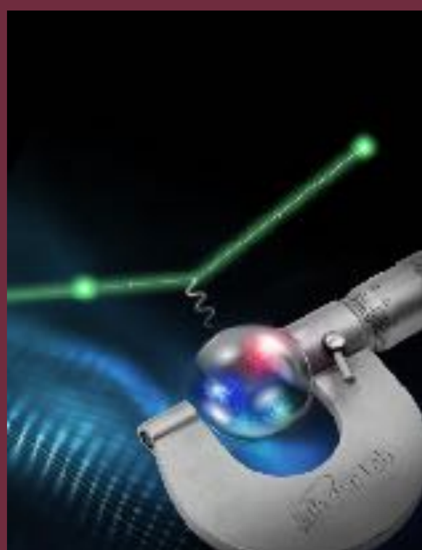
PR12-23-011

Precision Deuteron Charge Radius Measurement with Elastic Electron-Deuteron Scattering



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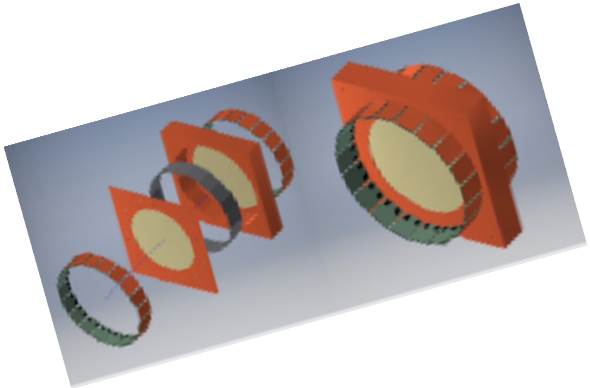
for the PRad Collaboration

Spokespersons (D. Dutta, F.Q.L. Friesen, H. Gao, A. Gasparian, D. Higinbotham, C. Howell, N. Liyanage & E. Pasyuk)

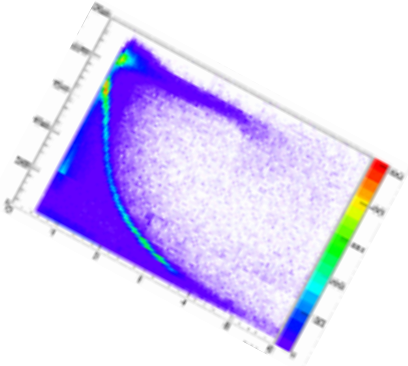
PRoton Radius

PAC 51 Meeting, July 24, 2023

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

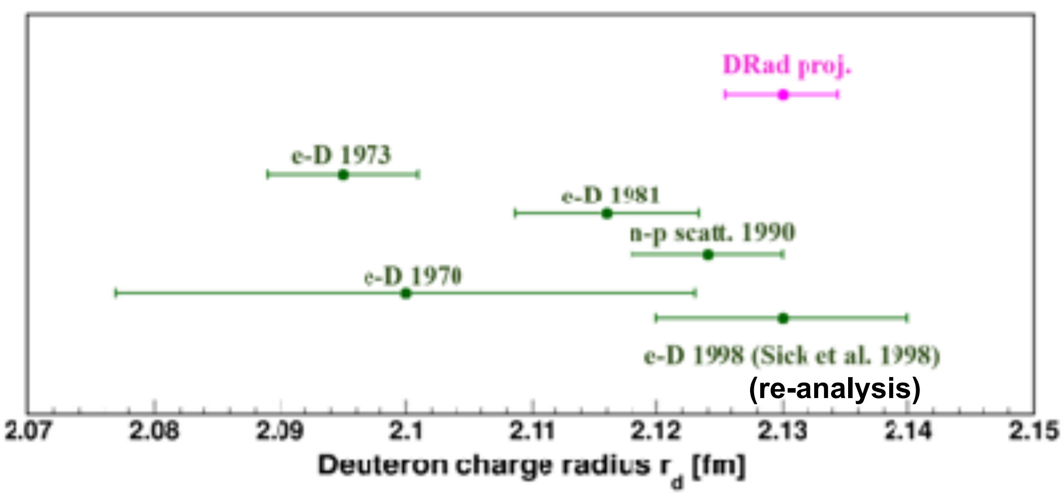


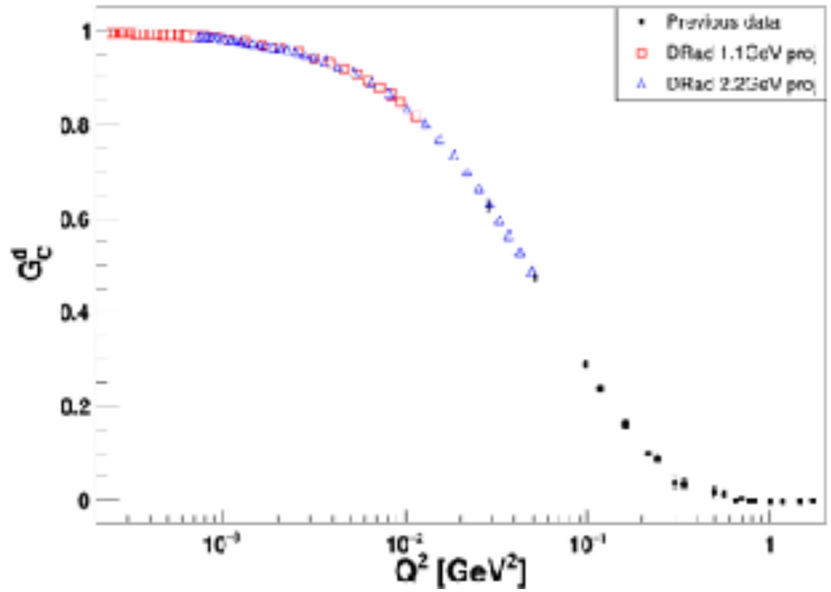
Executive Summary

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 0.21%

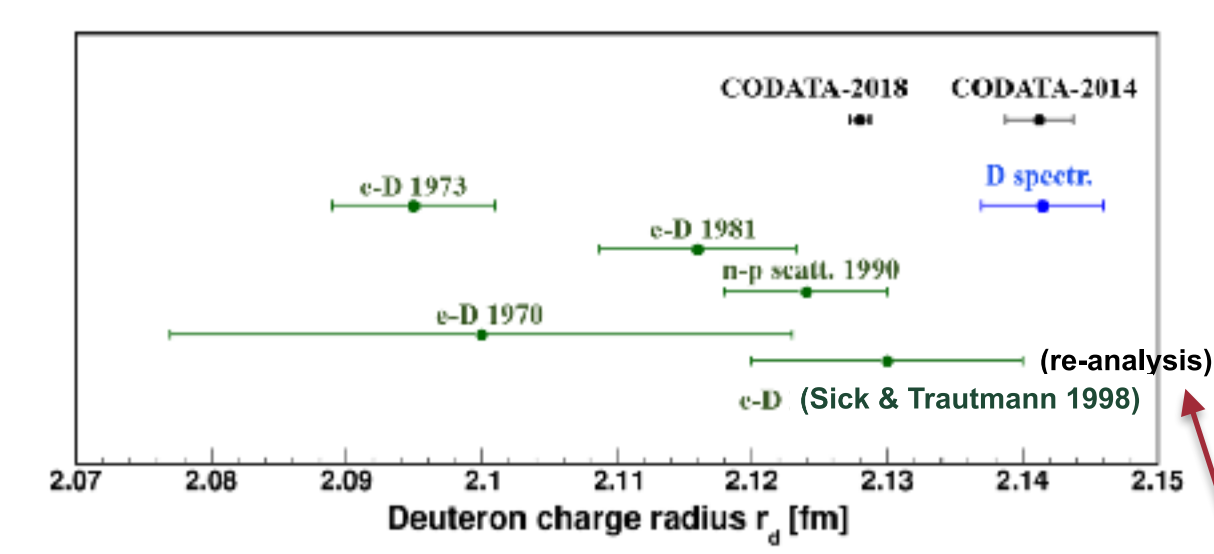
We will cover the Q^2 range of 2×10^{-4} to 5×10^{-2} GeV^2 probing the lowest Q^2 reached in e-D scattering experiments.

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

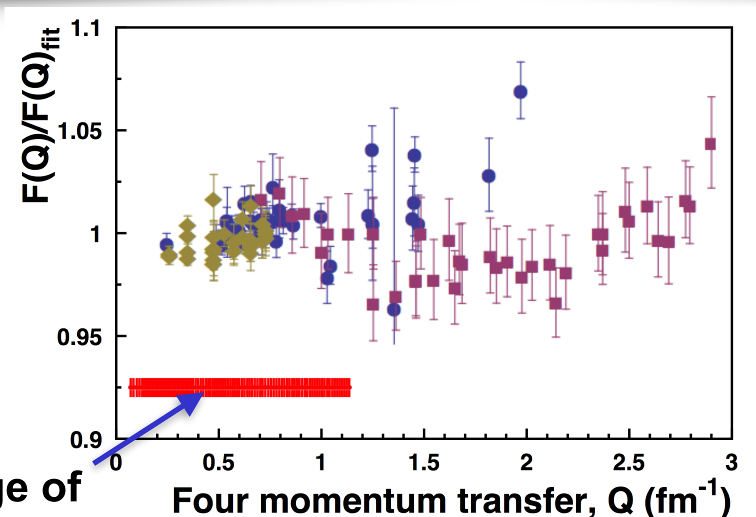




There is a urgent need for high precision *e-D* scattering data used to extract deuteron radius



- 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

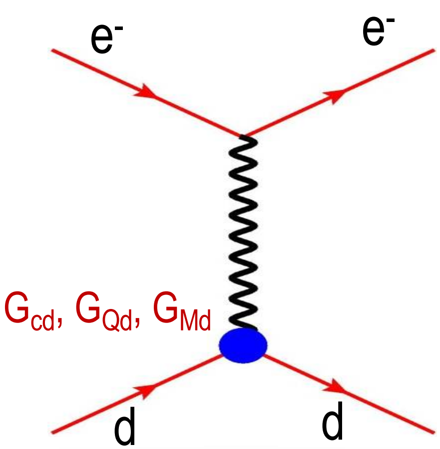
R.W. Berard et al. PLB 47,355, (1973)
cooled H_2 and D_2 gas measured ratio of *eD/ep* cross section; Q = [0.2 – 0.7] fm^{-1}

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:

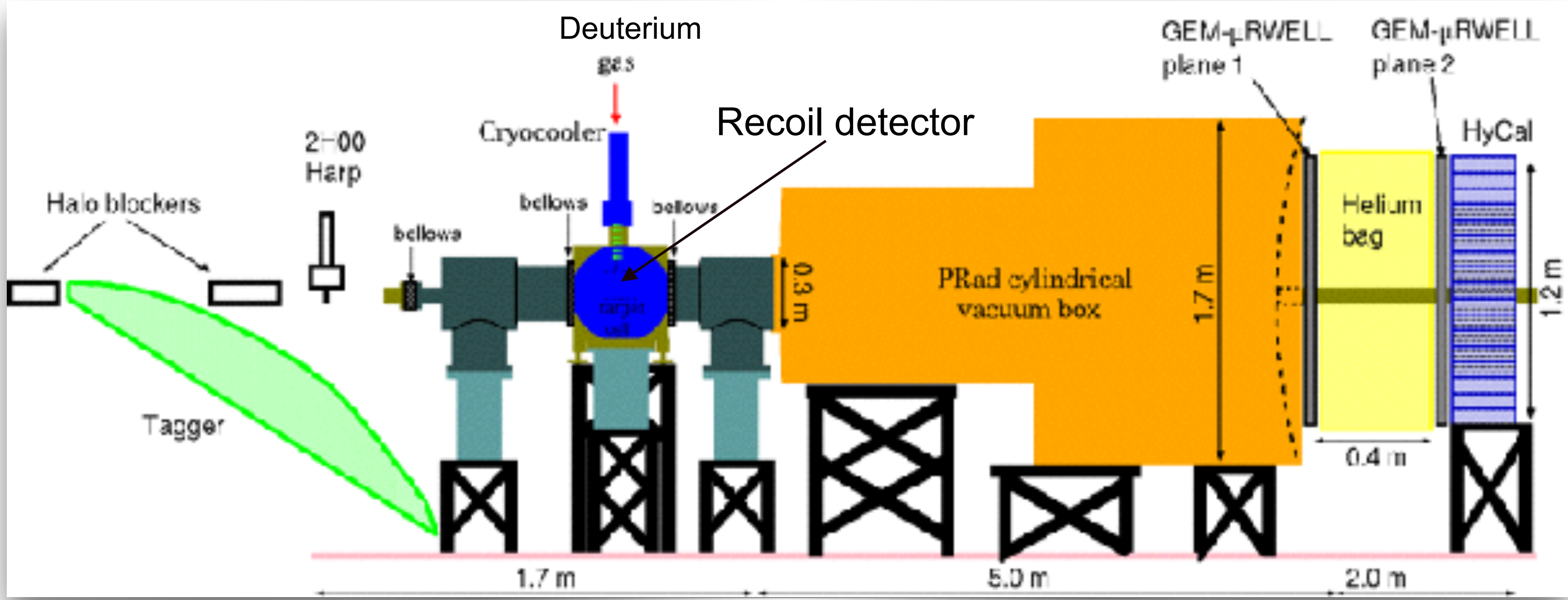
$$\begin{aligned} A(Q^2) &= G_{Cd}^2(Q^2) + \frac{2}{3}\eta G_{Md}^2(Q^2) + \frac{8}{9}\eta^2 G_{Qd}^2(Q^2) \\ B(Q^2) &= \frac{4}{3}\eta(1+\eta)G_{Md}^2(Q^2), \end{aligned}$$

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

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

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

DRad: a novel electron scattering experiment

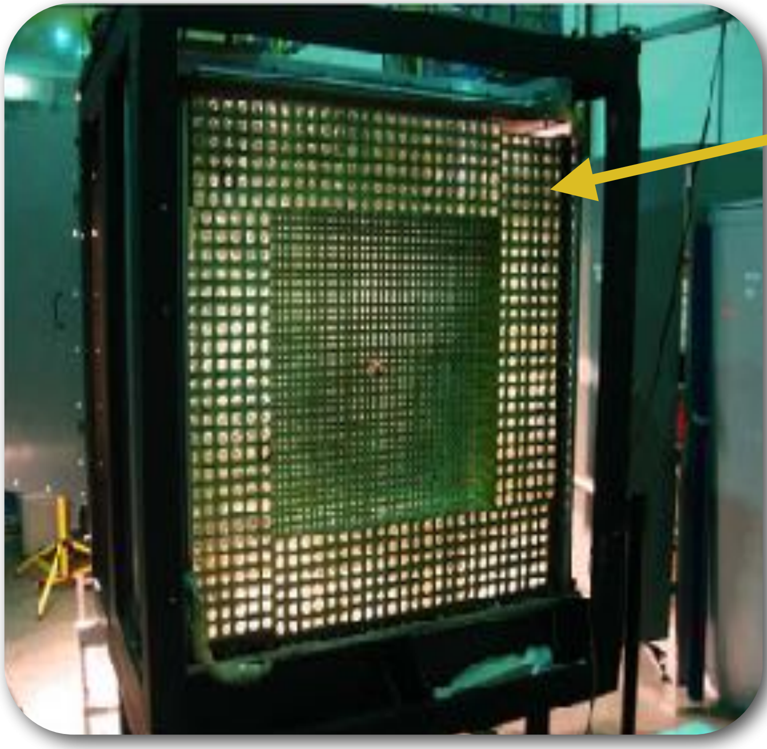


Will use the PRad-II setup with 1.1 GeV and 2.2 GeV electron beam

- **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 $2\times10^{-4} - 5\times10^{-2}$ 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$/\sqrt{E}$

