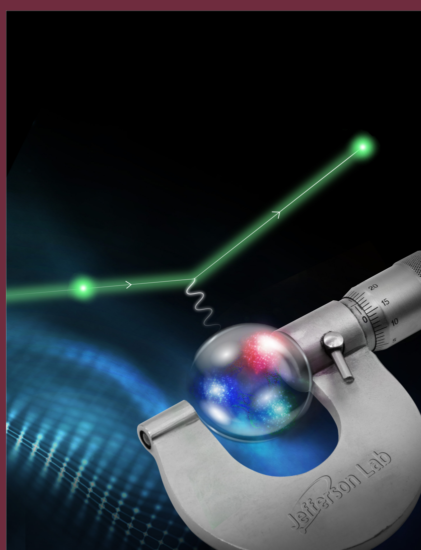
PR12-20-006

Precision Deuteron Charge Radius Measurement with Elastic Electron-Deuteron Scattering



PRoton Radius

Dipangkar Dutta

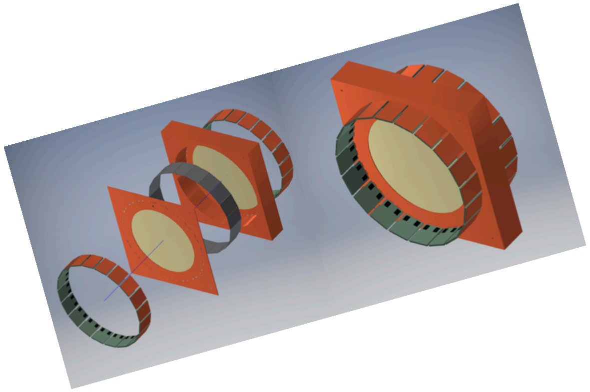
Mississippi State University

for the PRad Collaboration

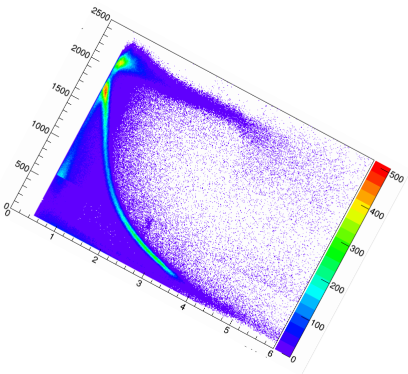
Spokespersons (**A. Gasparian*, H. Gao, D. Dutta, N. Liyanage, D. Higinbotham & E. Pasyuk**)

PAC 48 Meeting, Aug 10, 2020

Outline



- Executive summary
- Introduction & Motivation
- Proposed Experiment
    - Experimental method (The PRad method)
    - The equipment (PRad-II + recoil detector)
    - Systematic uncertainties
    - Beam request & projected results
- Conclusion

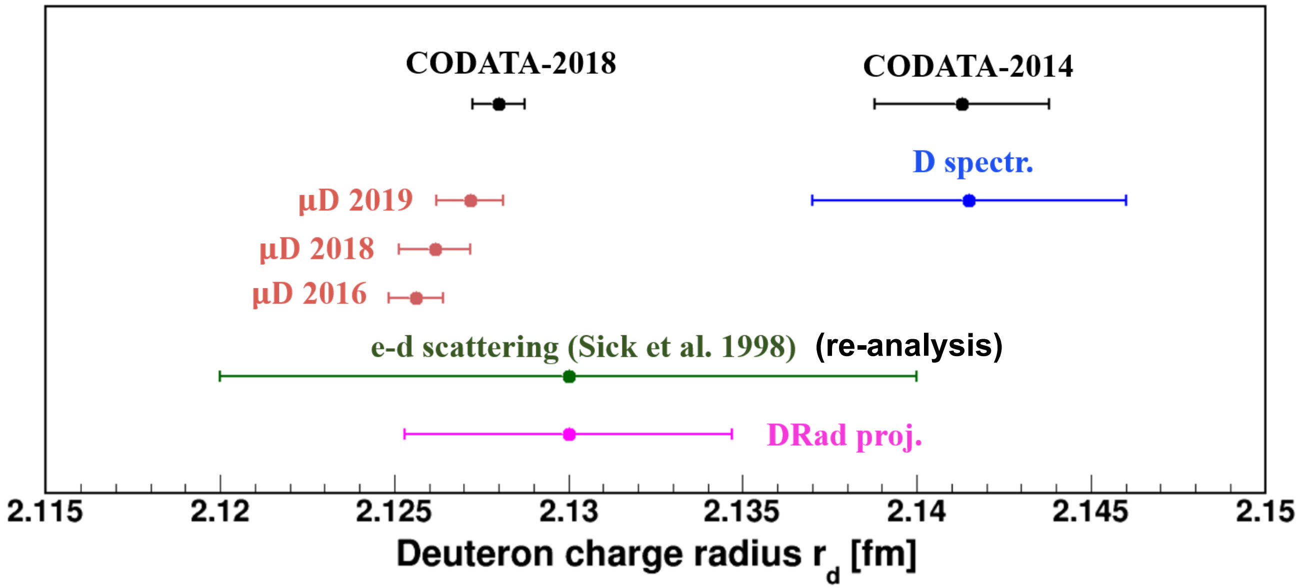


Executive Summary

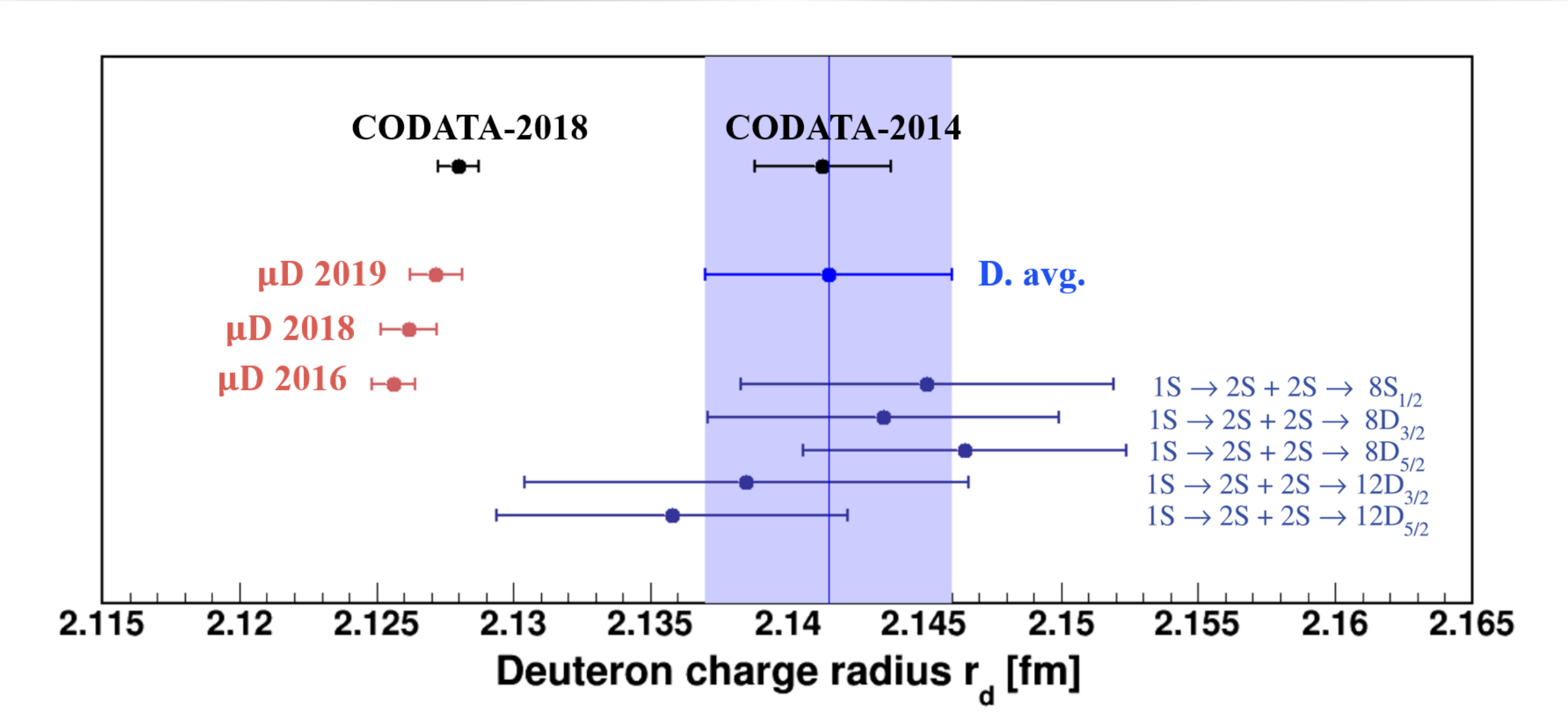
Using the PRad method, which has convincingly demonstrated the validity and advantage of the new calorimetric technique, we will measure the deuteron charge radius with a precision of 0.22%

We will cover the Q^2 range of $2\text{x}10^{-4}$ to $5\text{ x}10^{-2}$ GeV^2 probing the lowest Q^2 reached by e-D scattering experiments.

We will use the PRad-II setup along with a new recoil detector.

