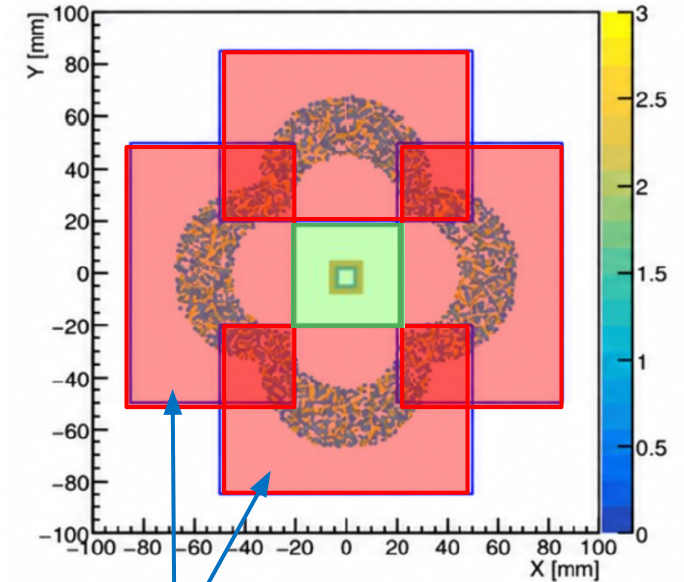


The Upgraded PRad-II Spectrometer

Veto Scintillators to separate Moller (ee) & Mott (ep) events



HyCal Acceptance Projected
to the Scintillator Plane

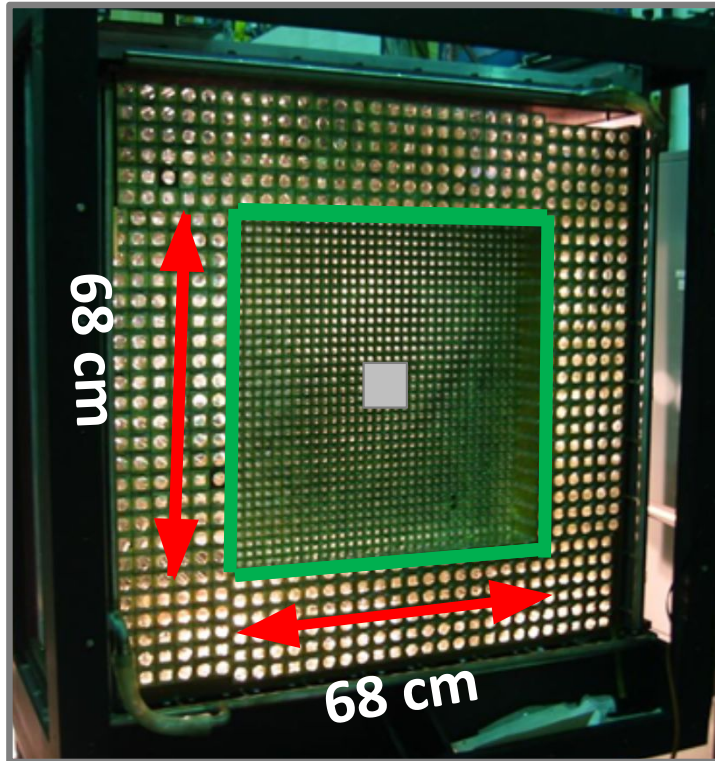


Veto Scintillators

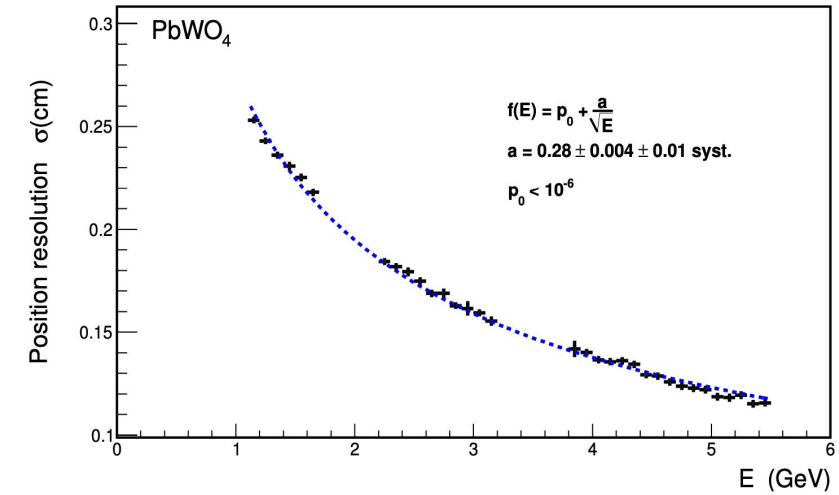
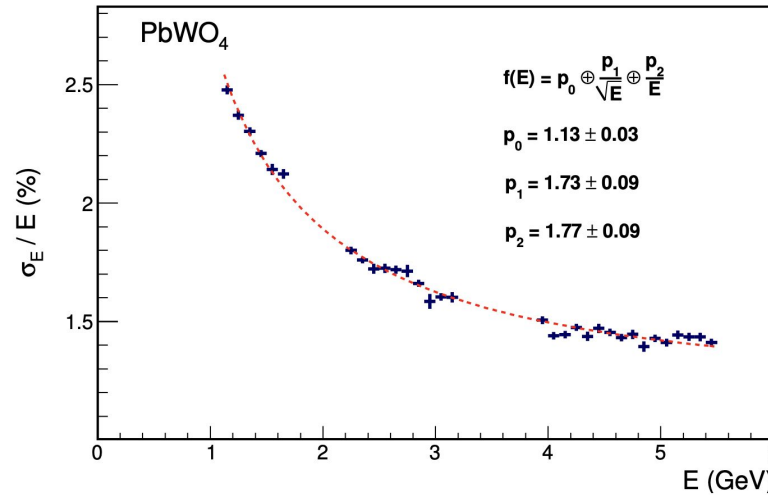
- **Identify Moller events:**

- Elastic e - p and Møller events overlap in $\theta \approx (0.5^\circ - 0.8^\circ)$ range at the lowest energy 0.7 GeV
- HyCal limit acceptance cannot detect Møller electron partner in this critical range
- Veto Scintillators detect Møller electron partner, provide clean separation of Moller and elastic e - p events

PbWO₄ Forward Calorimeter for PRad-II



*Four crystals are removed from
the center of calorimeter for
beam passage*



- Made of (34 x 34) PbWO₄ crystal modules, each with 2 x 2 x 18 cm³;
- Total detection area: 68 x 68 cm²
- Fully azimuthal coverage for forward angles $\theta = [0.47^\circ - 3.78^\circ]$
- Energy & position resolution: $\sigma_E/E = 2.6\%/\sqrt{E}$; $\sigma_{xy} = 2.5\text{mm}/\sqrt{E}$
- Readout by Flash ADC250 with sub-nanosecond timing resolution
 - Allows sophisticated triggering algorithms with cluster finding

PRad-II Electron Beam Parameters

- Required beam parameters for PRad-II:

