PR12-23-011

Precision Deuteron Charge Radius Measurement with Elastic Electron-Deuteron Scattering

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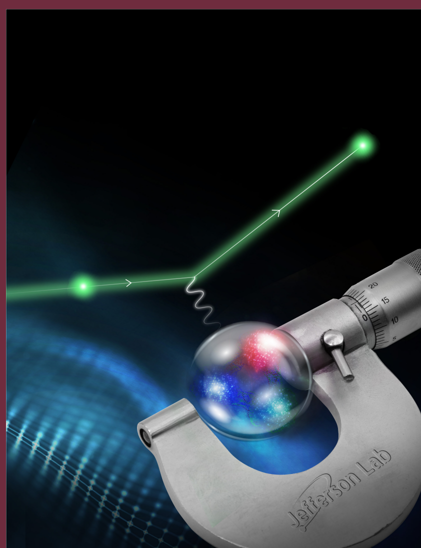
for the PRad Collaboration

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



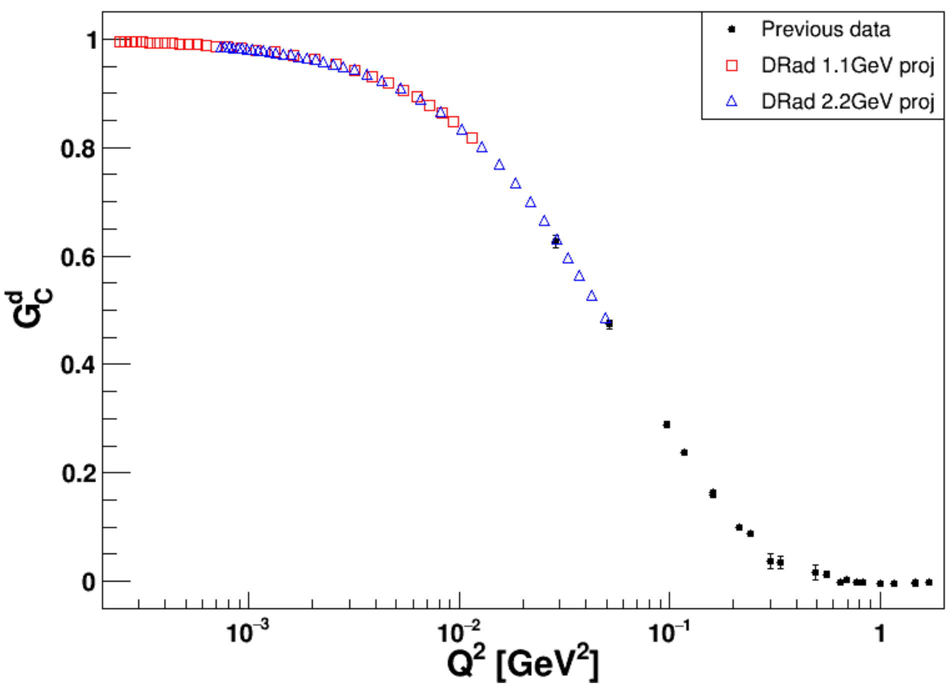
PAC 51 Meeting, July 25, 2023

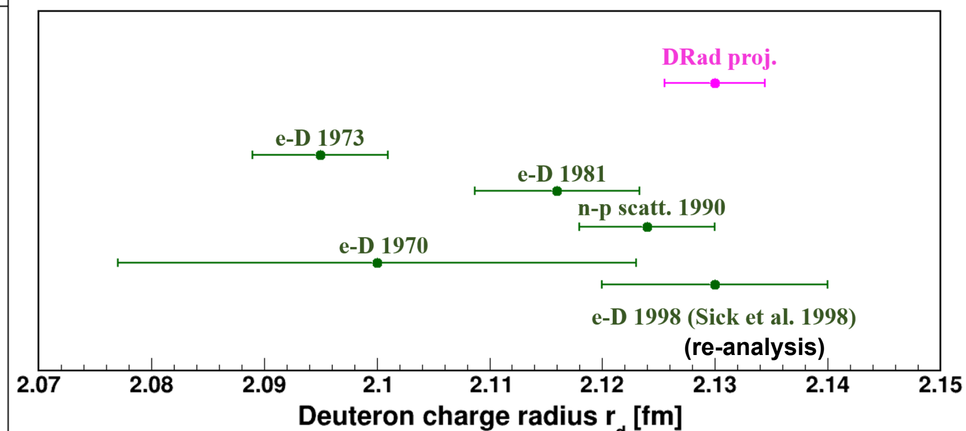
Executive Summary

Using the well-demonstrated PRad method, we will measure the e-D scattering cross-section with high precision at very small angles covering the Q^2 range of 2×10^{-4} to 5×10^{-2} GeV^2 (the lowest Q^2 reached in e-D experiments).

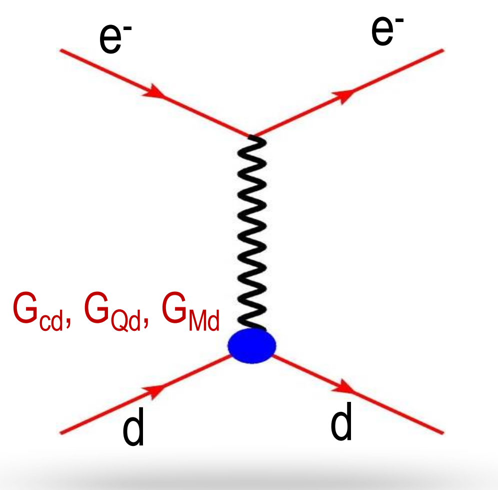
This will allow us to extract the charge form factor with a precision of 0.1-0.4% and the deuteron charge radius with a precision of 0.2%

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





We will measure the charge form factor in eD elastic scattering using the PRad technique, covering the low Q^2 region



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:

$$A(Q^2) = G_{Cd}^2(Q^2) + \frac{2}{3}\eta G_{Md}^2(Q^2) + \frac{8}{9}\eta^2 G_{Qd}^2(Q^2)$$

$$B(Q^2) = \frac{4}{3}\eta(1+\eta)G_{Md}^2(Q^2),$$

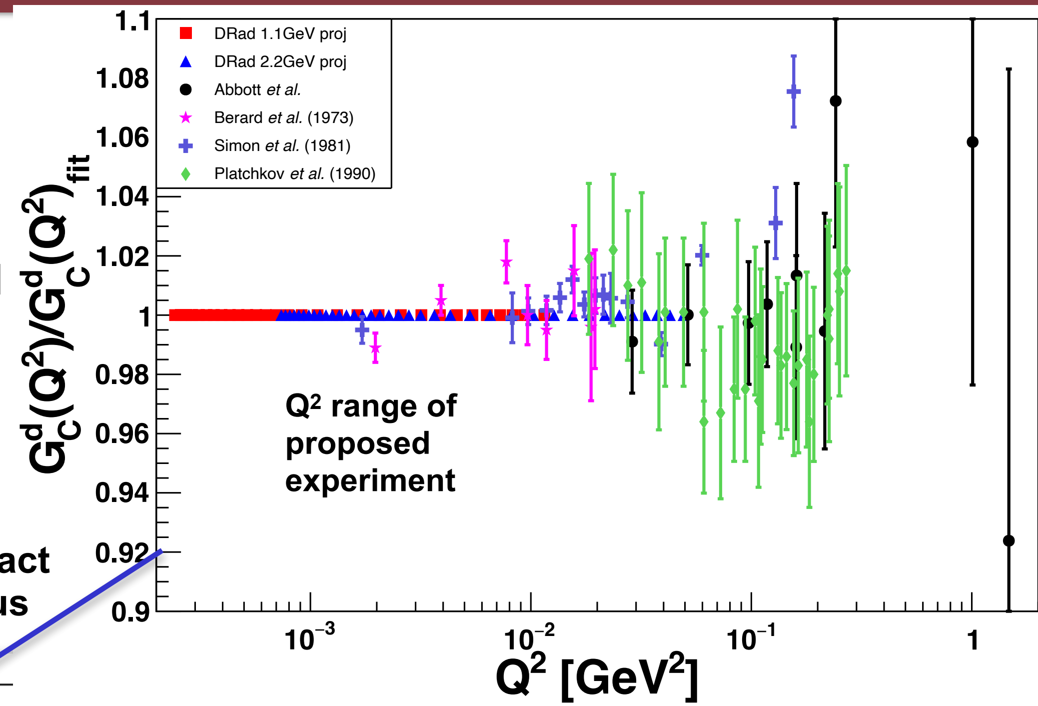
$$\eta = Q^2/4m_d^2$$

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

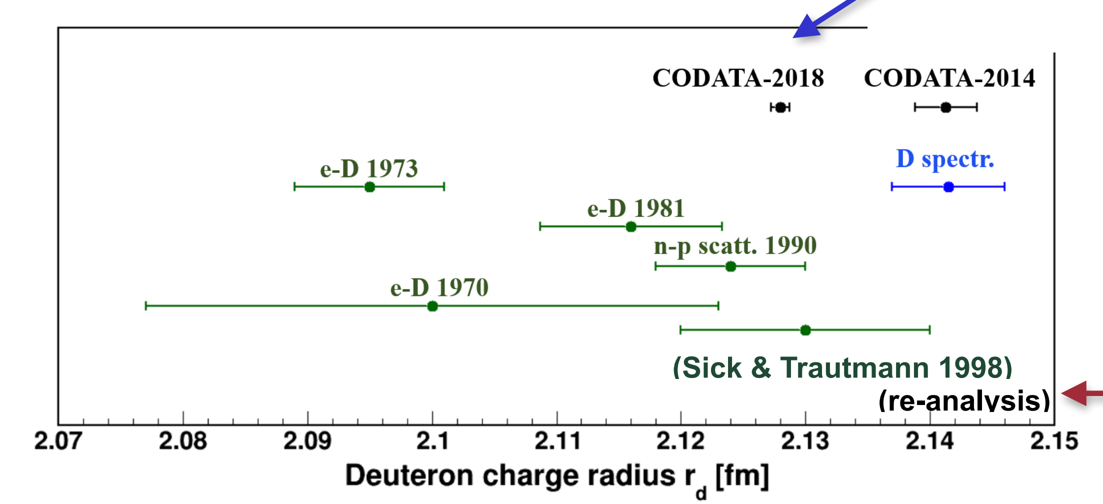
$$r_d^2 = -6\frac{dG_C}{dQ^2}\Big|_{Q^2\to 0} = -3\frac{dA}{dQ^2}\Big|_{Q^2\to 0} + \frac{G_M^2(0)}{2M_d^2}, \quad \text{with} \quad G_M(0) = \frac{M_d}{M}\mu_d, \; \frac{G_M^2(0)}{2M_d^2} \approx 0.0163\ \text{fm}^2.$$

There is a urgent need for high precision *e-D* scattering cross section and charge form factor data

- existing data from old methods
- large uncertainty
- all used magnetic spectrometer method
- normalized *eD* to *ep* cross section
- large bgd. from target windows