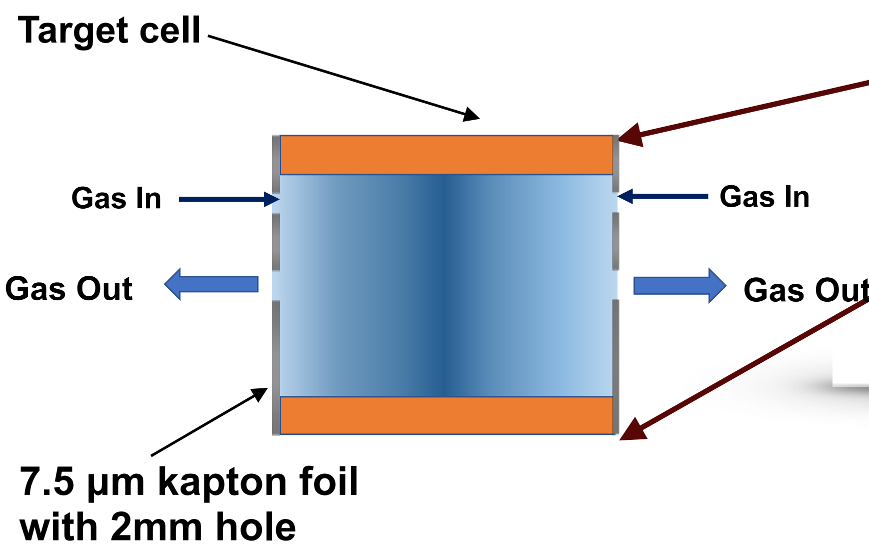
Convert to FADC based readout of HyCal

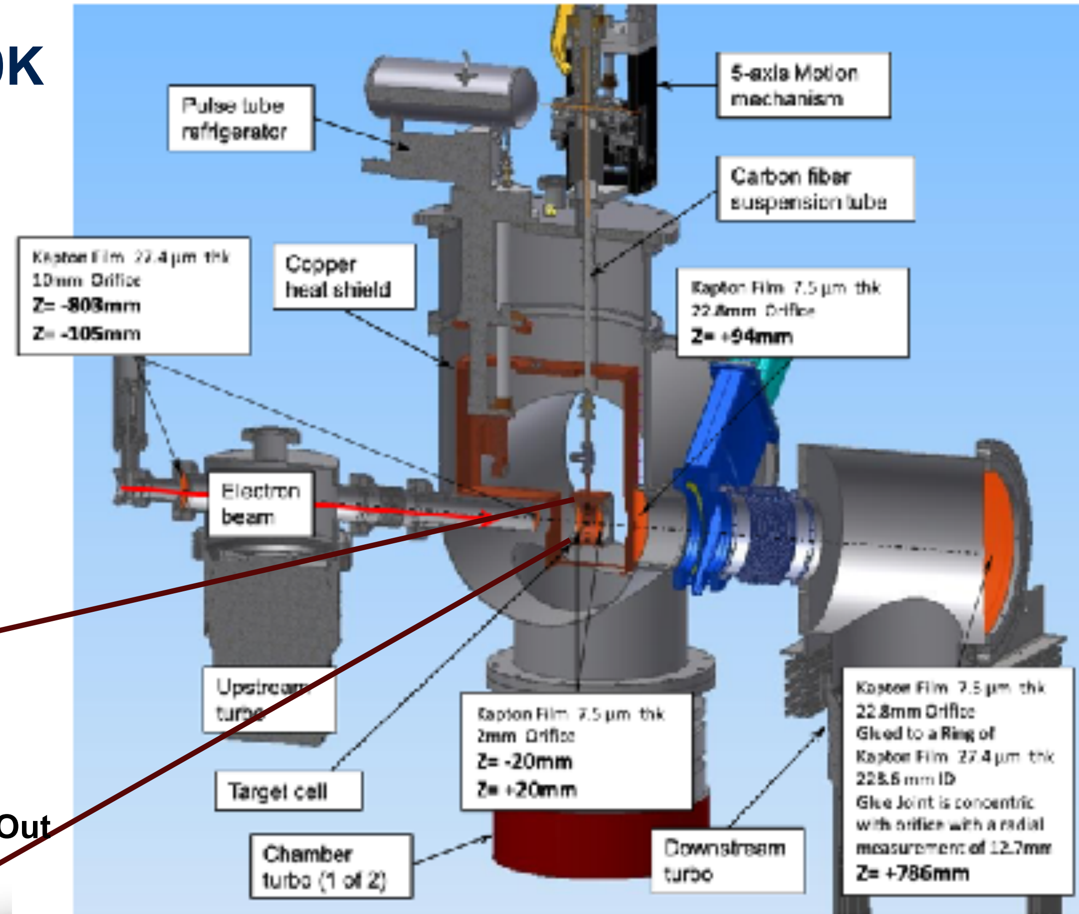
- **$PbWO_4$ calorimeter (118x118 cm^2)**
- **57x57 matrix of 2.05 x 2.05 cm^2 x18 cm $PbWO_4$**
- **5.5 m from the target,**
- **0.5 sr acceptance**

The DRad experiment will use the PRad windowless target with a redesigned target cell.

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

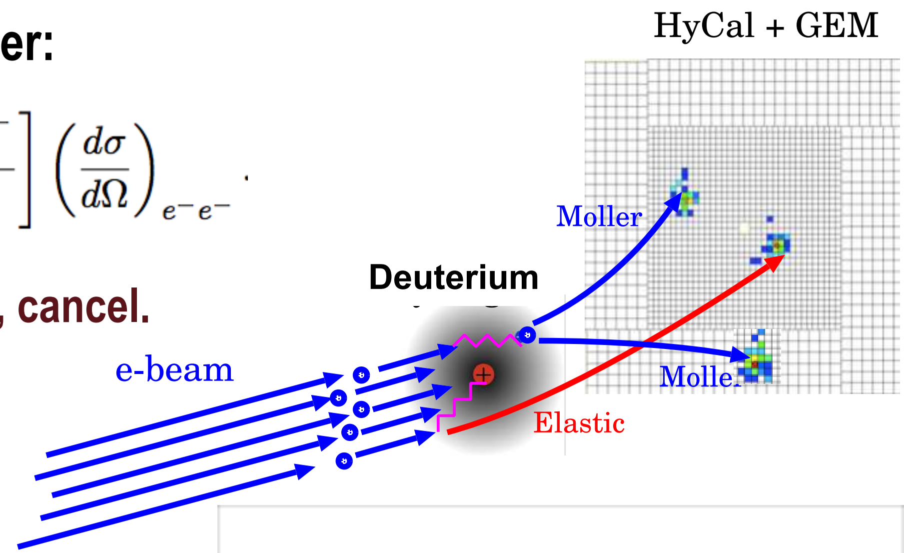
Systematic uncertainties will be controlled by simultaneously detecting e-D elastic and Møller events

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

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

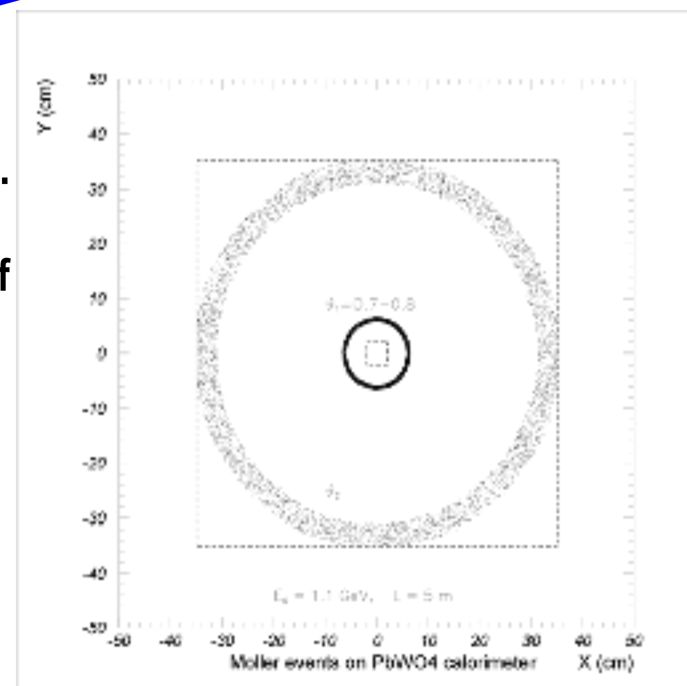
Two major sources of systematic errors, N_e and N_{tgt}, cancel.

But, need relative det. efficiency ε_{det}

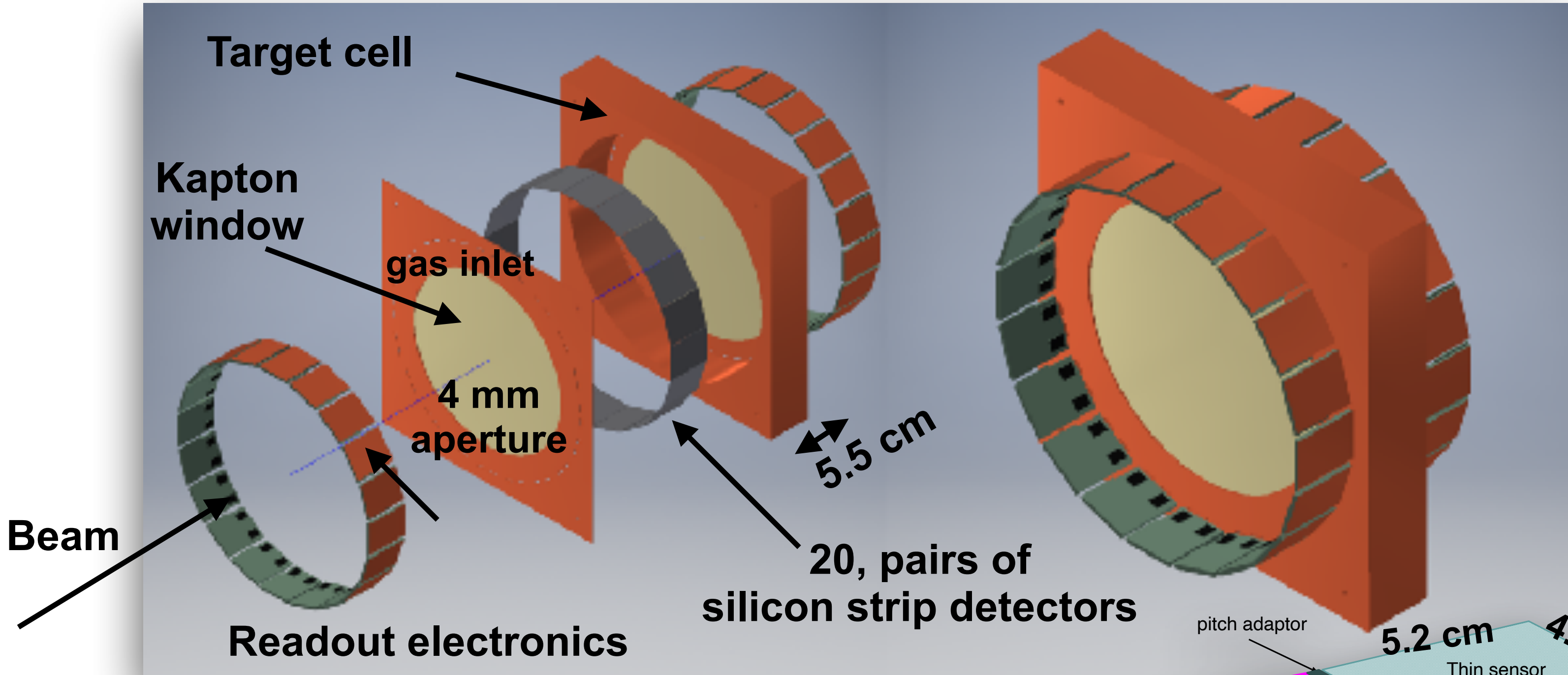


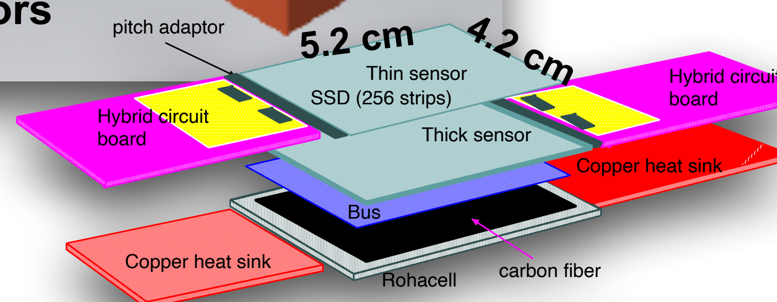
- **Geom. acceptances and detection efficiencies will be extracted during *ep* → *ep* calibration run with hydrogen gas in target cell.**
- **Deuteron detection efficiencies will be obtained from the ratio of deuteron/proton detection efficiencies measured at TUNL using the 5-15 MeV p/D beams from the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





material budget < 1% r.l.

Based on CLAS12 Barrel Si tracker (SVT)

- 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.

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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

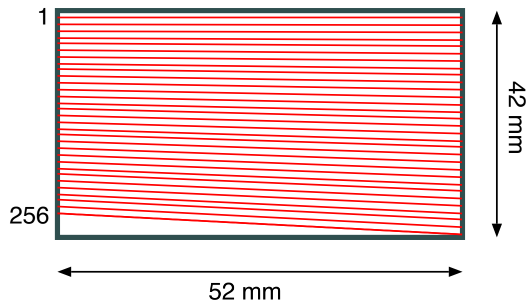
WAFER SIZE	STANDARD SILICON THICKNESSES AVAILABLE
3-inch	20, 30, 40 µm
4-inch	40, 50, 65, 80, 100, 140, 250, 300, 500, 1000, 1500 µm
6-inch	150, 200, 300, 400, 500, 675 µm

NTD

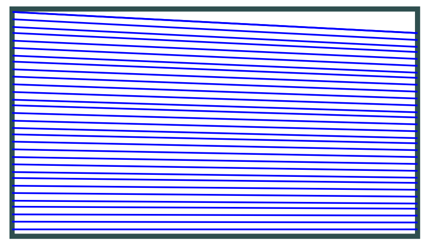
Neutron transmutation doped n type silicon is offered for applications where low resistivity variation across the wafer is required. This material has a much higher depletion voltage that regular high resistivity n-type material.

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

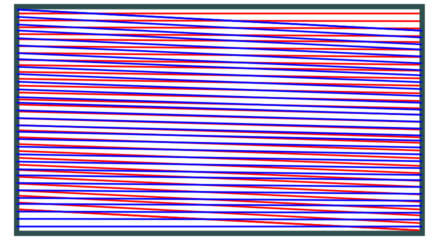
thin layer (inner)



thick layer (outer)

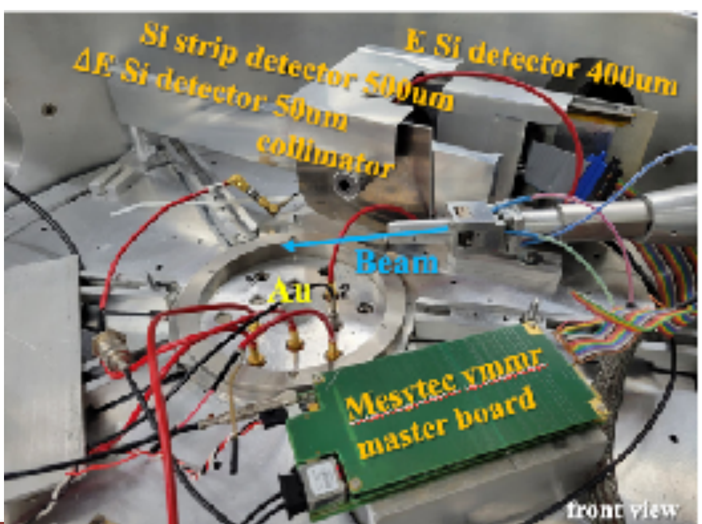


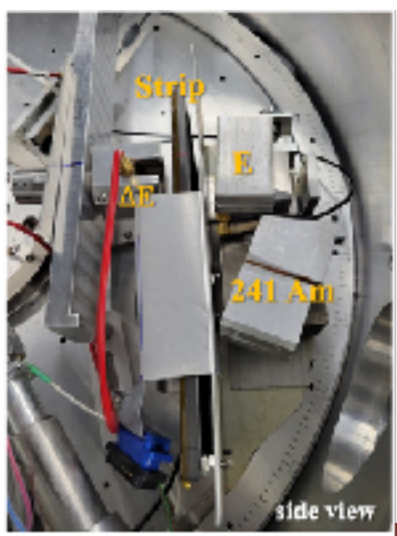
intersection of layers

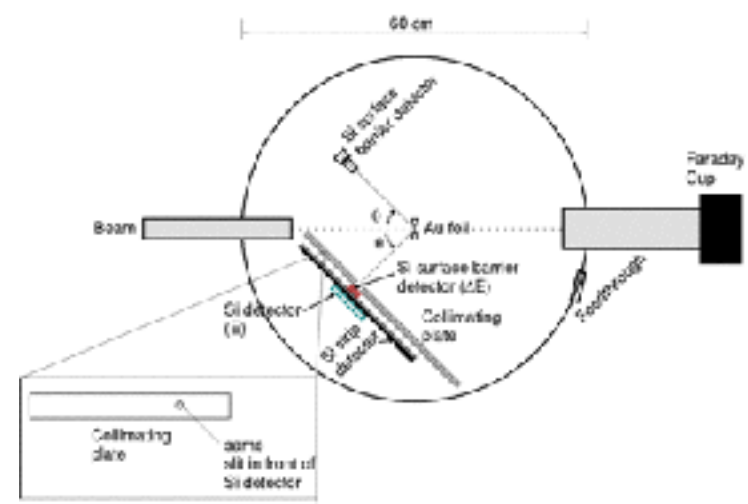


256 strips with linearly varying angles of 0 - 3 deg to minimizes dead zones.
The strips will have a constant pitch of ~200 micron (~1/85 deg^{-1}).
The angular resolution of $\delta\varphi \lesssim 5$ mrad and $\delta\theta \lesssim$ 10-20 mrad.