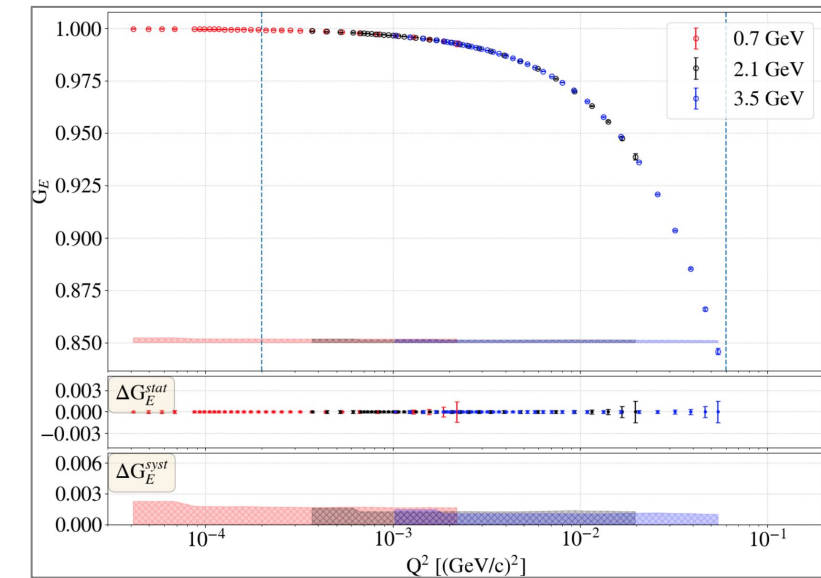
Energy (GeV)	current (nA)	polarization (%)	size (mm)	position stability (mm)	beam halo
0.7	20	Non	< 0.1	≤ 0.1	$\sim 10^{-7}$
2.2	350	Non	< 0.1	≤ 0.1	$\sim 10^{-7}$
3.5	700	Non	< 0.1	≤ 0.1	$\sim 10^{-7}$

- Three energies were chosen:

- The 0.7 GeV beam is critical to reach the lowest Q^2
- The 2.2 & 3.5 GeV beams provide constraint on $G_E(Q^2)$ fit and systematic cross-checks
- Practical CEBAF constraints

- A typical CEBAF beam profile: during previous PRad experiment showing a beam size of $\sigma_x = 0.01$ mm & $\sigma_y = 0.02$ mm

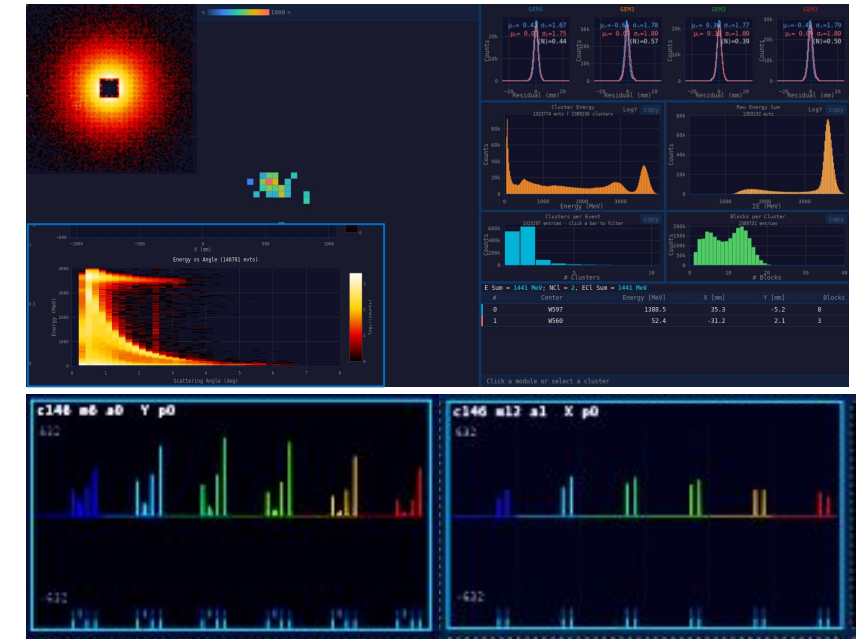
Simulated PRad-II Uncertainties on G_E



Beam tuning in PRad-II Control Room, April 2026

PRad-II Run Status

- **PRad-II commissioning completed in 27th April 2026**
 - Used a 2.1 GeV electron beam
 - Monitoring of all detectors
 - All subsystems deployed
- **PRad-II physics data taking successfully completed!**
 - Production run period: 27th April 2026 – 25th June 2026
 - High-quality data sets collected at three beam energies and corresponding beam currents:
 - 0.7 GeV at 50 nA:
 - 2.2 GeV at 350 nA
 - 3.5 GeV at 700 nA