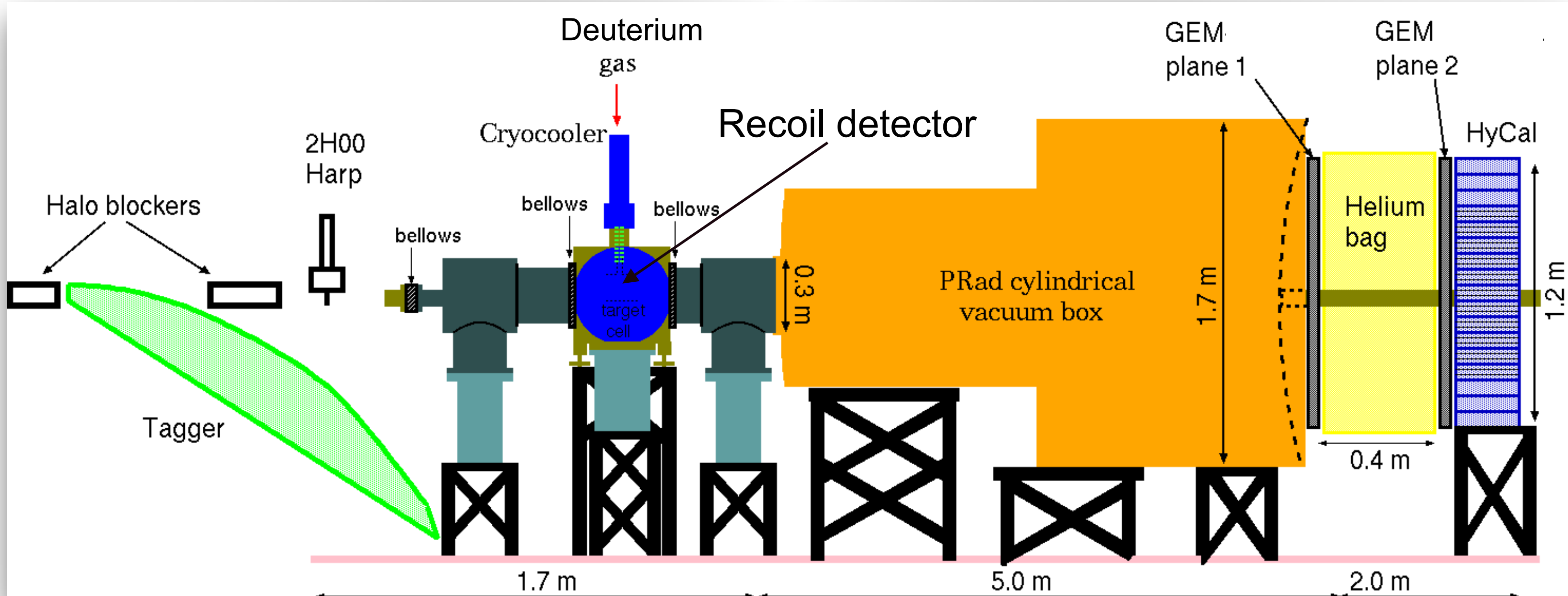
used to extract charge radius



Most recent extraction of charge radius is a reanalysis of old data.

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

DRad: a novel electron scattering experiment

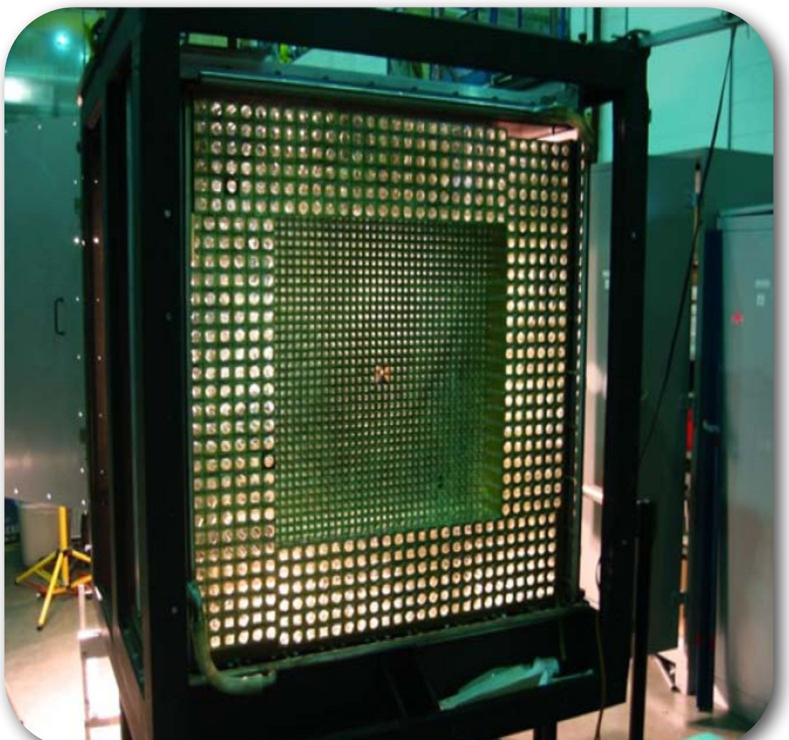


Will use the PRad-II setup with 1.1 GeV and 2.2 GeV electron beam

- **High resolution $PbWO_4$ 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 *$2x10^{-4}$ – $5x10^{-2}$ GeV^2* (lower than all previous electron scattering expts.)**
- **Add a cylindrical recoil detector for ensuring elasticity of reaction.**
- **Precise extraction of the charge form factor and charge radius r_D**

The DRad experiment will use a magnetic spectrometer free method to measure the cross section at low Q^2

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



HyCal: Convert to FADC based readout

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

- **$PbWO_4$ 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**

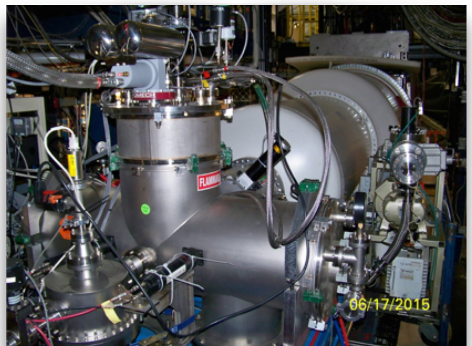
Position resolution improved to 72 μm with two planes of GEM based coordinate detectors

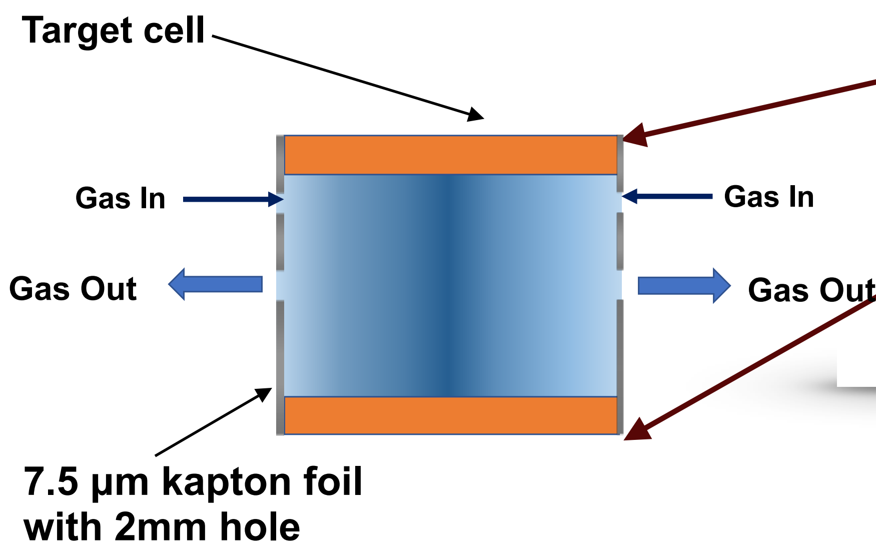
The DRad experiment will use the PRad windowless target with a redesigned target cell.

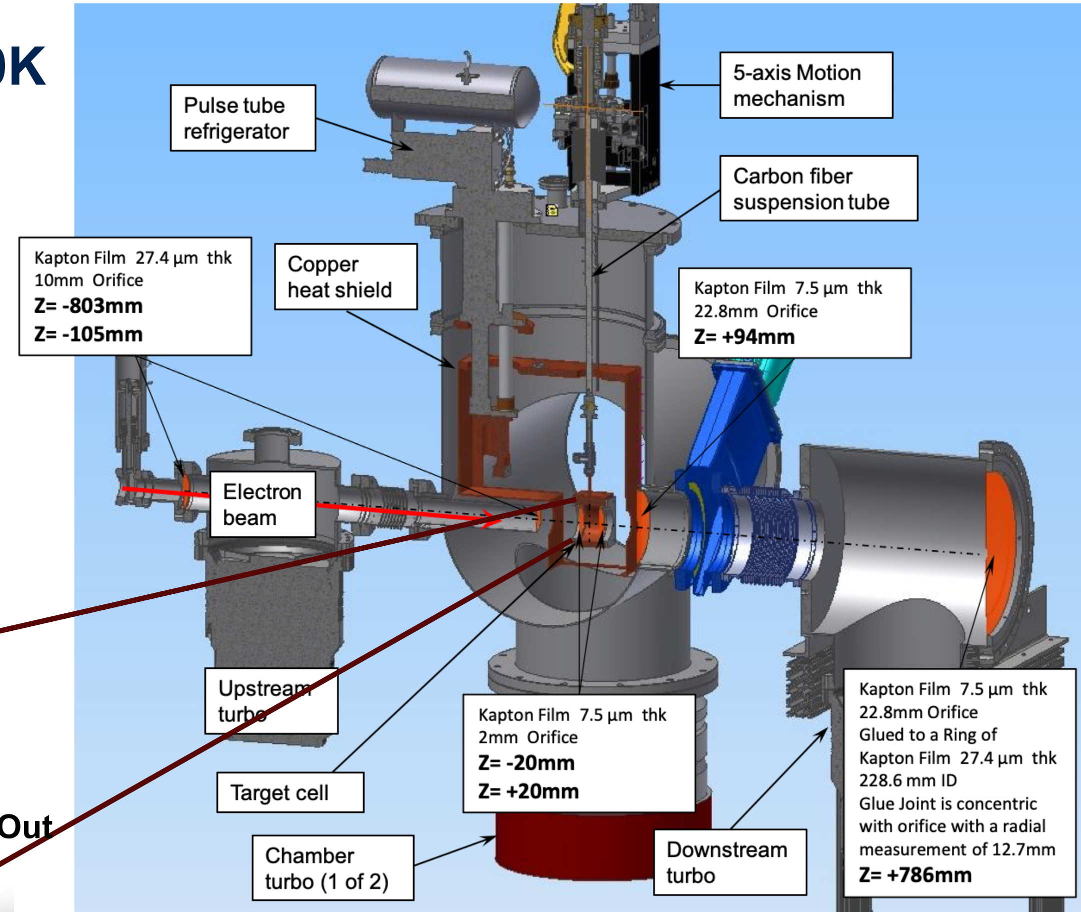
A cryo-cooled windowless gas flow target.

density:

~1×10^{18} atoms/cm^2 cooled to 40K





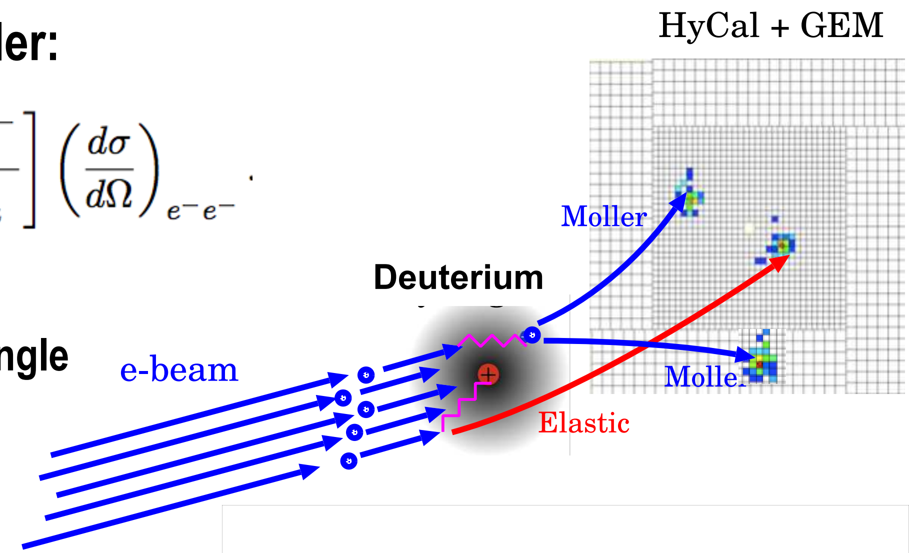


Empty target runs to be used for background subtraction

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

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

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

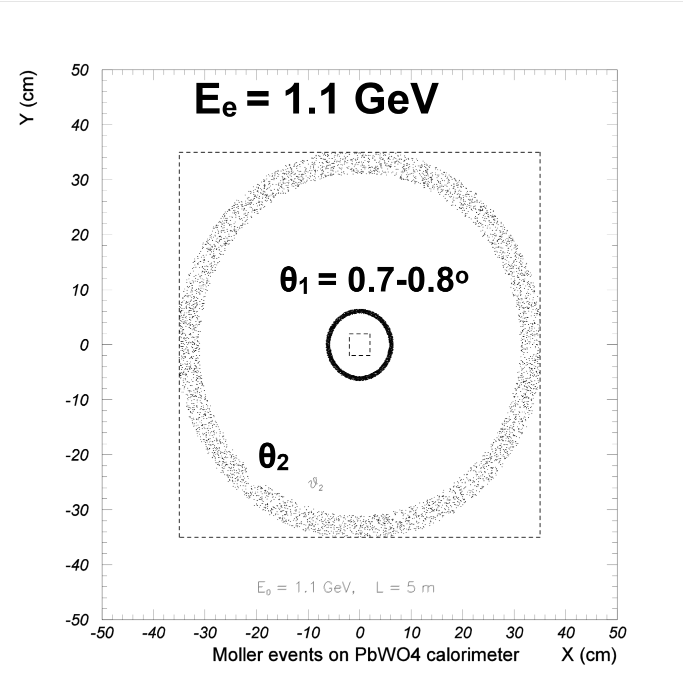


Møller events will be detected in two-electron and/or single electron modes within the HyCal acceptance.