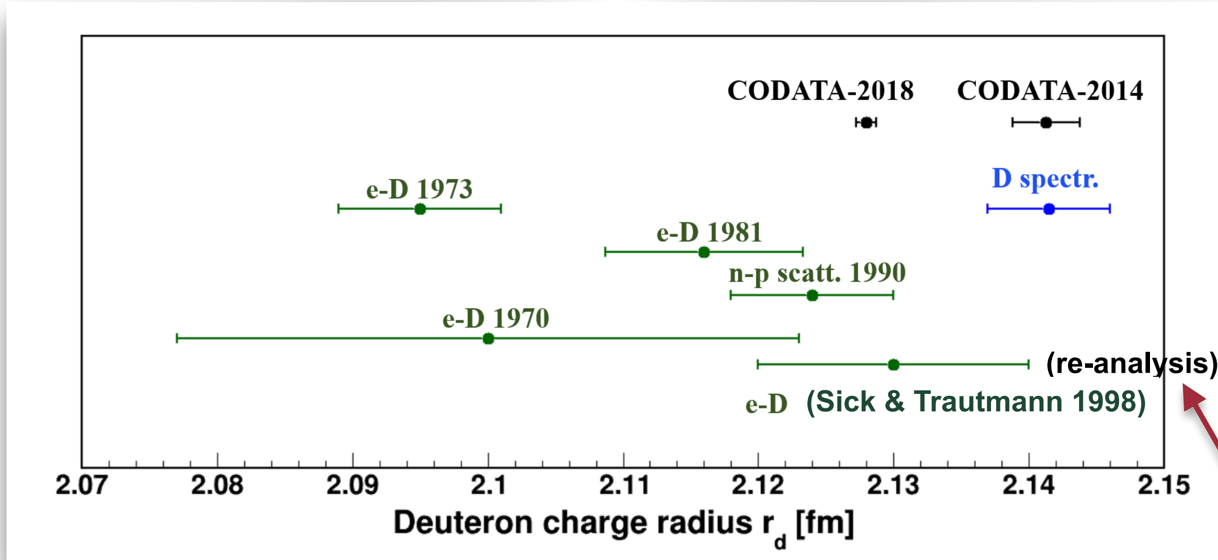


The "deuteron radius puzzle" unfolded soon after the "proton radius puzzle" but with less fanfare.

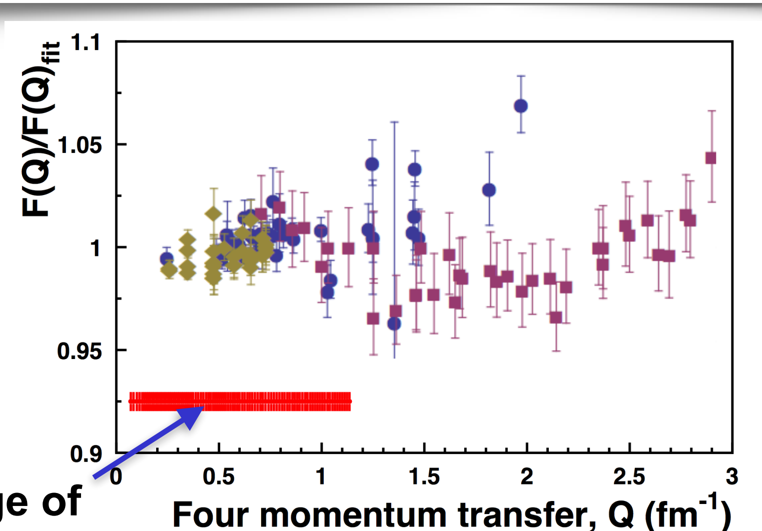


A ~6 σ discrepancy between r_D from ordinary D and μD spectroscopy was observed a few years after the "proton radius puzzle" came to the fore.

To date *e-D* scattering has not played any significant role in addressing the "deuteron radius puzzle"



- some data over 40 yrs old
- large uncertainty
- most recent result is a reanalysis of old data
- all used magnetic spectrometer method
- normalized *eD* to *ep* cross section
- large bgd. from target windows



Q^2 range of proposed experiment

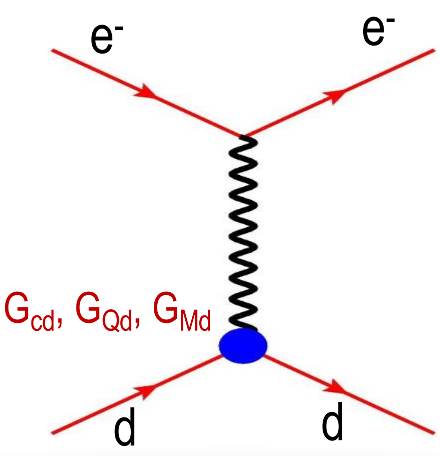
R.W. Berard et al. PLB 47,355, (1973)
cooled H_2 and D_2 gas measured ratio of *eD/ep* cross section; Q = [0.2 – 0.7] fm^{-1}

G.G. Simon et al. NPA 364, 285 (1981)
gas and liquid targets; Q = [0.2 – 2.0] fm-1

S. Platchkov, et al. NPA 510, 740 (1990)
LH2 and LD2 targets; Q = [0.7 – 4.5] fm^{-1}

Situation points to a urgent need for a new high precision *eD* experiment

The slope of the $G_C(Q^2)$ form factor at $Q^2 = 0$ is used to extract r_D from elastic e-D scattering.



In the limit of first Born approximation, elastic *eD*- scattering is written in terms of the $A(Q^2)$ and $B(Q^2)$ structure functions.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{NS}[A(Q^2) + B(Q^2)\tan^2\theta/2]$$

$\frac{d\sigma}{d\Omega}|_{NS}$ is for elastic scattering from point-like spinless particle, & $A(Q^2)$ and $B(Q^2)$ are related to deuteron charge (G_{Cd}), electric quadrupole (G_{Qd}) and magnetic dipole (G_{Md}) form factors:

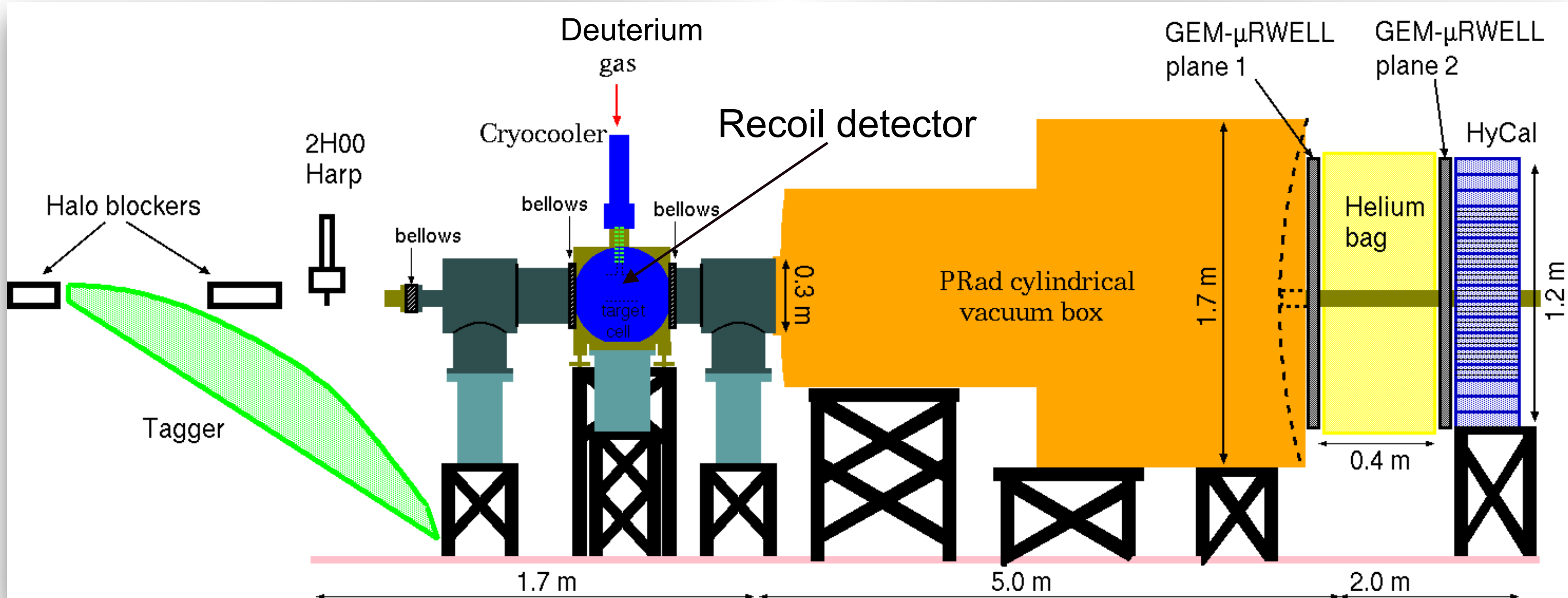
$$\begin{aligned} A(Q^2) &= G^2_{Cd}(Q^2) + \frac{2}{3}\eta G^2_{Md}(Q^2) + \frac{8}{9}\eta^2 G^2_{Qd}(Q^2) \\ B(Q^2) &= \frac{4}{3}\eta(1+\eta)G^2_{Md}(Q^2), \end{aligned}$$

$$\eta = Q^2/4m_d^2$$

At low Q^2 contribution from G_{Qd} and G_{Md} are small, and the deuteron rms charge radius is defined as:

$$r_d^2 = -6\frac{dG_C}{dQ^2}\bigg|_{Q^2\to 0} = -3\frac{dA}{dQ^2}\bigg|_{Q^2\to 0} + \frac{G_M^2(0)}{2M_d^2}, \quad \text{with } G_M(0) = \frac{M_d}{M}\mu_d\,, \ \frac{G_M^2(0)}{2M_d^2} \approx 0.0163\ \text{fm}^2.$$