HyCal & GEM Event Monitoring

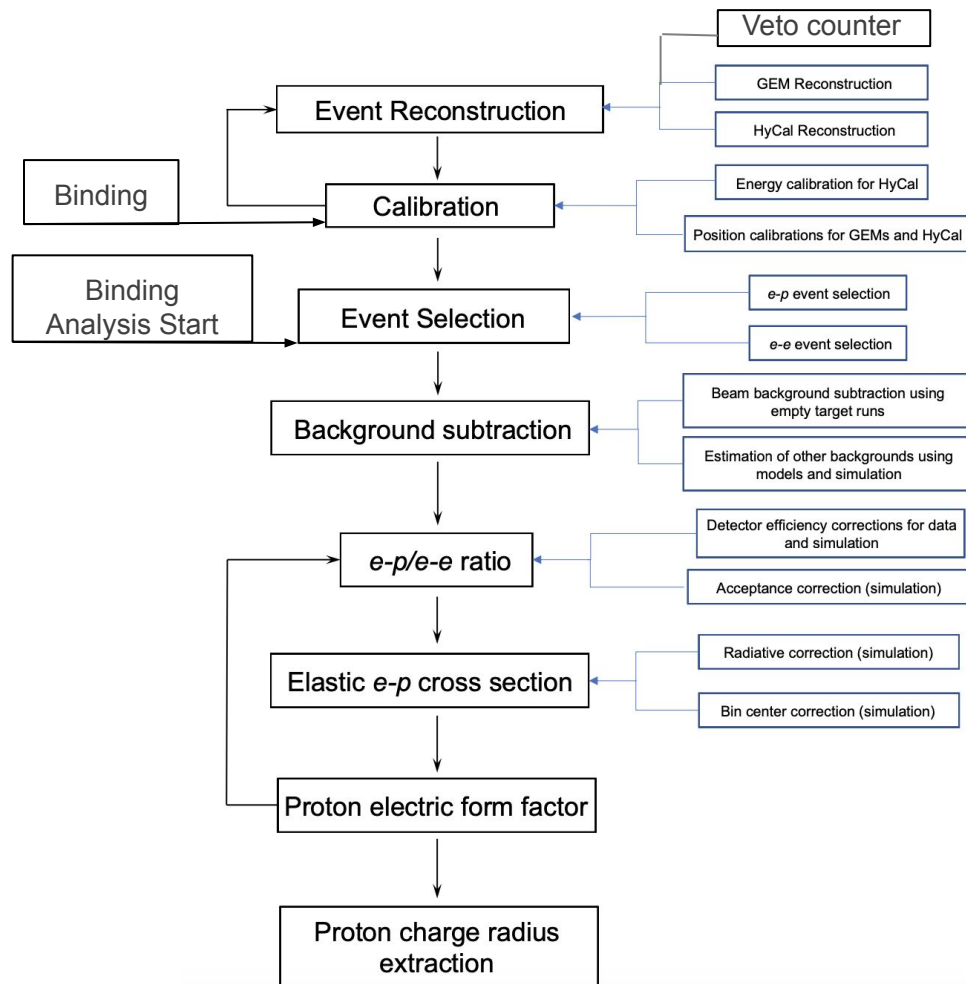
PRad-II Significantly Surpassed PRad

In Many Performance Parameters

	PRad-II	PRad
Vacuum Chamber	0.012 mTorr	0.5 mTorr
H ₂ cell /chamber pressure	1030 / 4.3 mTorr	470 / 2.7 mTorr
H ₂ gas flow	1300 sccm	600 sccm
H ₂ gas density	5.5×10^{18} H/cm²	2×10^{18} H/cm ²
Beam current	up to 700 nA	50 nA
Luminosity	2.6×10^{31} /cm²	6×10^{29} /cm ²
Beam background	~ 2% of <i>ep</i> events	~10 - 30% of <i>ep</i> events
DAQ rates	20-25 kHz	4-5 kHz
GEMs	2-planes with tracking	1-plane, no tracking
Veto counter (Q ² range)	~ 10^{-5} GeV²	~ 10^{-4} GeV ²
HyCal	only PbWO ₄ + FADC readout	PbWO ₄ + Pb-glass

PRad-II: Ongoing Analysis

- Flow chart for the data analysis



- Graduate students:

- Yining Liu (**Duke**)
- Buddhiman Tamang, Erik Wrightson (**MSU**)
- Yuan Li, Mingyu Li (**Shandong University**)
- Nithya Kularatne (**UVA**)

- Postdocs:

- Aruni Nadeeshani (**MSU**)
- Zhiwan Xu (**Argonne**)
- Yi Yu (**Duke**)
- Andrew Schick (**JLab**)

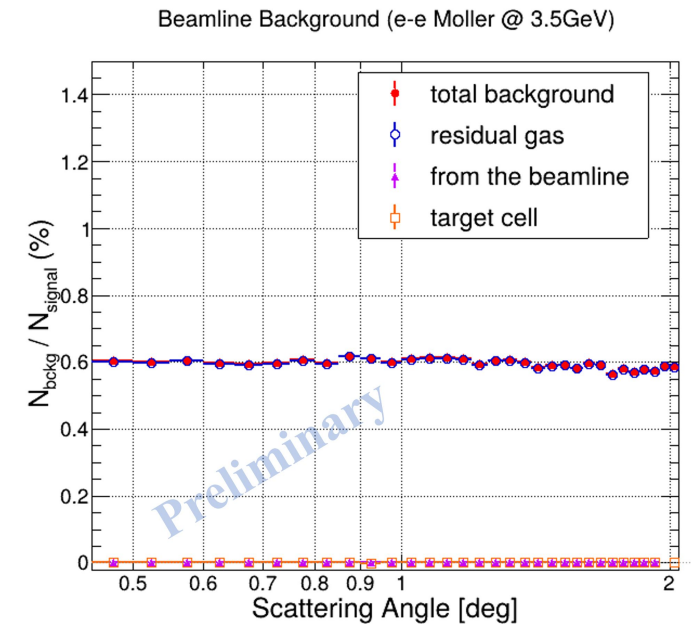
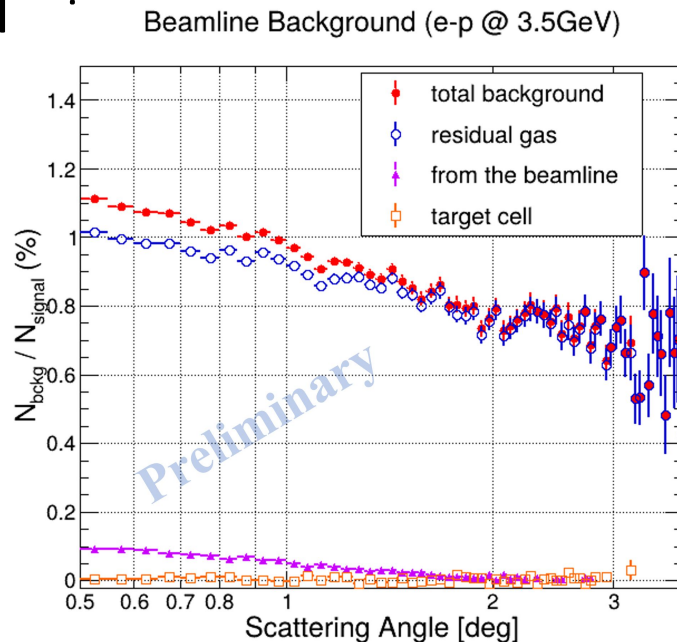
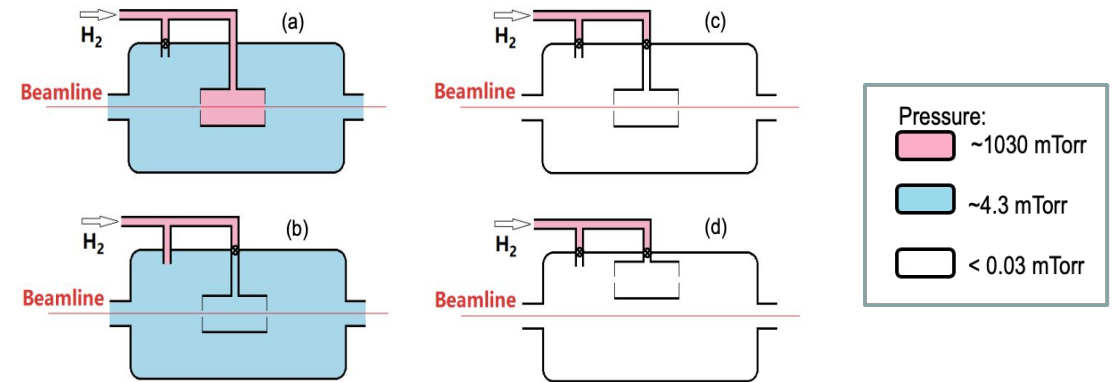
- Former PRad Graduate students leading PRad-II analysis

- Xinzhan Bai (Staff Scientist Staff, JLab)
- Chao Peng (Staff Scientist, Argonne)
- Weizhi Xiong (Prof. of Physics, Shandong University)