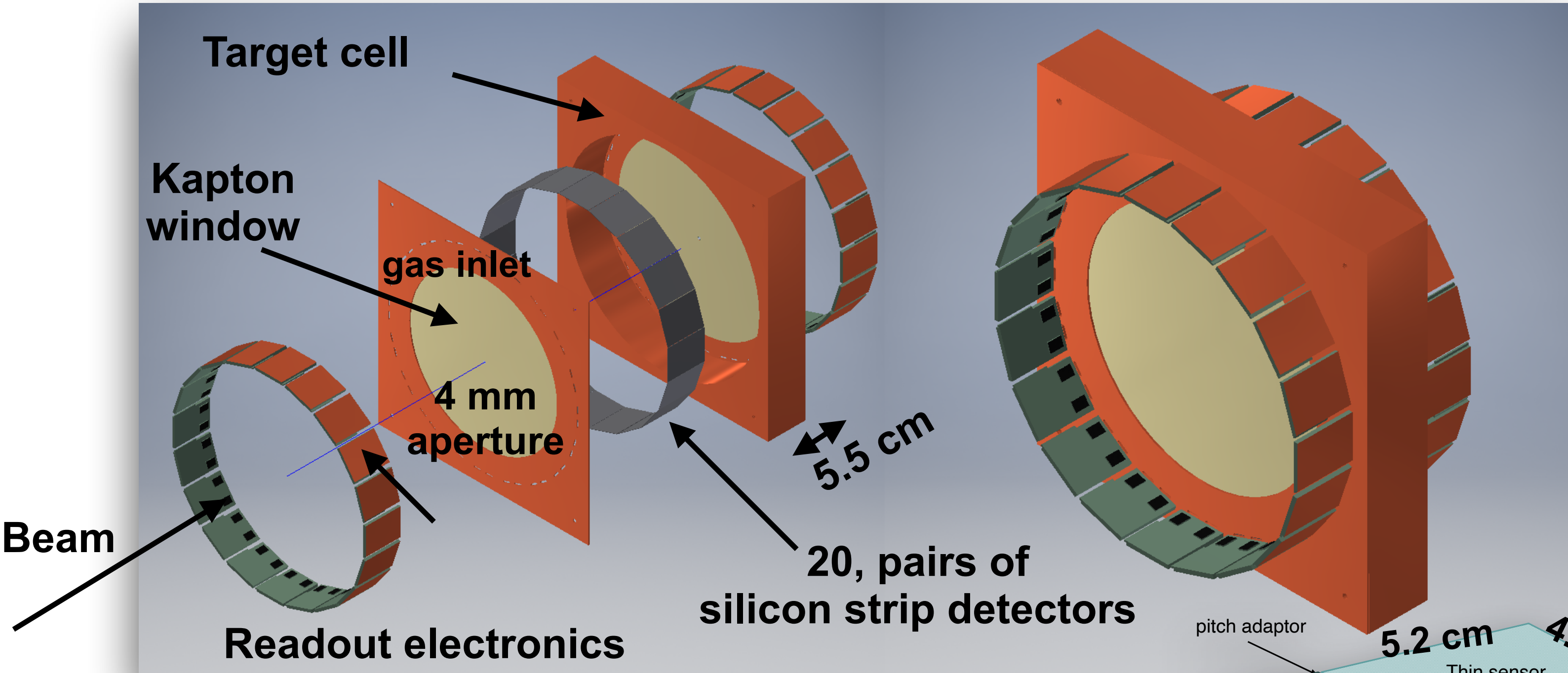
Two major sources of systematic errors, N_e and N_{tgt}, cancel.

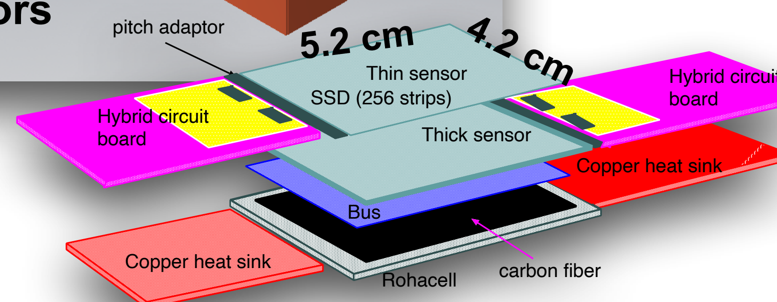
But, need relative det. efficiency ε_{det}

- **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.**



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);
- 20 segment arrangement with R=13 cm radius (to be optimized);
- 256 strips on each segment, 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			

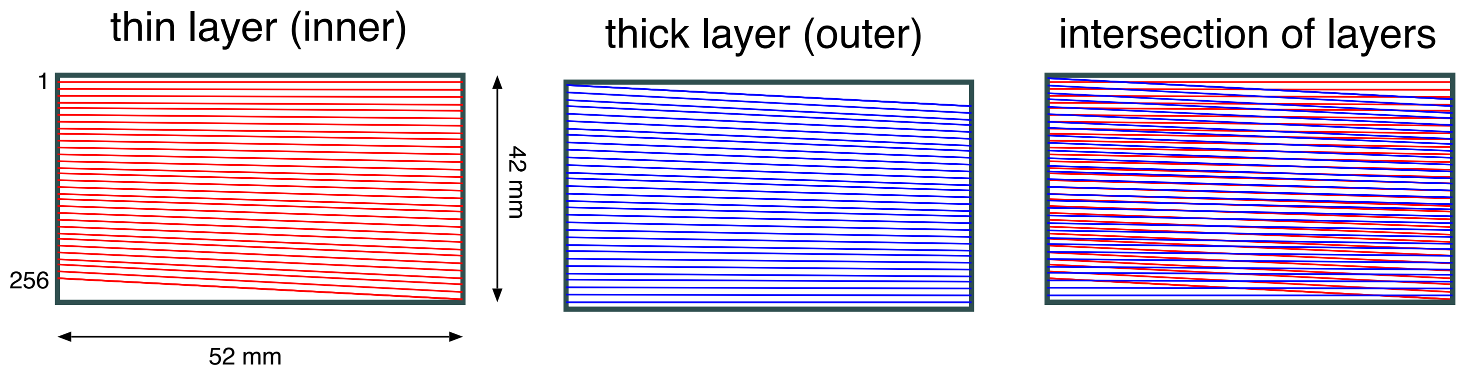
* R&D

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

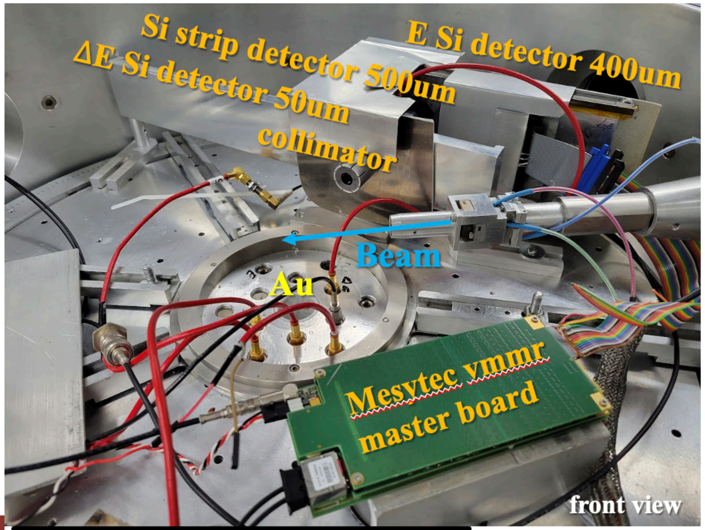
Neutron transmutation doped n-type silicon is offered for applications where low resistivity variation across the wafer is required. This material has a much higher depletion voltage that regular high resistivity n-type material.

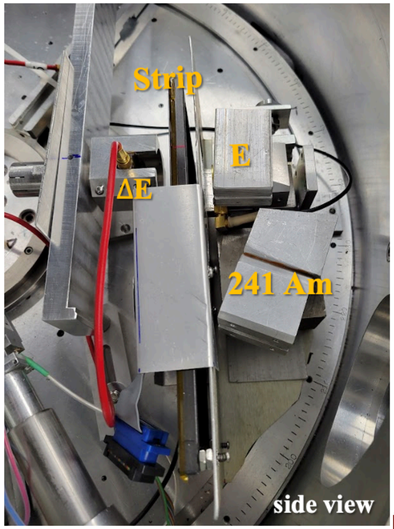
The elasticity of e-D scattering will be ensured with a cylindrical Si-strip based recoil deuteron detector.

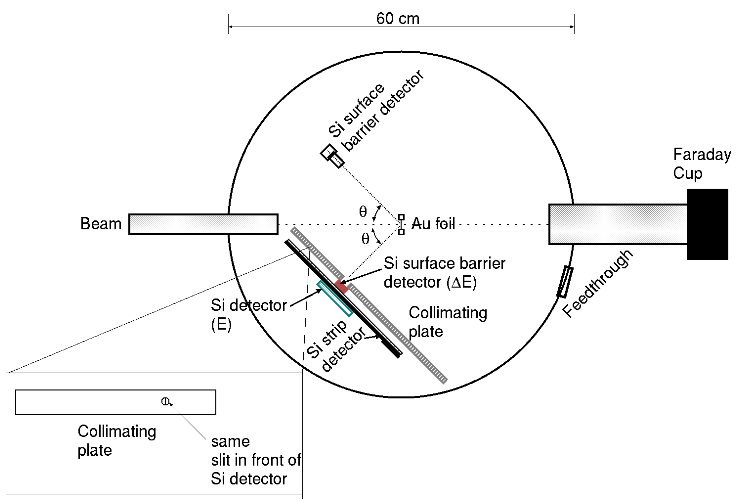


256 strips with linearly varying angles of 0 - 3 deg to minimizes dead zones.
The strips will have a constant pitch of ~200 micron (~1/85 deg^{-1}).
The angular resolution of $\delta\varphi \lesssim$ 5 mrad and $\delta\theta \lesssim$ 10-20 mrad.

