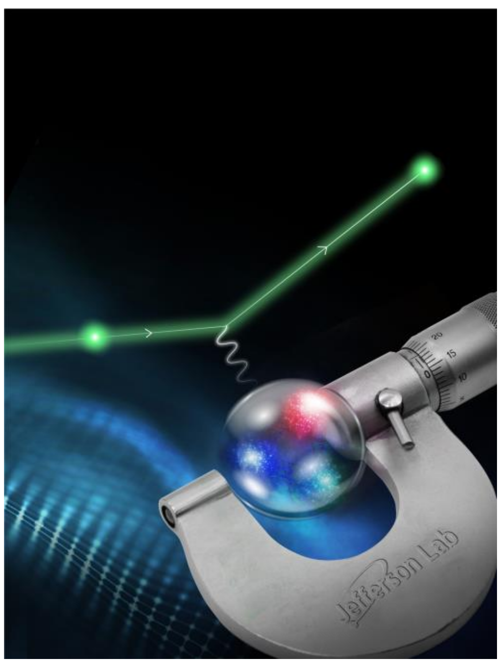
Duke UNIVERSITY

Jefferson Lab

The Proposed Deuteron Charge Radius Experiment (DRad) at Jefferson Lab



Spokespersons **(A. Gasparian, H. Gao, D. Dutta, N. Liyanage, D. Higinbotham & E. Pasyuk)**

Jingyi Zhou

Duke University

For the DRad Collaboration

2022 Frontiers and Careers in Nuclear and Hadronic Physics

Outline

- Introduction and deuteron charge radius puzzle
- DRad experimental apparatus
- Studies for the DRad experiment
- Summary and Outlook

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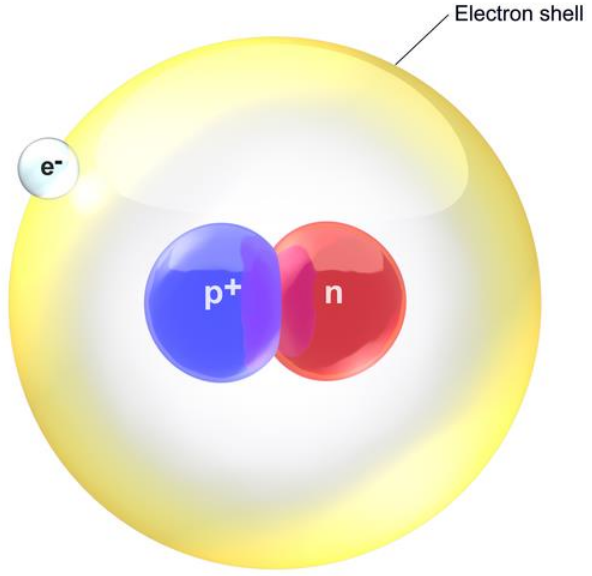
Deuteron

- The simplest and lightest nucleus in nature
- The only bound two-nucleon system
- Excellent laboratory to study QCD in nuclei, and effective neutron target
- Various theoretical calculations

- Deuteron rms charge radius: an ideal observable to compare experiments with theories



Hydrogen-2, deuterium
mass number: 2

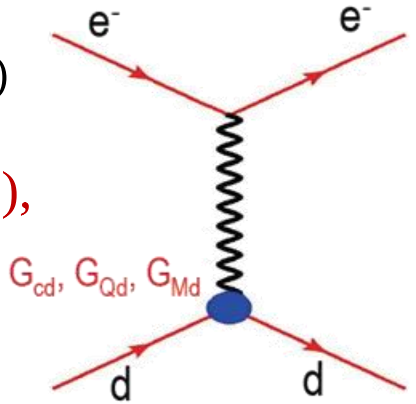
$$r_d \equiv \sqrt{\langle r_d^2 \rangle} \equiv \sqrt{-6 \frac{dG_C^d(Q^2)}{dQ^2}\bigg|_{Q^2=0}}$$

Q^2 : Four momentum transfer
G_C^d : Deuteron charge form factor

Deuteron rms charge radius from unpolarized e-d elastic scattering

- In the Born approximation (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}\right] \qquad Q^2 = 4EE'\sin^2(\theta/2)$$



A and B are structure functions related to the deuteron charge (G_C^d), magnetic (G_M^d) and quadrupole (G_Q^d) form factors:

$$A(Q^2) = {G_C^d}^2(Q^2) + \frac{2}{3}\tau {G_M^d}^2(Q^2) + \frac{8}{9}\tau^2 {G_Q^d}^2(Q^2)$$

$$B(Q^2) = \frac{4}{3}\tau(1+\tau){G_M^d}^2(Q^2) \qquad \tau = Q^2/(4M_d^2)$$

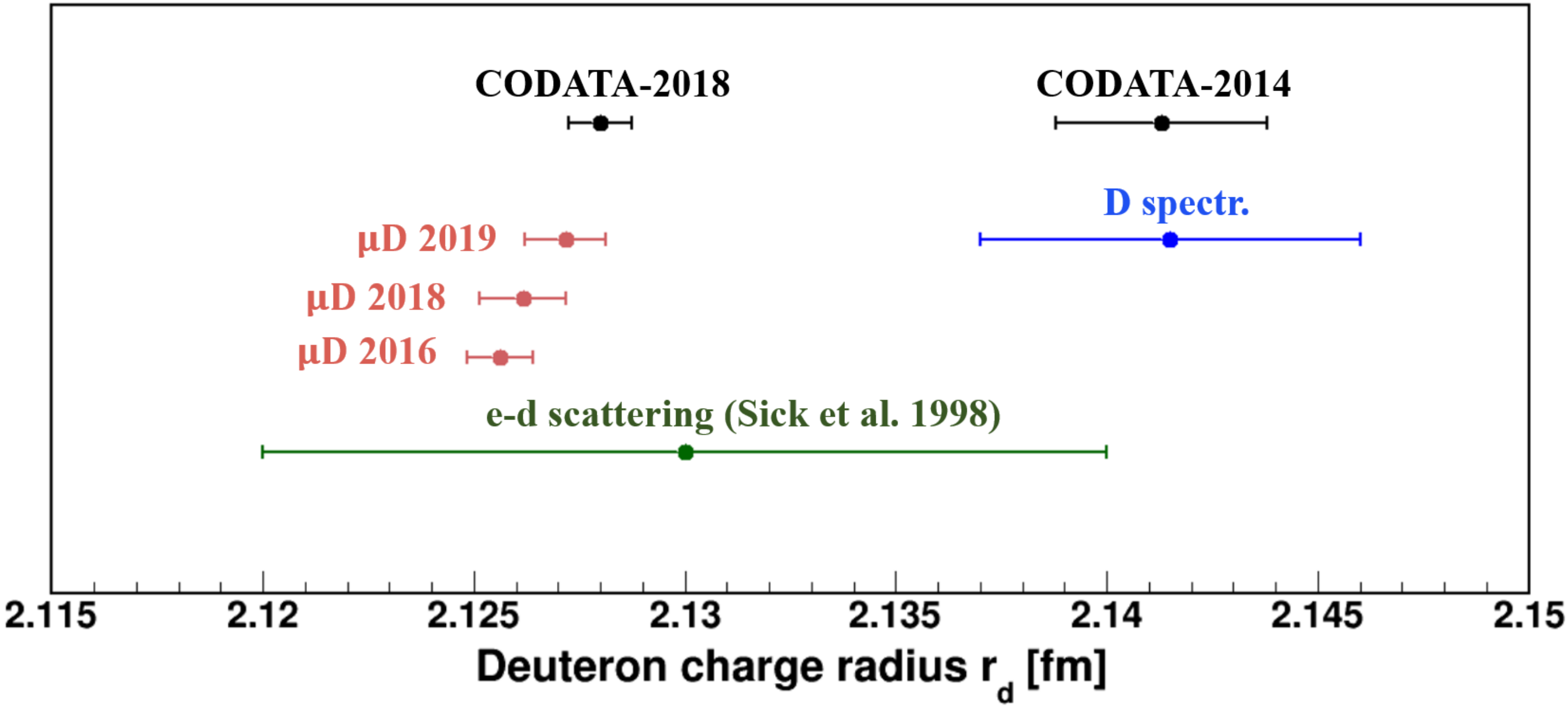
- At very low Q^2(DRad), cross section dominated by G_C^d, one may extract G_C^d assuming G_M^d and G_Q^d in certain forms.