DRad: a novel electron scattering experiment

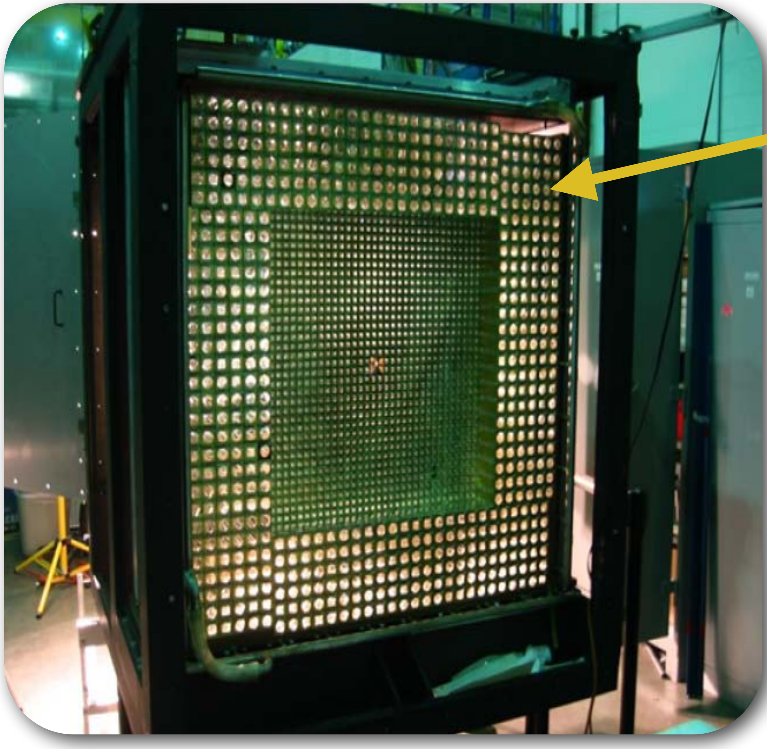


Will use the PRad-II setup with 1.1 GeV and 2.2 GeV electron beam

- **High resolution, all $PbWO_4$ calorimeter (magnetic spectrometer free)**
- **Windowless, high density gas flow target (reduced backgrounds)**
- **Simultaneous detection of elastic and Møller electrons (control of systematics)**
- **Vacuum chamber with one thin window, & two GEM chambers (better resolution)**
- **Q^2 range of *2×10^{-4} – 5×10^{-2} GeV^2* (lower than all previous electron scattering expts.)**
- **Add a cylindrical recoil detector for ensuring elasticity of reaction.**
- **Essentially model independent extraction of r_D**

The DRad experiment will use a magnetic spectrometer free method to measure r_D

Allows coverage of extreme forward angle (0.7^o - 7.5^o) in a single setting and complete azimuthal angle coverage.
Q^2 range of *$2x10^{-4} – 5x10^{-2}$ GeV^2* **(lower than all previous e-D scattering experiments)**



Upgraded HyCal: replace lead-glass modules with $PbWO_4$ modules to have uniform high resolution.

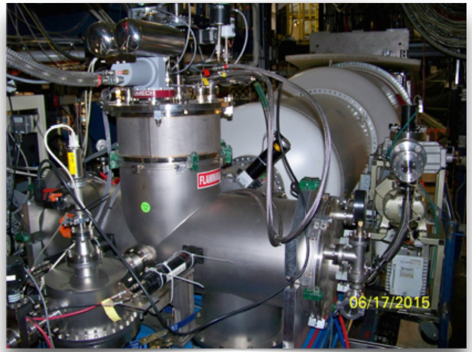
$PbWO_4$ resolution:
$\sigma_E/E = 2.6\%/\sqrt{E}$; $\sigma_{xy} = 2.5\ mm/\sqrt{E}$

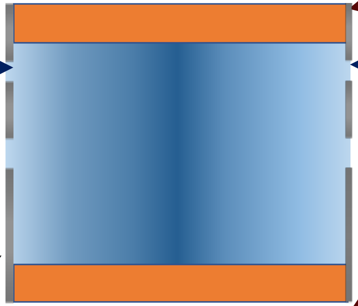
Convert to FADC based readout of HyCal

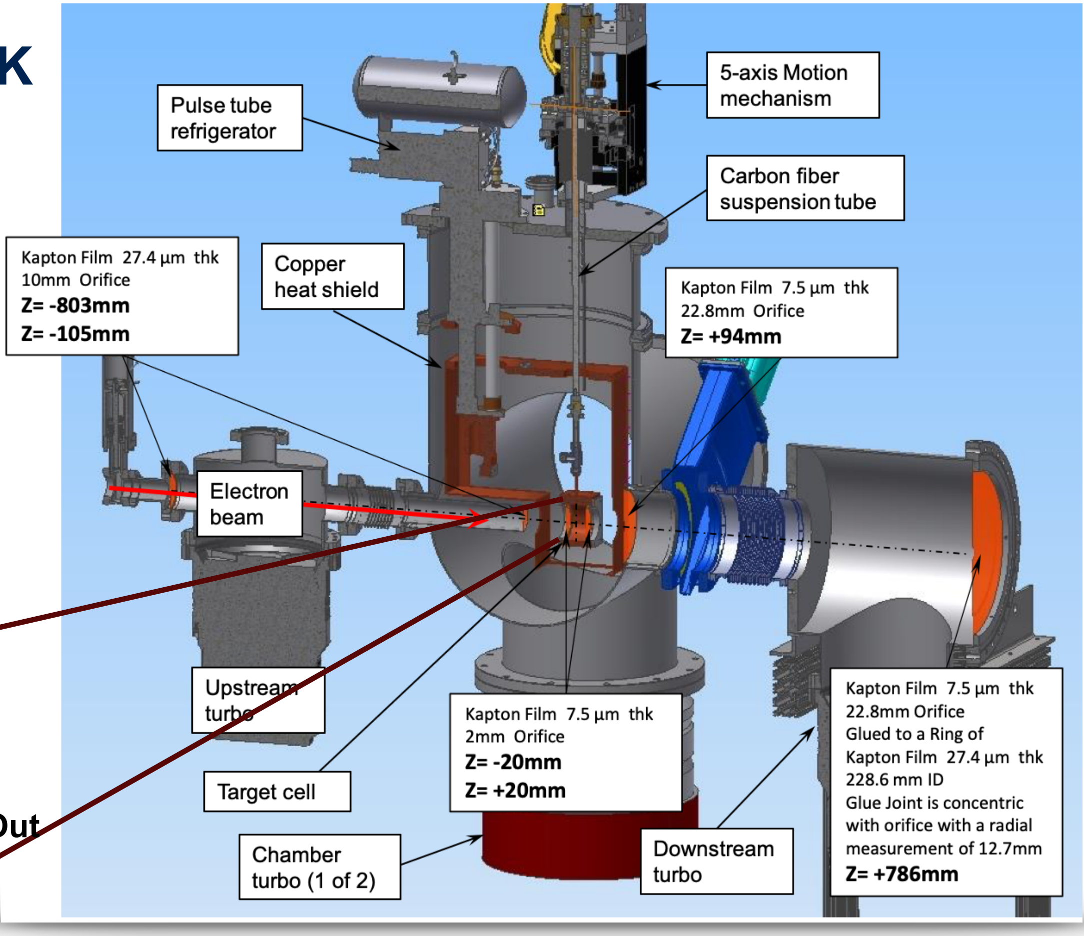
- **$PbWO_4$ calorimeter ($118x118\ cm^2$)**
- **57x57 matrix of $2.05 \times 2.05\ cm^2 \times 18$ cm $PbWO_4$**
- **5.5 m from the target,**
- **0.5 sr acceptance**

A cryo-cooled windowless gas flow target.

density:
~2x10[18] atoms/cm[2] cooled to 20K







Empty target runs to be used for background subtraction

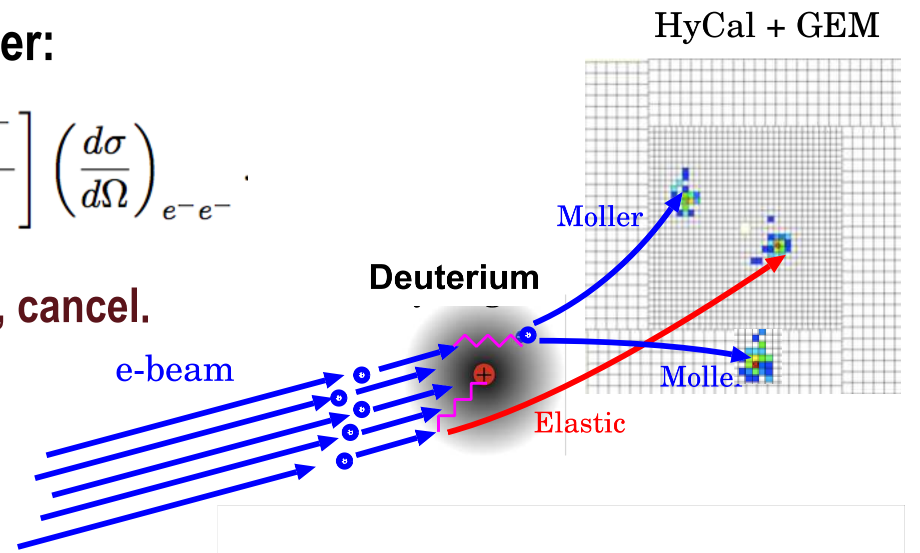
Systematic uncertainties will be controlled by simultaneously detecting e-D elastic and Møller events

- ***eD* cross section measured relative to Møller:**

$$\left(\frac{d\sigma}{d\Omega}\right)_{ed}(Q_i^2) = \left[\frac{N_{\rm exp}^{\rm yield}(ed \to ed \text{ in } \theta_i \pm \Delta\theta)}{N_{\rm exp}^{\rm yield}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\rm geom}^{e^-e^-}}{\varepsilon_{\rm geom}^{ed}} \cdot \frac{\varepsilon_{\rm det}^{e^-e^-}}{\varepsilon_{\rm det}^{ed}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}.$$

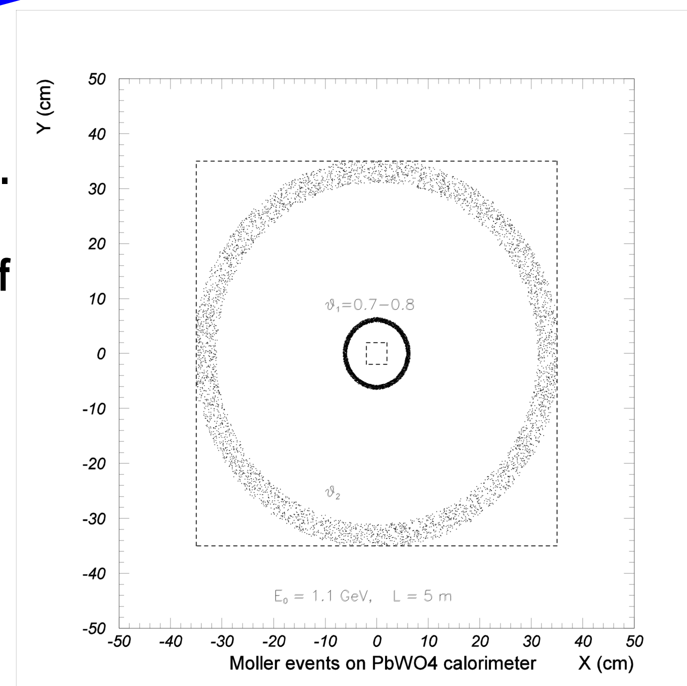
Two major sources of systematic errors, N_e and N_{tgt}, cancel.