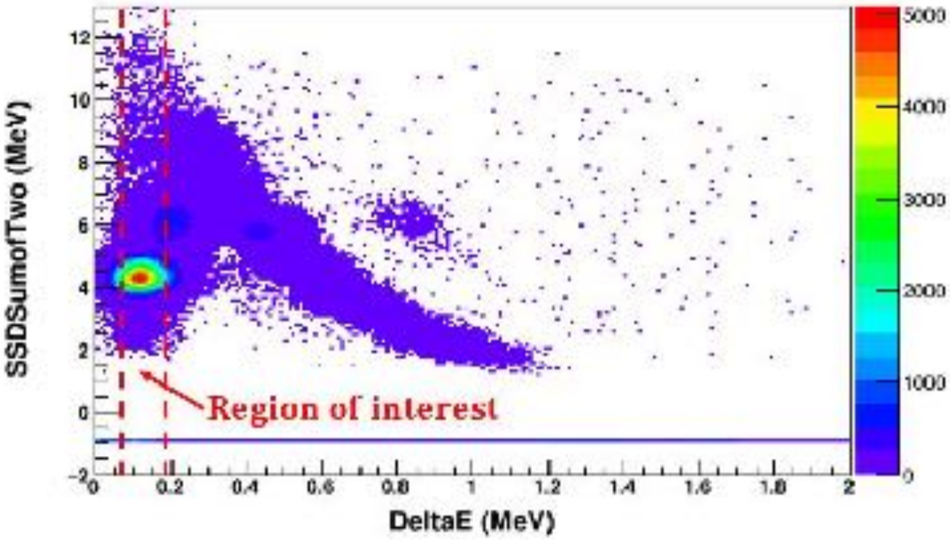
The recoil detector will be calibrated using *ep* elastic running on hydrogen and with the 5-15 MeV p/D beam from the Tandem accelerator at TUNL (recently validated).

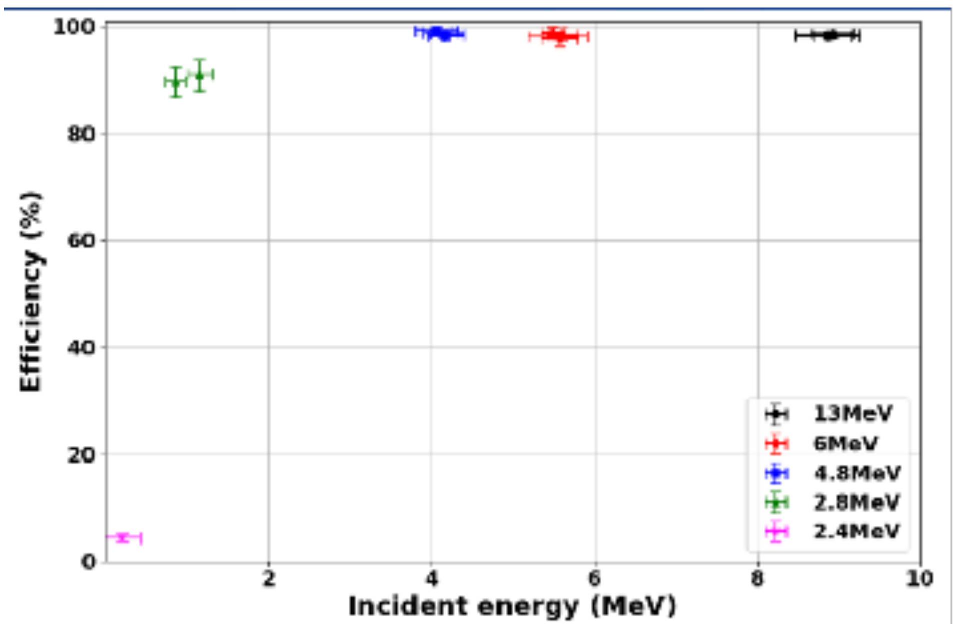




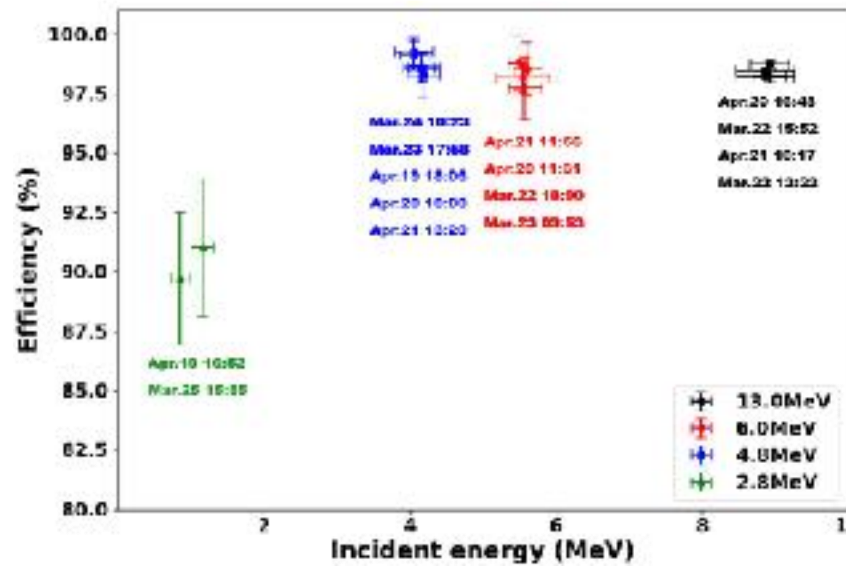


The recoil detector calibration scheme validated using 5-15 MeV p/D beam from the Tandem accelerator at TUNL





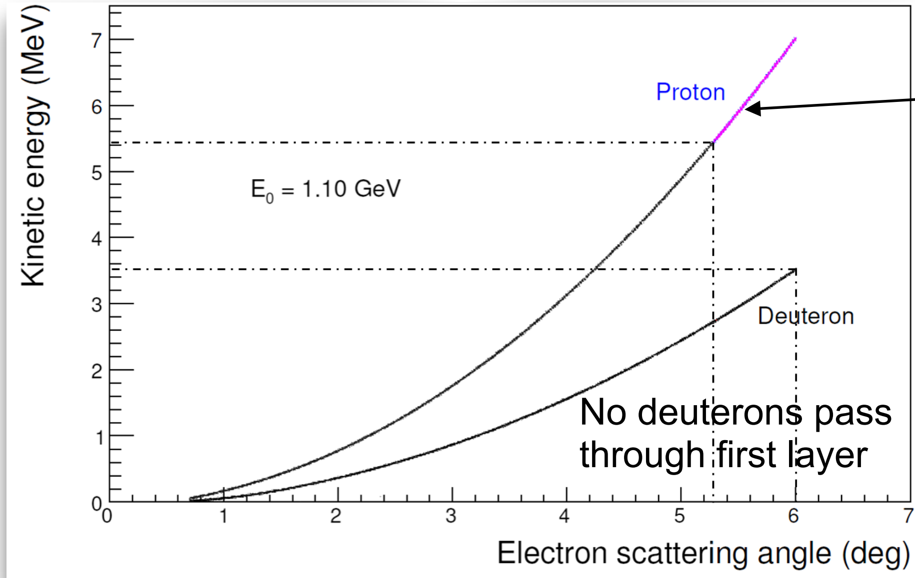
Efficiency $\eta(I,E) = \frac{N_{SSD}(I,E)}{N_{ROI}(I,E)}$



New spokespersons (F.Q.L. Friesen & C. Howell) from TUNL/Duke will build the SSD recoil detector

Plots and analysis courtesy of J. Zhou

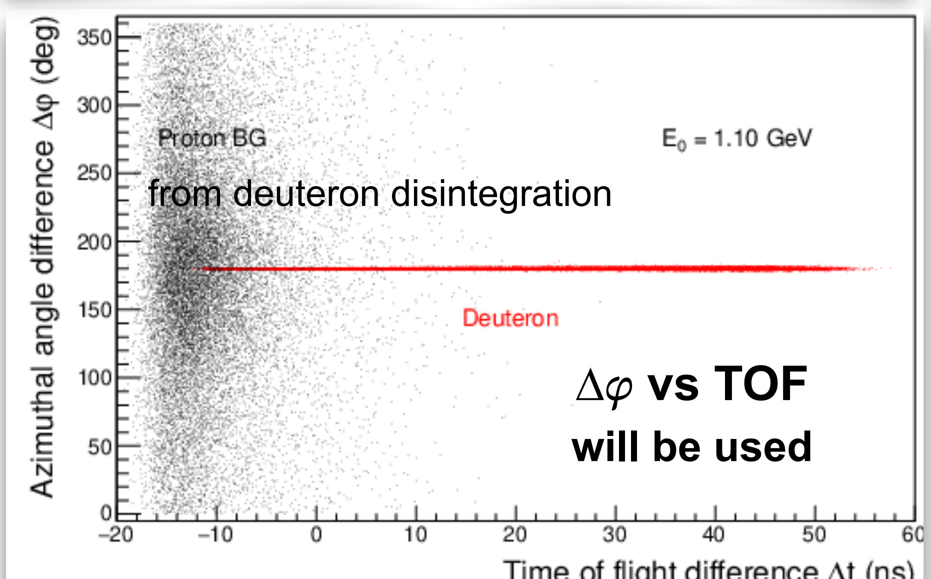
Particle identification at 1.1 GeV will use recoil detection and its time difference with the HyCal.

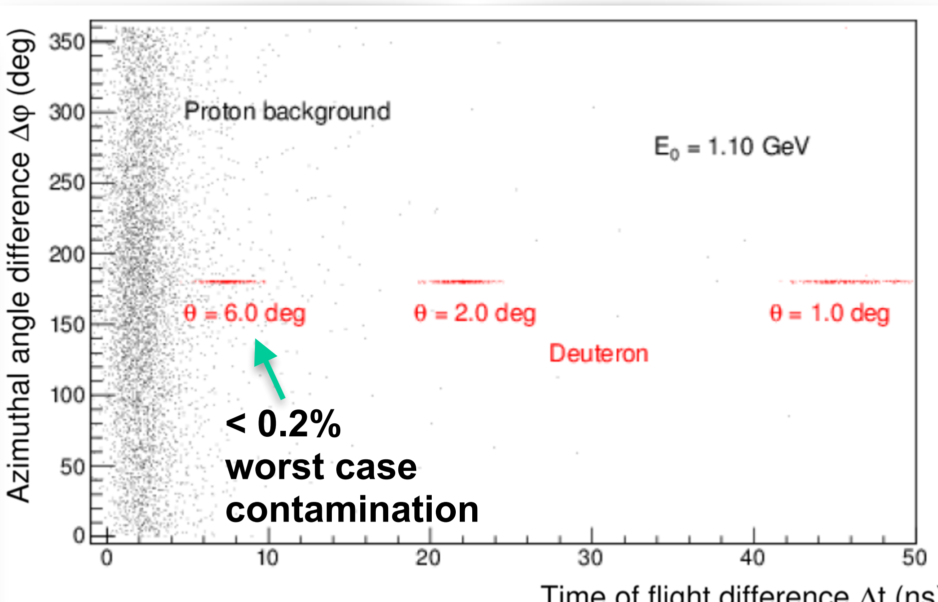


Protons that pass through first (inner) layer

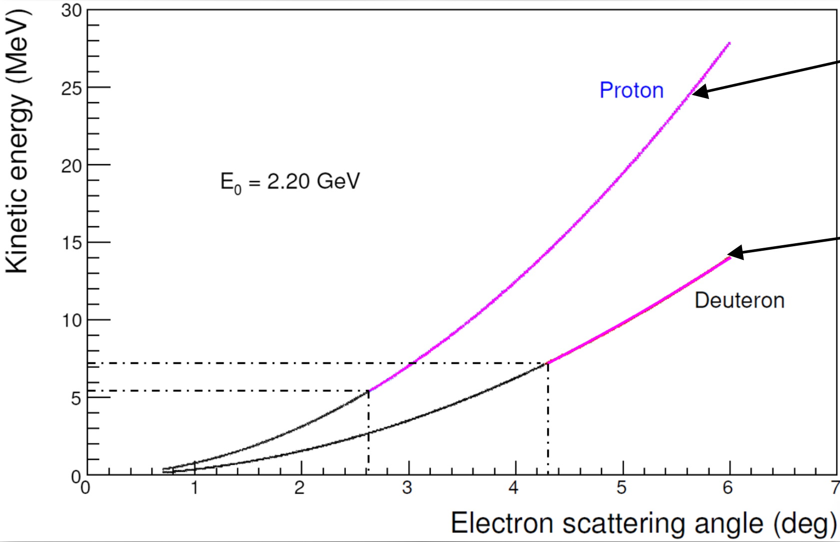
For large part of 1.1 GeV kinematics the deuterons do not disintegrate, but still the deuteron must be detected to ensure elastic scattering.

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





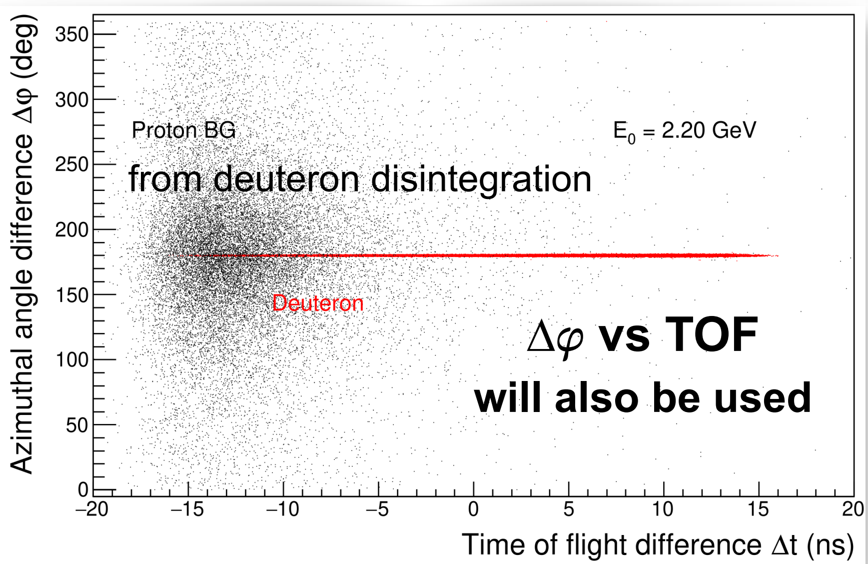
Particle identification at 2.2 GeV will use recoil detection and its time difference with the HyCal.

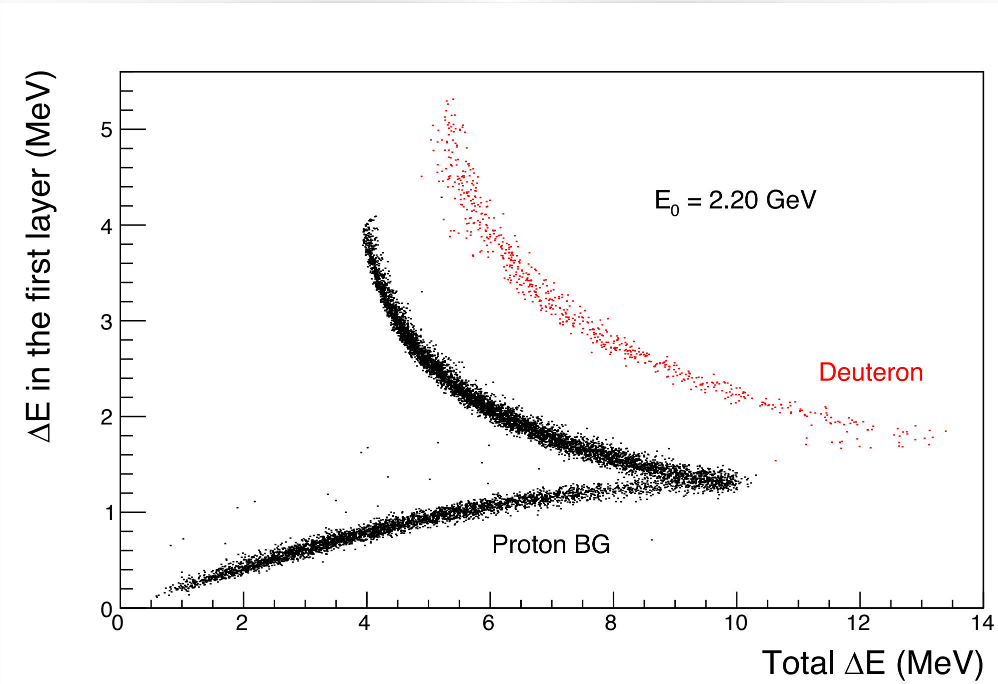


Protons that pass through first (inner) layer

Deuterons that pass through first (inner) layer

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





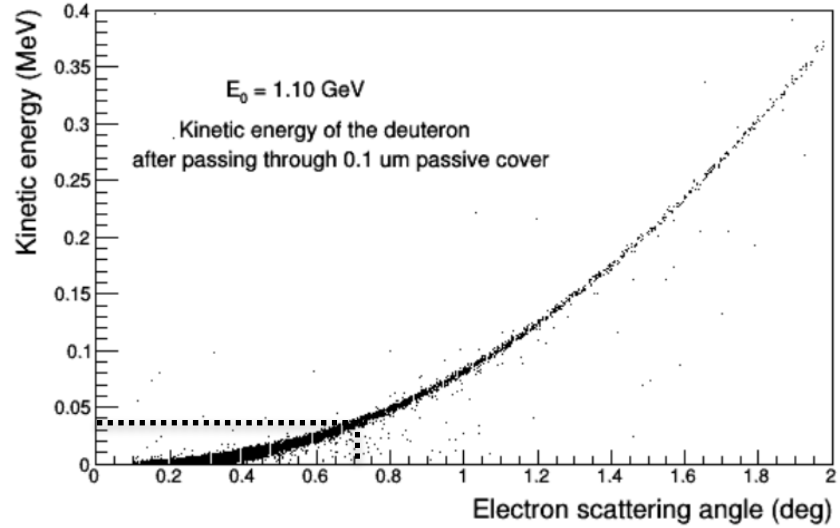
The recoil detector can detect deuterons with kinetic energy > 40 keV

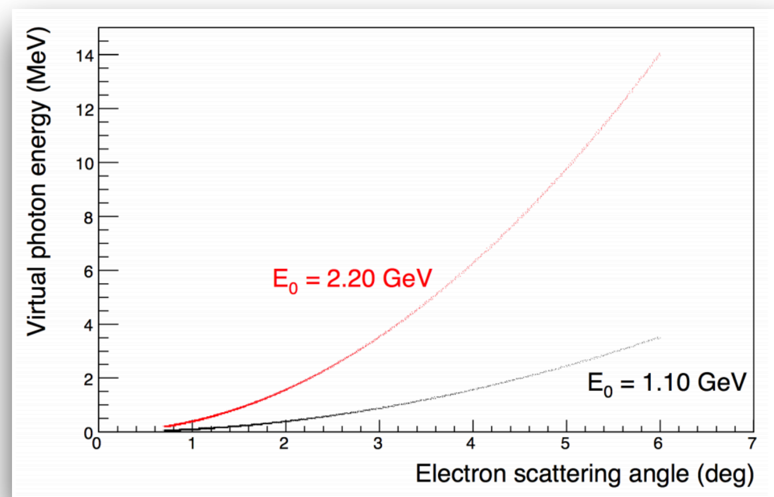
Comprehensive Geant4 simulation of the experiment was developed and used for studying the detection thresholds and backgrounds.