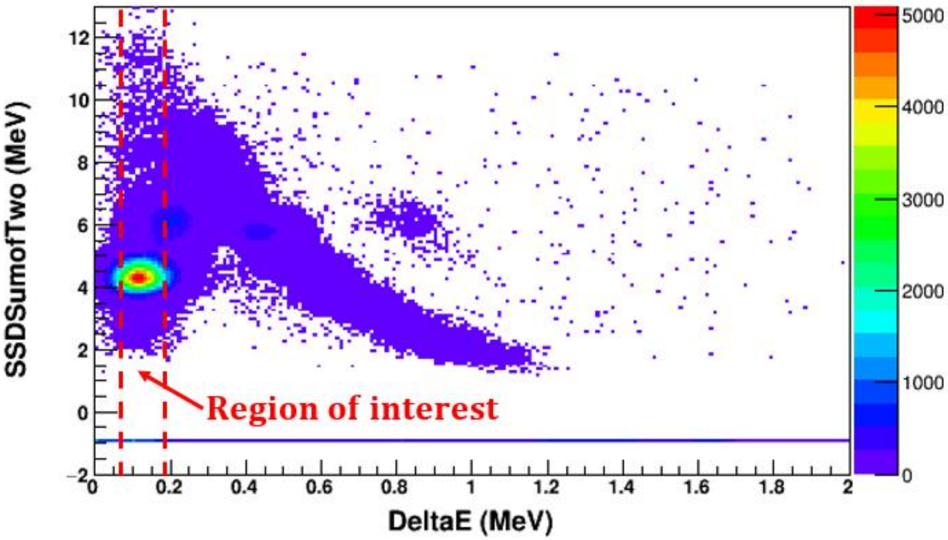
The recoil detector will be calibrated using *ep* elastic running on hydrogen and with the 5-15 MeV p/D beam from the Tandem accelerator at TUNL (recently validated).



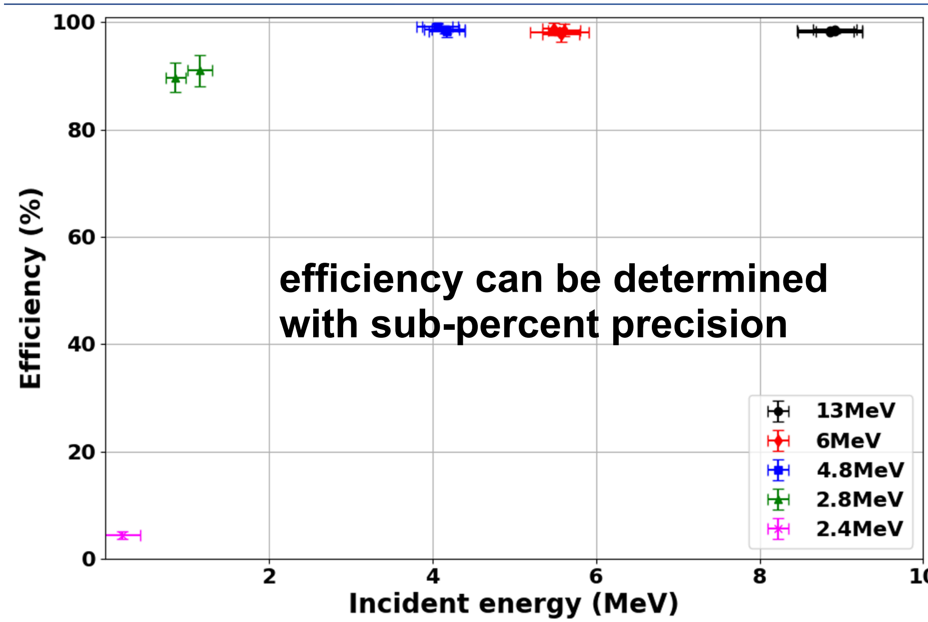


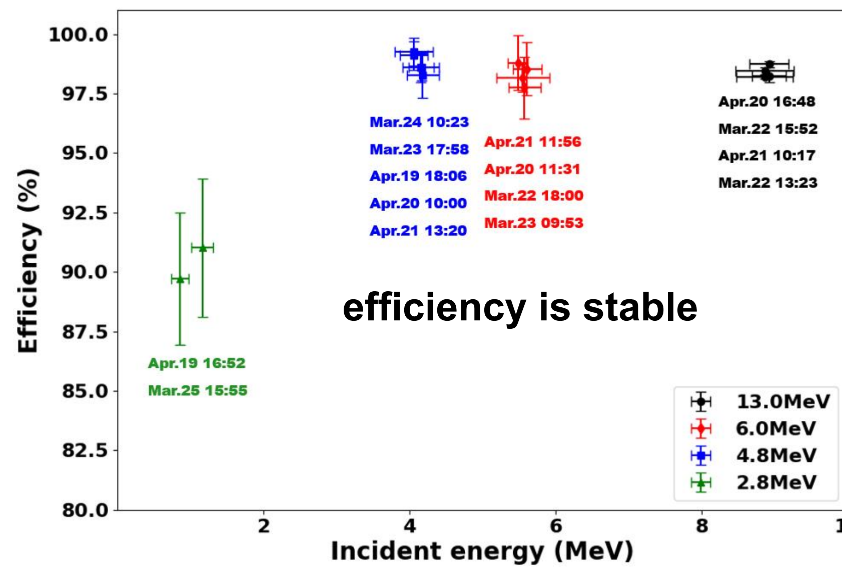


As recommended by the PAC- recoil detector calibration scheme validated using 5-15 MeV p/D beam at TUNL



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





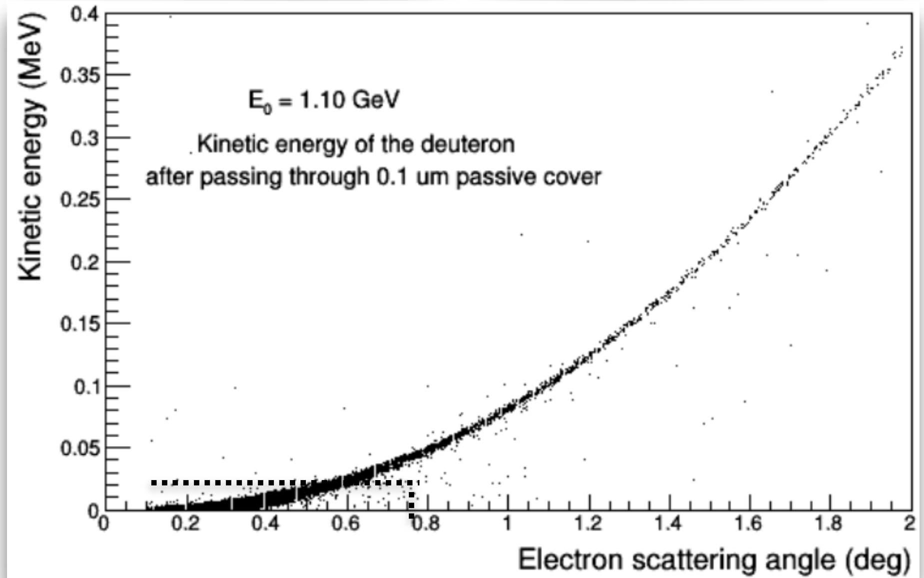
New spokespersons (F.Q.L. Friesen & C. R. Howell) from TUNL/Duke will build the SSD recoil detector

Plots and analysis courtesy of J. Zhou

A comprehensive Geant4 simulation was used for studying the detection thresholds and backgrounds.

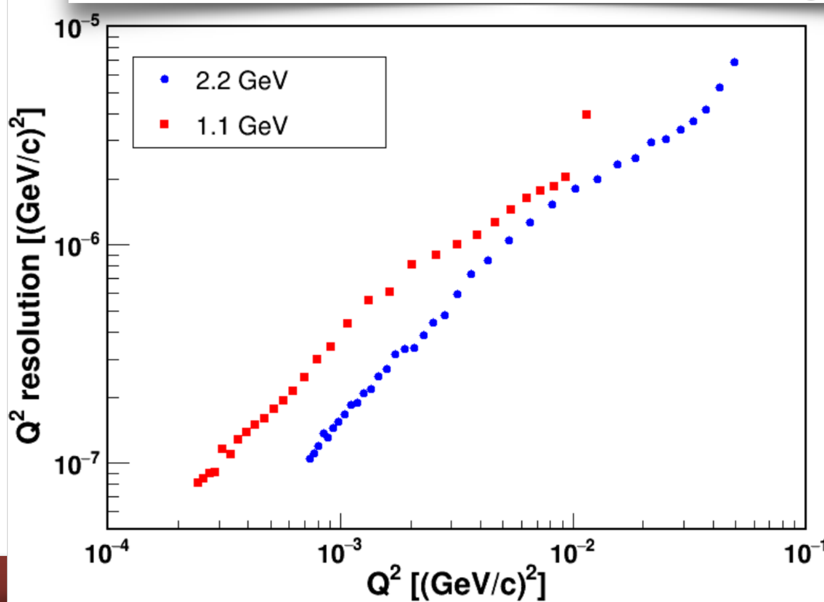
The recoil detector can detect deuterons with kinetic energy > 40 keV

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

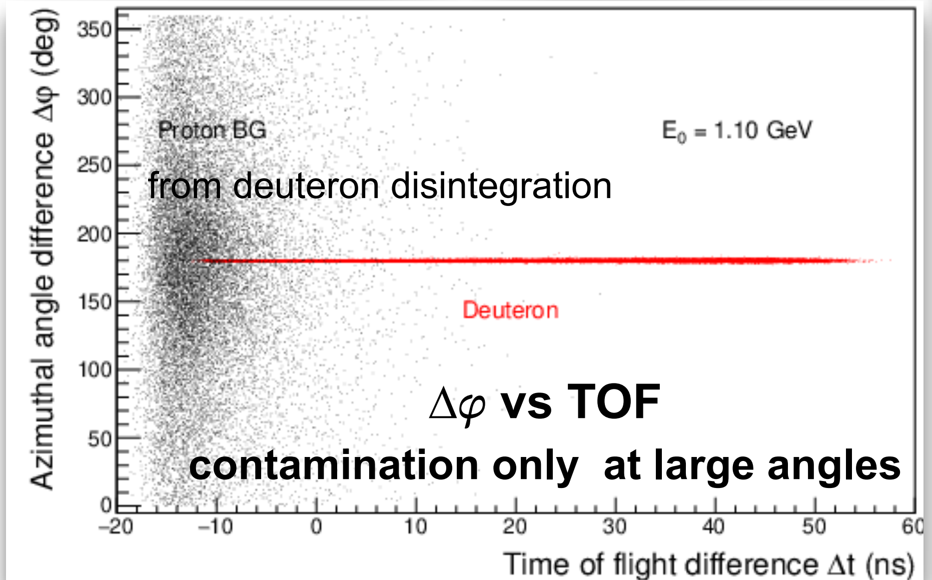


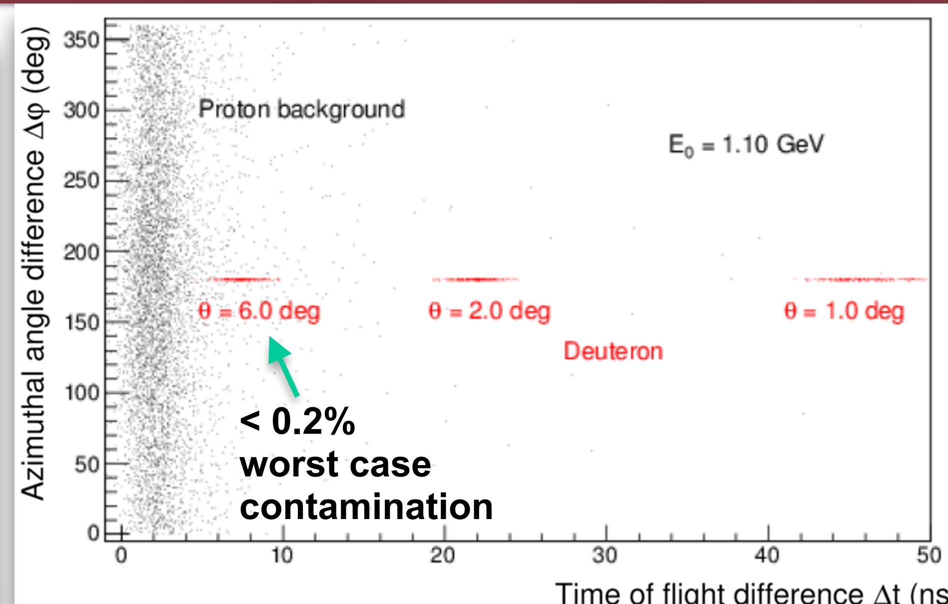
Deuteron will recoil at large polar angles θ_d = [83^0 - 89^0];