But, need relative det. efficiency ε_{det}

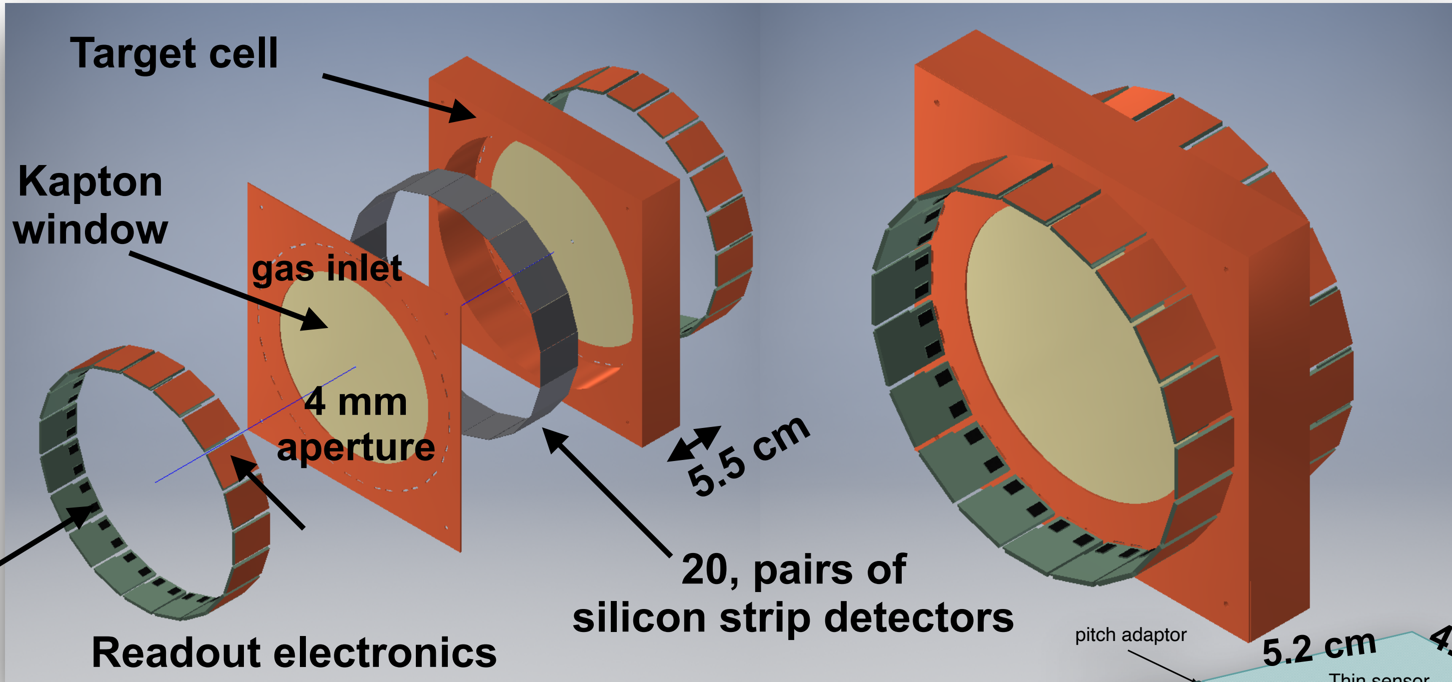


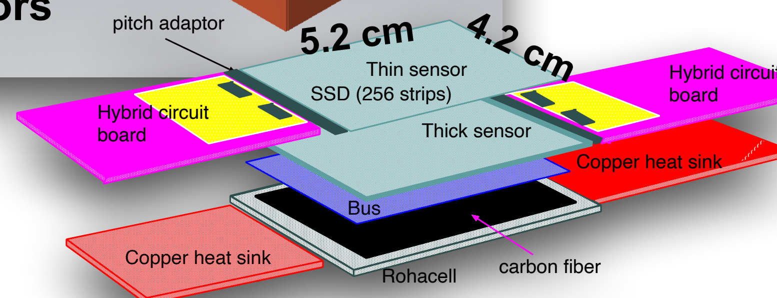
- **Geom. acceptances and detection efficiencies will be extracted during *ep* → *ep* calibration run with hydrogen gas in target cell.**
- **Deuteron detection efficiencies will be obtained from the ratio of deuteron/proton detection efficiencies measured at TUNL using the 5-15 MeV p/D beams from the Tandem accelerator.**

Møller events will be detected in two-electron and/or single electron modes within the HyCal acceptance.



The elasticity of e-D scattering will be ensured with a cylindrical Si-strip-based recoil deuteron detector.





Based on CLAS12 Barrel Si tracker (SVT)

material budget < 1% r.l.

- consists of 20 panels of twin, single-sided Si-strip detectors (size; 42x52 mm^2);
- thickness: inner, ≈ 200 μm, outer ≈ 300 μm (to be optimized);
- dodecagon arrangement with R=13 cm radius;
- 256 strips on each sensor, angular resolution: $\delta\varphi \leq 5$ mrad, $\delta\theta \leq 20$ mrad
- Passivation layer ~ 0.1 μm (can be as low as 0.01 μm).

Thin passivation layer Si-strip detectors are routinely available.

Micron Semiconductor Ltd

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Ohmic / Junction Window Type

SILICON SENSOR OPTIONS

Window Type

The range of dead layer windows available with the in-house Varian 300 XP ion implanter are listed below. Window types refer to the junction of a device, but can also be achieved on the ohmic side upon request.

WINDOW TYPE	DEAD LAYER	MINIMUM ENERGY THRESHOLD	
		Electron	Proton
2	500 nm	4 KeV	90 KeV
7	300 nm	2 KeV	70 KeV
9	100 nm	1K eV	20 KeV
9.5	50 nm	500 eV	10 Kev
10*	10 nm	100 eV	1 Kev
PSD			

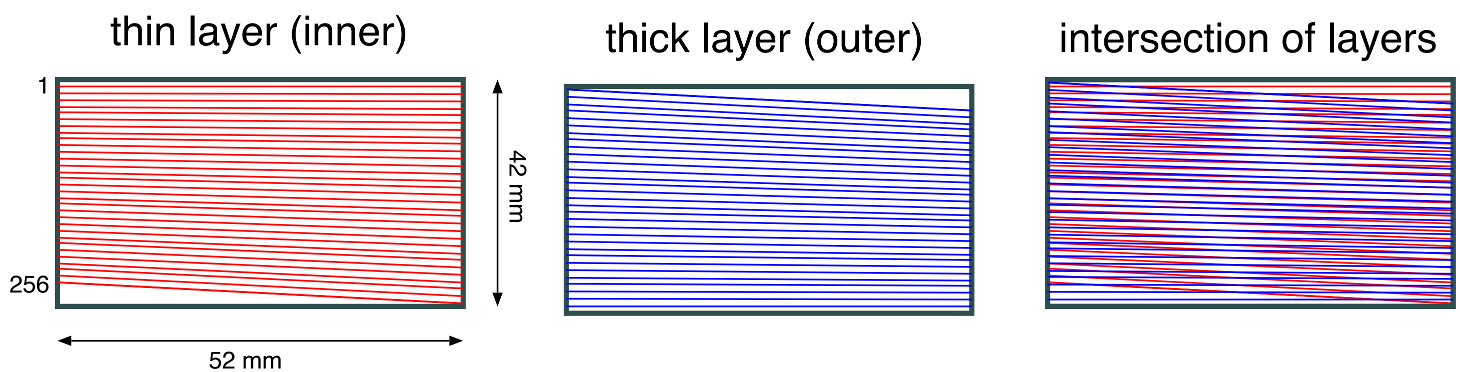
* R&D

WAFER SIZE	STANDARD SILICON THICKNESSES AVAILABLE
3-inch	20, 30, 40 μm
4-inch	40, 50, 65, 80, 100, 140, 250, 300, 500, 1000, 1500 μm
6-inch	150, 200, 300, 400, 500, 675 μm

NTD

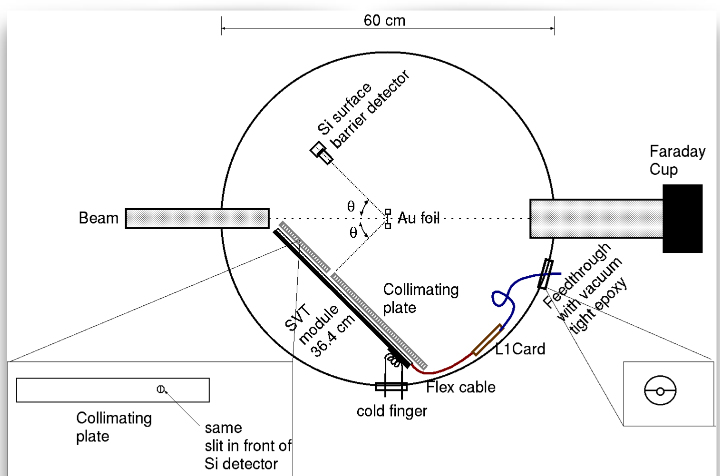
Neutron transmutation doped n-type silicon is offered for applications where low resistivity variation across the wafer is required. This material has a much higher depletion voltage that regular high resistivity n-type material.