PRad-II: Background Subtraction

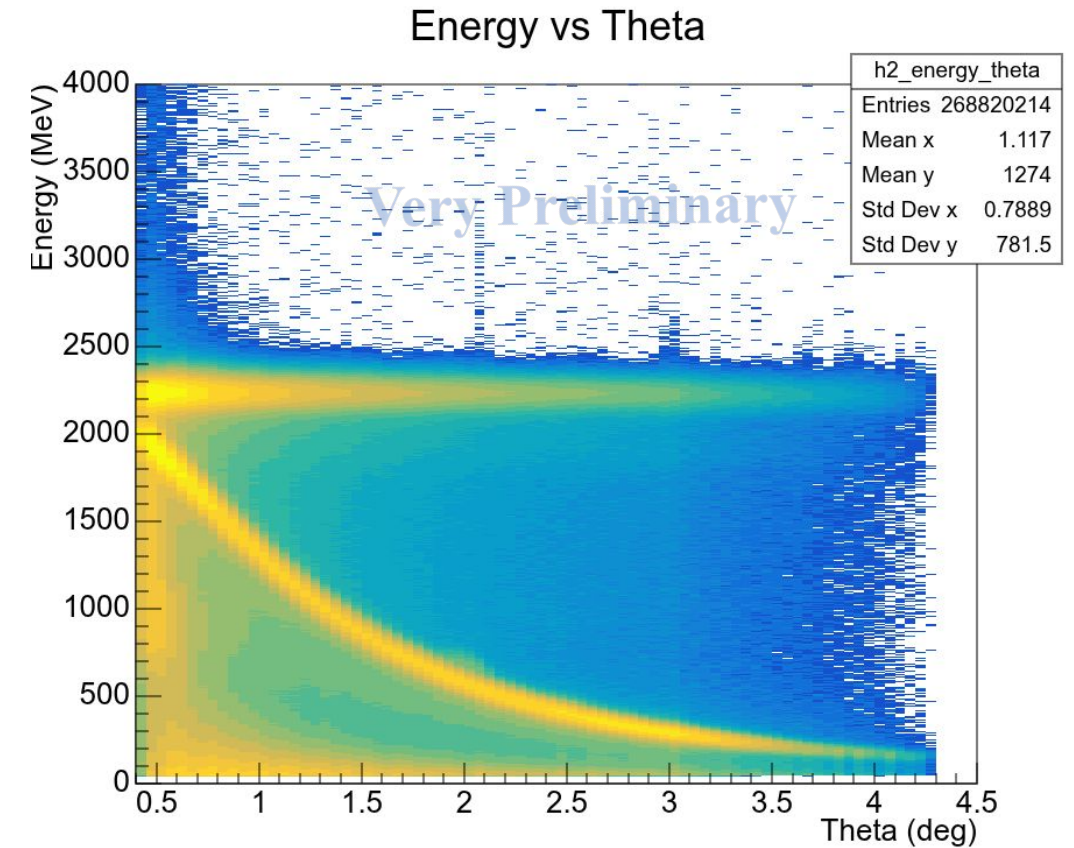
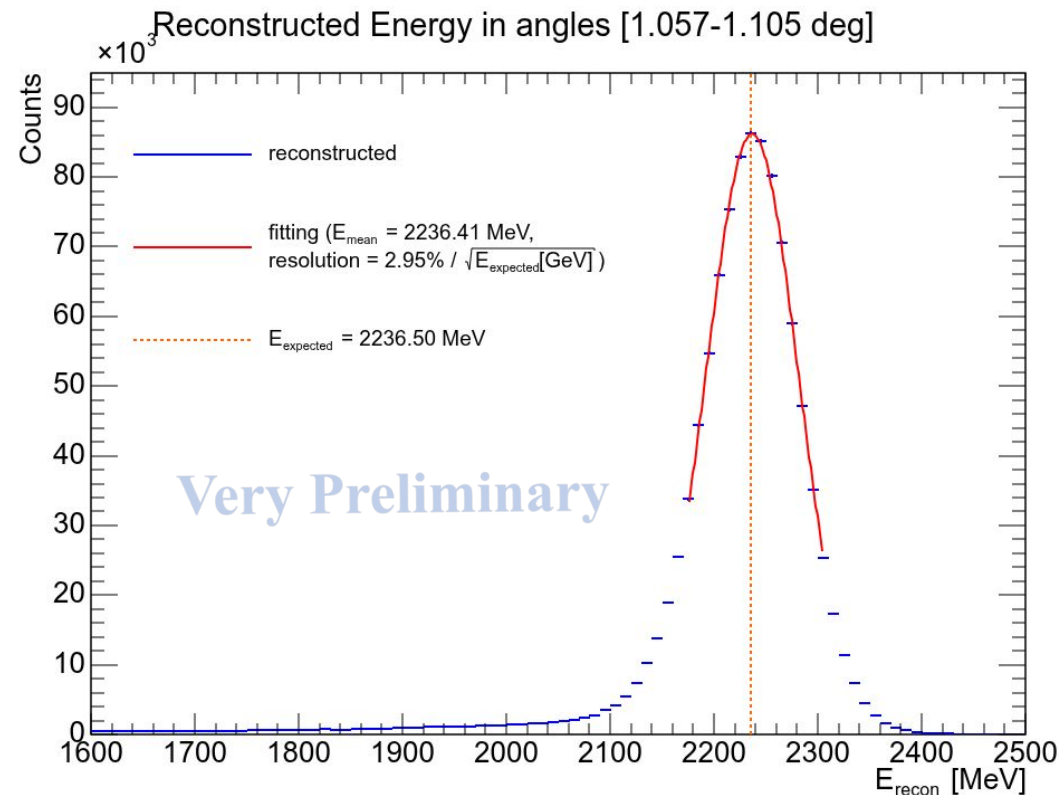
(Preliminary Data Analysis)

- Data with **different target configuration** was taken for background subtraction and systematic uncertainty study
- **Target density profile was simulated** COMSOL finite element analysis
- **Preliminary results:**
 - e - p background rate $< 1.2\%$ at all angles.
 - e - e background rate $\sim 0.6\%$ at all angles.



PRad-II: Reconstructed Energy vs. Scattering Angle

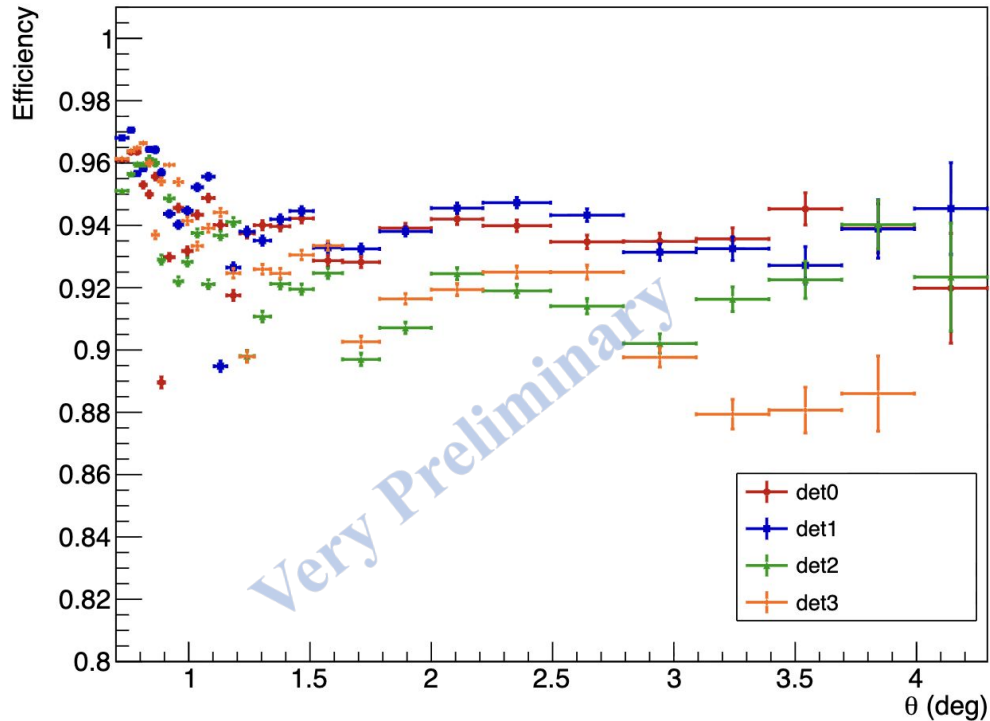
(Preliminary Data Analysis)