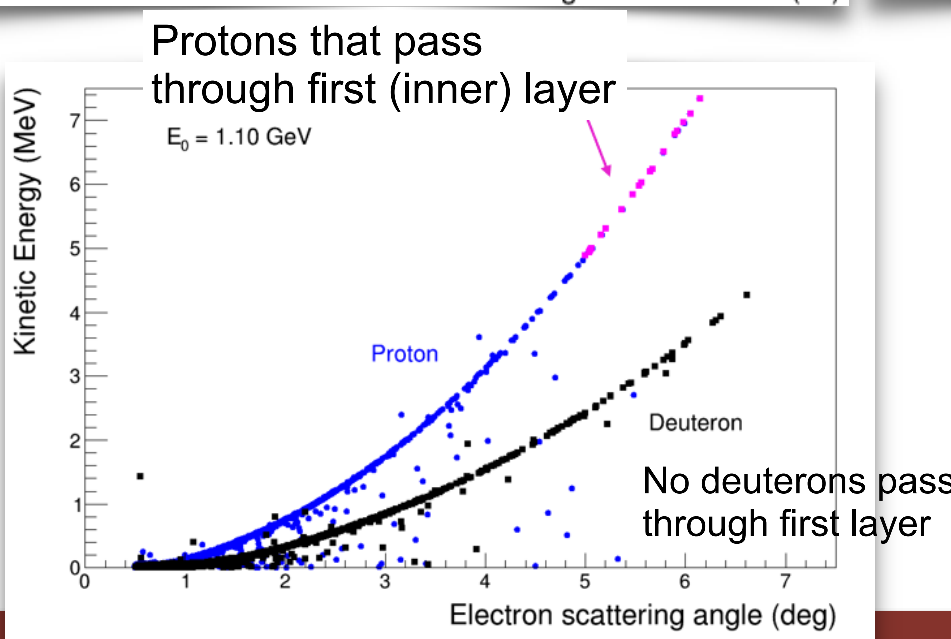
At both 1.1 and 2.2 GeV beam energy $\theta_e = 0.7^o - 6.0^o$ can be detected giving a Q^2 coverage of *$2\times10^{-4} - 5\times10^{-2}$ GeV^2* with high resolution.



Particle identification at 1.1 GeV will use co-planarity of the recoil deuteron as the primary method.



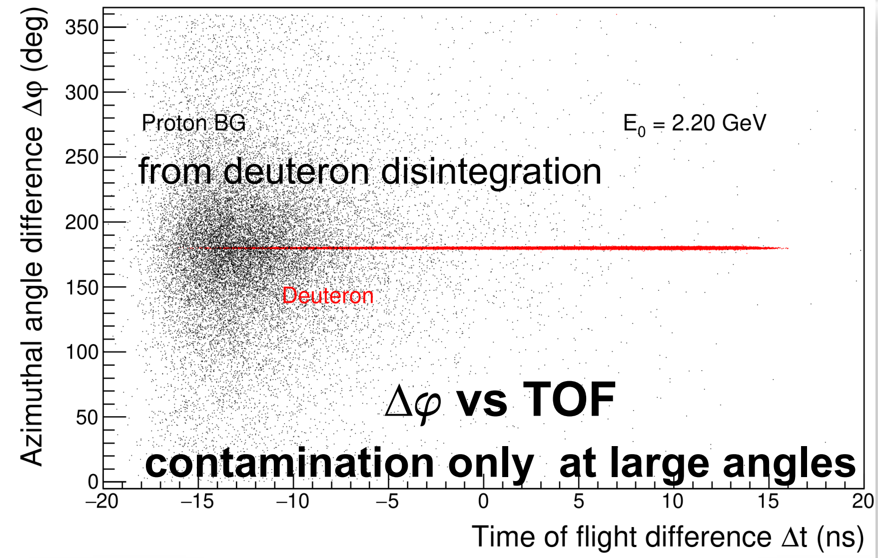




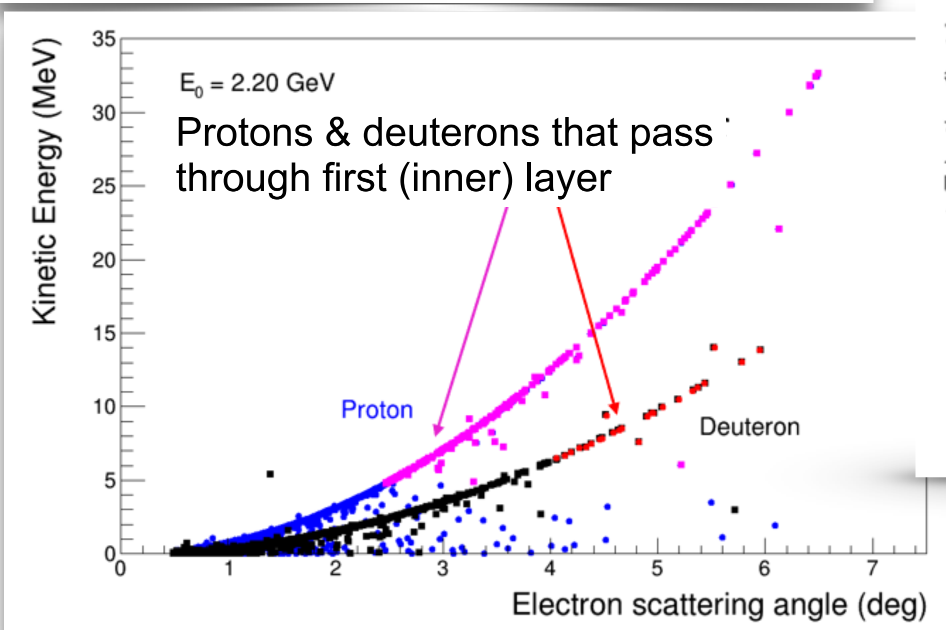
PID relies primarily on the co-planarity of e-D elastic scattering.

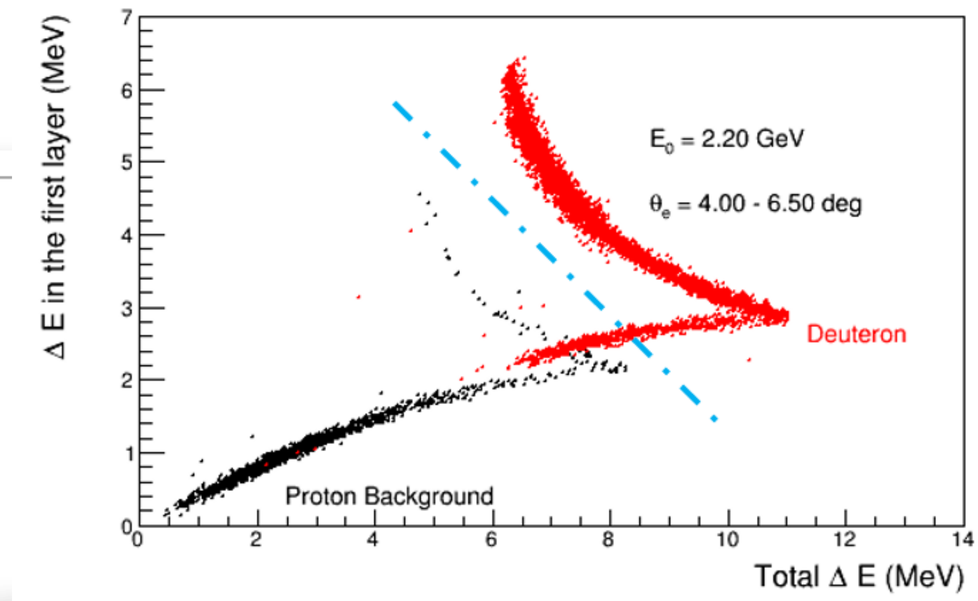
For large part of 1.1 GeV kinematics the deuterons do not disintegrate, but still the deuteron must be detected to ensure elastic scattering.

Particle identification at 2.2 GeV will use co-planarity and energy deposited in recoil detector



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

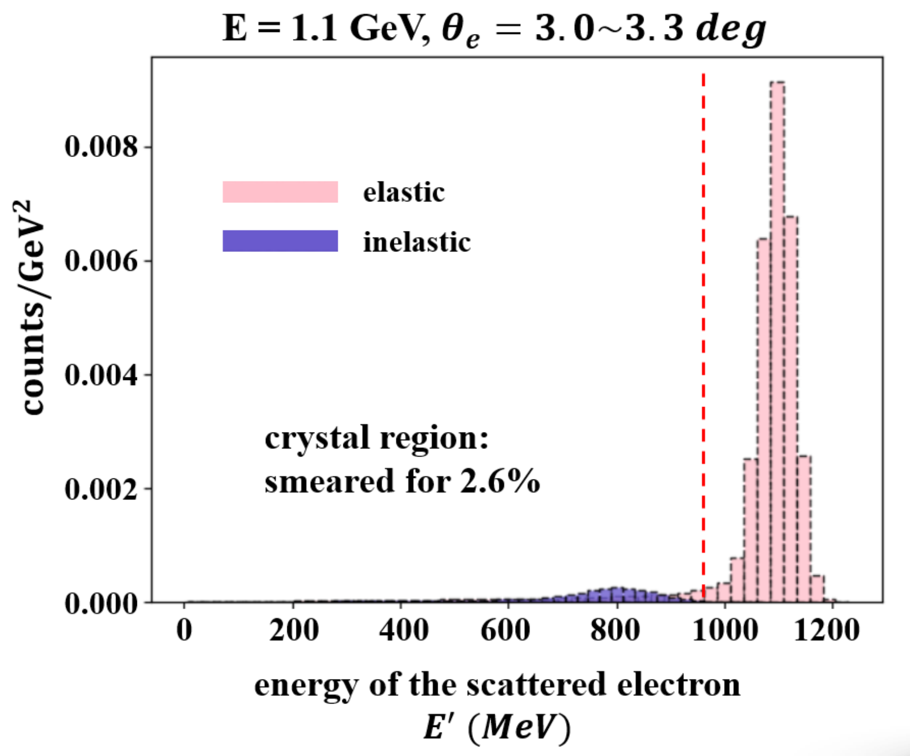


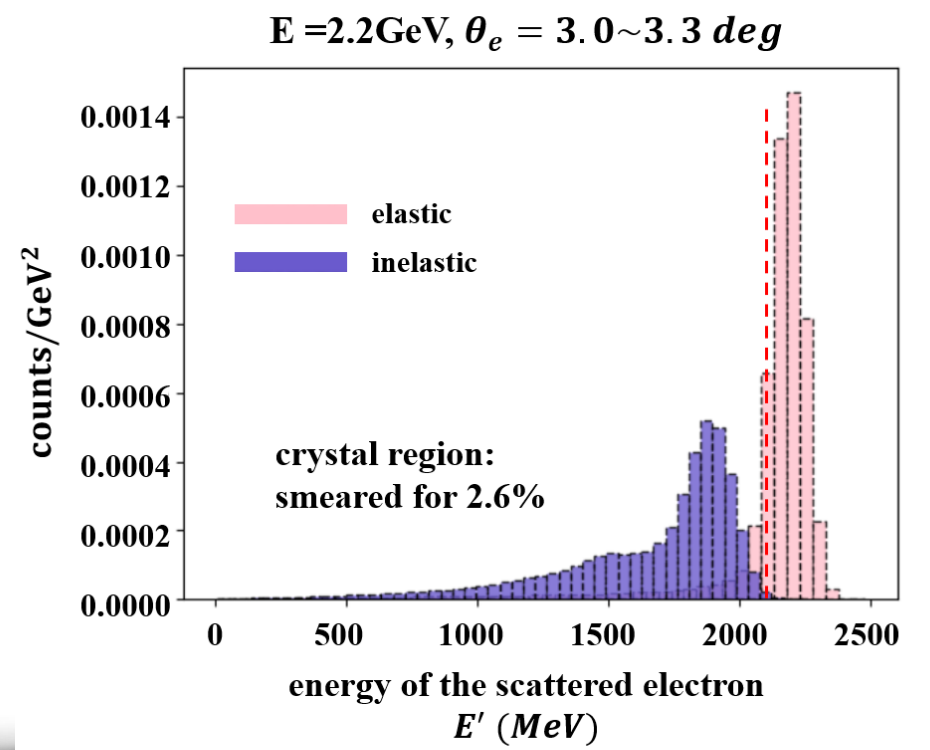


Deuteron electro-disintegration and inelastic scattering are the two major sources of background.