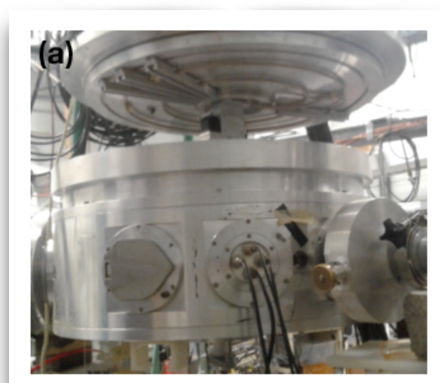
The elasticity of e-D scattering will be ensured with a cylindrical Si-strip based recoil deuteron detector.



256 strips with linearly varying angles of 0 - 3 deg to minimizes dead zones.
The strips will have a constant pitch of ~200 micron (~1/85 deg^{-1}).
The angular resolution of $\delta\varphi \lesssim 5$ mrad and $\delta\theta \lesssim 10\text{-}20$ mrad.

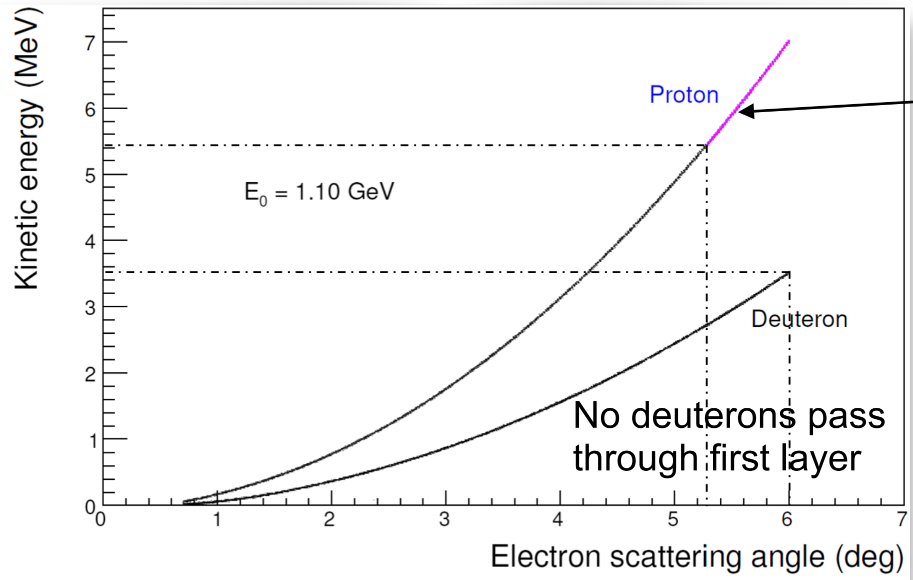
The recoil detector will be calibrated using *ep* elastic running on hydrogen and with the 5-15 MeV p/D beam from the Tandem accelerator at TUNL.





Preparations are underway for a test using a single SVT module from Hall-B. (delayed by COVID)

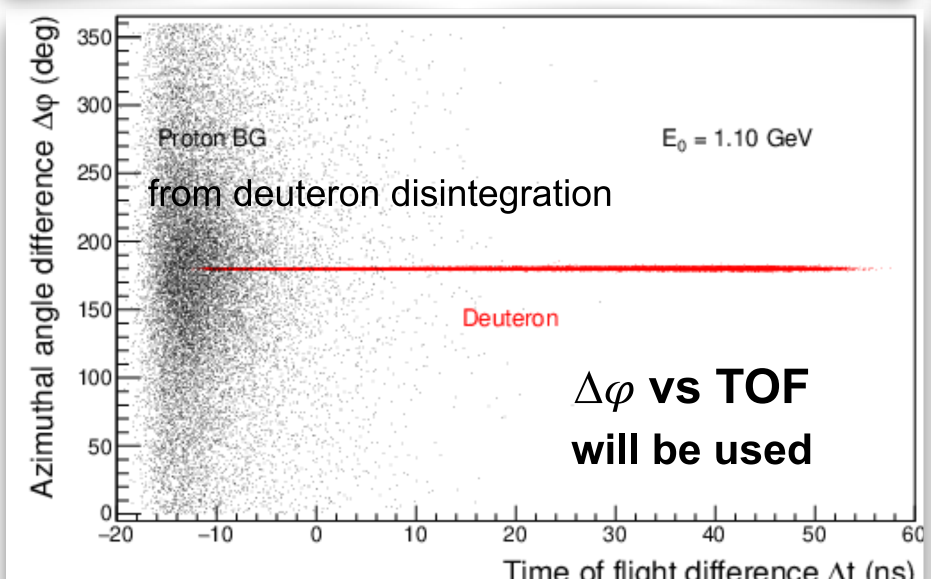
Particle identification at 1.1 GeV will use recoil detection and its time difference with the HyCal.

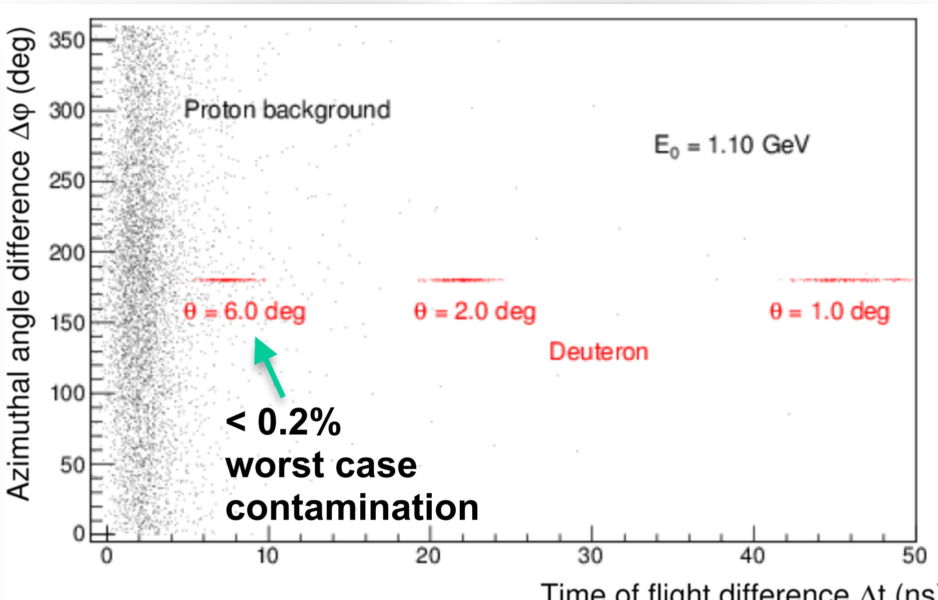


Protons that pass through first (inner) layer

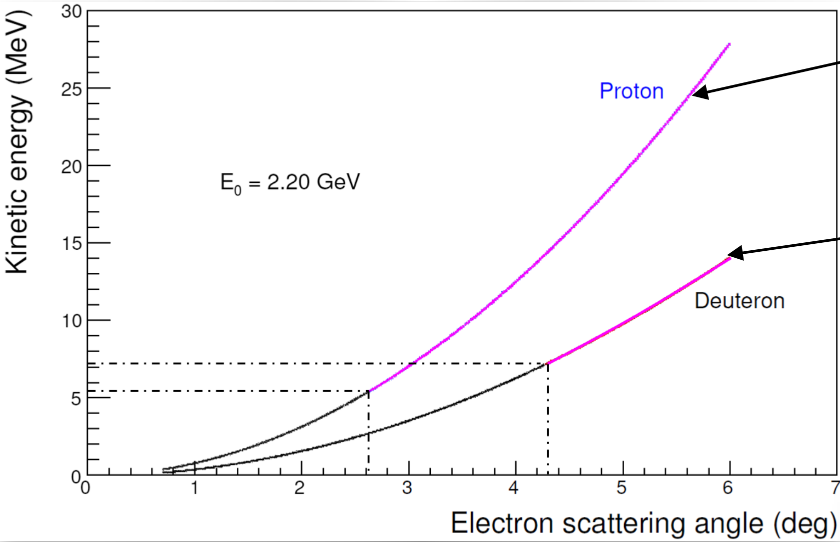
For large part of 1.1 GeV kinematics the deuterons do not disintegrate, but still the deuteron must be detected to ensure elastic scattering.

PID relies on the co-planarity of e-D elastic scattering.





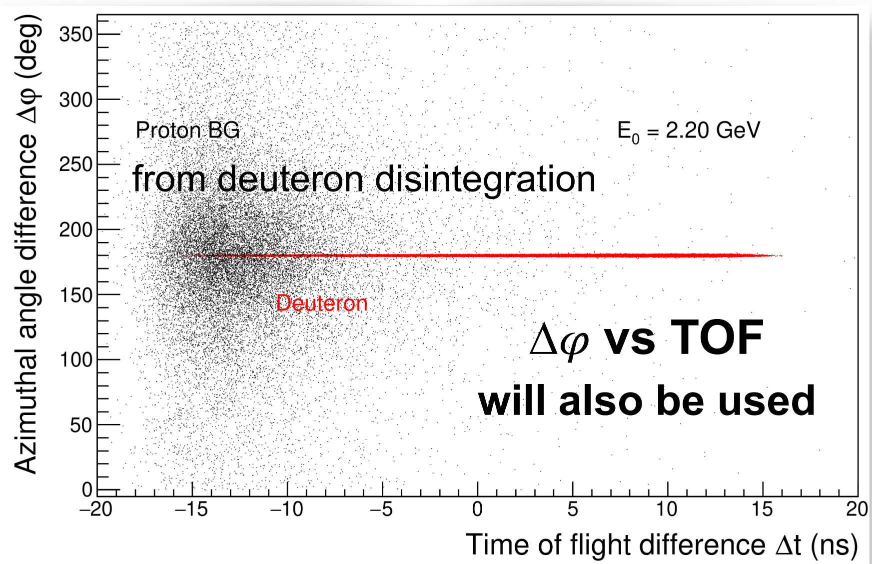
Particle identification at 2.2 GeV will use recoil detection and its time difference with the HyCal.