GEM Tracking Performance and Vertex Reconstruction

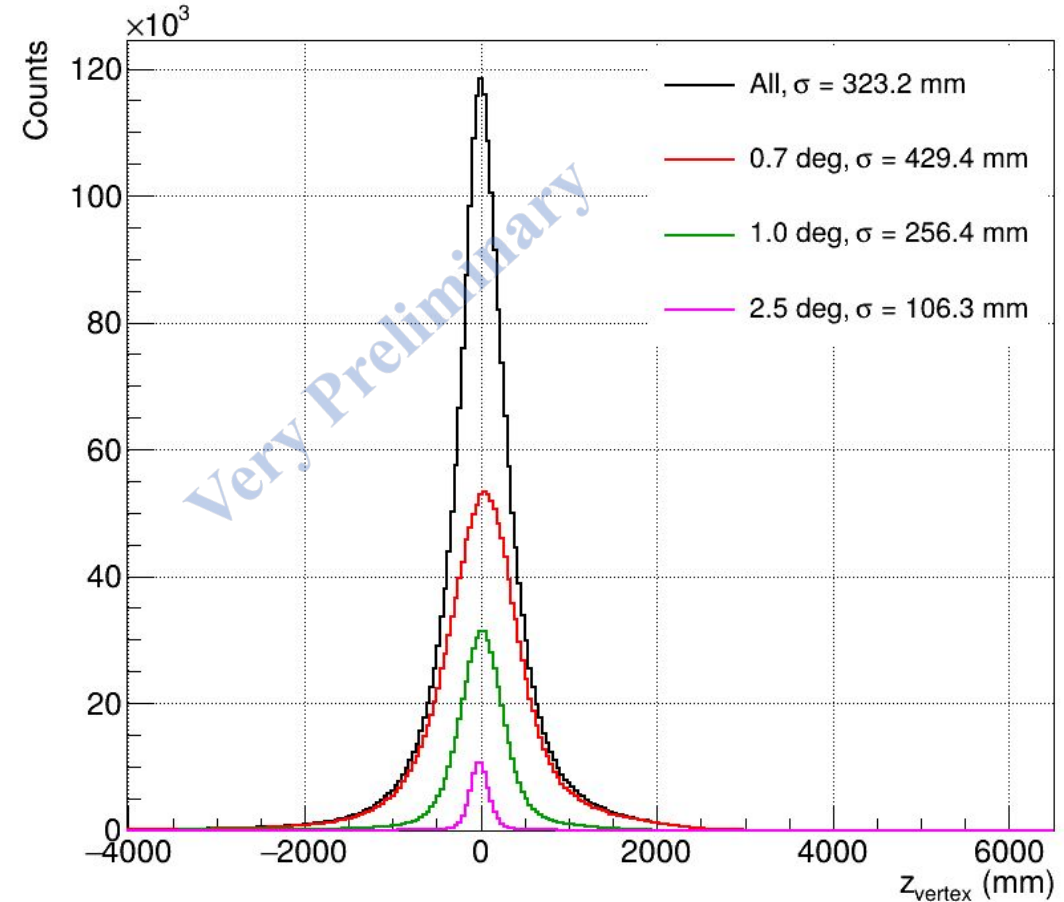
(Preliminary Data Analysis)

GEM Efficiency vs. Scattering angle

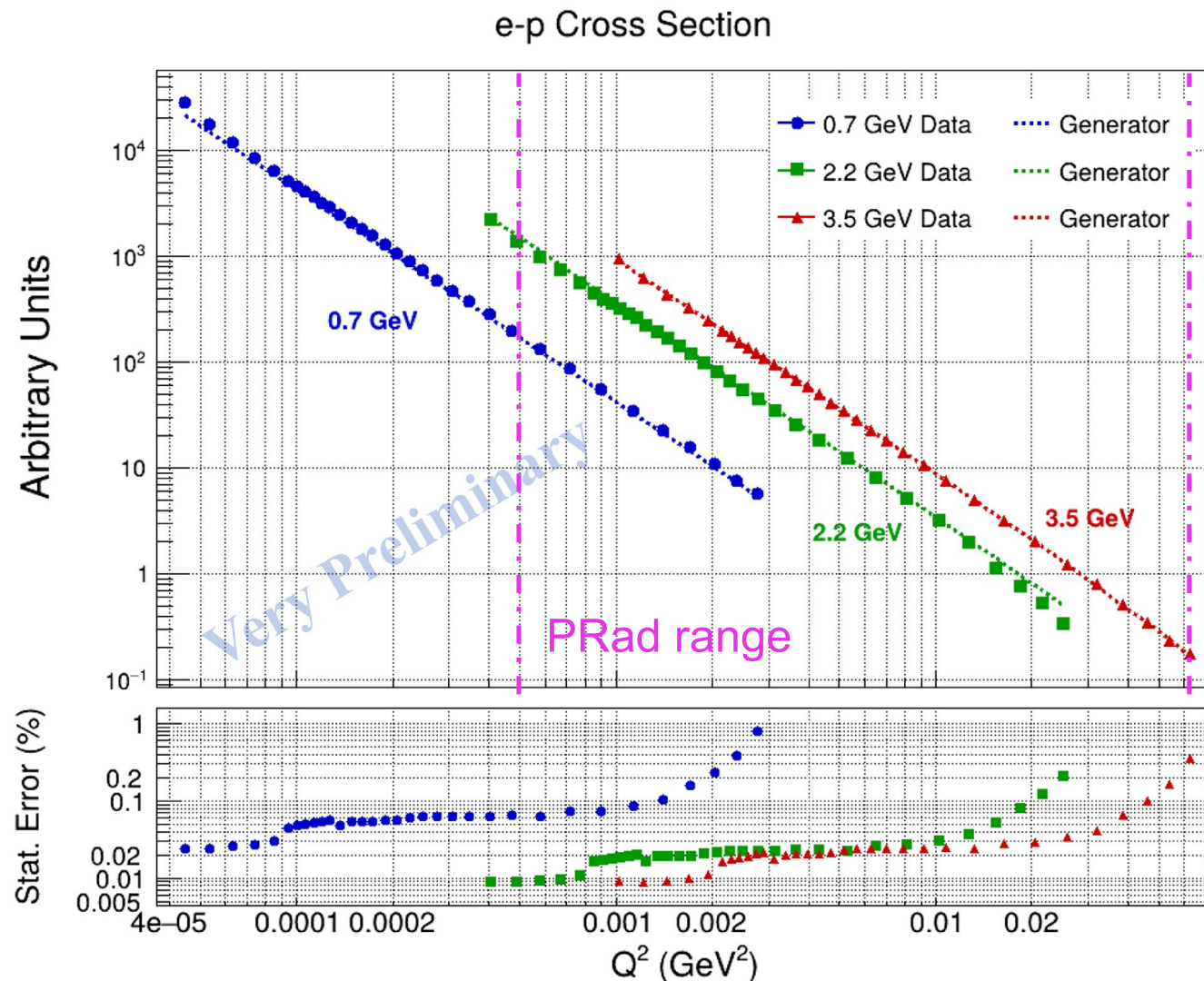


- GEM efficiency: **92% - 94%**
- Stable performance across PRad-II beam energies