- The rms charge radius can be obtained from the slope of the charge form factor G_C^d at $Q^2 = 0$:

$$r_d \equiv \sqrt{\langle r_d^2 \rangle} \equiv \sqrt{-6\left.\frac{dG_C^d(Q^2)}{dQ^2}\right|_{Q^2=0}}$$

The deuteron charge radius puzzle

Independent of the famous "*Proton Charge Radius Puzzle*"



- ~6σ discrepancy between μD spectroscopy results and CODATA-2014 value
- Uncertainties in previous e-d experiments are too large to resolve the puzzle

Previous e-d scattering Experiments at Low Q^2 Range

Four experiments had been used for the modern extraction of deuteron charge radius from e-d elastic scattering:

◆ R.W. Berard et al. Phys. Rev. Lett. B47,355 (1973):

Used cooled H2 and D2 gas to measured ratio of *ed/ep* cross sections
$Q^2 = [4 \times 10^{-2} - 5 \times 10^{-2}]\mathrm{fm}^{-2}$

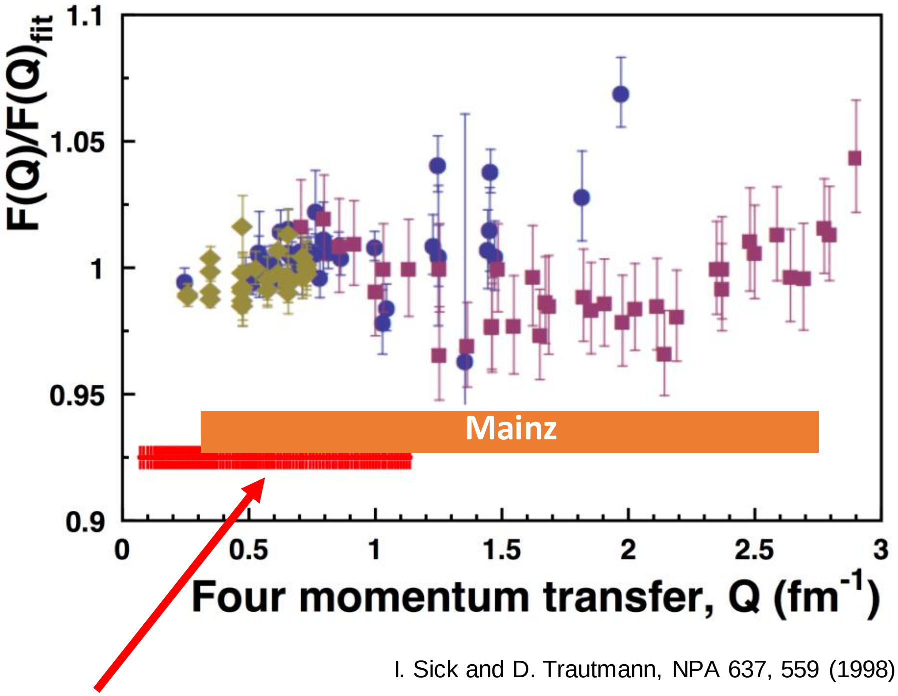
● G.G. Simon et al. Nucl. Phys. A364, 285 (1981):

different gas and liquid targets:
$Q^2 = [4 \times 10^{-2} - 4]\mathrm{fm}^{-2}$

■ S. Platchkov, et al. Nucl. Phys. A510, 740, (1990)

different LH2 and LD2 targets
$Q^2 = [5 \times 10^{-2} - 20]\mathrm{fm}^{-2}$

Mainz experiment: Initial State Radiation(ISR):
$Q^2 = [5 \times 10^{-2} - 7]\mathrm{fm}^{-2}$



I. Sick and D. Trautmann, NPA 637, 559 (1998)

Previous experiments used:

- magnetic spectrometer method;
- different types of targets;
- normalized *e-d* to *e-p* cross sections;
- Initial state radiation

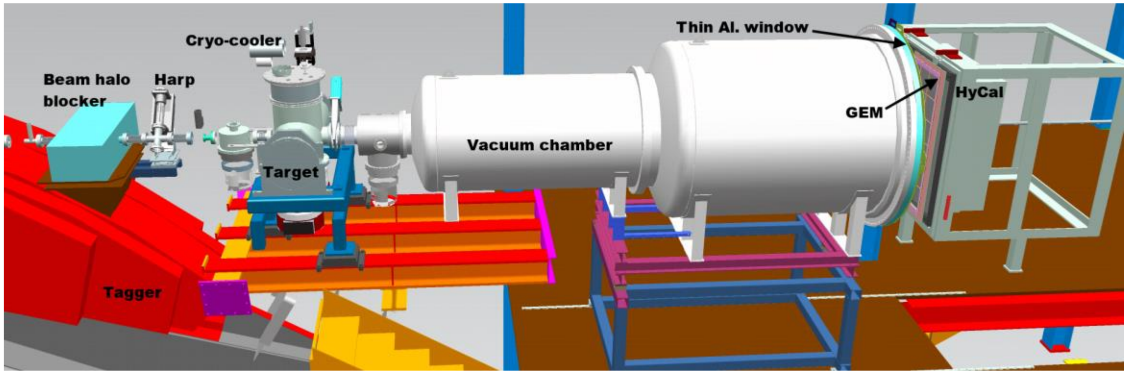
We propose a new independent method to measure *e-d* elastic cross sections with high accuracy.

$$Q^2 = [5 \times 10^{-3} - 1.3]\mathrm{fm}^{-2}$$

The highlight of DRad experiment

DRad proposal: PR12-20-006

- Measure *e-d* elastic cross sections at very low Q^2 range: $[5 \times 10^{-3} - 1.3]\mathrm{fm}^{-2}$.
- Two beam energies, E = 1.1 and 2.2 GeV to increase Q^2 range and control systematics.



- Experimental method based on PRad method and upgraded PRad-II (PR12-20-004):

[*W. Xiong et al*. Nature 466 (2010) 213-216; *H. Gao and M. Vanderhaeghen*, Rev. Mod. Phys. **94**, 015002]

- Magnetic-spectrometer-free calorimetric experiment;
- Windowless deuterium/hydrogen gas flow target to reduce background;
- Two planes of tracking detector for better scattered electron tracking (PRad-II);
- Cylindrical recoil detector for reaction elasticity (new);
- Veto counters for timing (PrimEx veto counters)