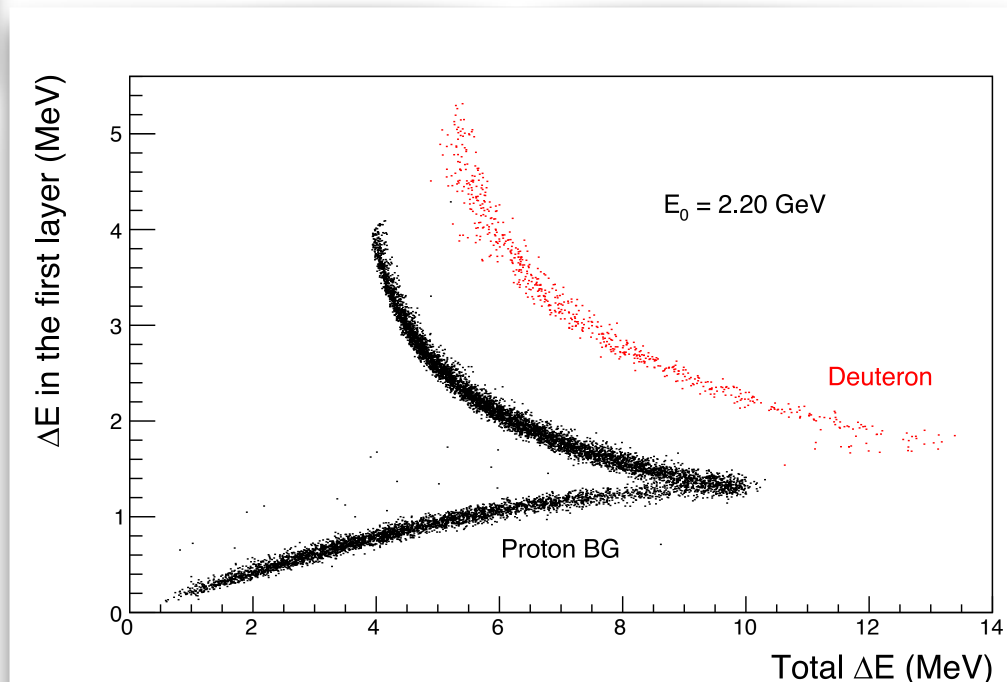


Protons that pass through first (inner) layer

Deuterons that pass through first (inner) layer

PID relies on the co-planarity of e-D elastic scattering.





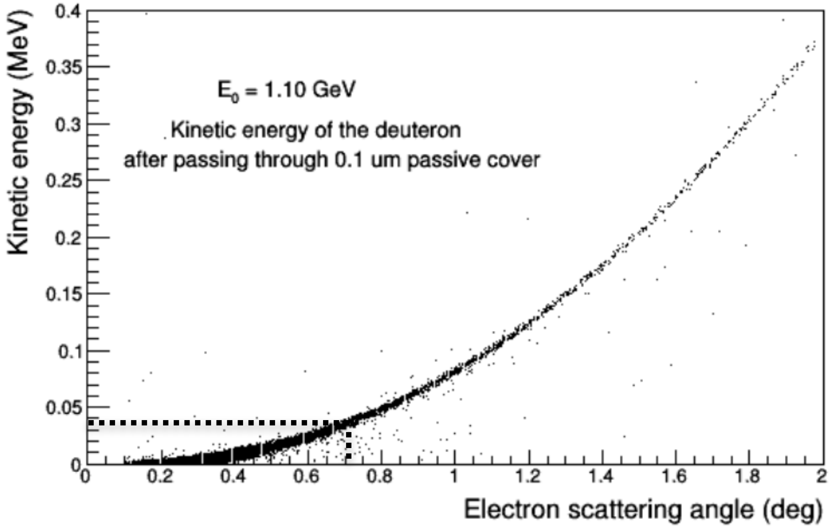
The recoil detector can detect deuterons with kinetic energy > 40 keV

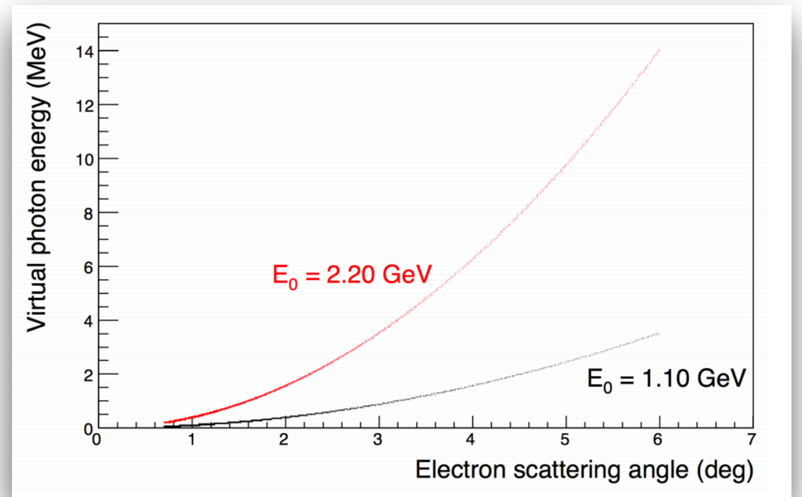
Comprehensive Geant4 simulation of the experiment was developed and used for studying the detection thresholds and backgrounds.

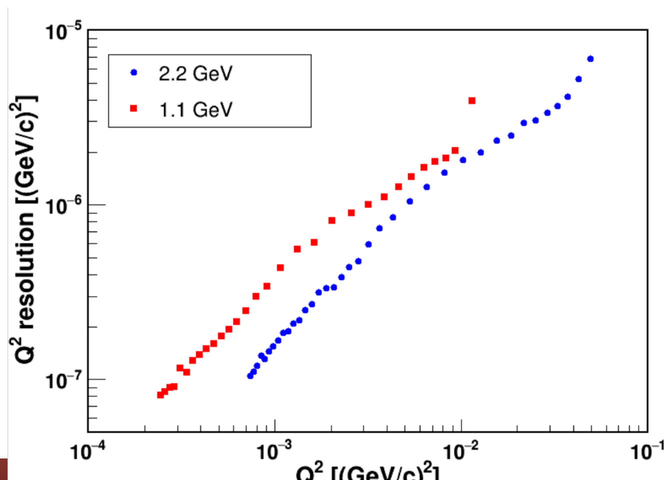
Deuteron will recoil at large polar angles θ_d = [83^0 - 89^0];

Passivation (dead) layer on the Si-strip detector assumed ~0.1 μm, as low as 0.01 μm is available from Micron semiconductors.

At both 1.1 and 2.2 GeV beam energy $\theta_e = 0.7^o - 7.5^o$ can be detected giving a Q^2 coverage of *$2x10^{-4} – 5x10^{-2}$ GeV^2* with high resolution.



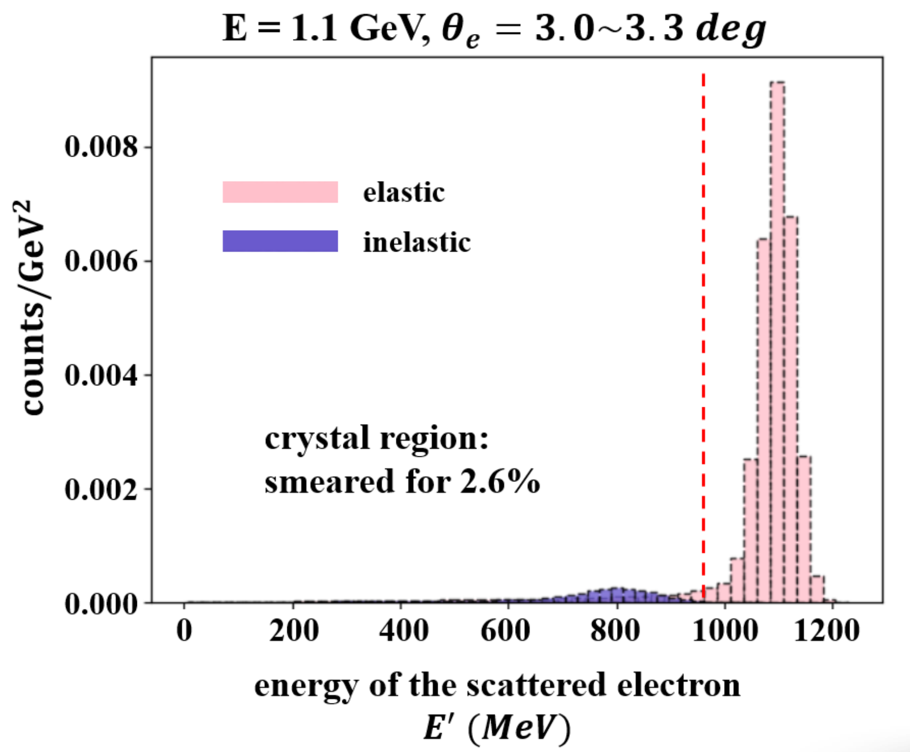


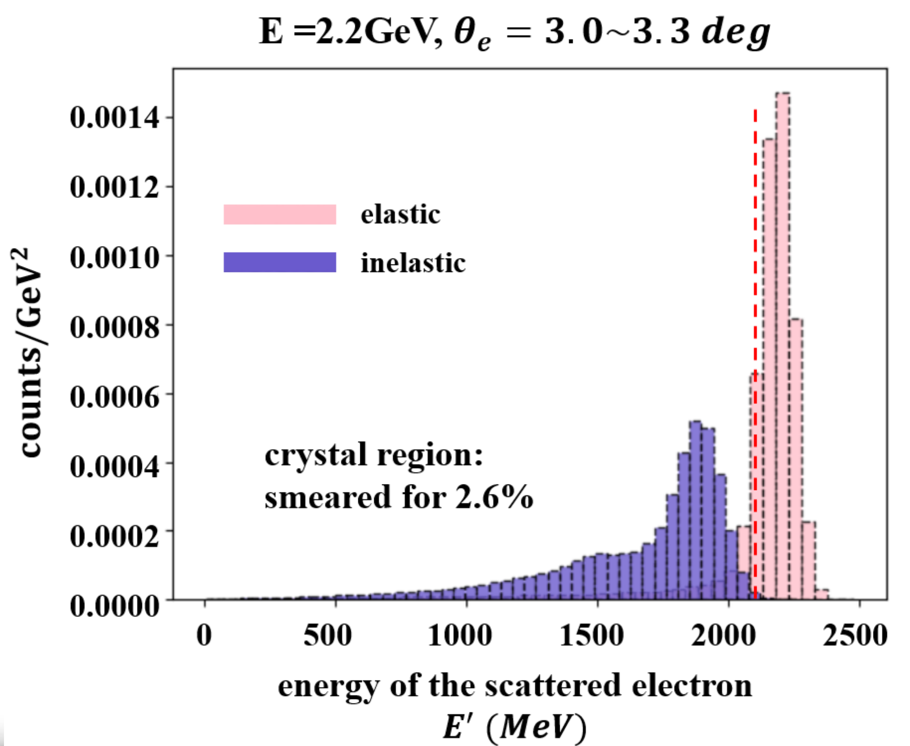


Deuteron electro-disintegration and inelastic scattering are the two major sources of background.