Reconstructed Vertex Z of e-p Events at 2.2 GeV



PRad-II: Preliminary Analysis Result on ep Cross Section

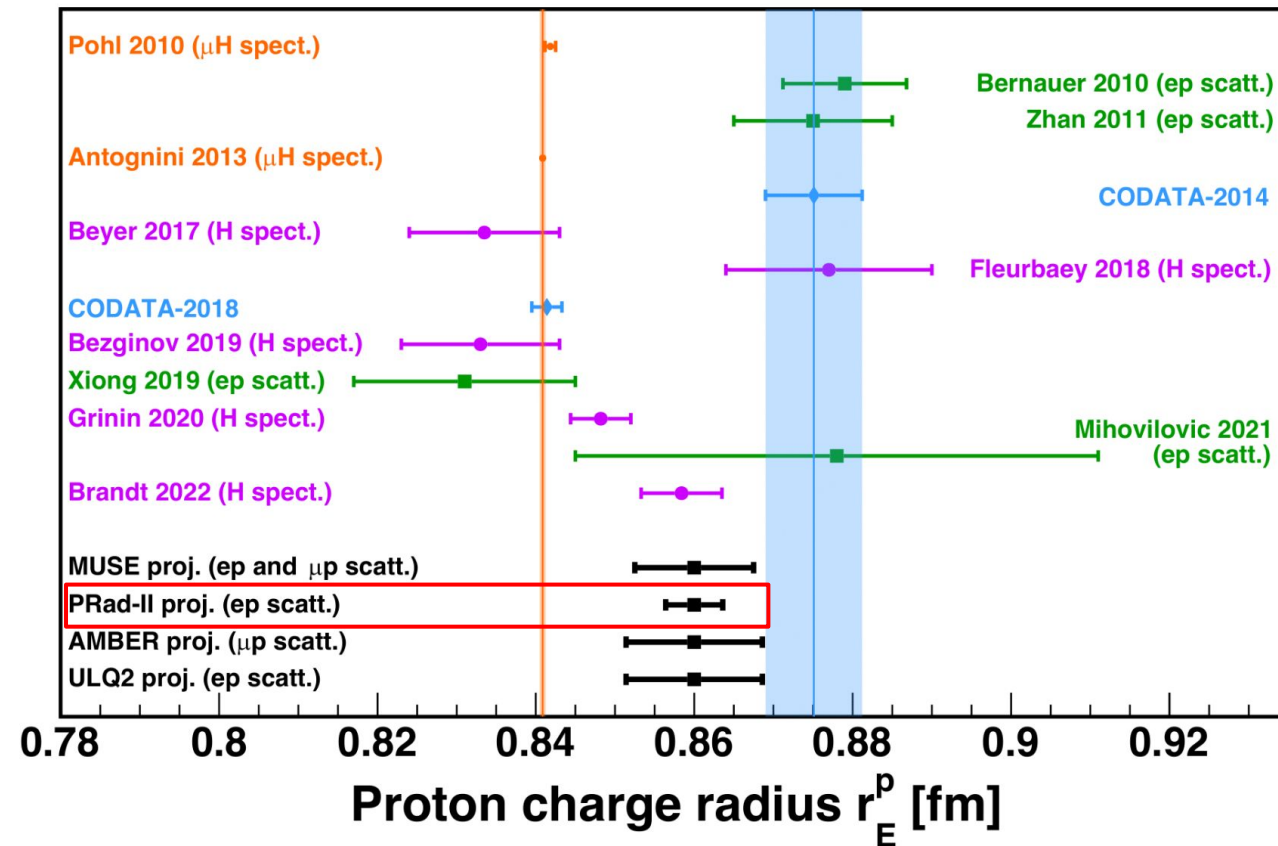


2 hrs of data
at each energy

Full data set

The PRad-II Experiment in Hall B at JLab

An upgrade of the PRad Experiment



PRad-II Projected uncertainty: $\delta_r \sim 0.0046$ fm

Summary and Outlook

- **PRad-II achieved all its statistical goals**
- **Analysis is moving fast and steady**
 - Finish detectors calibration by the end of 2026
 - Optimizing tracking reconstruction with GEMs
 - Verifying blind analysis procedure with PRad data
- **Plan on extraction of Proton Charge Radius**
 - Having preliminary result in Fall 2027
 - Final publication in Spring 2028