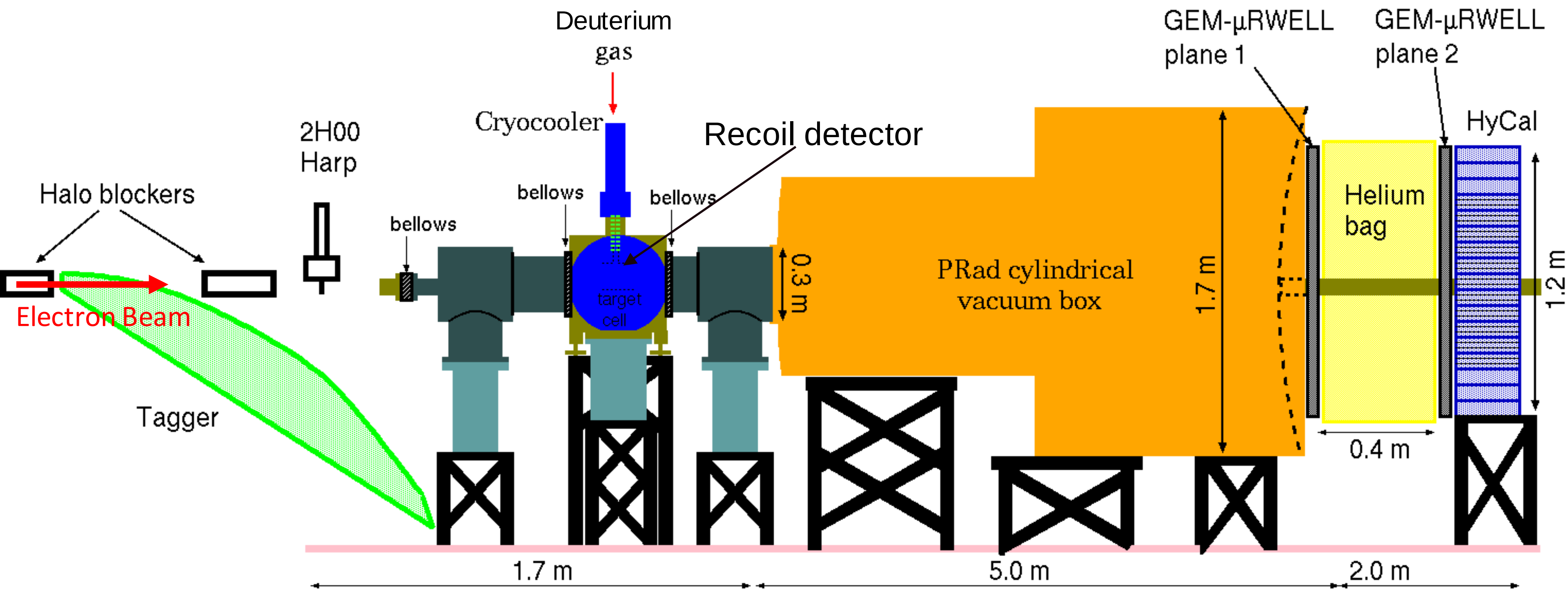
- That will allow:

➢ Measure cross sections in one kinematical settings for a large Q^2 range;
➢ Simultaneous detection of $ee \rightarrow ee$ Møller scattering process to control systematics;
➢ Measure e-d elastic cross section to subpercent precision

DRad experiment apparatus

@HallB JLab

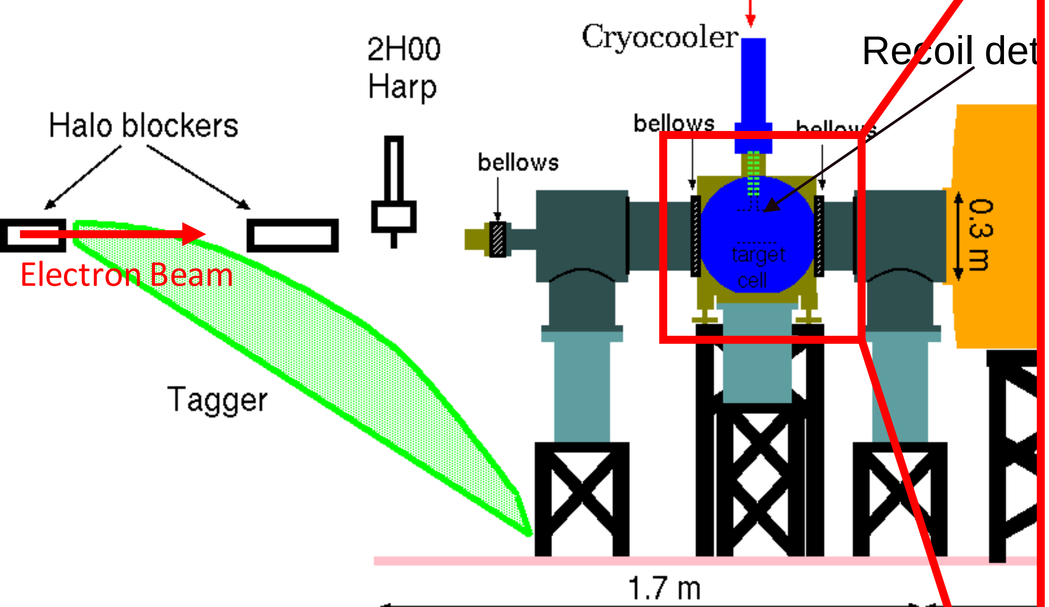
- $\theta_e = 0.6° - 7°$
- $\theta_d = 83° - 89°$

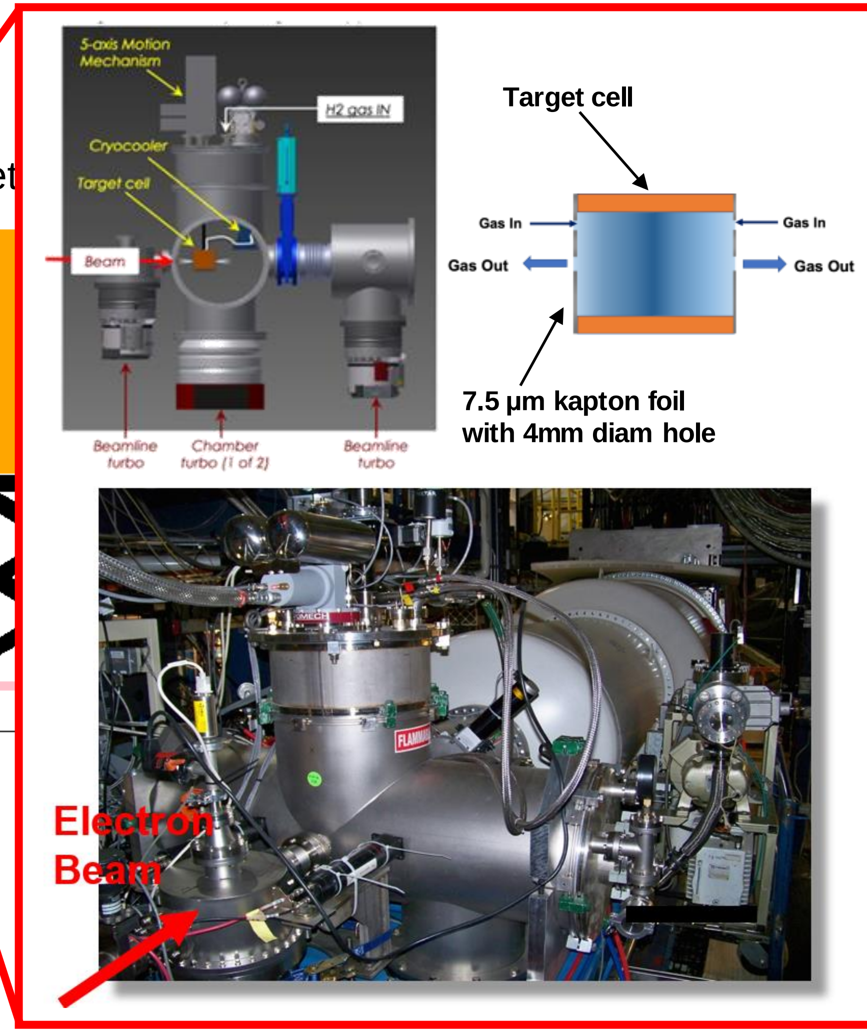


- Experimental technique based on PRad-II experiment(PR12-20-004), with a new two-layer cylindrical recoil detector for reaction elasticity