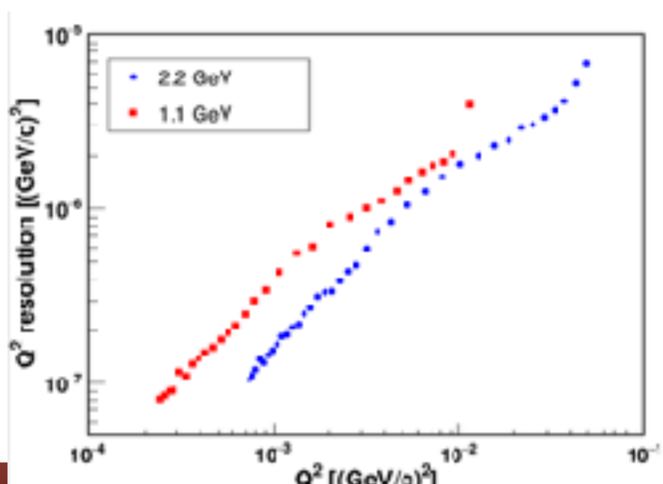
Deuteron will recoil at large polar angles θ_d = [83^0 - 89^0];

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 θ_e = 0.7° - 7.5° can be detected giving a Q^2 coverage of *2×10^{-4} – 5×10^{-2} GeV^2* with high resolution.



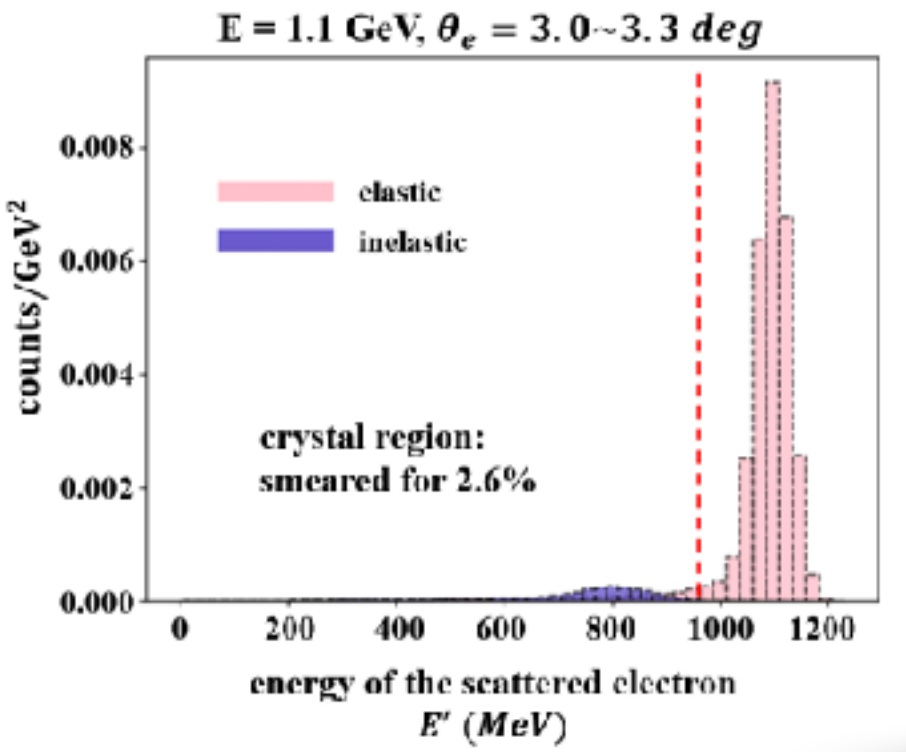


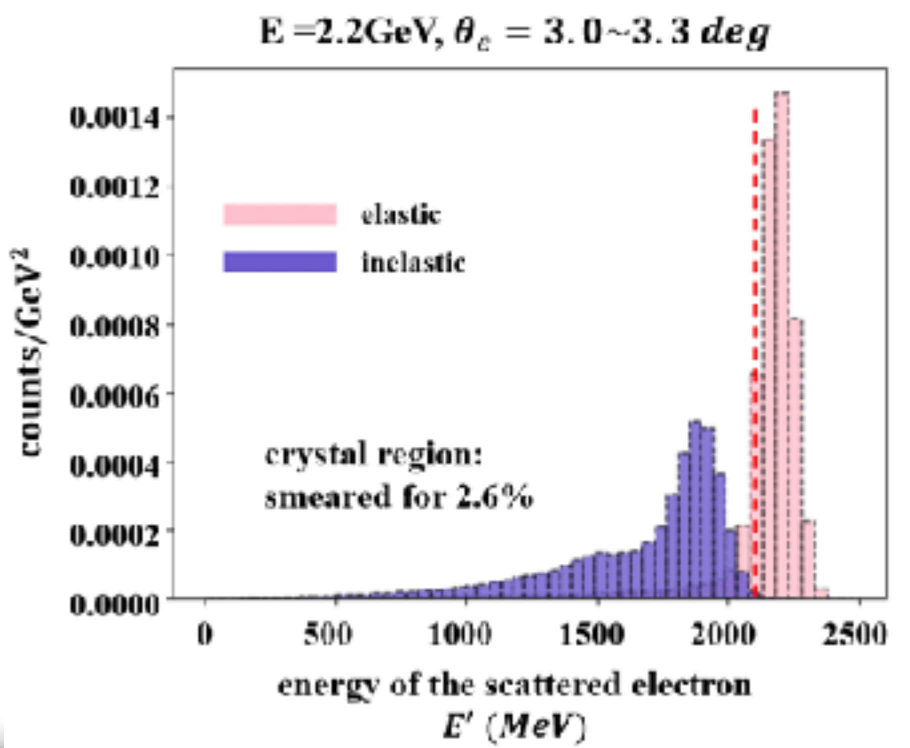


Deuteron electro-disintegration and inelastic scattering are the two major sources of background.

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

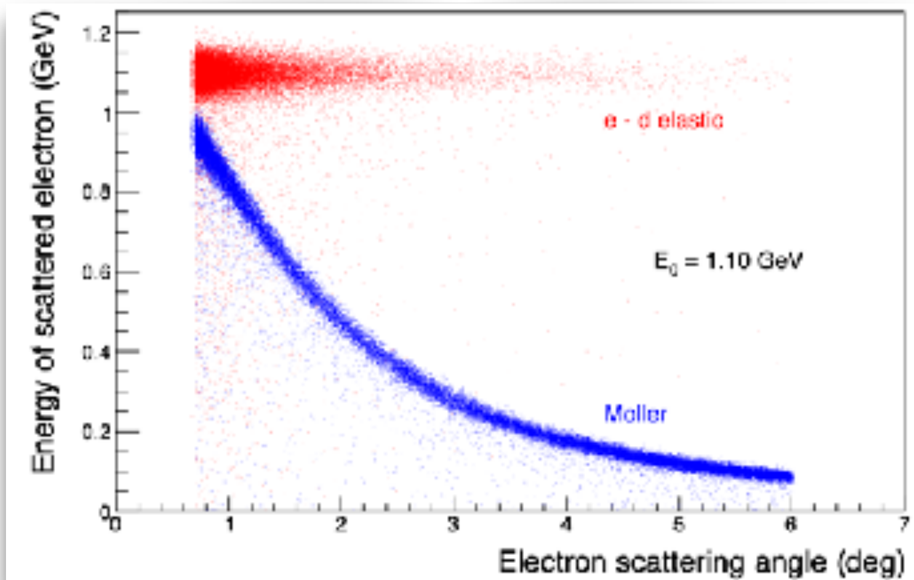
Electro-disintegration rates are < 6% of the elastic rates.
inelastic rates are < 1% of the elastic rates





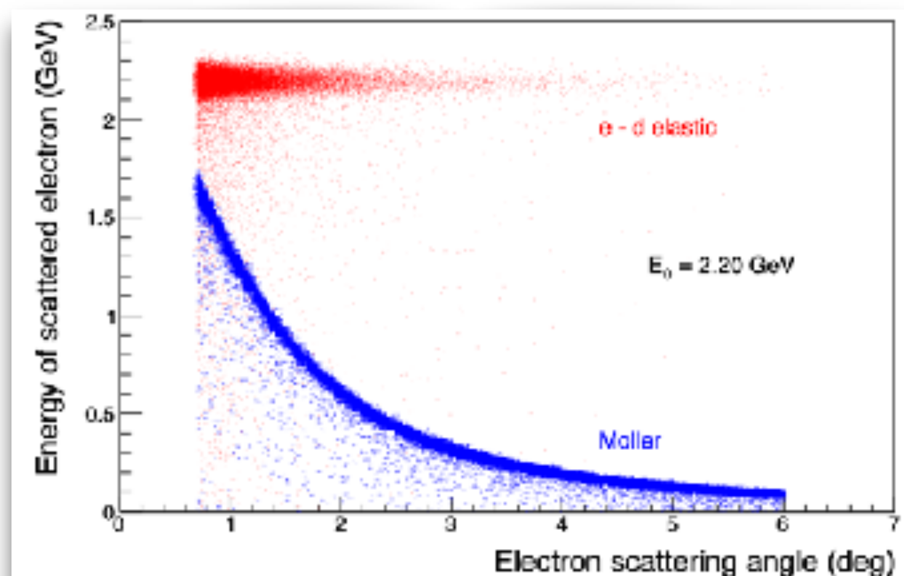
Elastic *e-D* and Møller events can be cleanly separated over the full angular range [0.7^0 - 7.5^0]

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

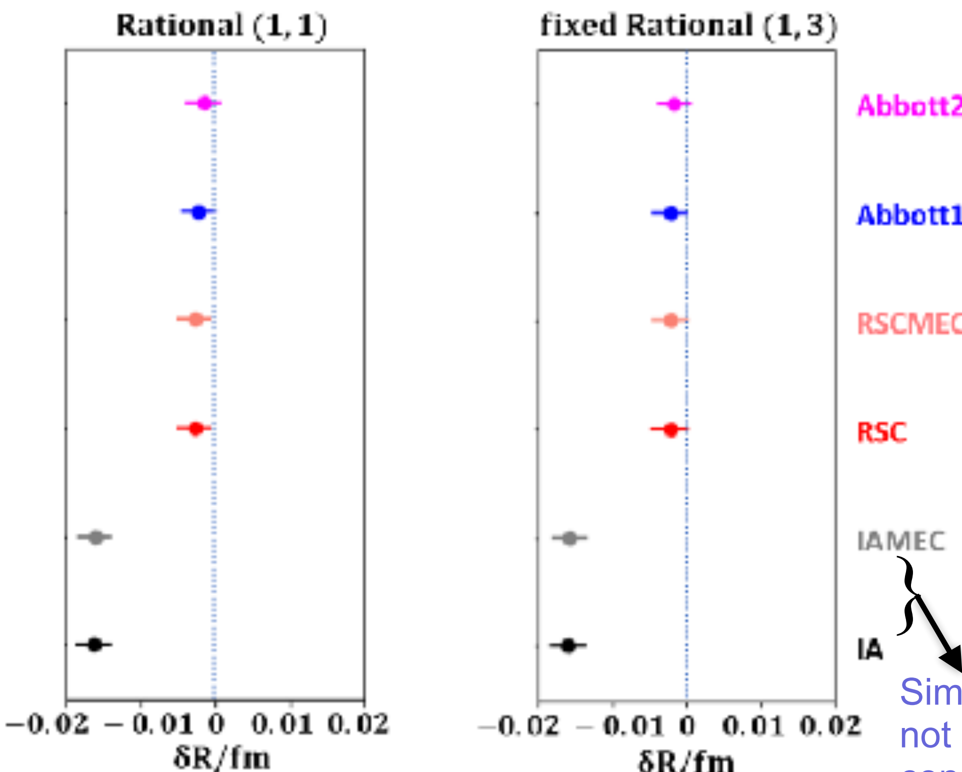
The internal and external radiation has been included for both *e-D* and Møller scattering.



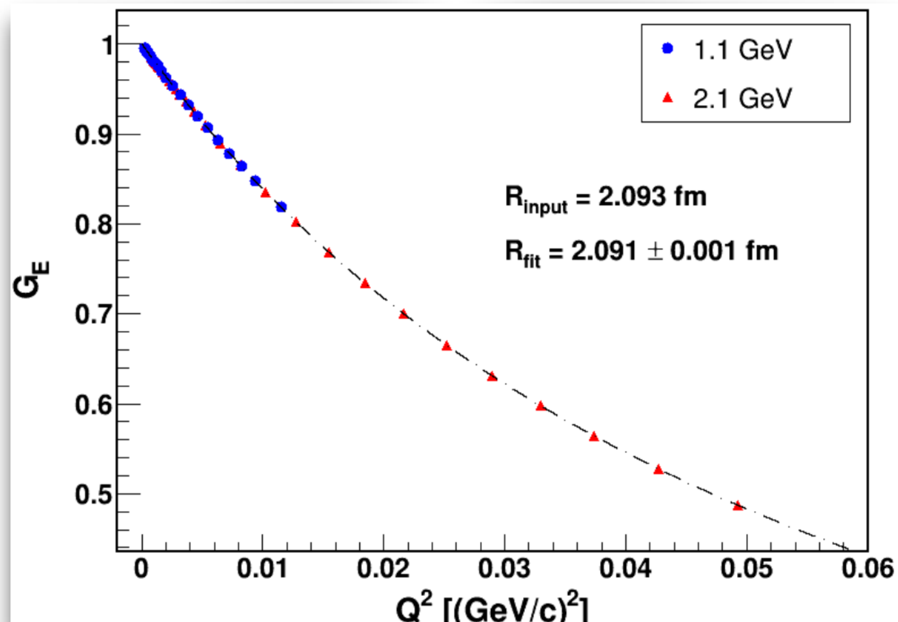
A wide range of functional forms were systematically tested for their robustness in extracting r_D.

- 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} = 2x10^{18} D atoms/cm^2
  Beam intensity: I_e ~30 nA (N_e = 1.875x10^{11} e$^-$/s)

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

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

$$\approx 519 \text{ events/s} \approx 44.7 \text{ M events/day}$$

Rates are high, however,
for 0.5% stat. error for the last Q^2= 1.3x10^{-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*

$$N_{ed} \approx 43 \text{ events/s} \approx 3.7 \text{ M events/day}$$

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 the maximum power allowed on the Hall-B Faraday cup is no longer a limit.