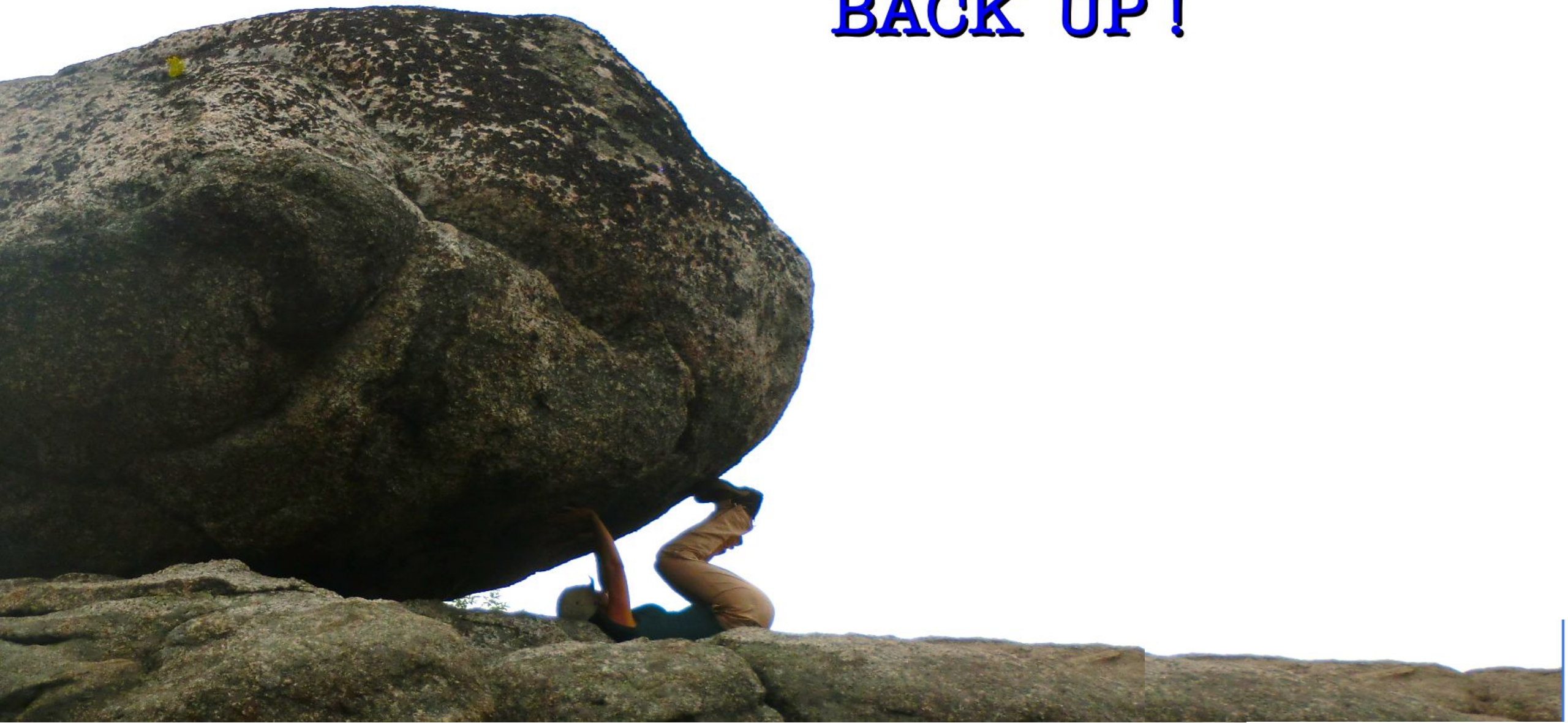


PRad-II End-Run Collaboration Meeting

Thank you for your attention!

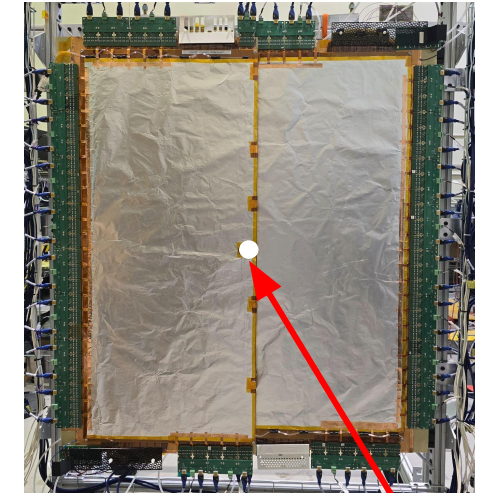
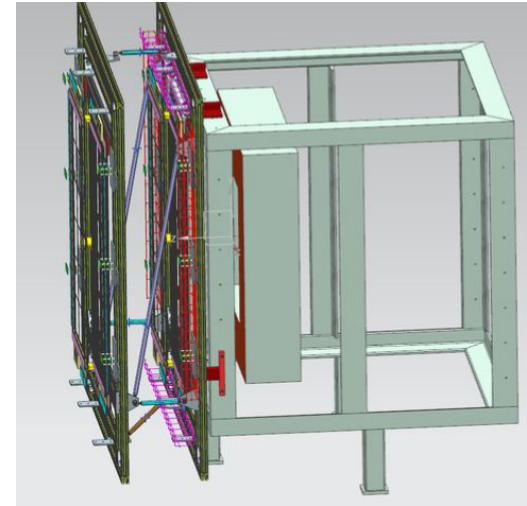
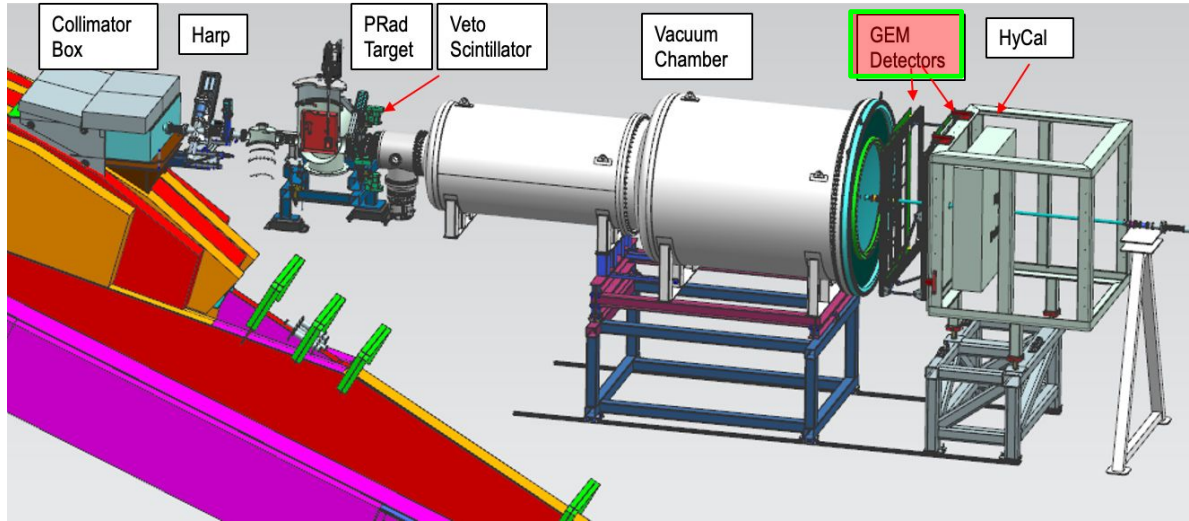
CONTACT: HTN3R@VIRGINIA.EDU

BACK UP !



The Upgraded PRad-II Spectrometer

GEM Tracking System



- **Two layers of Gas Electron Multiplier (GEM) detectors for tracking:**
 - Low material budget $\Rightarrow$ Minimizes multiple scattering
 - High detection efficiency ($> 95\%$) $\Rightarrow$ Reduces statistical uncertainty
 - Good position resolution ($\sigma = 7 \mu\text{m}$) $\Rightarrow$ Improves resolution of the setup
 - Large active area ($105 \times 125 \text{ cm}^2$) with built-in hole $\Rightarrow$ Provide fully azimuthal coverage for forward angles $\theta = [0.47^\circ - 3.78^\circ]$

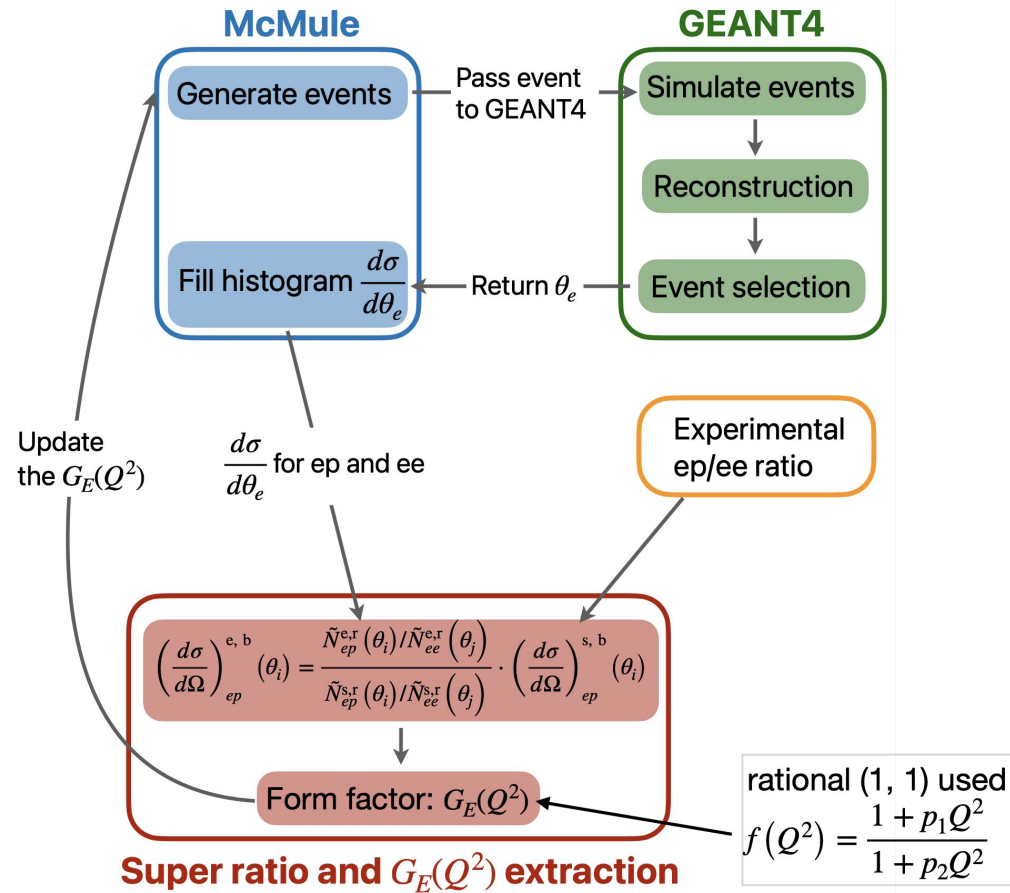
A built-in hole of 4 cm radius at the center of GEM layers for beam passage