Both major backgrounds included in the comprehensive simulation.
Other minor background such as coherent pion production also studied.

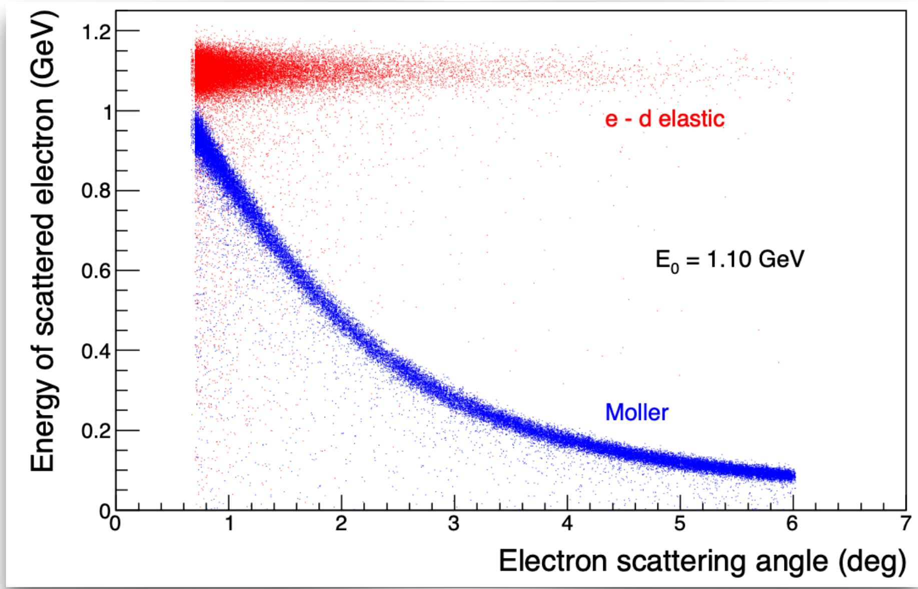
Electro-disintegration rates are < 6% of the elastic rates.
inelastic rates are < 1% of the elastic rates





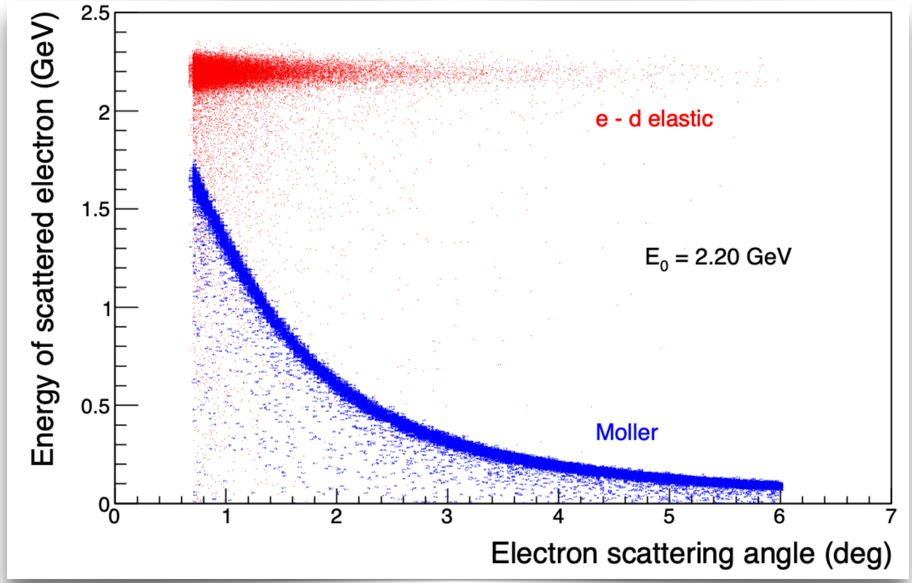
Elastic *e-D* and Møller events can be cleanly separated over the full angular range [0.7⁰ - 7.5⁰]

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



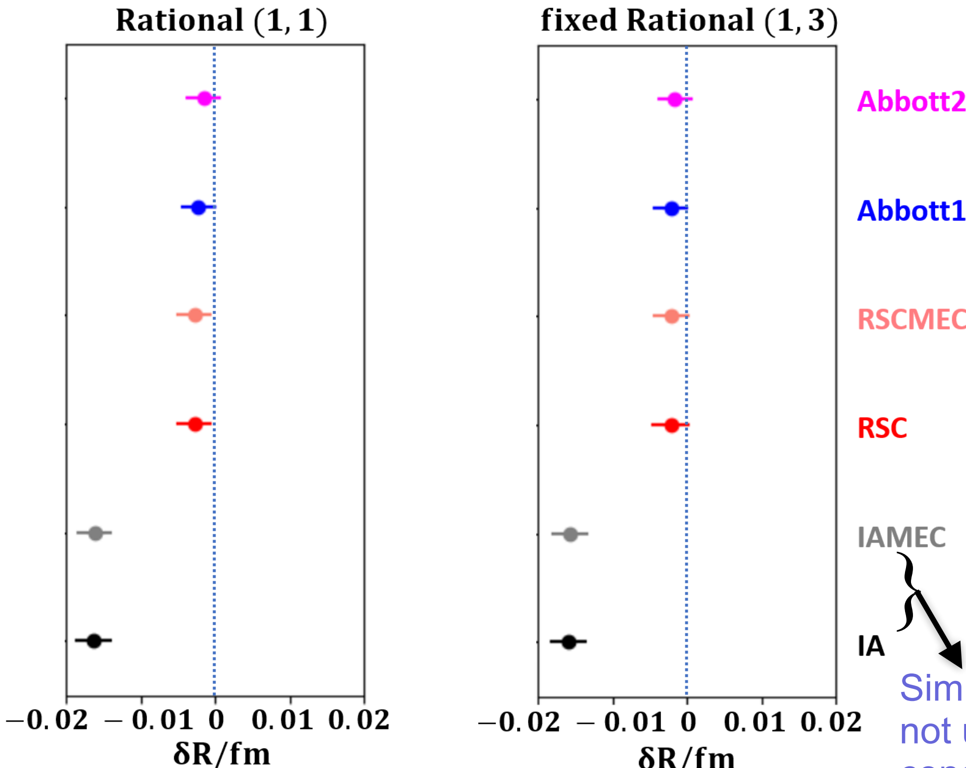
The simulated energy vs. scattering angle distribution of *e-D* elastic and Møller scattered electrons

The internal and external radiation has been included for both *e-D* and Møller scattering.

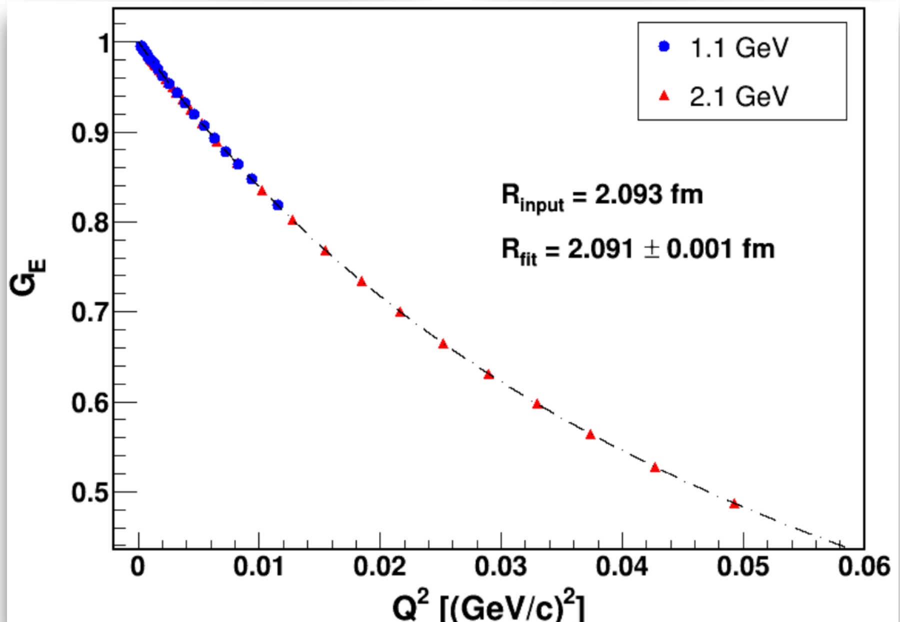


A wide range of functional forms were systematically tested for their robustness in extracting r_D.

- 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**



Simplistic models, not used to draw conclusions



Bias from fitter ~ 0.065%

The robustness = root mean square error (RMSE)

δR = difference between the input and extracted radius
σ = statistical variation of the fit to the mock data

$$\mathrm{RMSE} = \sqrt{(\delta R)^2 + \sigma^2},$$

A total of 40 PAC days of beam time is requested for the high precision extraction of r_D.