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

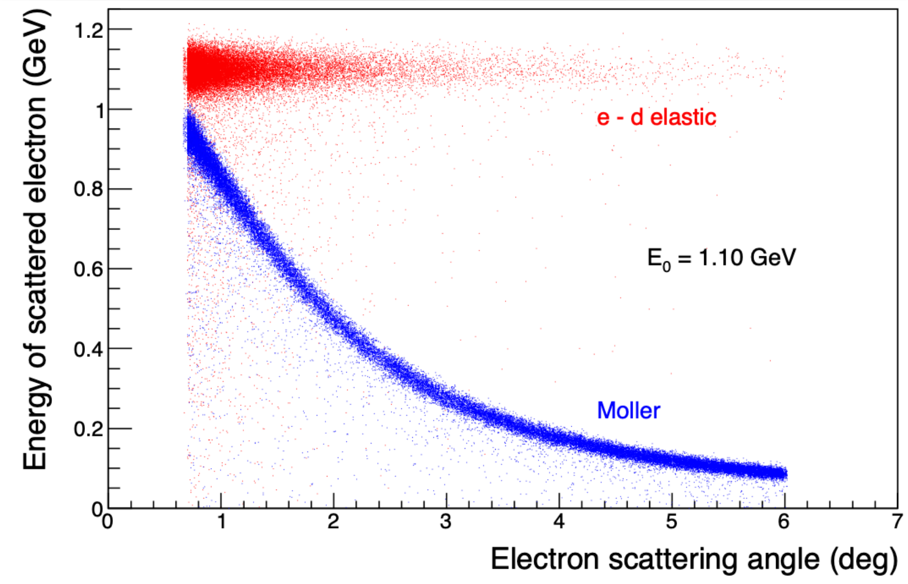
Electro-disintegration rates are < 6% of the elastic rates.
inelastic rates are < 1% of the elastic rates





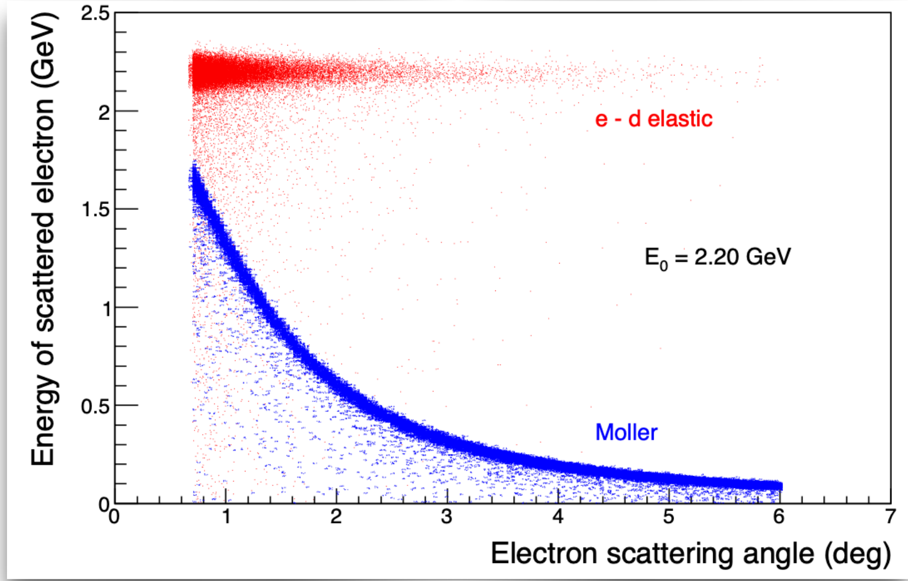
Elastic *e-D* and Møller events can be cleanly separated over the full angular range [0.7⁰ - 6.0⁰]

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

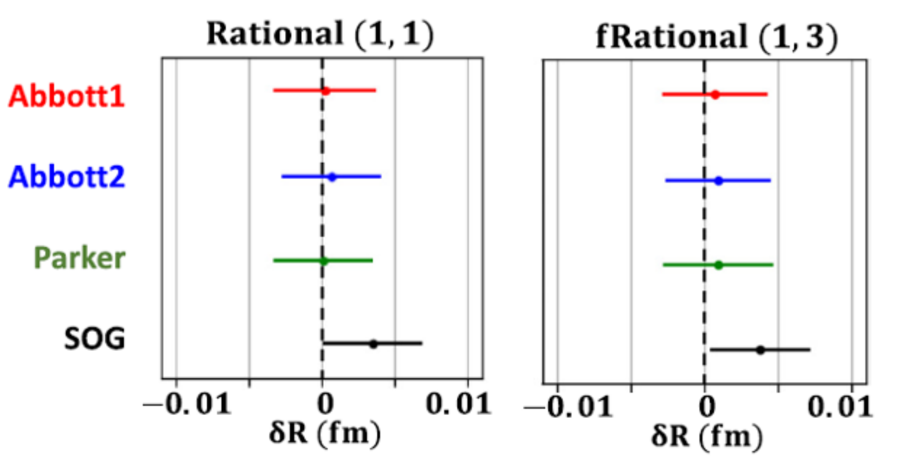
The internal and external radiation has been included for both *e-D* and Møller scattering.

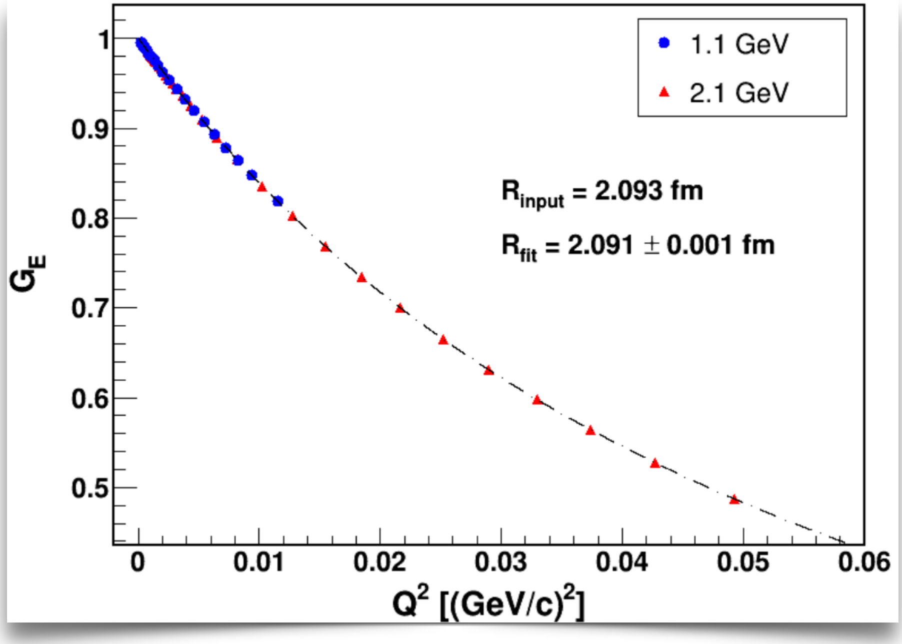


A wide range of functional forms were systematically tested for their robustness in extracting r_D.

- 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**





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

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

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

A total of 40 PAC days of beam time is requested for the high precision extraction of charge form factor and 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

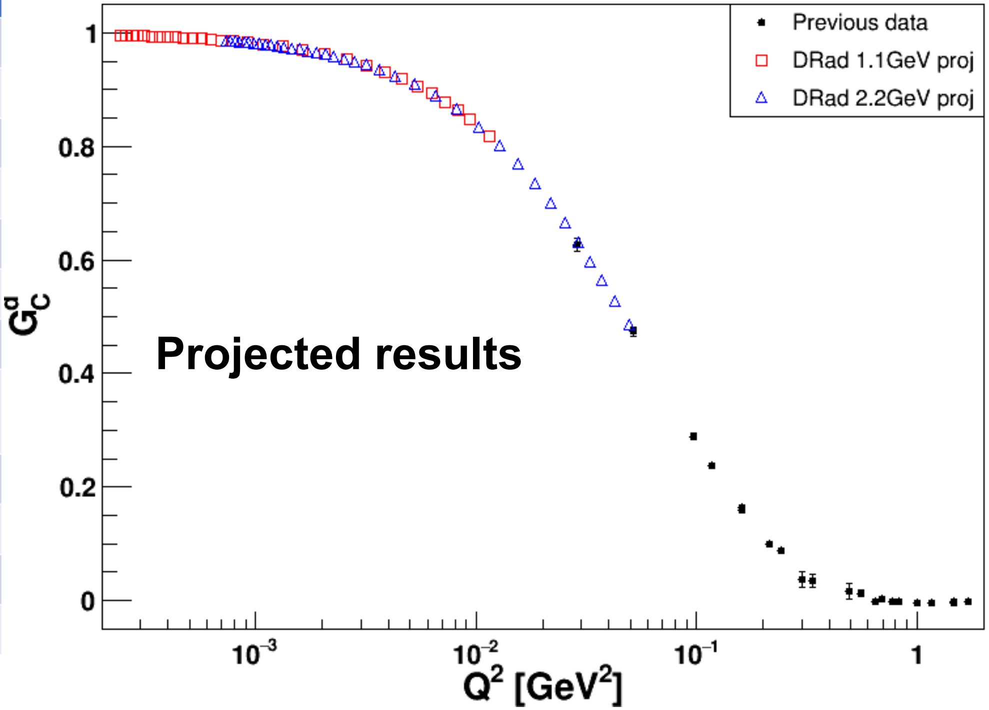
to have ~ 0.5 % stat. error for the last Q^2 bins
we request 16 days for this energy run.