Strategy for the NNLO Radiative Correction

(Preliminary Study)

Yi Yu (DUKE)

DNP Meeting, 11 - 14 October 2026)



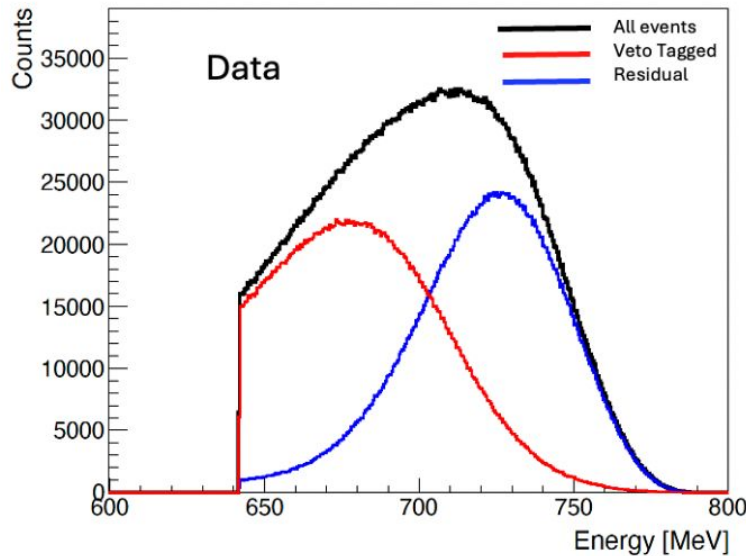
- **Simulation, analysis and cross section calculation**
 - McMule calls GEANT4 and feeds an event into GEANT4
 - GEANT4 returns reconstructed kinematics
- **Form super ratio and extract form factor**
 - Form super ratio with yields from data and cross section from simulation
 - Born level cross section & extract form factor
- **Iteration**
 - Fit form factor with rational (1, 1), update the form factor input to McMule
 - Repeat until extracted radius converges

Møller and Elastic ep Event Separation

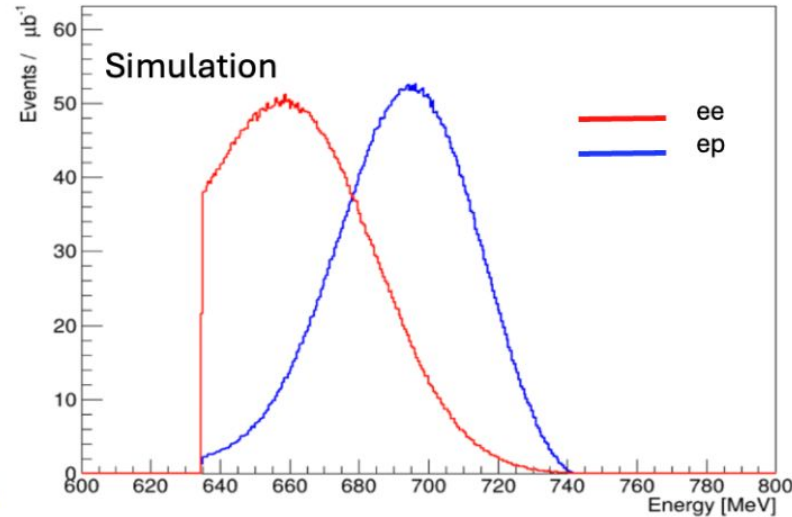
Buddhiman Tamang (MSU)

DNP Meeting, 11 - 14 October 2026)

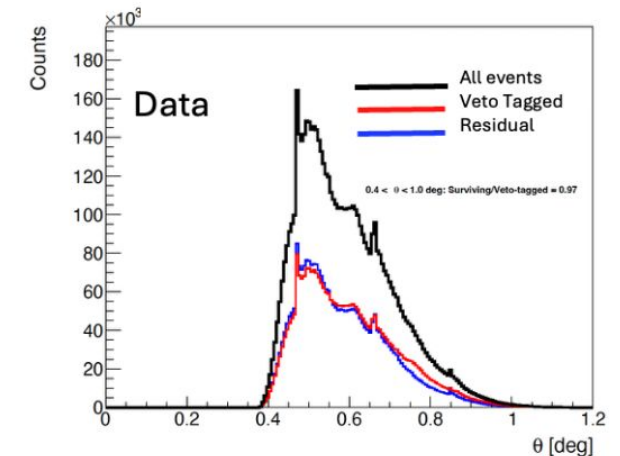
Data: Energy Distribution before and after veto



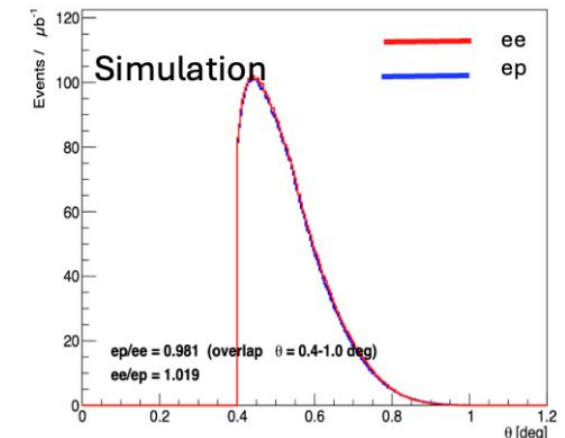
Simulation: Energy Distribution



Data: Angular Distribution before and after veto



Simulation: Angular Distribution



- Beam energy ≈ 728.9 MeV; scattering angles 0.4° – 1.0°
- Veto-tagged events: Møller candidates; surviving events: ep candidates
- Yield ratios agree closely: surviving/veto-tagged = 0.97 in data; $ep/ee = 0.98$ in simulation (event generator only).

Prad-II Projected Systematic Uncertainties

Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0015
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0025
Beam background	0.0039	0.0014
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p model	0.0006	0.0005
Total syst.	0.0115	0.0043
Total uncertainty	0.0137	0.0046