DRad experiment apparatus

Windowless gas flow target





- 29 cm diam x 5.5 cm long target cell
- 4 mm diam holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} atoms / cm^2
- remove major background source

Nucl.Instrum.Meth.A 1003 (2021) 165300

DRad experiment apparatus

Si-strip Cylindrical Recoil Detector inside the target cell

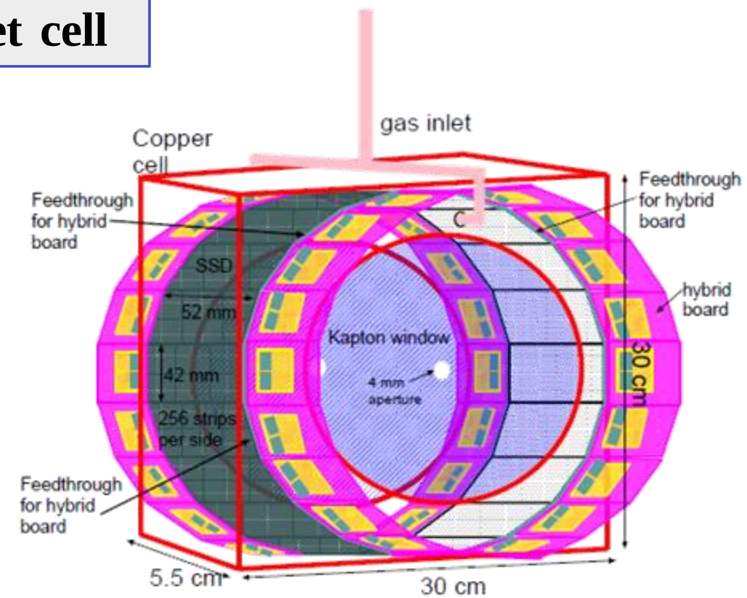
Detect recoil particles, provide two major information:

- Timing
- Azimuthal angle

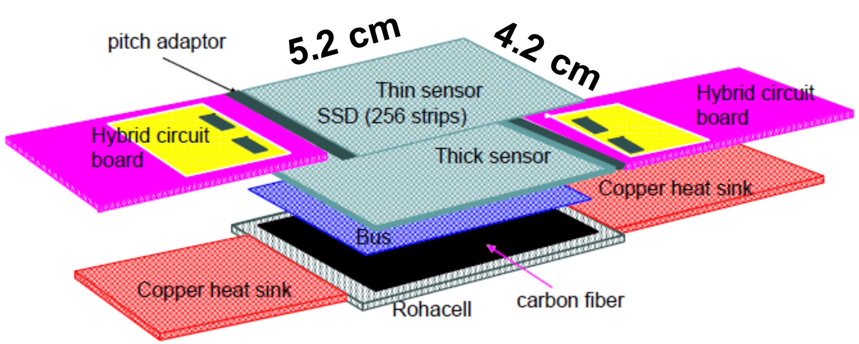
Based on the CLAS12 Barrel Silicon Tracker (SVT)

- 20 panels of twin, single sided Si-strip detectors (42x52 mm^2), 20 sided polygon arrangement with around 13 cm radius
- Thicknesses:
  200 µm (inner layer), 300 µm (outer layer)
- 256 strips on each sensor:
  angular resolution 5 mrad (ϕ) 20 mrad (θ)
- Inactive SiO_2 layer can be as thin as 0.5 um

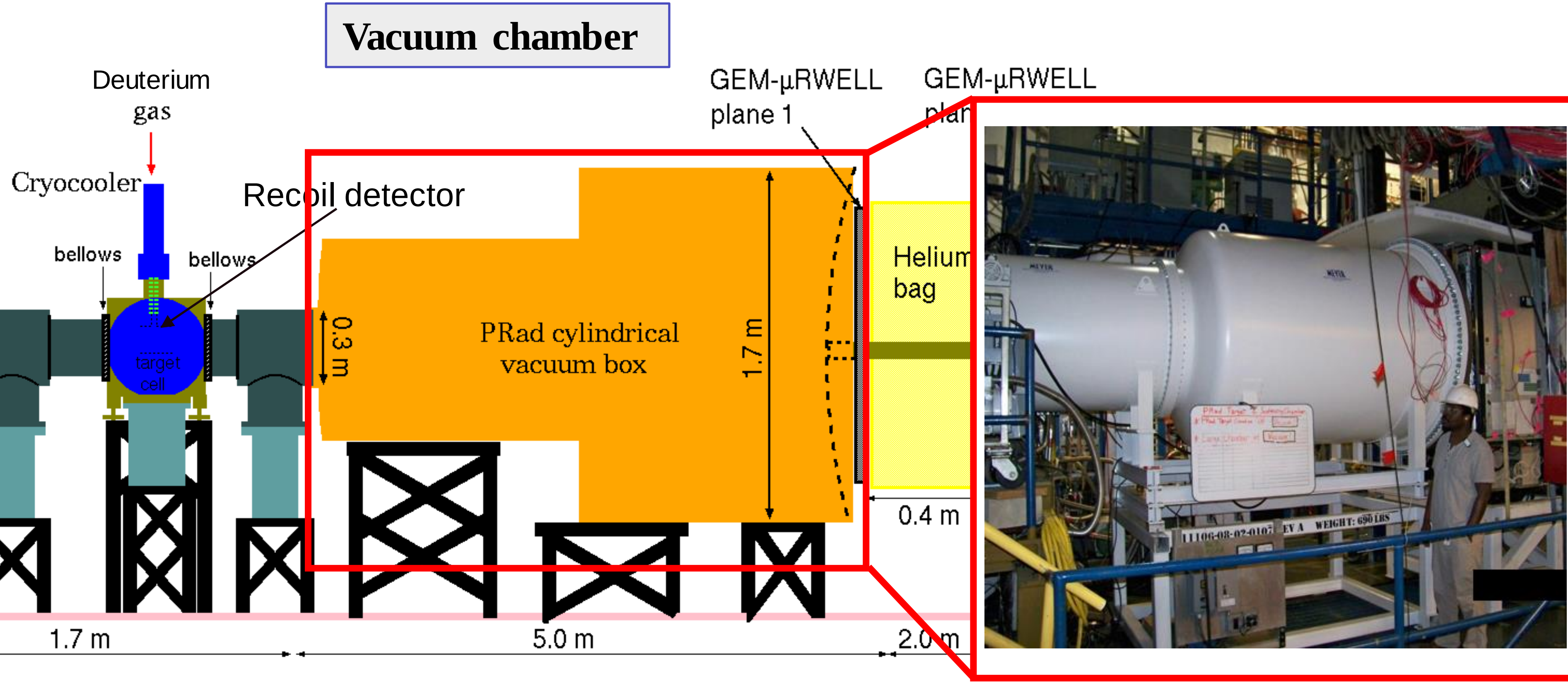
CLAS12 Technical Design Report, 2008 (`https://www.jlab.org/Hall-B/clas12_tdr.pdf`);
CLAS12 Detector documentation (`http://clasweb.jlab.org/clas12offline/docs/detectors/html/svt/introduction.html`)