	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 0.21%, about factor of 2 better than the best extraction to date

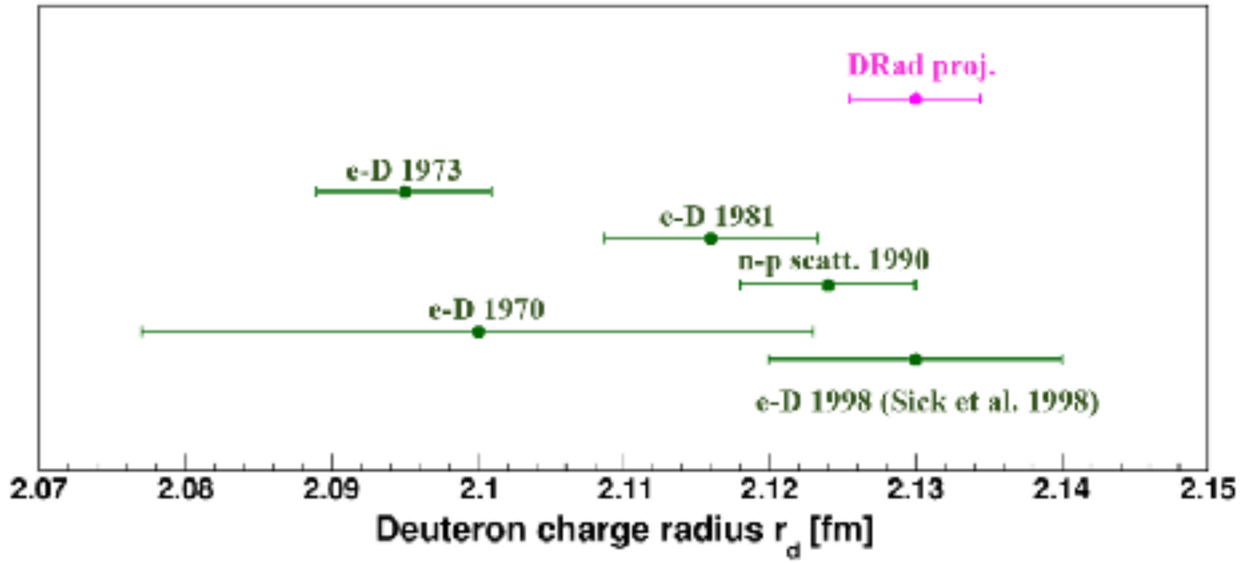
Item	Uncertainty (%)
Event selection	0.110
Radiative correction	0.090
HyCal response	0.043
Geometric acceptance	0.022
Beam energy	0.008
Total correlated terms	0.13

Item	Uncertainty (%)
Statistical uncertainty	0.05
Total correlated terms	0.13
GEM efficiency	0.03
Inelastic e-d process	0.024
Efficiency of recoil detector	0.15
Total	0.21

Estimated from 10,000 mock data sets smeared by systematic and statistical uncertainties.

systematic uncertainty = $(R_{smear} - R_{unsmear})/R_{unsmear}$

Projected results



We have addressed the issues raised by PAC-48 during our previous submission of this proposal.

PR12-20-006

Scientific Rating: N/A

Recommendation: Deferred

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

Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, D. W. Higinbotham, E. Pasyuk, N. Liyanage

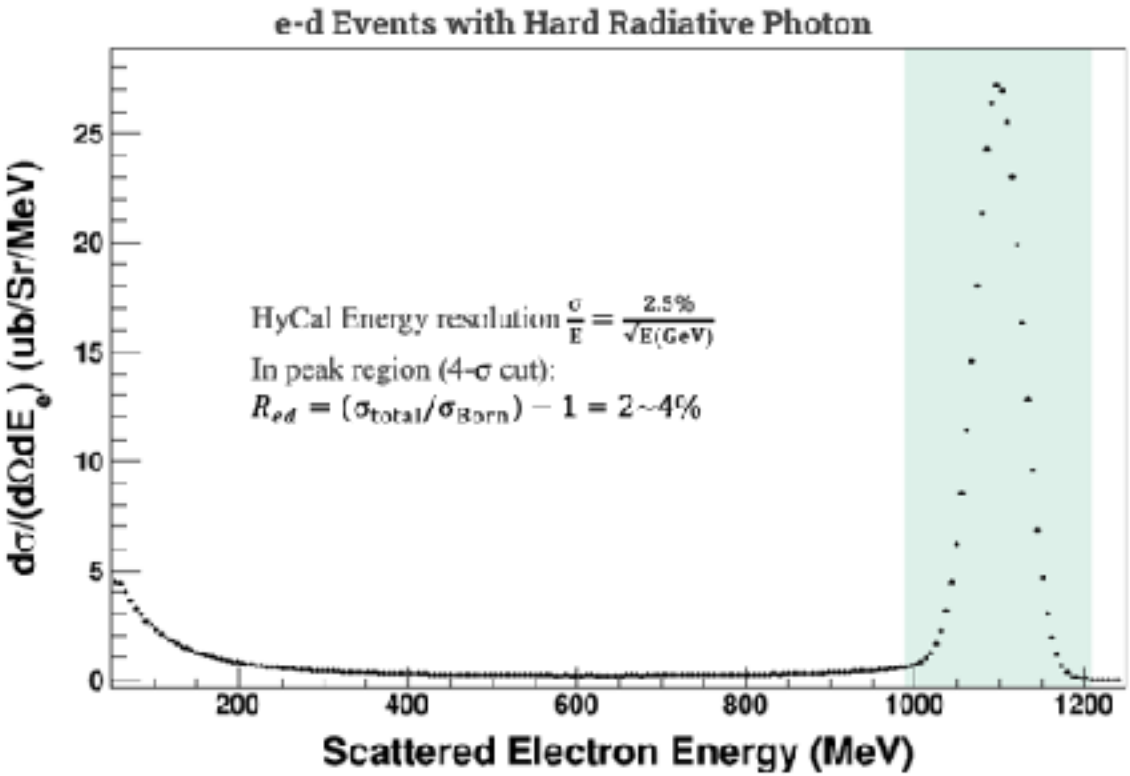
Issues: For *ed* scattering, radiative corrections are not known precisely and are even more difficult to calculate than for *ep* scattering. In addition, the PAC finds that the physics case outlined in the proposal is not compelling enough to anticipate the resolution of these issues. Nevertheless, valuable electron scattering data at low values of Q^2 would complement the presently scarce data set on the deuteron.

The PAC suggests to carefully address the issues on radiative corrections (where the proponents currently rely on external support, which is presently focused on new calculations for the *ep* case) and to readdress the issue of deuteron breakup reactions, using more sophisticated model descriptions.

Summary: The PAC welcomes the proposed precision measurement of elastic *ed* scattering down to very small values of Q^2 and the extraction of the deuteron charge radius complementary to atomic spectroscopy measurements. It also appreciates the further use of the innovative PRad II setup. However, the potential for interpretation for the measurement cannot be evaluated at this time, as this depends on radiative correction calculations that are not expected in the near future. Moreover, the projected precision is not high enough to have an impact on the present inconsistencies of the radius extraction using electronic and muonic deuterium. Therefore, the proposal is deferred.

New radiative correction calculations have been carried out (see next slide).

New radiative corrections calculations for e-D scattering have been completed



uncertainty:
1.1 GeV: 0.06%~0.09%
2.2 GeV: 0.10%~0.15%

- The complete elastic e-d NLO cross section including the lowest order radiative corrections beyond the ultrarelativistic limit has been calculated
- Based on the ansatz in the PRad RC calculation and used the Bardin-Shumeiko infrared divergence cancellation method *(I. Akushevich et al. Eur. Phys. J. A 51.1(2015), p. 1. DOI: 10.1140/epja/i2015-15001-8)*
- A generator is developed and the total correction to the elastic e-d Born cross section in the DRad kinematics is calculated
- The uncertainty of the NLO calculation is estimated, taking into account higher-order contributions, calculation assumptions, and differences between various recipes
- The paper is to be submitted to arXiv and European Physical Journal A

Slide courtesy of J. Zhou

Response to selected TAC questions

Summary

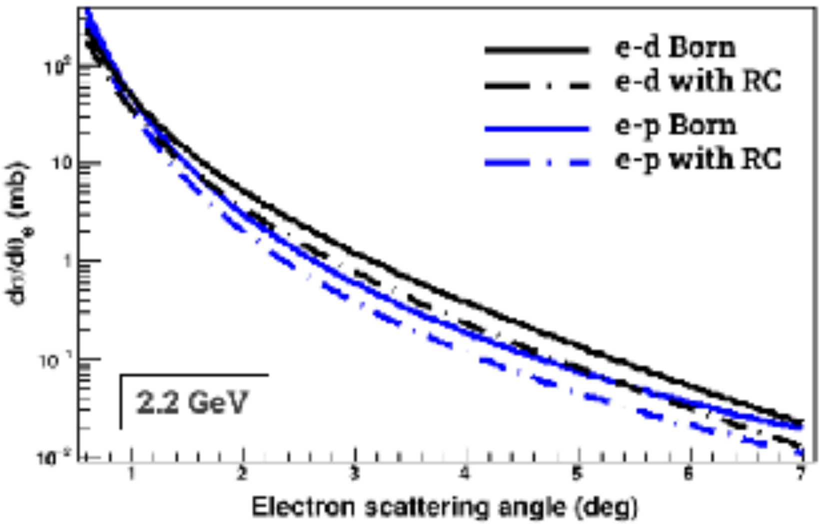
- **We propose a new high-precision measurement of the deuteron charge radius from e-D scattering.**
- **The proposed experiment is based on the magnetic-spectrometer-free calorimetric technique successfully demonstrated by the PRad experiment.**
  - ✓ **It will use the same setup proposed for the PRad-II experiment + a recoil detector.**
  - ✓ **Cylindrical Si-strip-based recoil detector.**
- **This will allow us:**
  - ✓ **to reach the lowest Q^2 ($\sim 2\times10^{-4}$ GeV^2) in e-D scattering experiment.**
  - ✓ **cover a large Q^2 range (2×10^{-4} - 5×10^{-2} GeV^2) in a single stationary experimental setup.**
  - ✓ **measure the deuteron charge radius with a precision of 0.21%**
- **Requesting a total of 40 PAC days of beam time at 1.1 and 2.2 GeV beam energy.**

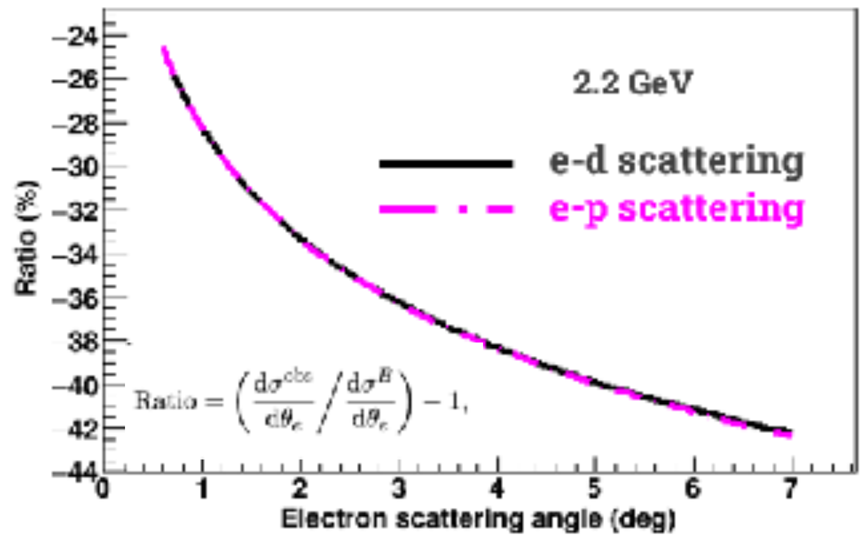
Acknowledgement: The PRad collaboration, specially students and post-docs.

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

Backup Slides

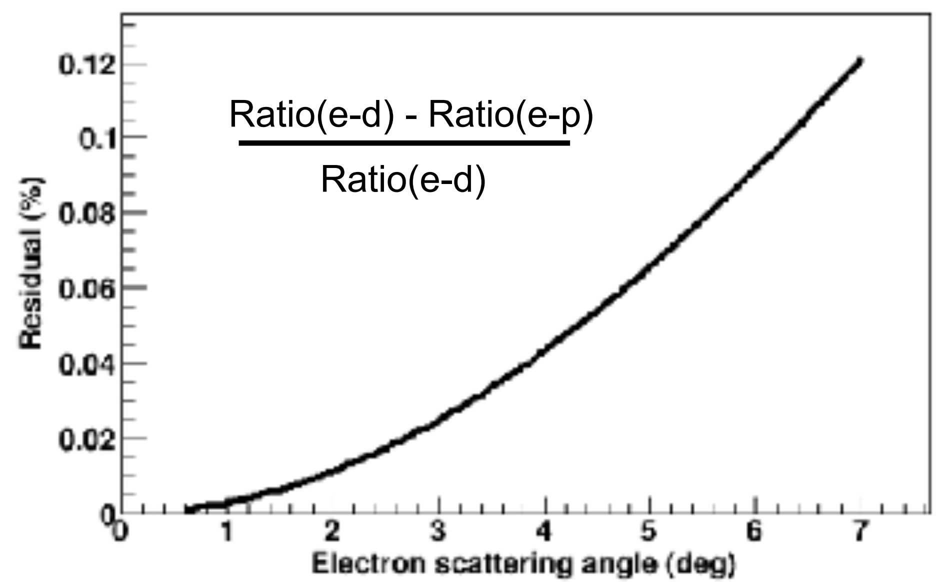
New radiative corrections calculations for e-D scattering have been completed





Lowest order radiative corrections to e-D scattering beyond the ultra-relativistic limit is complete (to be submitted soon)

J. Zhou, V. Khachatryan, H. Gao, A. Ilyichev, I. Akushevich, C. Peng, S. Srednyak and W. Xiong, "Lowest-order QED radiative corrections beyond the ultra-relativistic limit in unpolarized electron-deuteron elastic scattering for the proposed DRad experiment at Jefferson Laboratory", to be submitted to arXiv and European Physical Journal A



New radiative corrections calculations for e-D scattering have been completed

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

PR12-17-009

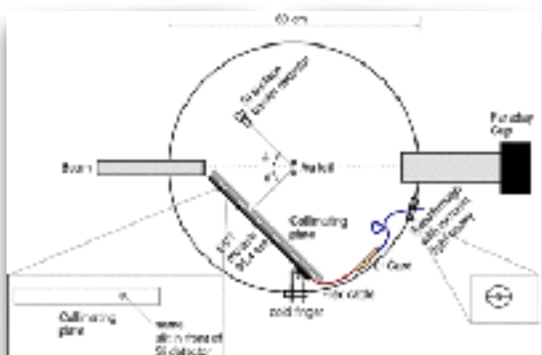
Scientific Rating: N/A

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

Ryoto IWAI[1], Mikio SAKURAI[1], Aldo ANTOGNINI[1,2], Ivana BELOSEVIC[1], Malte HILDEBRANDT[2], Klaus KIRCH[1,2], Andreas KNECHT[2], Angela PAPA[2,3] and Alexey STOYKOV[2]

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.