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. 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

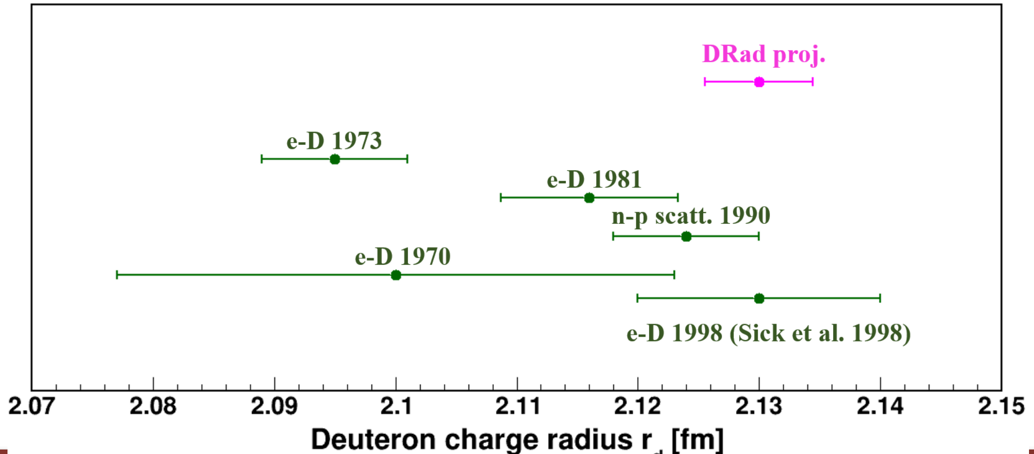
The estimated total uncertainties on the extracted form factor is 0.1-0.4%, about factor of 2 better than the best extraction to date

Item	dσ/dΩ (%)	G_C (%)
Event Selection	0.06 ~ 0.34	0.03 ~ 0.17
Radiative correction	0.06 ~ 0.15	0.03 ~ 0.08
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	**0.3 ~ 0.7**	**0.1 ~ 0.4**



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

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



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

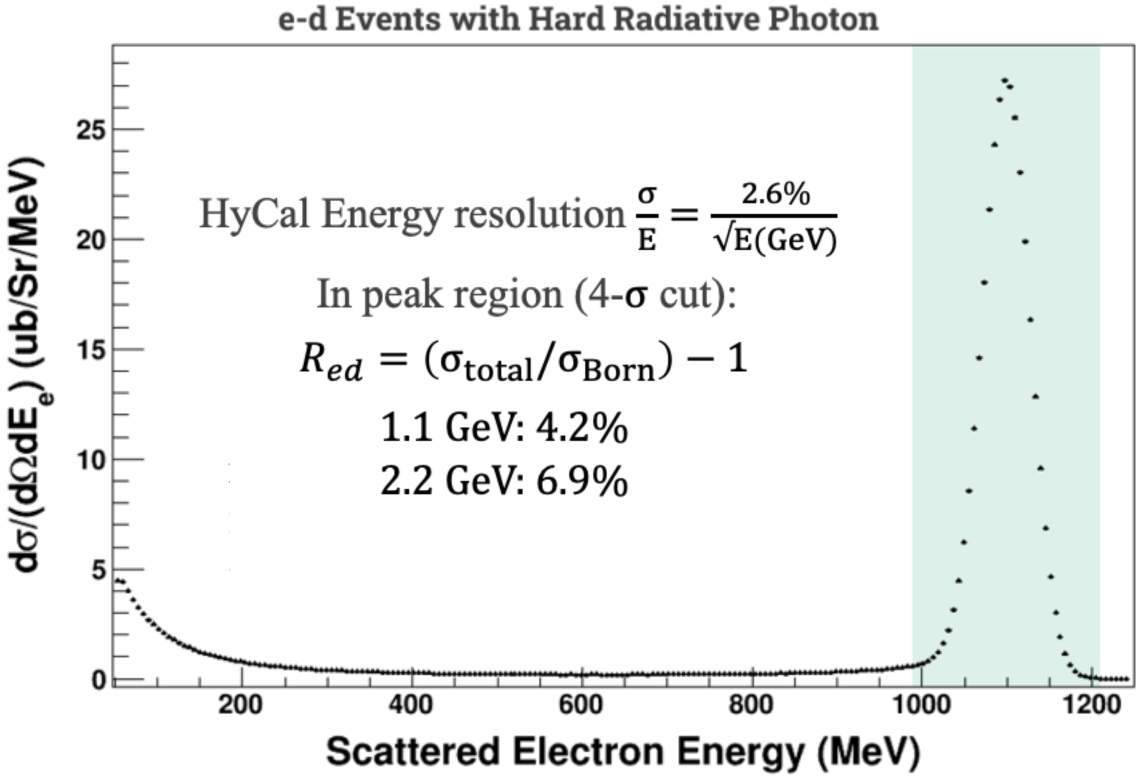
Issues: For *ed* scattering, radiative corrections are not known precisely and are even more difficult to calculate than for *ep* scattering. In addition, the PAC finds that the physics case outlined in the proposal is not compelling enough to anticipate the resolution of these issues. Nevertheless, 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 submitted to arXiv (2307.09680) and European Physical Journal A

Slide courtesy of
J. Zhou / V. Khachatryan

Response to selected TAC questions

3. No discussion is provided on how the Si-strips will work in close proximity to 20 K, a temperature that is so low that it is not clear if Si detectors can operate.

The upgraded Hall-B beam dump will allow us to operate the target at 40-70K instead of 20K, while increasing the beam current to maintain the same luminosity. Si detectors have been shown to work at these higher temperatures.

9. The amount of gas in the beamline outside the target cell was minimized using differential pumping with very large turbomolecular pumps. The speed of these pumps will not be the same for H2 and D2, so the ratio of target gas to background gas will not be the same. Proponents should be aware of this.

   Yes, these were included in our target simulations and in our discussions with the target group. During the PRad, the target chamber ran at a pressure of about 3 mbar. At this pressure, based on the manufacturer's pumping curves (confirmed by test on 4He by the target group using the PRad setup) they should about twice the pumping speed for D2 and hence the chamber pressure will be 1.5 mbar.

Summary

- We propose a new high-precision measurement of the deuteron charge form factor 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 (~2×10^{-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 form factor to a precision of 0.1-0.4% and radius to 0.2%
- 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 in part by NSF-MRI grant PHY-1229153 and
US DOE grant DE-FG02-07ER41528

Backup Slides

Response to selected TAC questions

5. The planned Si-based recoil detector included in the proposal is a detector that requires significant levels of design and optimization, not to mention potential R&D and a significant cost projection. There is no discussion in the proposal about who is responsible for this system at any level. As it is a critical part of the experimental plans, such discussions must be advanced and developed. The performance and reliability of the silicon detectors at cryogenic temperatures is not clear. It is not clear if the requirements and experimental needs have been discussed with

We have been in constant communication with Yuri Gotra and others about the CLAS12 CVT detectors and spares. Recently C. Howell and F. Friesen from TUNL/Duke joined the proposal as co-spokespersons. They played a major role in validating the proposed calibration and efficiency measurement of Si-strip detectors using the TUNL proton and deuteron beam. They will also be responsible for designing, building and testing the Si-strip based recoil detector. We also expect to utilize TUNL's design and engineering resources for this task and for the installation of the detector into the target cell.

The constituent technologies and capabilities needed in the final system are not individually novel (resolution, etc). The challenges involve the details of integrating the detectors with the target. Some next steps in the R&D effort involve identifying, procuring, instrumenting, and testing candidate strip detector modules with candidate preamplifiers. This choice of modules will guide the details of the design of the array. We are investigating commerically available multiplexing options The testing will also involve measuring the performance of detectors low temperatures to establish limits on the target temperature for candidate systems. This limit is expected to be near 60 K, but higher temperatures could also be accommodated by increasing the beam flux. In our experience, getting the detectors wire bonded to pitch adapters in small volume can be challenging. In the past we have leaned on resources at Fermilab's detector facilities rather than using commercial options.

Response to selected ITAC questions

3. The sensitivity of the experiment requires careful and controlled energy calibrations of the HyCal for each beam energy setting. For such an operation in the past, the calibration was done sending the electron beam to the photon tagger focal plane counters. However, these were removed for 12 GeV operation in Hall B. Re-installation is possible, but this is a non-trivial exercise. Also, the tagger scattering chamber has relatively poor vacuum due to degradation of the chamber window. This affects the beam photon energy resolution. Plans should be communicated of how the energy calibration can be performed without using the tagger, exploiting the new FADC readout and its enhanced capabilities.

Based on the experience of calibrating HyCal during the PRad experiment we have developed plans to use Hall B Photon Tagger for the proposed DRad and PRad-II experiments. They are:
a) The use of the photon tagger will be limited to minimize the re-assembling of the focal plane counters, and the associated electronics and power supplies.
b) It is planned to use 25% of the photon tagger focal plane for the HyCal energy calibration, linearity, and detection efficiency measurements.
c) Only three intervals of the focal plane detectors (both T-counters and corresponding E-counters) will be used: upper T1-T5, middle T28-T33, and lower T56-T61.
d) Recover the 10^{-5} r.l. Au foil radiator.
e) We plan on addressing the poor vacuum in the large downstream chamber with a new Al window for the tagger chamber and additional pumps in the same manner as planned for the PRad-II experiment.

If the tagger cannot be recovered, there is another, less precise, but feasible method; use the electron beam on a thin radiator to produce pi0 and use the photons from its decay to calibrate the tagger. With the upgrade of the DAQ to FADCs, the PMT signals do not have to be split between triggering vs digitization. This implies that the gain matching could be performed with cosmics.

The recovery of the Tagger is highly desirable for high precision experiments such as DRad and PRad-II.

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

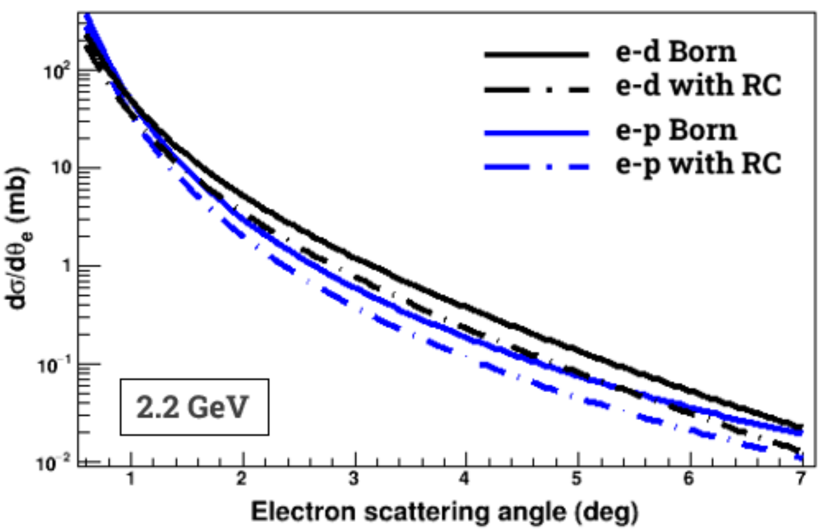
The range of dead layer windows available with the in-house Varian 300 XP ion implanter are listed below. Window types refer to the junction of a device, but can also be achieved on the ohmic side upon request.

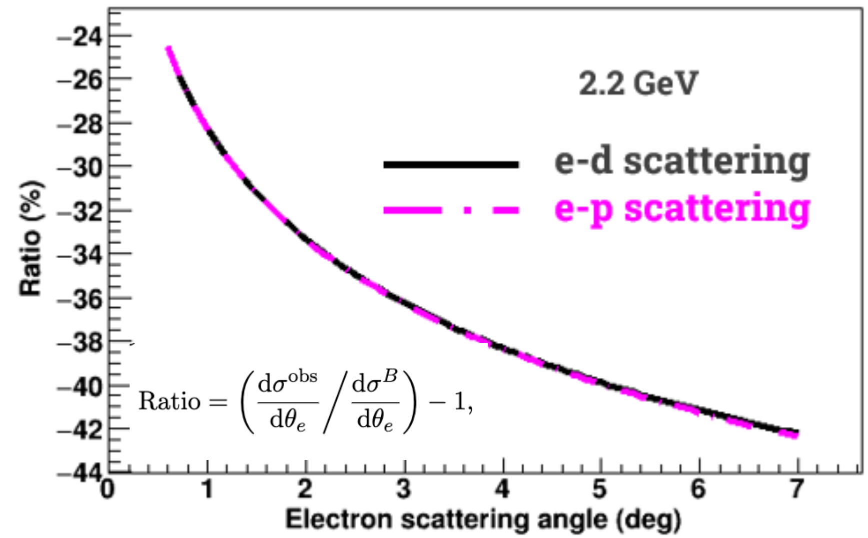
WINDOW TYPE	DEAD LAYER	MINIMUM ENERGY THRESHOLD	
		Electron	Proton
9	100 nm	1K eV	20 KeV