Single pair of Si-strip detectors



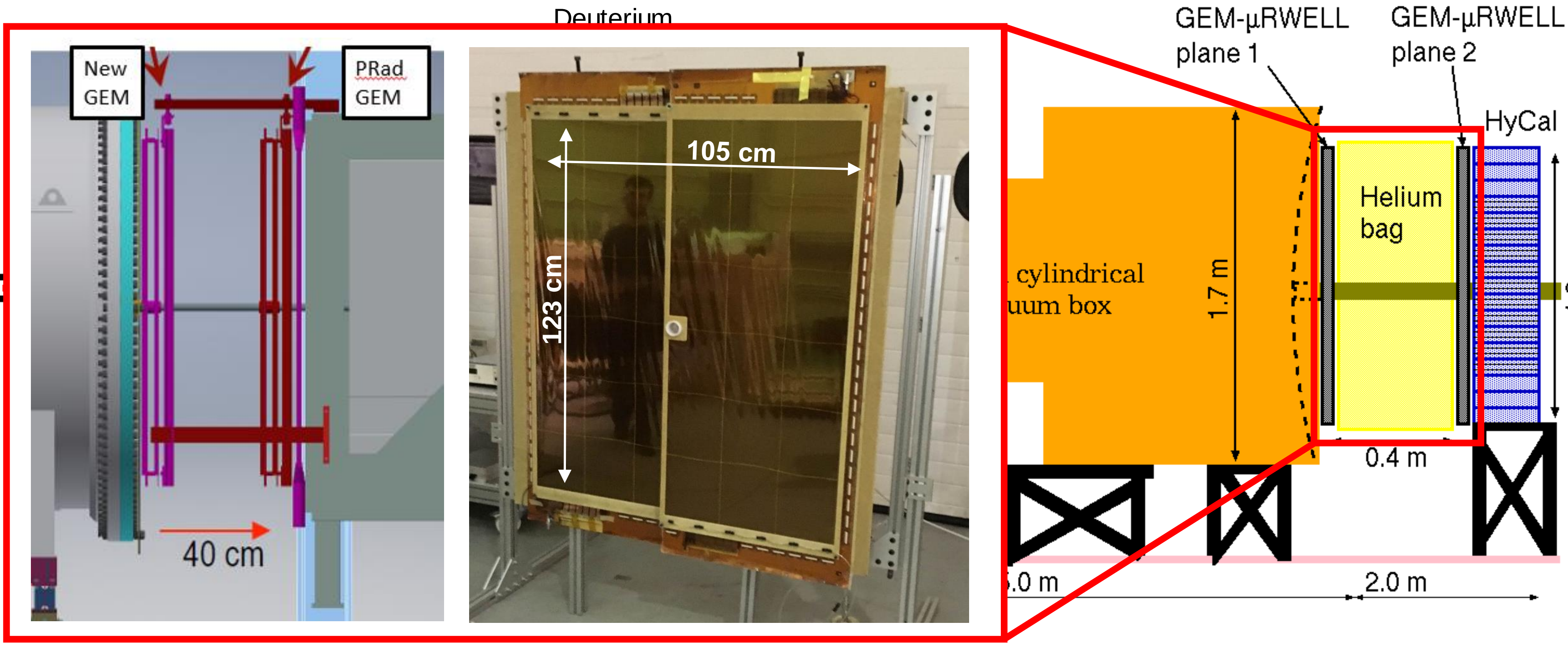
DRad experiment apparatus



- 5 m long two stage vacuum chamber, further remove possible background source from the electron multiple scattering
- Vacuum chamber pressure: 0.3 mTorr

DRad experiment apparatus

Tracking detectors

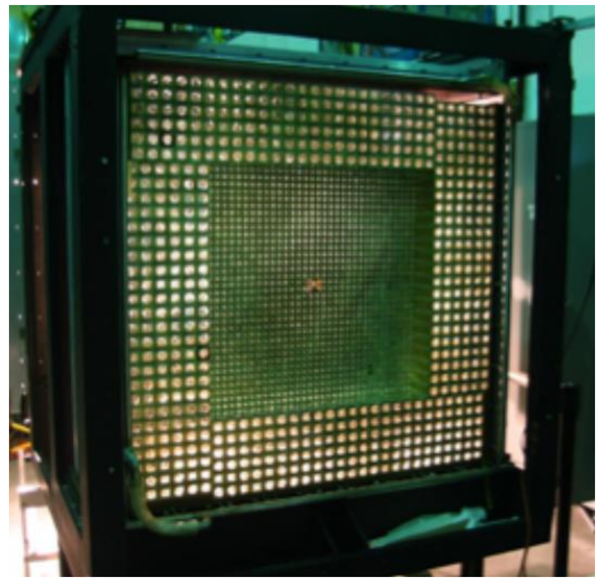


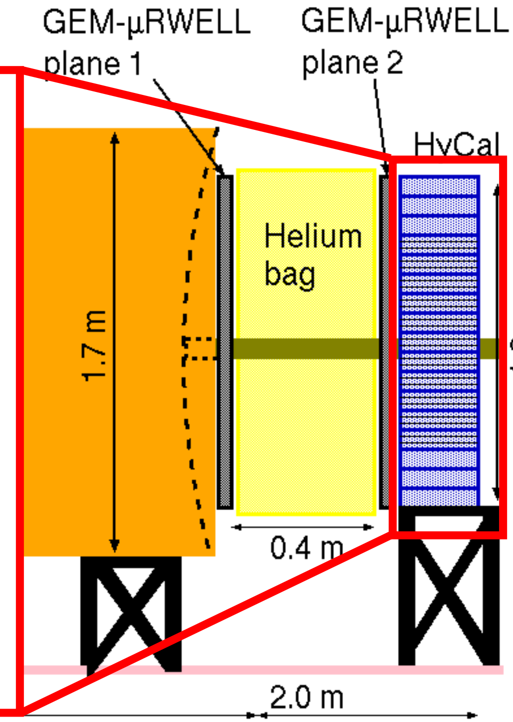
- Each GEM plane: two large area GEM chambers, small overlap region in the middle
- Provide excellent tracking for the scattered electrons
- Better control of beam line background from the upstream collimator, especially at very small angles (electron scattering angle less than 1 deg)

DRad experiment apparatus

Upgraded Hybrid Calorimeter (HyCal)

- High resolution and efficiency
- 5.5 m from the target
  - Inner 1156 $PbWO_4$ modules
  - Outer 576 lead-glass modules
- Scattering angle coverage: $\sim 0.6^\circ$ to 7.5°
- Full azimuthal angle coverage



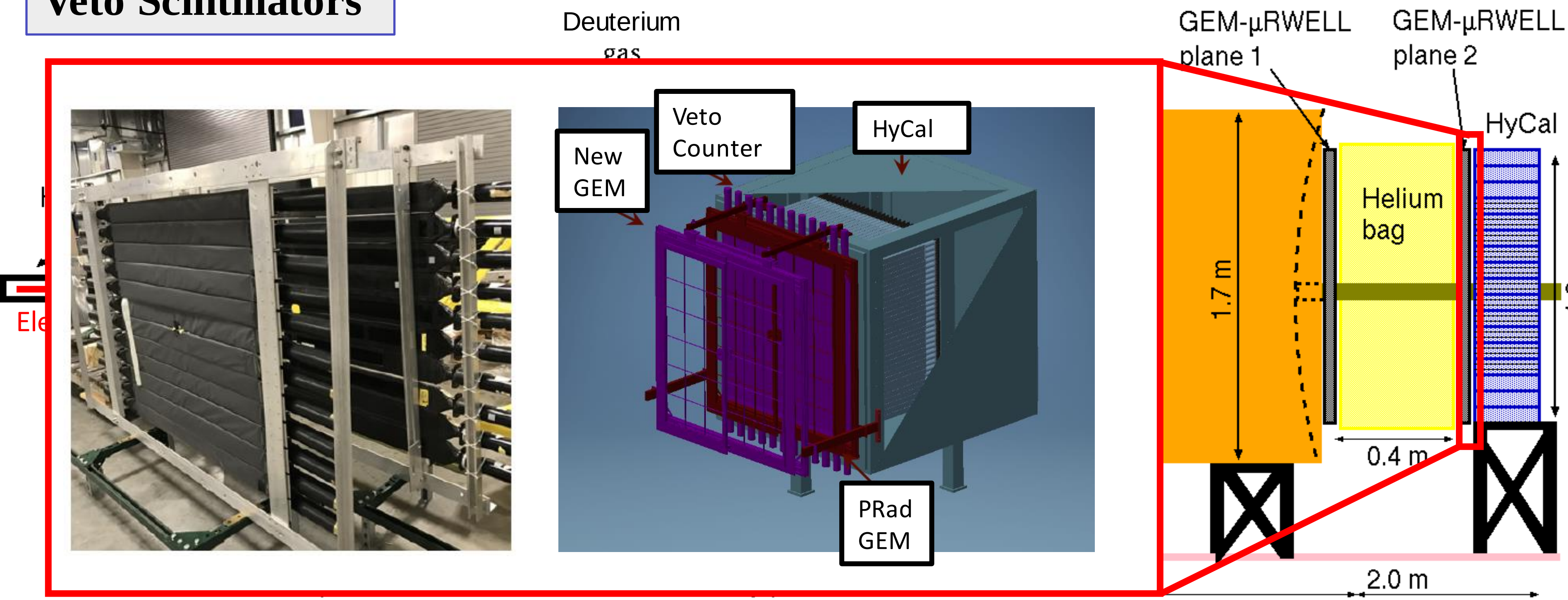


Upgraded HyCal:

- Replace lead-glass modules with $PbWO_4$ modules to have more uniform and better resolution, suppress inelastic contribution
- Convert to FADC based readout to increase data taking rate

DRad experiment apparatus

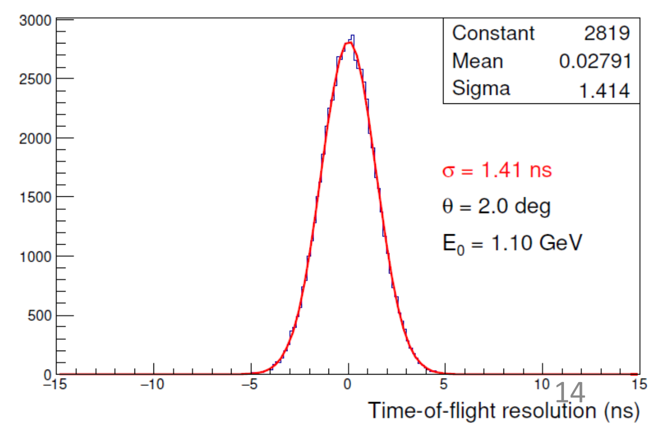
Veto Scintillators



- The major background for the e-d elastic scattering is the e-d inelastic breakup process:

  e+d → e+p+n

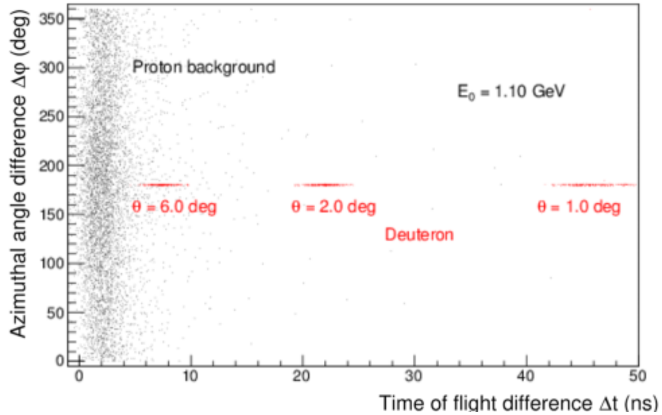
- Particle identification between deuteron and proton: measure the time-of-flight difference between the recoil detector and the HyCal Calorimeter.

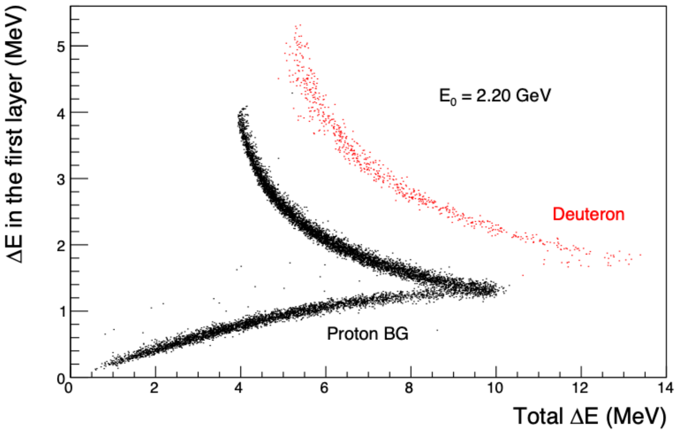


PID and Event selection

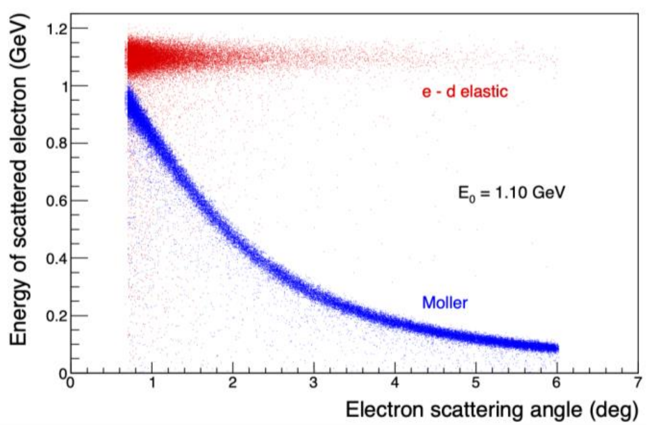
Comprehensive Geant4 simulation of the experiment was developed and used for studying the detection thresholds and backgrounds.

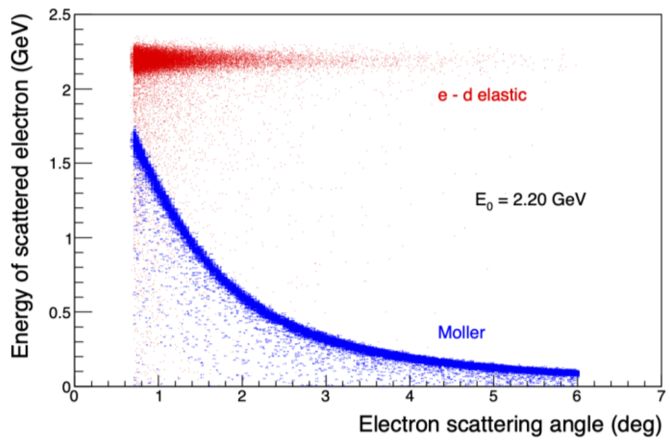
- ❑ Proton from breakup vs elastic recoil deuteron (Electro-disintegration rates are < 6% of the elastic rates)



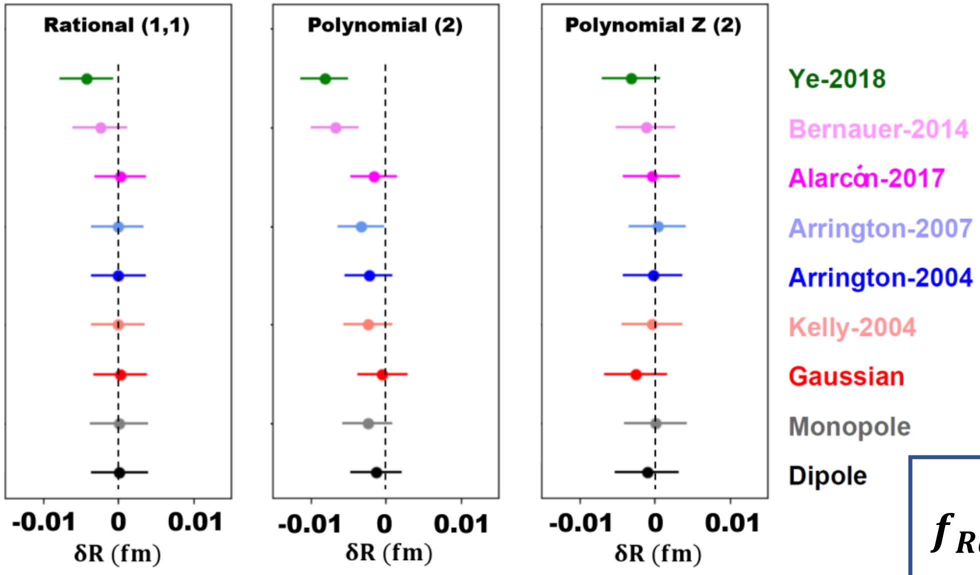


- ❑ Møller event vs e-d elastic event





The robust fitter study for PRad vs DRad



X.Yan *et al.* PRC98,025204 (2018)