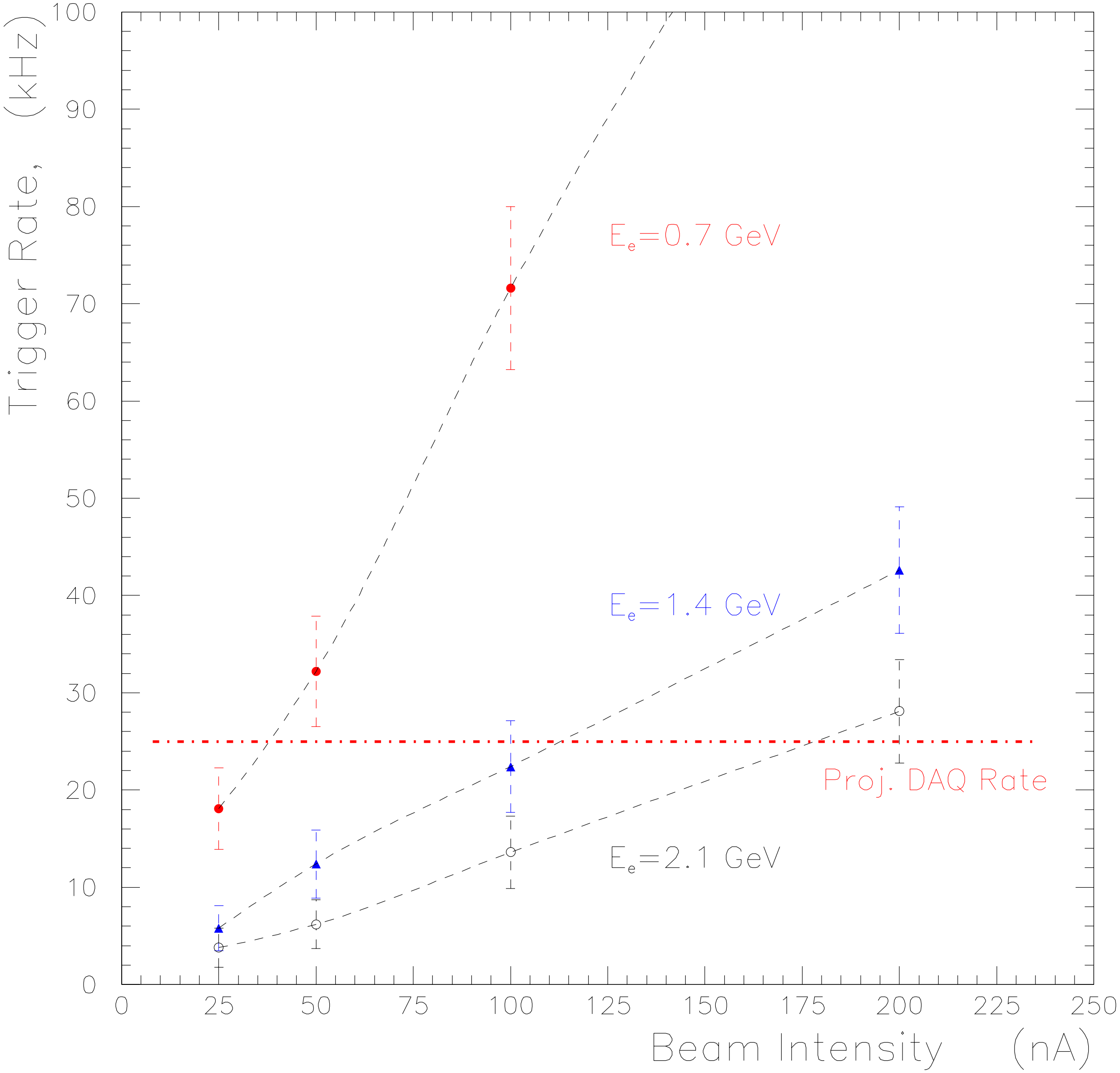
SILICON SENSOR OPTIONS

Window Type

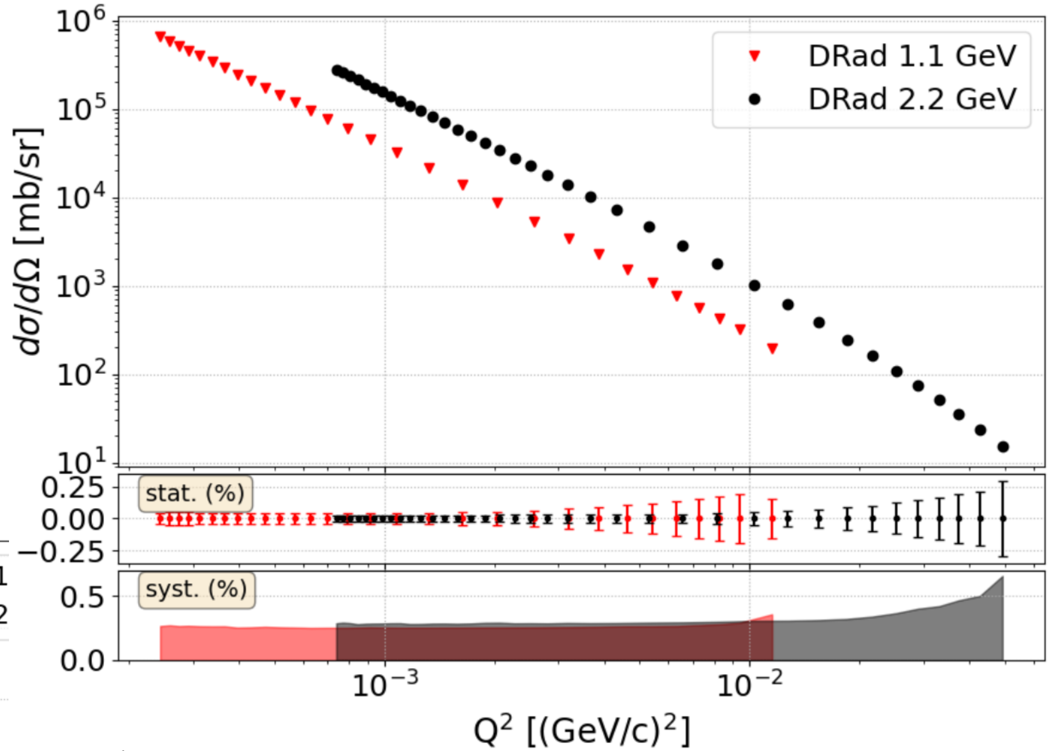
The range of dead layer windows available with the in-house Varian 300 XP ion implanter are listed below. Window types refer to the junction of a device, but can also be achieved on the ohmic side upon request.

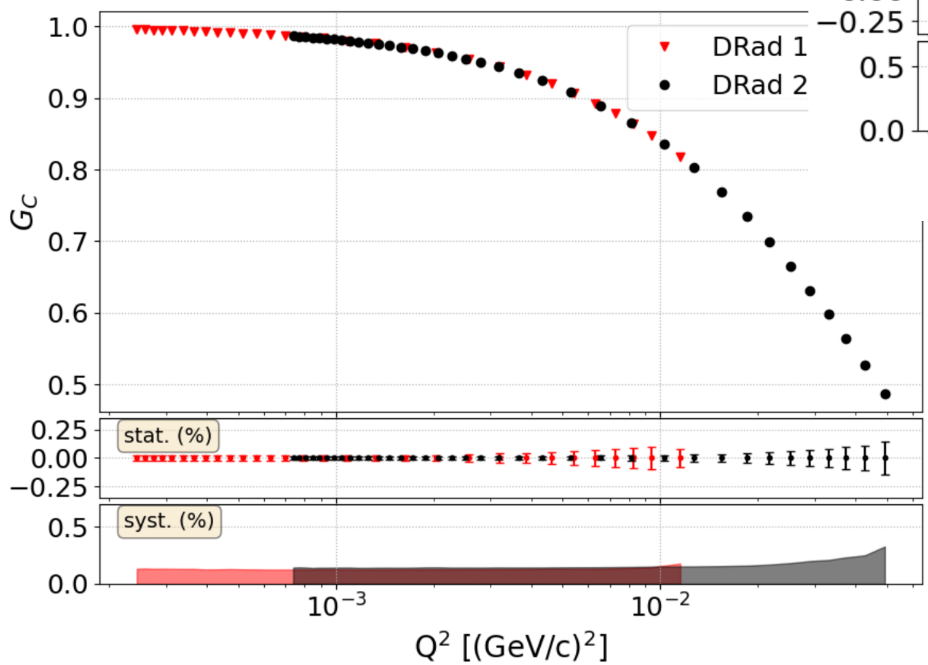
WINDOW TYPE	DEAD LAYER	MINIMUM ENERGY THRESHOLD	
		Electron	Proton
9	100 nm	1K eV	20 KeV

The projected trigger rates



The projected cross sections and form factor

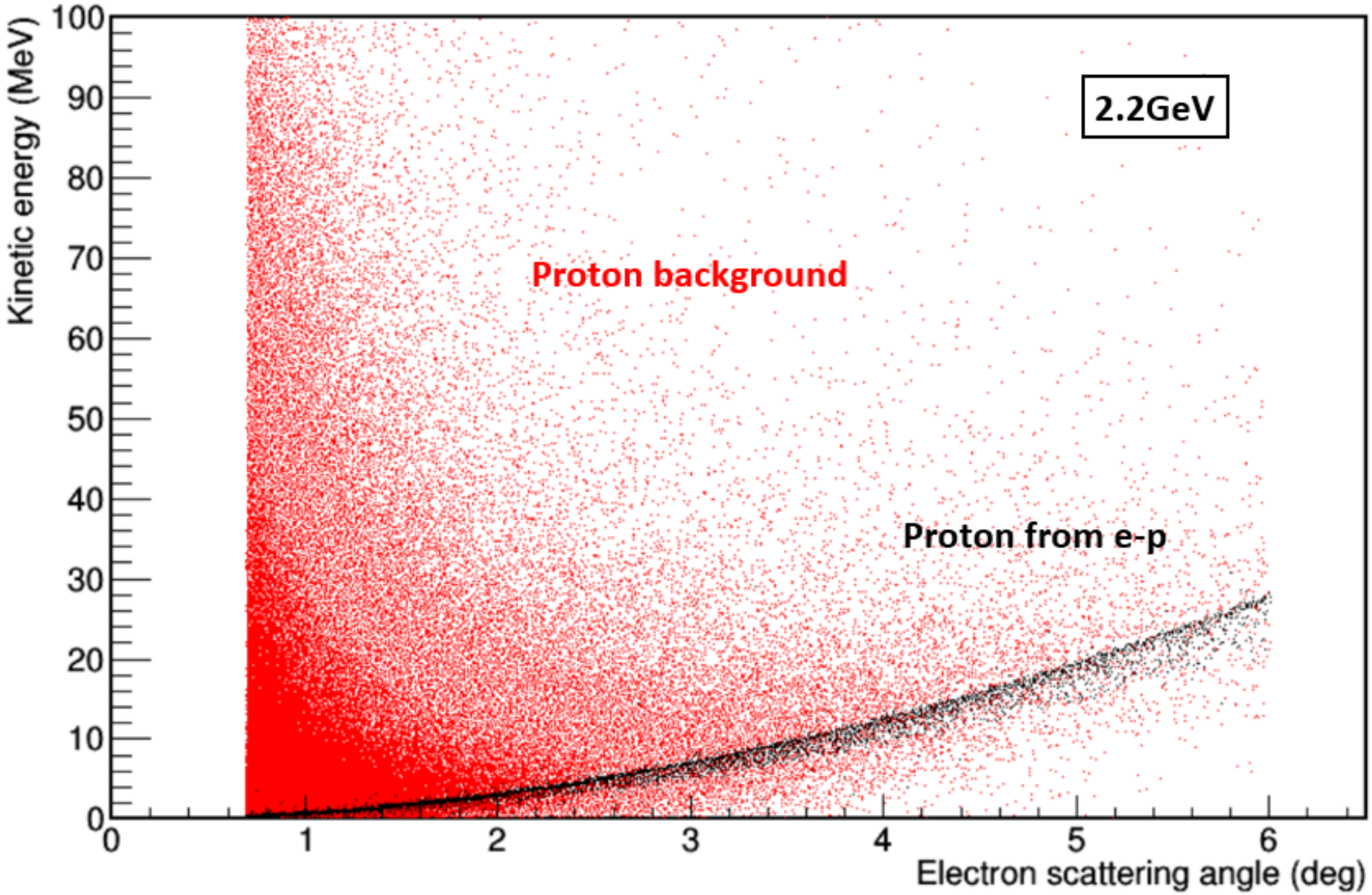




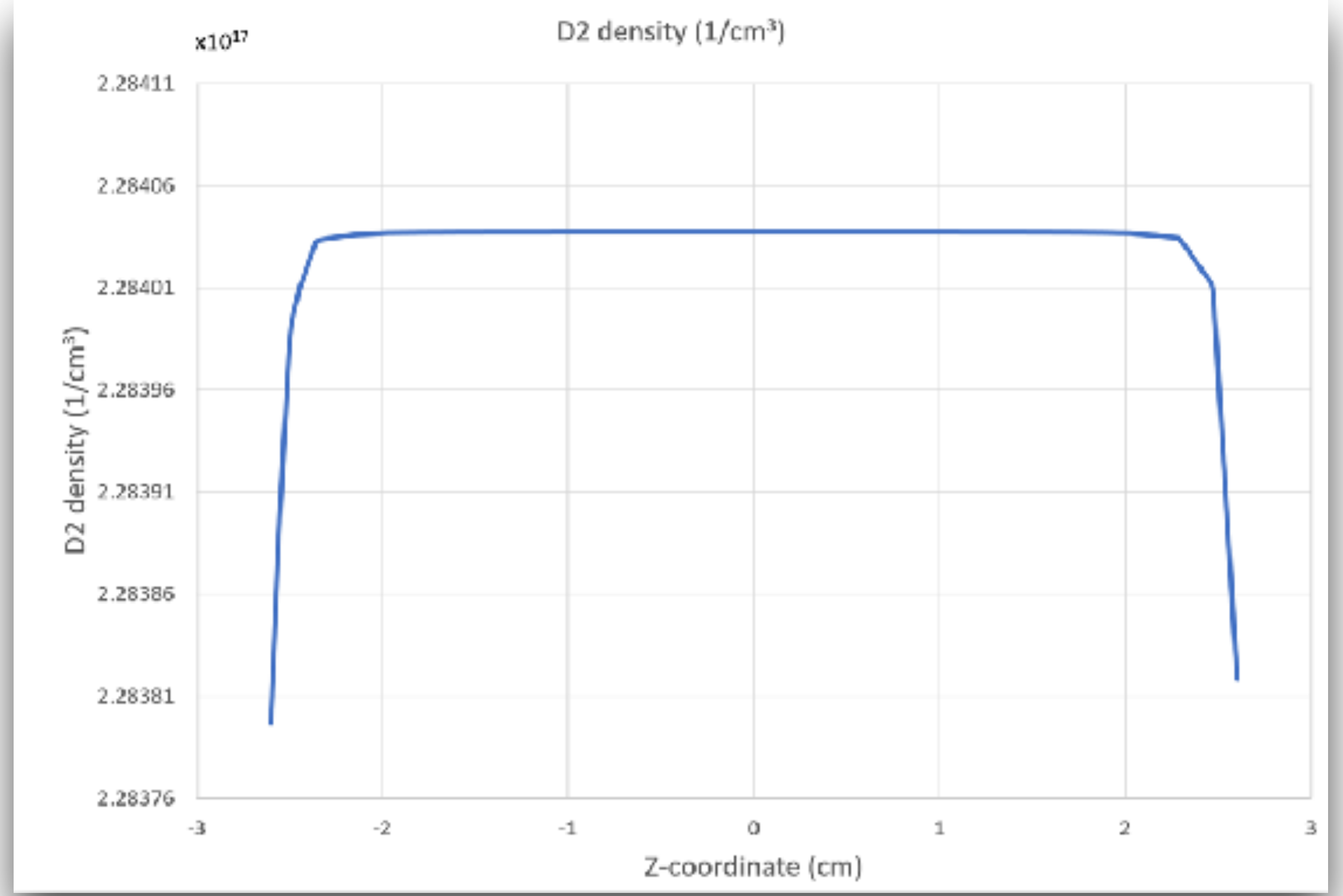
The projected uncertainty for cross section and form factor

Item	dσ/dΩ (%)	G_C (%)
Event Selection	0.06 ~ 0.34	0.03 ~ 0.17
Radiative correction	0.23 ~ 0.24	0.11 ~ 0.12
GEM efficiency	0.01 ~ 0.22	negligible ~ 0.11
HyCal response	negligible ~ 0.38	negligible ~ 0.19
Acceptance	0.03 ~ 0.04	0.01 ~ 0.02
Beam energy	0.06 ~ 0.23	0.03 ~ 0.11
Inelastic ed	negligible ~ 0.2	negligible ~ 0.1
Efficiency of recoil detector	0.13	0.06
Bias from the fitter	-	-
Total systematic	**0.25 ~ 0.65**	**0.13 ~ 0.33**
statistical	**0.02 ~ 0.29**	**0.01 ~ 0.14**
Total uncertainty	**0.25 ~ 0.72**	**0.13 ~ 0.36**

Simulated *ep* elastic and *eD* quasi-elastic scattering



Target gas profile along z



uncertainty of the acceptance of the Recoil Detector

Since the Recoil Detector is inside the target cell, the acceptance of it is very sensitive to the scattering vertex. The gas distribution will influence the scattering vertex. By varying the gas profile, we will study how the gas influence the cross section and the radius.