- Target thickness: $N_{tgt} = 2\text{x}10^{18}$ D atoms/cm^2
  Beam intensity: I_e ~30 nA ($N_e = 1.875\text{x}10^{11}$ e$^-$/s)

1) for E_0= 1.1 GeV, Total rate for *ed → ed*

$$N_{ed} = N_e \text{ x } N_{tgt} \text{ x } \Delta\sigma \text{ x } \varepsilon_{geom} \text{ x } \varepsilon_{det}$$

≈ 519 events/s ≈ 44.7 M events/day

Rates are high, however,
for 0.5% stat. error for the last Q^2= $1.3\text{x}10^{-2}$ (GeV/c)^2 bin
8 days are needed.

2) for E_0= 2.2 GeV, I_e ~70 nA Total rate for *ed → ed*

N_{ed} ≈ 43 events/s ≈ 3.7 M events/day

to have ~ 0.5 % stat. error for the last Q^2 bins
we request 16 days for this energy run.

The choice of beam current is based on the expected maximum data rate allowed by the new GEM detector DAQ (25 kHz), the expected trigger rate for the calorimeter and maximum power allowed on the Hall-B Faraday cup (160 W).

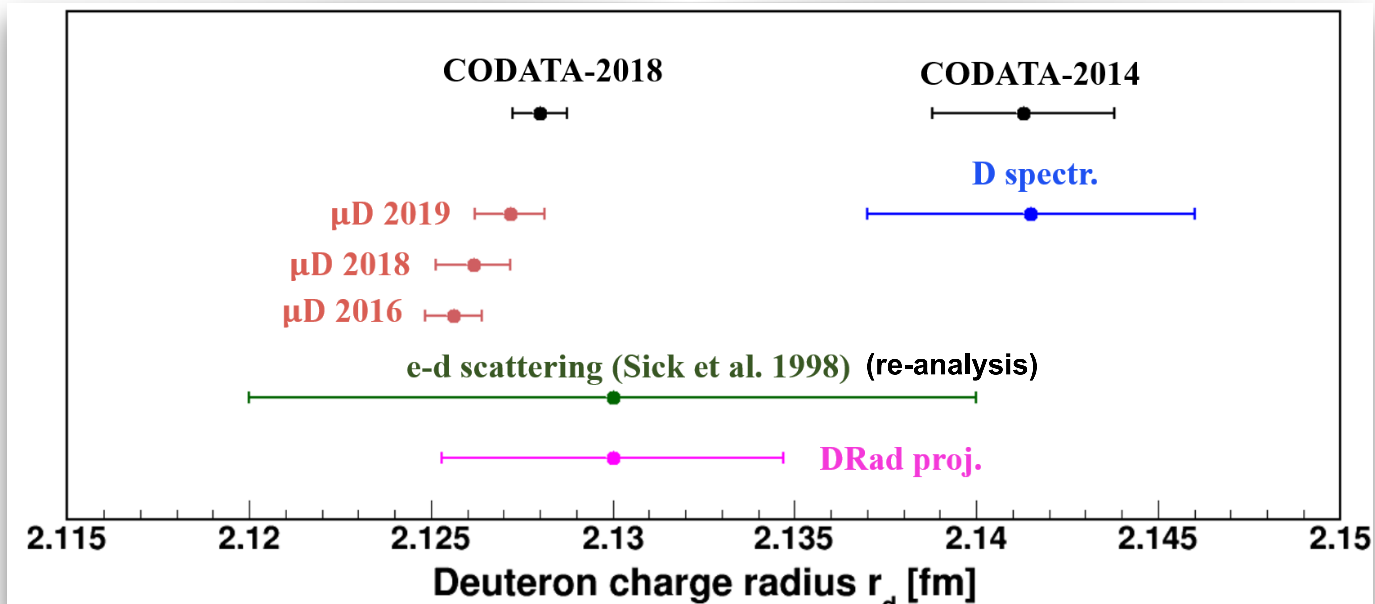
	Time (days)
Setup checkout, calibration	3.5
Recoil detector commissioning	2
Recoil detector calibration with hydrogen gas	3
Statistics at 1.1 GeV	8
Energy change	0.5
Statistics at 2.2 GeV	16
Empty target runs	7
Total	40

The estimated total uncertainties on the extracted r_D is 0.22%, about factor of 2 better than the best extraction to date

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
Bias from the fitter	0.065
Efficiency of recoil detector	0.15
Total	0.22

Projected results



We have addressed the issues raised by PAC-45 during our previous submission of this proposal.

PR12-17-009

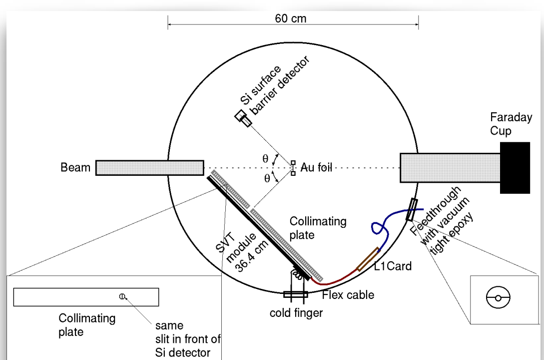
Scientific Rating: N/A

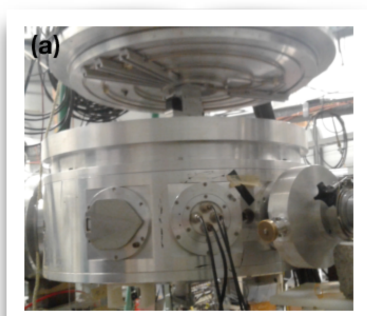
Recommendation: Deferred

Title: Precision Deuteron Charge Radius Measurement with Elastic Electron-Deuteron Scattering

Spokesperson: A. Gasparian (contact person), H. Gao, D. Dutta, N. Liyanage, E. Pasyuk

Summary: While the present target accuracy of this proposal is large as compared to the effect, the PAC finds the proposal potentially interesting and encourages the authors to scrutinize the final error in $\delta r_d/r_d$ once the PRad analysis is finished. A possibility to substantially reduce the experimental error on $\delta r_d/r_d$ seems to be very attractive but needs to be worked out in detail. A method to calibrate the efficiency of the silicon strip detector for low energy deuterons with energies as expected in this proposal for the low q^2 intervals needs to be thoroughly worked out. The systematic error while extrapolating from measurements with protons from elastic scattering or from higher energy deuterons needs to be quantitatively understood.





The recoil detector will be calibrated using *ep* elastic running on hydrogen and with the 5-15 MeV p/D beam from the Tandem accelerator at TUNL.

Preparations are underway for a test using a single SVT module from Hall-B. (delayed by COVID)

Response to selected TAC questions

12. The proposed recoil detector is based on Si strips technology. At our knowledge, there is no established practice of using such a detector at 20K (CERN demonstrated operations at 70K only). Such a low T can be problematic not only for sensors but for services, cables, and everything

response: The electronics and cables are located outside the target cell and are not exposed to the 20K gas, and thus they will not be operating at 20K. Furthermore, if needed they will be wrapped in super-insulation or heating tapes. The Si-sensors themselves will indeed be inside the target cell, and thus at 20K. Although Si-strip detectors have not been studied at 20K other solid state detectors such as SiPMs have been studied at temperatures as low as 4K. They were found to perform well and have lower noise and faster response times at these low temperatures.

Proc. 5th Int. Workshop New Photon-Detectors (PD18)
JPS Conf. Proc. **27**, 012005 (2019)
https://doi.org/10.7566/JPSCP.27.012005

Characterization of Cryogenic SiPM Down to 6.5 K

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Response to selected TAC questions

13. The recoil deuterons and protons, for calibration, at 1.1 GeV elastic scattering will have <0.5 MeV and <1 MeV kinetic energy at 2 degrees. It is not clear if detector will be sensitive to this low energy recoils. The Si coating can affect the minimum p and d kinetic energy sensitivity. The demanding spec (1-2 μm) should be demonstrated to be feasible by the vendor and tested by proponents.

response: Micron Semiconductor provides standard Si-strip detectors with passivation layers ranging in thickness from 0.5 μm to 0.01 μm and they quote a proton detection threshold of 1 keV for the detectors with a 0.01 μm thick passivation layer. They also provide a special material (Neutron Transmutation Doped) that can achieve very high uniformity ($< 5\%$ variation) for a passivation layer with a thickness of 0.03 μm. Our simulations also indicate that the low energy recoil deuterons in the 0.7-7.5 degree angular range can be detected in the proposed Si-strip detector.

SILICON SENSOR OPTIONS

Window Type

The range of dead layer windows available with the in-house Varian 300 XP ion implanter are listed below. Window types refer to the junction of a device, but can also be achieved on the ohmic side upon request.

WINDOW TYPE	DEAD LAYER	MINIMUM ENERGY THRESHOLD	
		Electron	Proton
9	100 nm	1K eV	20 KeV

Summary

- **We propose a new high precision measurement of the deuteron charge radius from e-D scattering to address the *"deuteron radius puzzle"*.**
- **The proposed experiment is based on the magnetic-spectrometer-free calorimetric technique successfully demonstrated by the PRad experiment.**
  - ✓ **It will use the same setup proposed for the PRad-II experiment + a recoil detector.**
  - ✓ **Cylindrical Si-strip-based recoil detector.**
- **This will allow us:**
  - ✓ **to reach the lowest Q^2 ($\sim 2\text{x}10^{-4}$ GeV^2) in e-D scattering experiment.**
  - ✓ **cover a large Q^2 range ($2\text{x}10^{-4}$ - $5\text{x}10^{-2}$ GeV^2) in a single stationary experimental setup.**
  - ✓ **measure the deuteron charge radius with a precision of 0.22%**
- **Requesting a total of 40 PAC days of beam time at 1.1 and 2.2 GeV beam energy.**

This work was supported by NSF-MRI grant PHY-1229153 and US DOE grant DE-FG02-07ER41528