- Used 9 models to reflect various reasonable approximations to the unknown true function of G_E^p
- Fitters: dipole, monopole, gaussian, rational, polynomial, poly-z, and continued fraction…
- Best fitter for PRad and PRad-II:

$$f_{Rational(1,1)}(Q^2) = p_0 \frac{1 + p_1^a Q^2}{1 + p_1^b Q^2} \qquad r_{\mathrm{fit}} = \sqrt{6(p_1^a - p_1^b)}$$

- $Rational(1,1)$ does not match G_C^d data at higher Q^2 range → search for possible new fitters
- Limited number of data-driven G_C^d parameterizations → generalize the robustness test method

Abbott I: $G_C^d(Q^2) = G_{C,0} \cdot \left[1 - \left(\frac{Q}{Q_C^0}\right)^2\right] \cdot \left[1 + \sum_{i=1}^{5} a_{ci} Q^{2i}\right]^{-1}$

Parker: $G_C^d(Q^2) = G_{C,0} \cdot \left[1 - \left(\frac{Q}{Q_C^0}\right)^2\right] \cdot \left[\prod_{i=1}^{5} (1 + |a_i| Q^2)\right]^{-1}$

Abbott II:

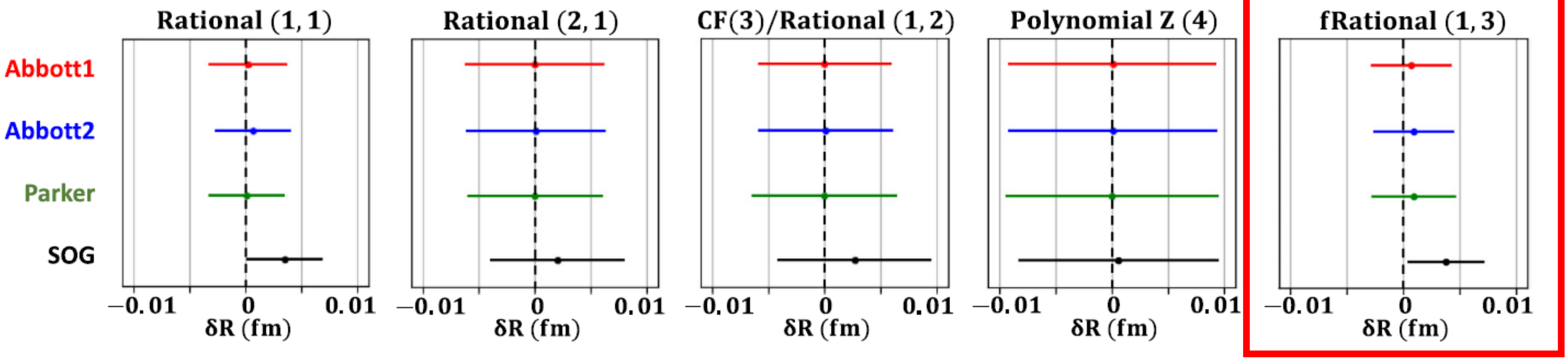
$$G_C^d(Q^2) = \frac{G^2(Q^2)}{(2\tau + 1)} \cdot \left[\left(1 - \frac{2}{3}\tau\right) g_{00}^+ + \frac{8}{3}\sqrt{2\tau}\, g_{+0}^+ + \frac{2}{3}(2\tau - 1) g_{+-}^+\right]$$

$$g_{00}^+ = \sum_{i=1}^{n} \frac{a_i}{\alpha_i^2 + Q^2} \qquad g_{+0}^+ = Q \sum_{i=1}^{n} \frac{b_i}{\beta_i^2 + Q^2} \qquad g_{+-}^+ = Q^2 \sum_{i=1}^{n} \frac{c_i}{\gamma_i^2 + Q^2}$$

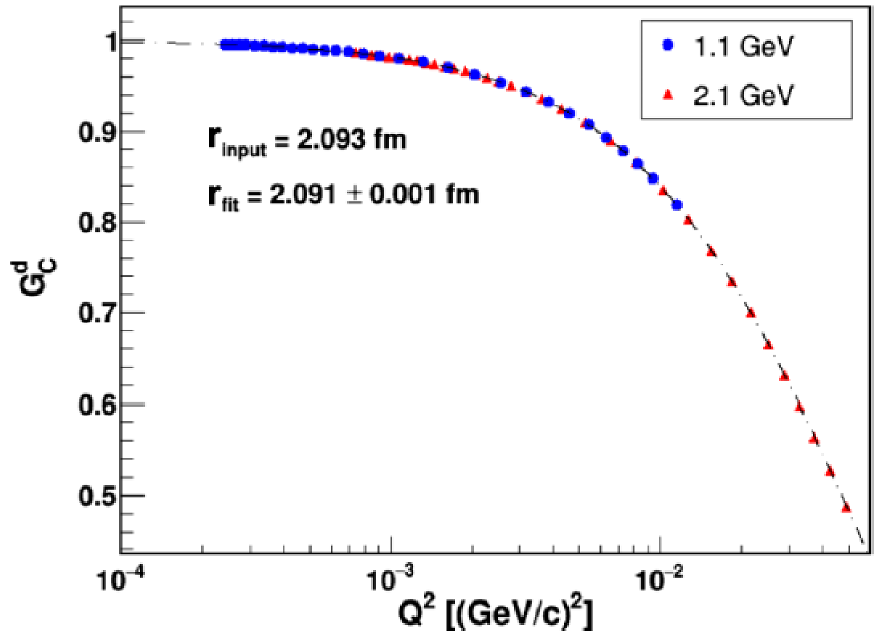
Sum-of-Gaussian(SOG):

$$G_C^d(Q^2) = G_{C,0} \cdot e^{-\frac{1}{4}Q^2\gamma^2} \cdot \sum_{i=1}^{N} \frac{A_i}{1 + 2R_i^2/\gamma^2} \cdot \left[\cos(QR_i) + \frac{2R_i^2}{\gamma^2} \frac{\sin(QR_i)}{QR_i}\right]$$

Model dependent study in r_d extraction



- Various functional forms were tested with modern parameterizations of the deuteron form factors, using DRad kinematic range and uncertainties.
- Fixed Rational (1,3) was identified as a robust fitter with lowest uncertainties