Gas profile: 5.5cm uniform+long tail(from PRad)

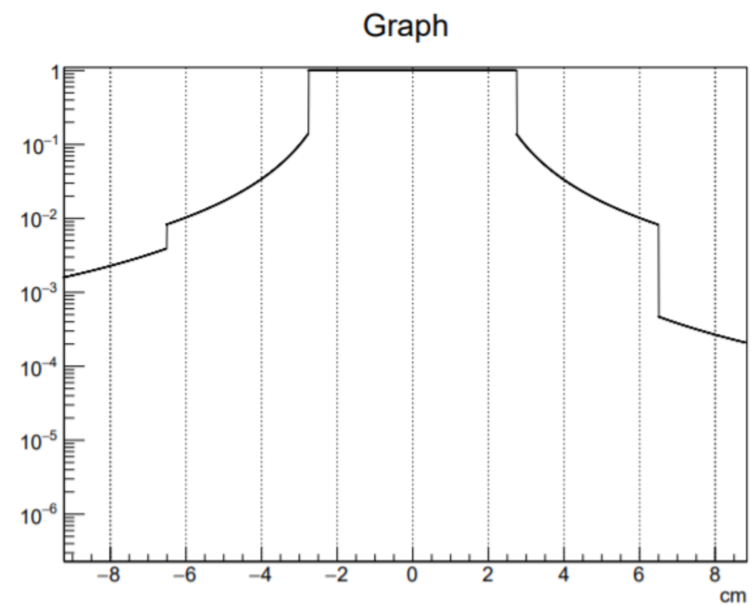
$$\frac{d\sigma}{d\Omega} \propto N_{yield} \qquad \frac{d\sigma/d\Omega|_{\text{uniform}}}{d\sigma/d\Omega|_{\text{tail}}} = \frac{N_{uniform}}{N_{tail}}$$

Relative uncertainty of cross section:

$$\Delta\sigma = \frac{\left|\frac{d\sigma}{d\Omega}_{uniform} - \frac{d\sigma}{d\Omega}_{tail}\right|}{\frac{d\sigma}{d\Omega}|_{\text{uniform}}} = \frac{|N_{tail} - N_{uniform}|}{N_{uniform}}$$

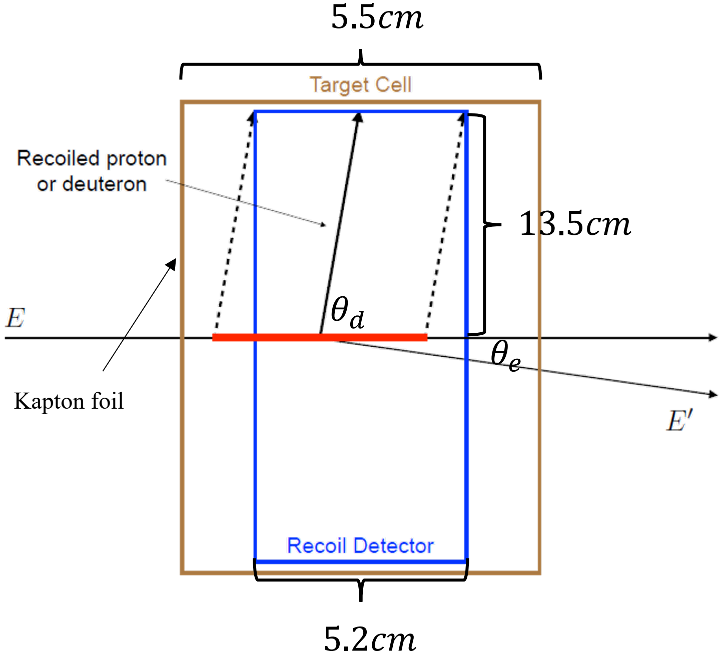
Relative uncertainty of the radius: $\Delta R = \frac{|R_{uniform} - R_{tail}|}{R_{uniform}}$

Gas profile from PRad



Optimization for the Recoil Detector acceptance

- Gas will leak through the 4mm diam aperture the windowless target
- The distribution of the gas in the cell will be influenced
- Uncertainty on the acceptance of the recoil detector is introduced



Design in the old proposal

Geometric acceptance of the Recoil Detector:

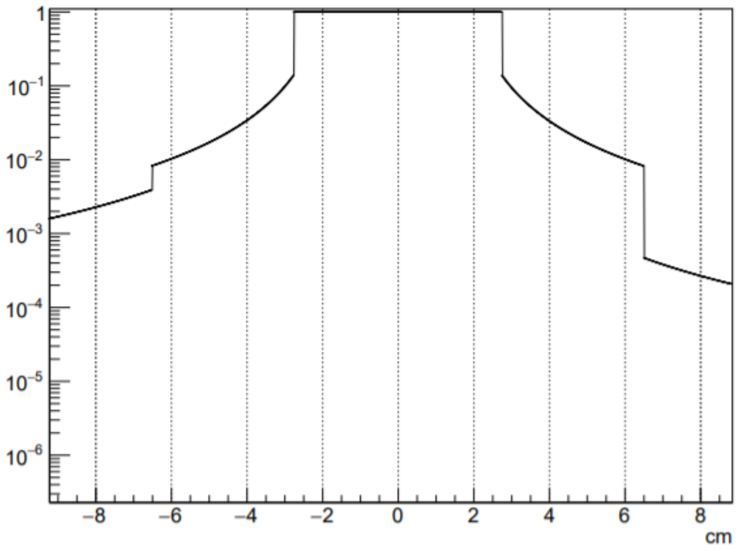
$$Z_{acc} = -3.72cm\ to\ 2.47cm(1{,}1GeV)$$
$$Z_{acc} = -4.14cm\ to 2.42cm(2.2GeV)$$

If the position of the aperture is in the geometric coverage of the recoil detector, the gas tail distribution will greatly influence the acceptance and introduce an uncertainty.

Dec 06, 2019 9

Optimization for the Recoil Detector acceptance

Gas profile: 5.5cm uniform+long tail(from PRad)



Relative uncertainty of the radius

$$\frac{\Delta R}{R} = \frac{|R_{uniform} - R_{tail}|}{R_{uniform}}$$

When the target cell is 5.5 cm(old desgin):

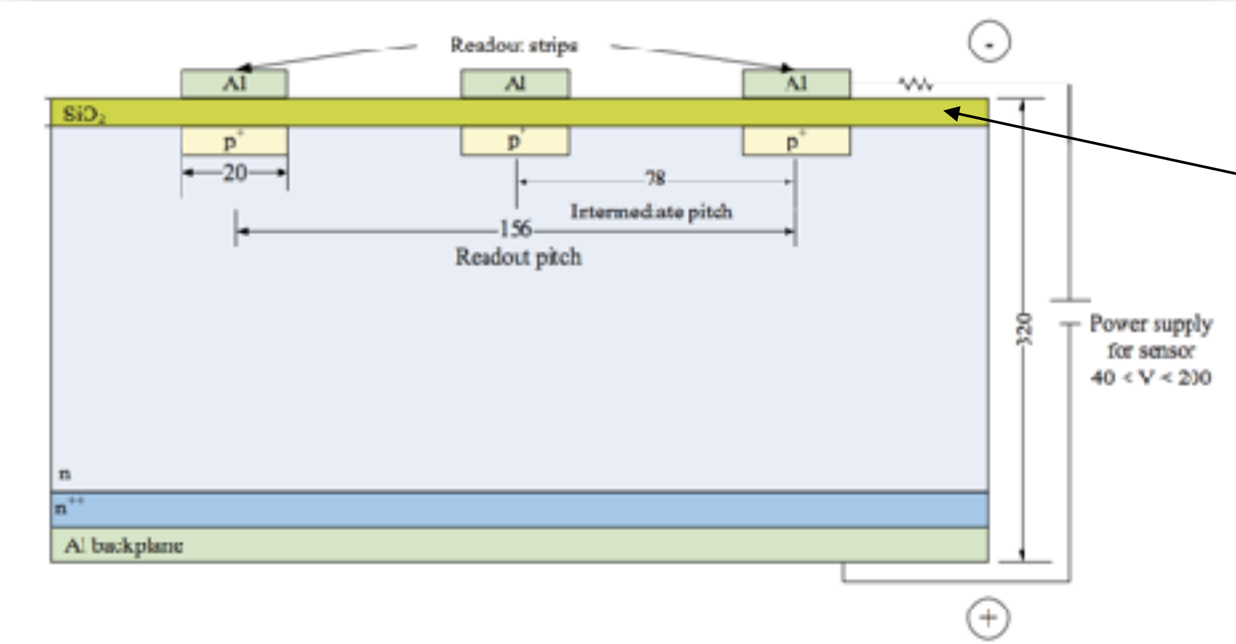
$$\frac{\Delta R}{R} = 0.19\%$$

When the target cell is extended to 8cm:

$$\frac{\Delta R}{R} = 0.02\%$$

- Once the tail of the gas is out of the geometric coverage of the Recoil Detector, the influence from tail of the gas is small.

SVT design and performance from CLAS12 data



thin SiO_2 passivation layer
(~0.1 micron)

Full depletion voltage	40 < V < 100 (25°C at <45% RH)
Total leakage current (at full depletion voltage)	< 1 nA/cm²
Interstrip capacitance	< 1.2 pf/cm
Strip to back side capacitance	< 0.2 pF/cm
Interstrip isolation (at 150 V)	> 1 GΩ
Resistance of Al electrode on strips	< 20 Ω/cm on strip
Dielectric of coupling capacitor	multiple thin layers of SiO_2 and Si_3N_4
Coupling capacitance	> 10 pf/cm
Break down voltage of capacitor	> 300 V
Total (strip) capacitance	($C_{tot} = C_{int} + C_{back}$ at 1 MHz) ≤ 1.3 pf/cm
Value of poly-silicon bias resistor	1.5 MΩ ± 0.5 MΩ
Single strip DC current	< 3 nA

SVT design and performance from CLAS12 data

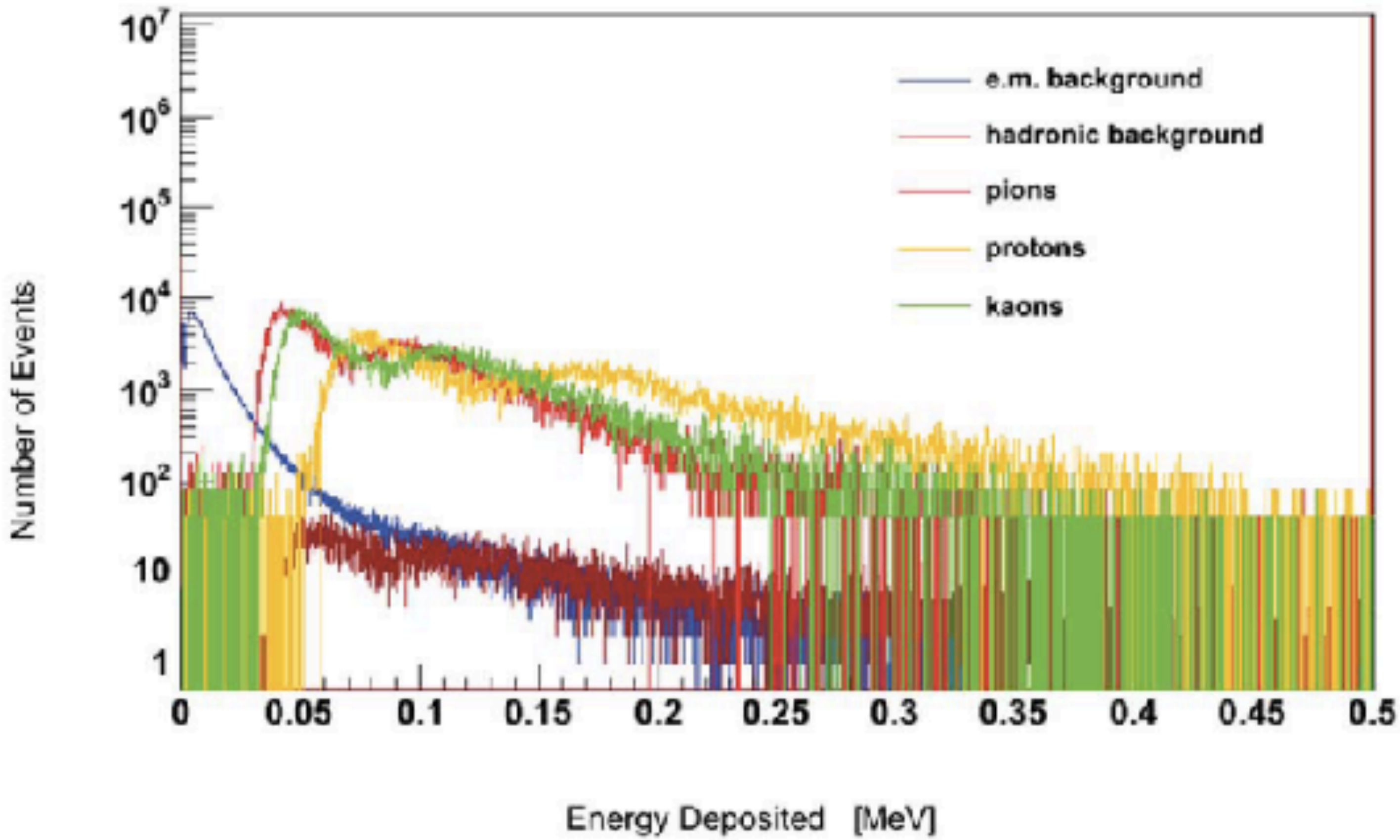


FIG. 3.2.4. The energy deposited for pion, proton, and kaon tracks, plus electromagnetic and hadronic backgrounds; signal $800 < p < 1000$ MeV.

M.A. Antonioli *et al.*, "The CLAS12 Silicon Vertex Tracker", Nucl. Inst. and Meth. A 962, 163701

SVT design and performance from CLAS12 data

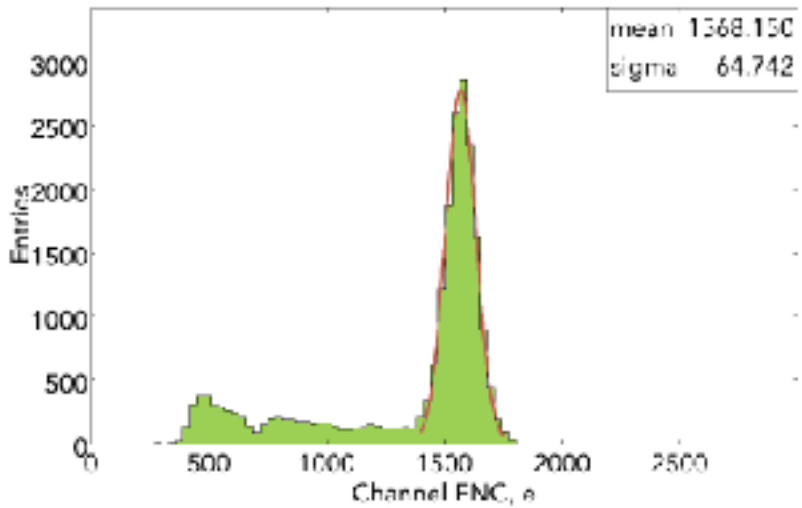


Figure 79: SVT ENC for all channels. The main peak corresponds to the full length strips (33 cm). The shoulder on the left side is related to the shorter strips.

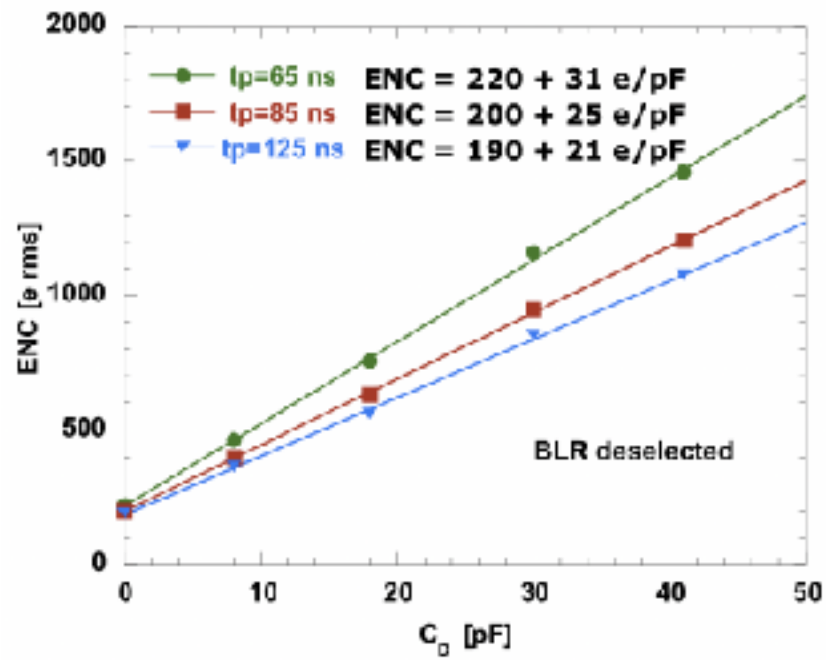


Figure 59: FSSR2 ENC vs. detector capacitance at different shaping time settings.

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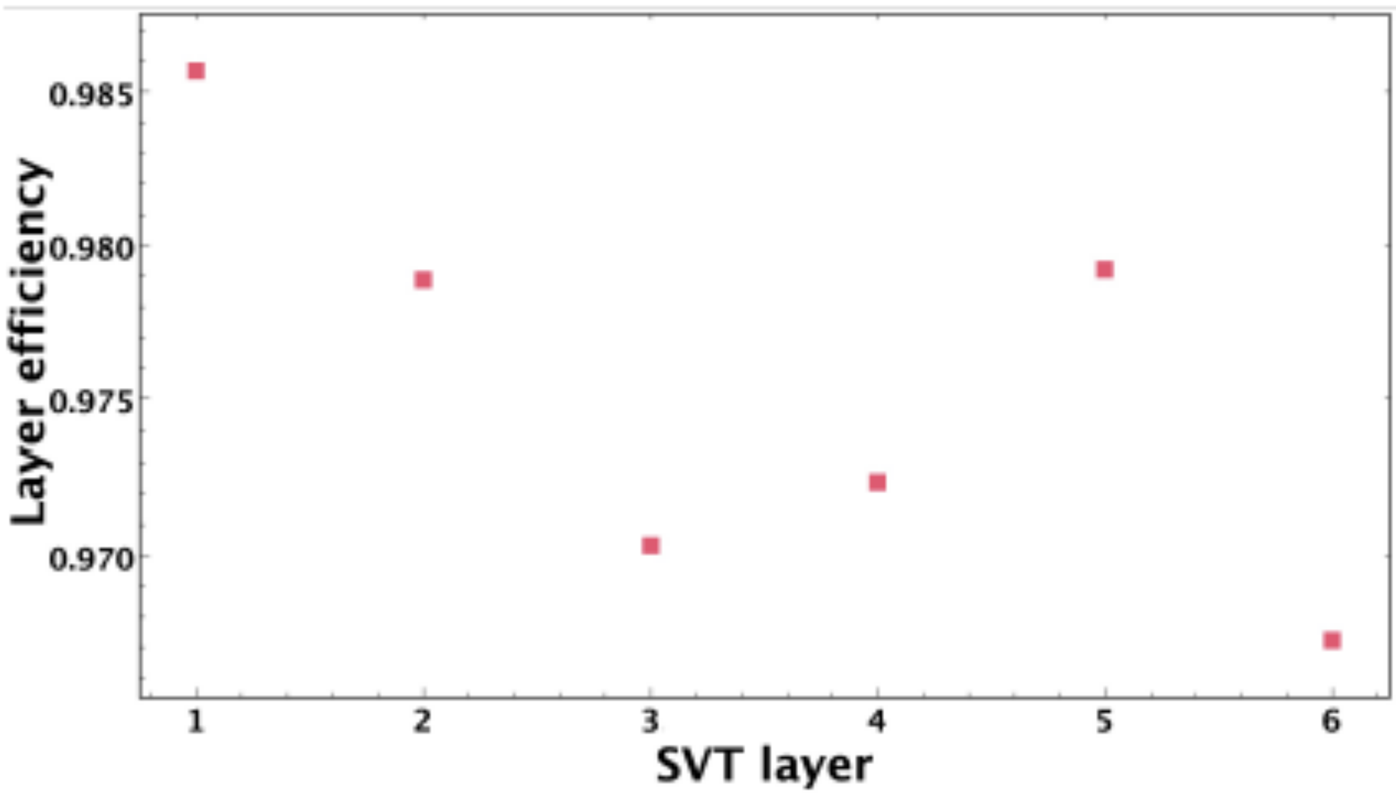
SVT design and performance from CLAS12 data



M.A. Antonioli *et al.*, "The CLAS12 Silicon Vertex Tracker", Nucl. Inst. and Meth. A 962, 163701

SVT design and performance from CLAS12 data

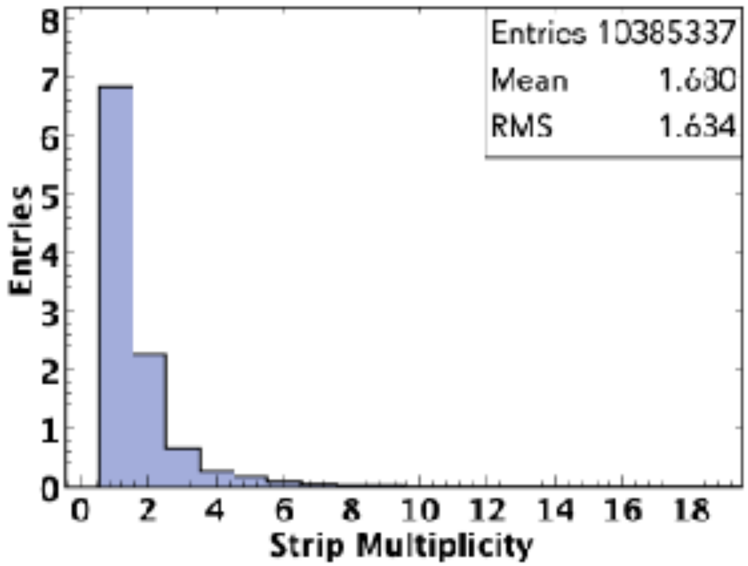


Figure 91: Strip multiplicity of the clusters in the cosmic run. The mean cluster size is in agreement with the simulated data.

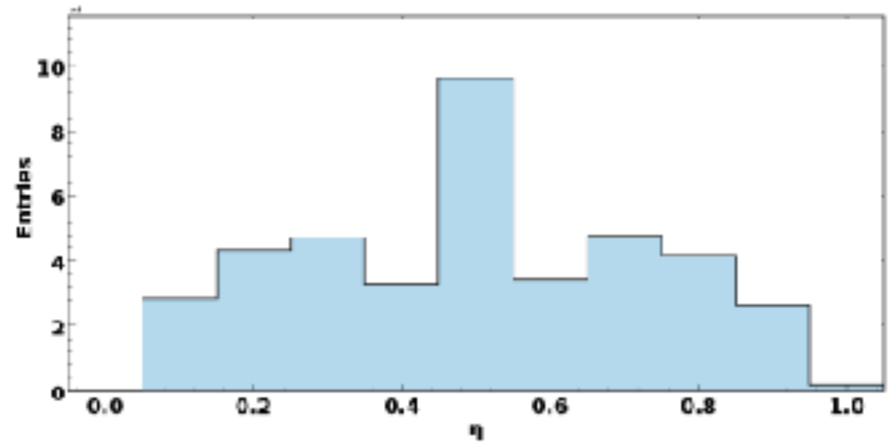


Figure 90: Charge sharing in the SVT sensor: η-function for the two-strip clusters.

The charge sharing among two adjacent strips was studied using the η-function (also referred as response function), defined for the 2-strip clusters as the ratio of the pulse height of the left strip to the pulse height of the cluster, independently of which strip has the higher charge (seed strip). Figure 90 shows the η-function obtained from the measurement of on-track clusters from the cosmic muons. The distribution was obtained without applying cuts on the selected tracks. The granular-

M.A. Antonioli *et al.*, "The CLAS12 Silicon Vertex Tracker", Nucl. Inst. and Meth. A 962, 163701

Expected timing resolution with HyCal using JLab FADCs

Results from tests of Hall-D FCAL (lead-glass calorimeter) using JLab 250 MHz FADCs

NIMA 726, 60 (2013)

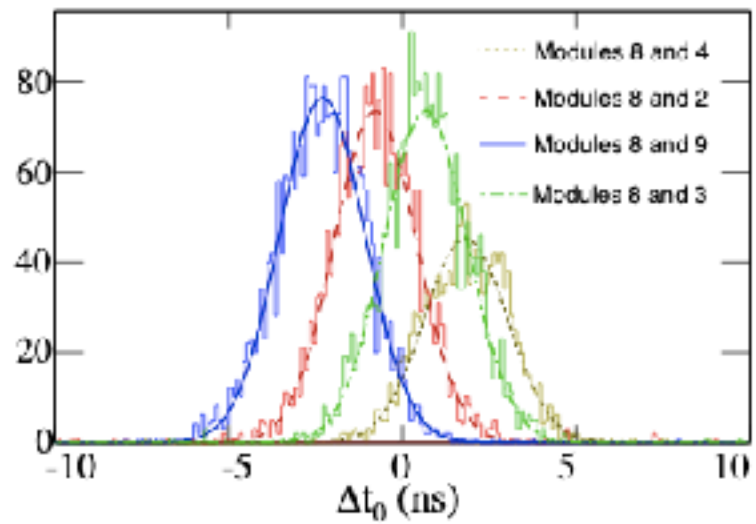


Figure 9: Distribution of $\Delta t_{0,ij}$ for a single module and four of its adjacent modules when all modules had $1000 < S_p < 2000$ ADC counts, together with Gaussian fit curves.

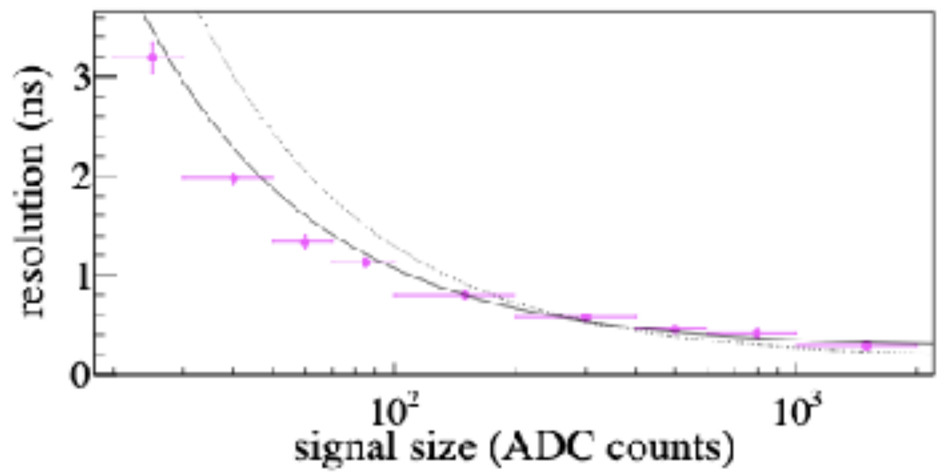


Figure 11: Final timing resolution for one module. The solid

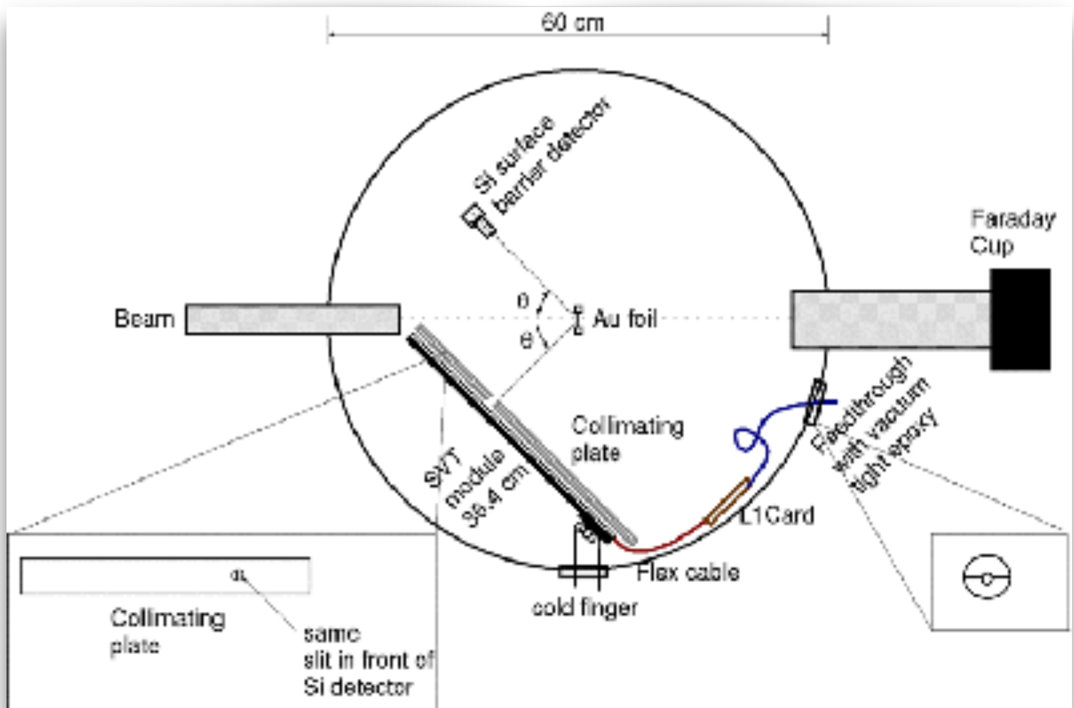
Conclusion: **timing resolution of 0.4 ns or better achievable for a single module with signal larger than 100 mV.**

Detector efficiency and calibration of recoil detector

The ratio of the geometric acceptances $\left(\varepsilon_{\mathrm{geom}}^{e^-e^-}/\varepsilon_{\mathrm{geom}}^{ed}\right)$ and the detection efficiencies $\left(\varepsilon_{\mathrm{det}}^{e^-e^-}/\varepsilon_{\mathrm{det}}^{ed}\right)$

Obtained from ***ep*** scattering runs by comparing the cross section from electrons only to cross sections from protons only & PRad data. This will give us proton detection efficiencies.

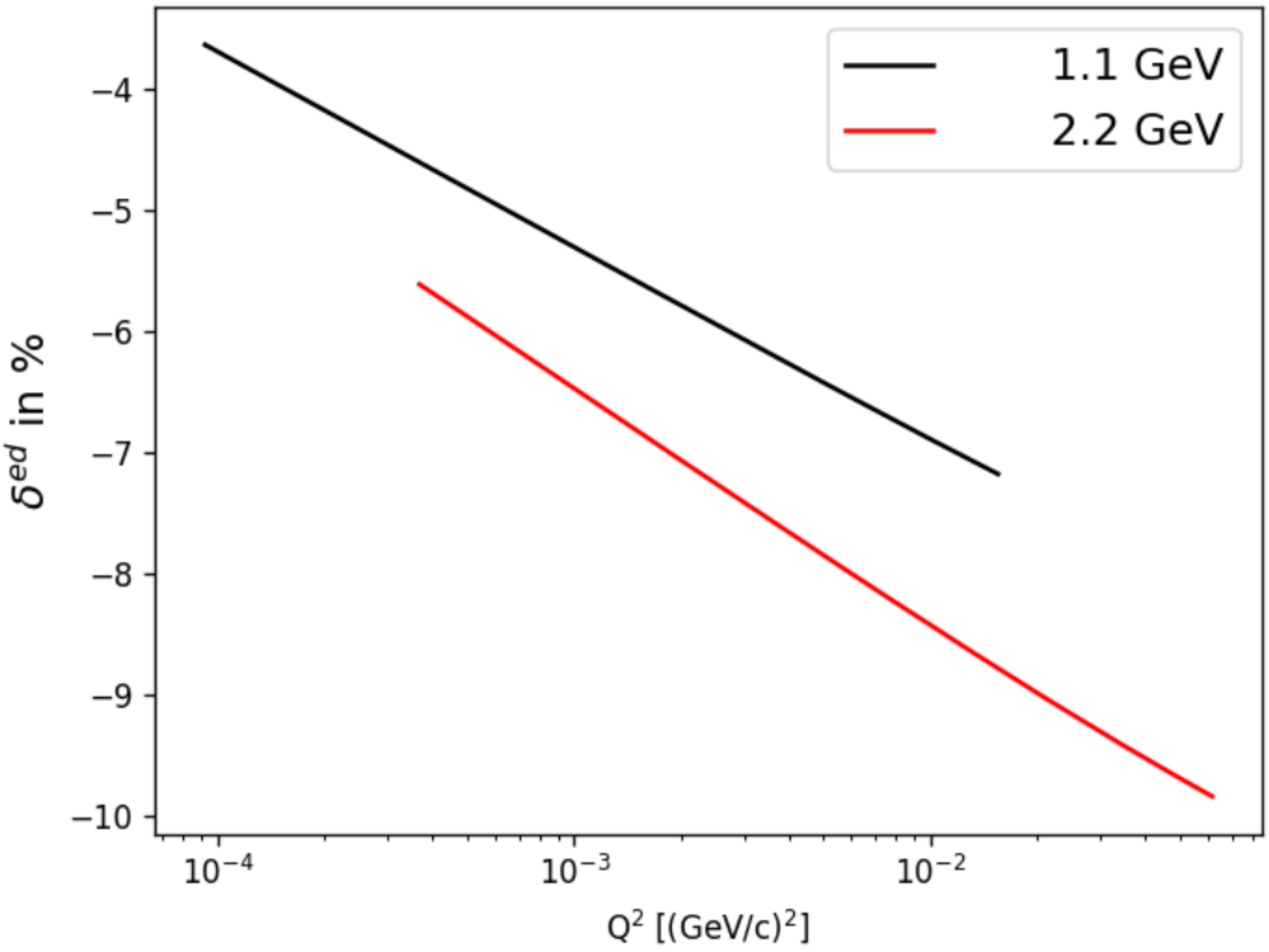
The deuteron detection efficiencies will be obtained from the ratio of deuteron to proton detection efficiencies measured at TUNL using the 5-15 MeV p/D beams from the Tandem accelerator.



Preparations for validation of this procedure is currently underway at TUNL (Duke University).

e-D radiative corrections

virtual-photon correction and the Bremsstrahlung correction in the soft-photon approximation.



The fixed rational (1,3) function used for robust fits.

$$f_{\text{Fixed\_Rational}\,(1,3)}(Q^2) = \text{Fixed Rational}\,(1,3) = p_0 \frac{1 + a_1 Q^2}{1 + b_1 Q^2 + (0.0416 \pm 0.0152) Q^4 + (0.00474 \pm 0.000892) Q^6},$$

$$R_D = \sqrt{6*(b_1 - a_1)}$$

Estimation of systematic uncertainties

A Monte-Carlo technique is used to evaluate the effects of these systematic uncertainties on the radius result. First of all, 10,000 data sets are generated based on the projected DRad cross section results. Then the data points are smeared by the systematic uncertainty sources at once, and a set of G_C^d data points is extracted from each set of the smeared cross section data. Then the extracted G_C^d data sets are fitted separately and a R_d value is extracted from each of these data sets. Lastly, the RMSE value (Eq. 29) of these extracted R_d values was assigned as the systematic uncertainty, where the bias in this calculation is the difference between the mean value R_{sys} obtained from these extracted radius results, and the mean value $R_{central}$ obtained from the extracted radius results including only statistical uncertainties. The relative systematic uncertainty on the radius is $|R_{sys} - R_{central}\ /R_{central}$.

A.Generator There are two generators for DRad for generating G_C values at given Q^2. They are two parameterizations based on the available experimental data. **Abbott1 and Abbott2**

To mimic the bin-by-bin statistical fluctuation of the data, the G_C pseudo-data statistical uncertainty is smeared by adding the G_C in each Q^2 bin with a random number following the Gaussian distribution,