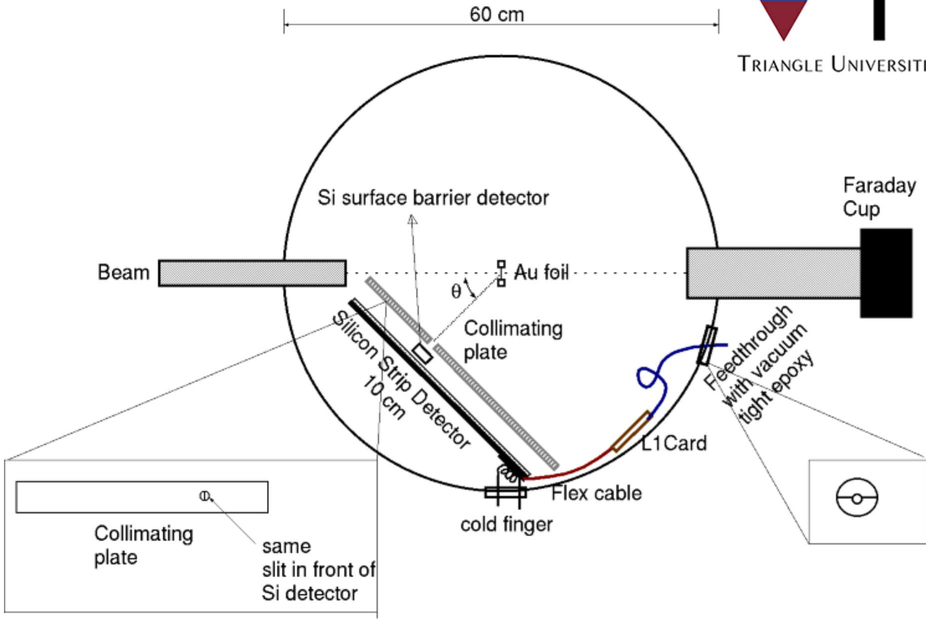


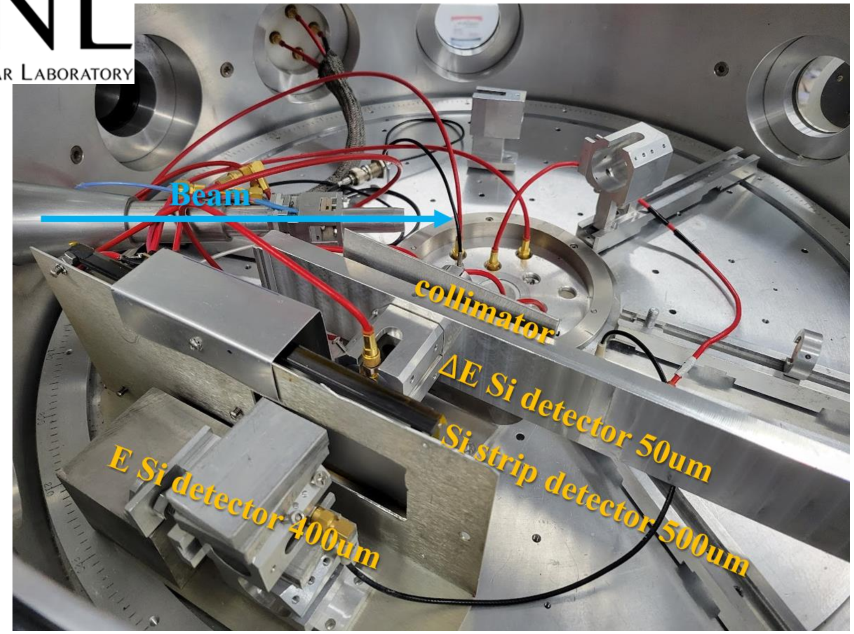
J.Zhou *et al*. PRC**103**, 024002 (2021)

$$f_{\text{fixed Rational}(1,3)}(Q^2) = p_0 \frac{1 + a_1 Q^2}{1 + b_1 Q^2 + b_{2,\text{fixed}} Q^4 + b_{3,\text{fixed}} Q^6}$$

$$r_{\text{fit}} = \sqrt{6(a_1 - b_1)}$$

The recoil detector calibration test at TUNL





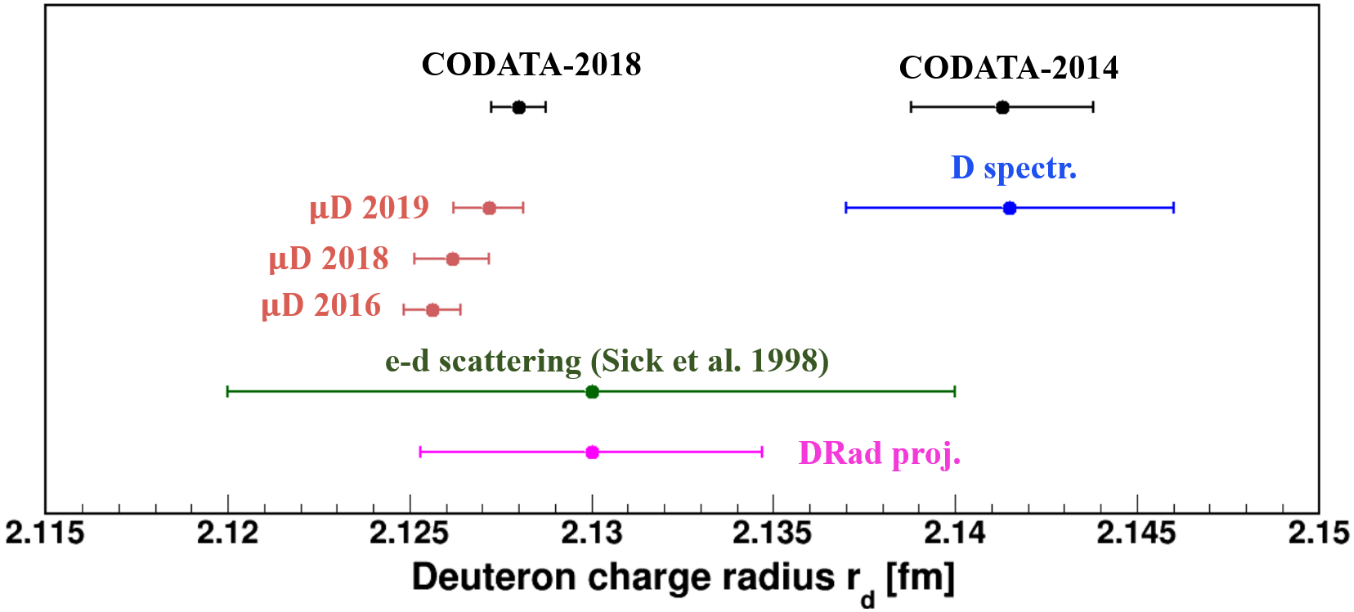
- The recoil detector will be calibrated using e-p elastic run on hydrogen and with the 2.5~13 MeV p/D beam from the Tandem accelerator at TUNL.

Detection efficiency: $\epsilon = \frac{N_{strip}}{N_{\Delta E}}$

Uncertainty estimation and projection

Item	Uncertainty (%)
Event selection	0.110
Radiative correction	0.090
HyCal response	0.043
Geometric acceptance	0.022
Beam energy	0.008
Total correlated terms	0.13

Item	Uncertainty (%)
Statistical uncertainty	0.05
Total correlated terms	0.13
GEM efficiency	0.03
Inelastic e-d process	0.024
Efficiency of recoil detector	0.15
Total	0.22



The most precise single measurement from e-d elastic scattering

Summary

- We propose a new experiment for the deuteron charge radius measurement to address the *"deuteron radius puzzle"* in nuclear physics.
- It is based on the PRad and proposed PRad-II experiment for the proton charge radius measurement:
  - Magnetic-spectrometer-free calorimetric experiment;
  - Windowless deuterium/hydrogen gas flow target to reduce background;
  - Cylindrical recoil detector for reaction elasticity;
  - Two tracking detectors for scattered electron tracking.
- That will allow:
  - Measure cross sections in one kinematical settings for a large Q^2 range $[2 \times 10^{-4} - 5 \times 10^{-2}]\ (GeV/c)^2$;
  - Simultaneous detection of $ee \to ee$ Møller scattering process;
  - Measure e-d cross section to subprecent precision
- **Expected R_d uncertainty : 0.22% (preliminary)**
- PRad analysis indicates: backgrounds well understood, proposed uncertainty can be achieved.

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