PRad equipment	PRad-II	DRad	X17	pi0 TFF	Group responsible
Target chamber	No change	No change	replace with large dia. pipe	No change	JLab target group
Target pumps	No change	may need more	No change	No change	JLab target group
Target cell	No change	larger dia. cell	not used	not used	JLab target group
5m long Vacuum chamber	more pump ports	same as PRad-II	same as PRad-II	same as PRad-II	Hall -B engineering
HyCal modules	LG to $PbWO_4$	same as PRad-II	inner $PbWO_4$ used	same as PRad-II	NCA&T and MSU
HyCal readout	fADC based readout	same as PRad-II	subset of PRad-II	same as PRad-II	JLab DAQ and MSU
Dynode based Trigger	FPGA based custom trigger	FPGA based custom trigger	FPGA based custom trigger	FPGA based custom trigger	JLab Fast electronics
GEM chambers	two new chambers	same as PRad-II	same as PRad-II	same as PRad-II	UVa and JLab detector group
GEM readout	MPD-APV system	same as PRad-II	same as PRad-II	same as PRad-II	UVa and JLab fast electronics
No Recoil detector	No change	new Si-strip recoil detector	No change	No change	Duke/TUNL and MSU
2 mm vacuum window	No change	No change	smaller 1 mm window	No change	Hall B engineering
solid target ladder	No change	No change	used as target target	used as target target	Hall B engineering
W shield for inner blocks	No change	No change	No change	New extended shields	UMass

Table 1: Changes in equipment relative to PRad

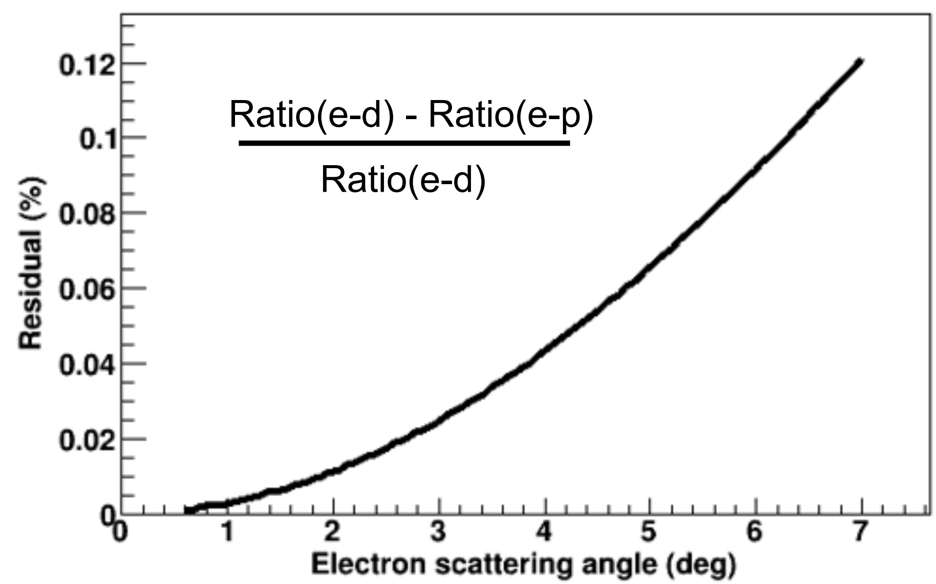
New radiative corrections calculations for e-D scattering have been completed



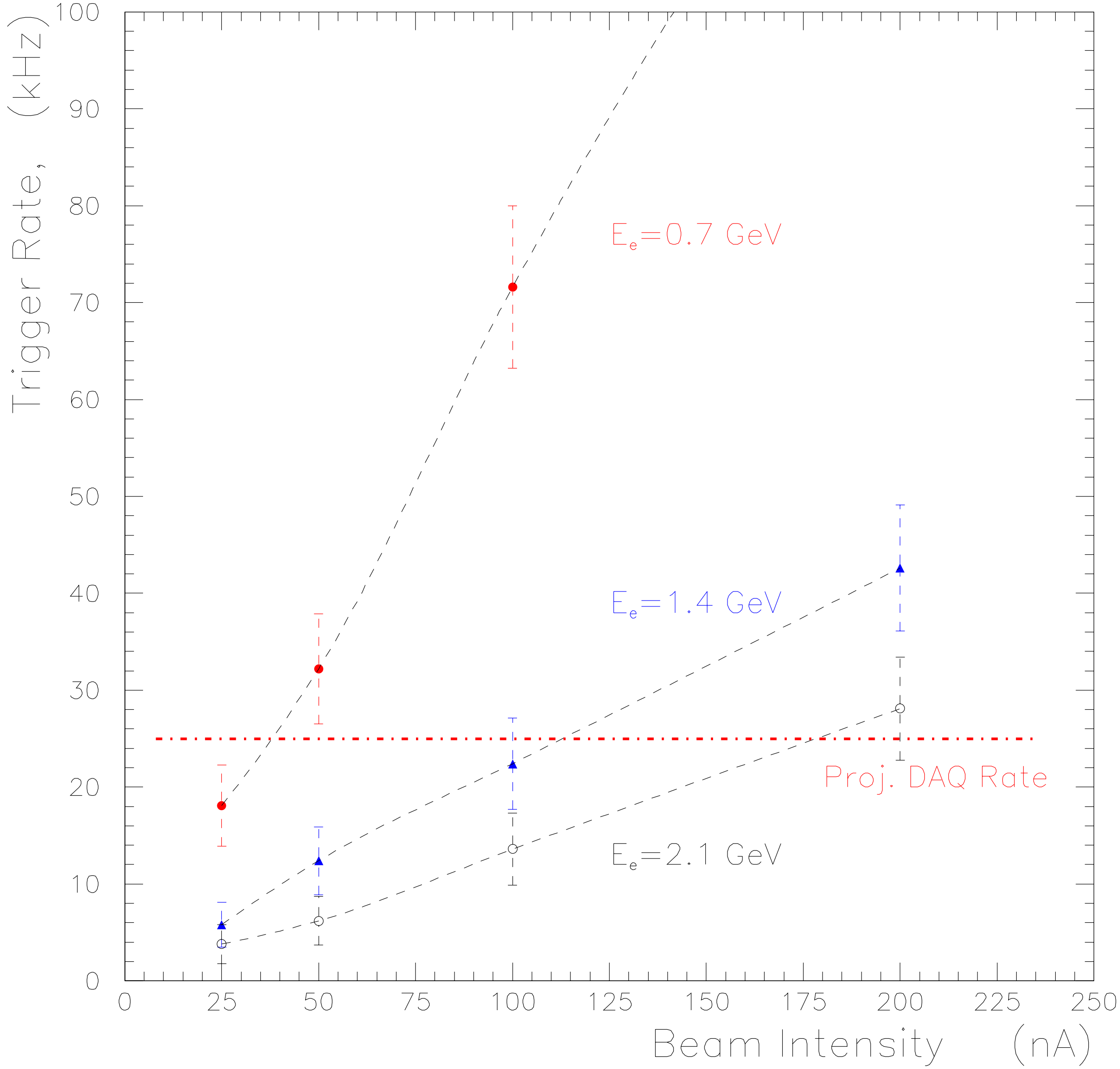


Lowest order radiative corrections to e-D scattering beyond the ultra-relativistic limit is complete and submitted to EPJ (available on arXiv)

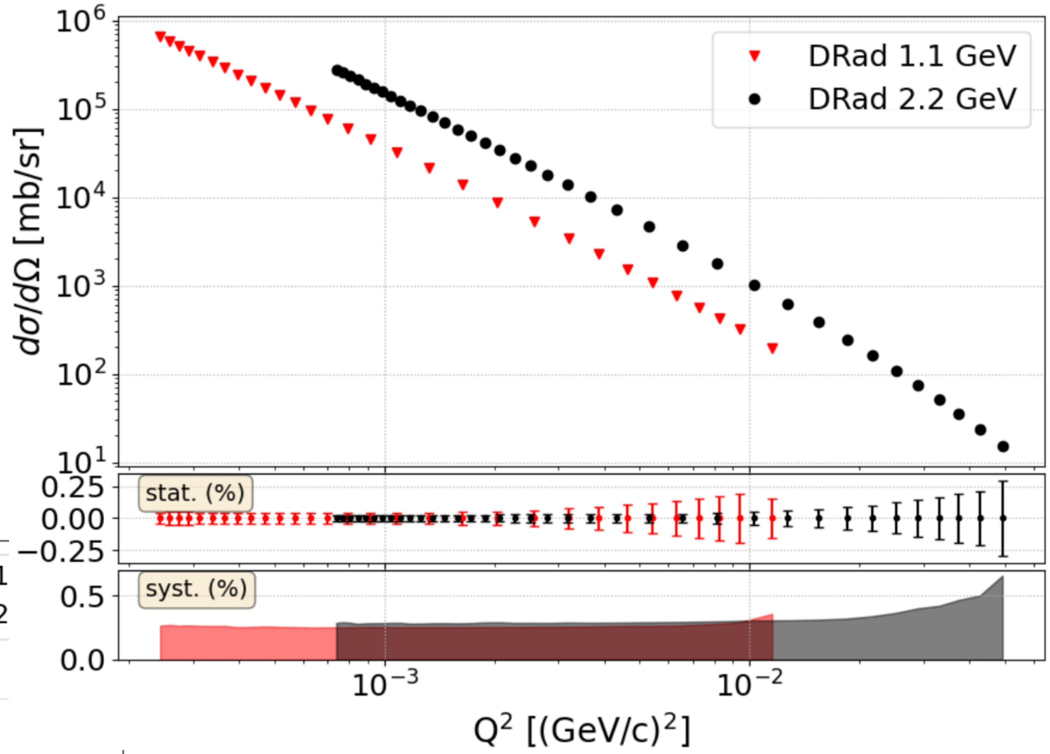
J. Zhou, V. Khachatryan, H. Gao, A. Ilyichev, I. Akushevich, C. Peng, S. Srednyak and W. Xiong, "Lowest-order QED radiative corrections beyond the ultra-relativistic limit in unpolarized electron-deuteron elastic scattering for the proposed DRad experiment at Jefferson Laboratory", to be submitted to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

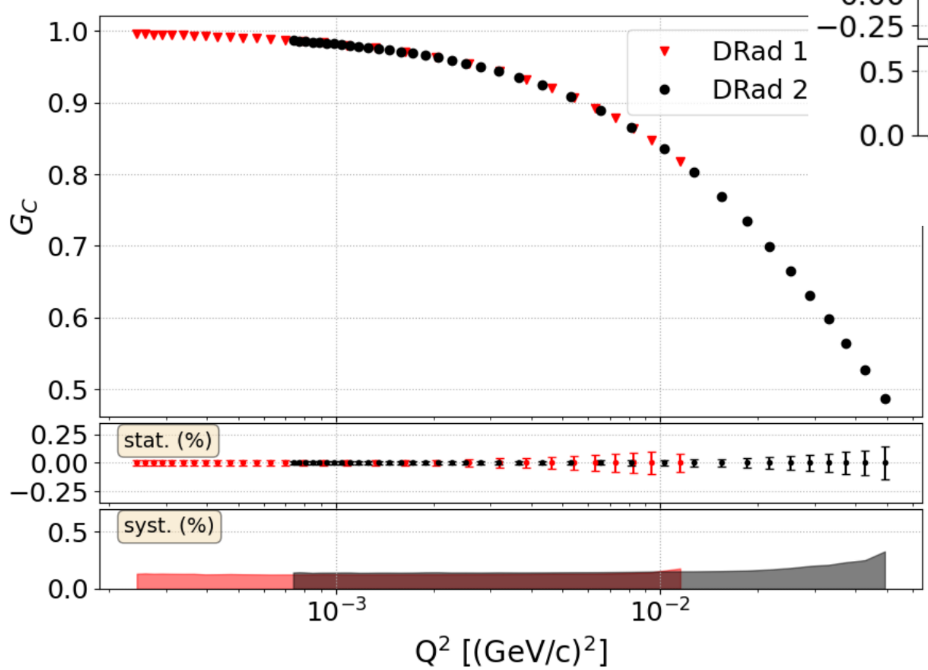


The projected trigger rates

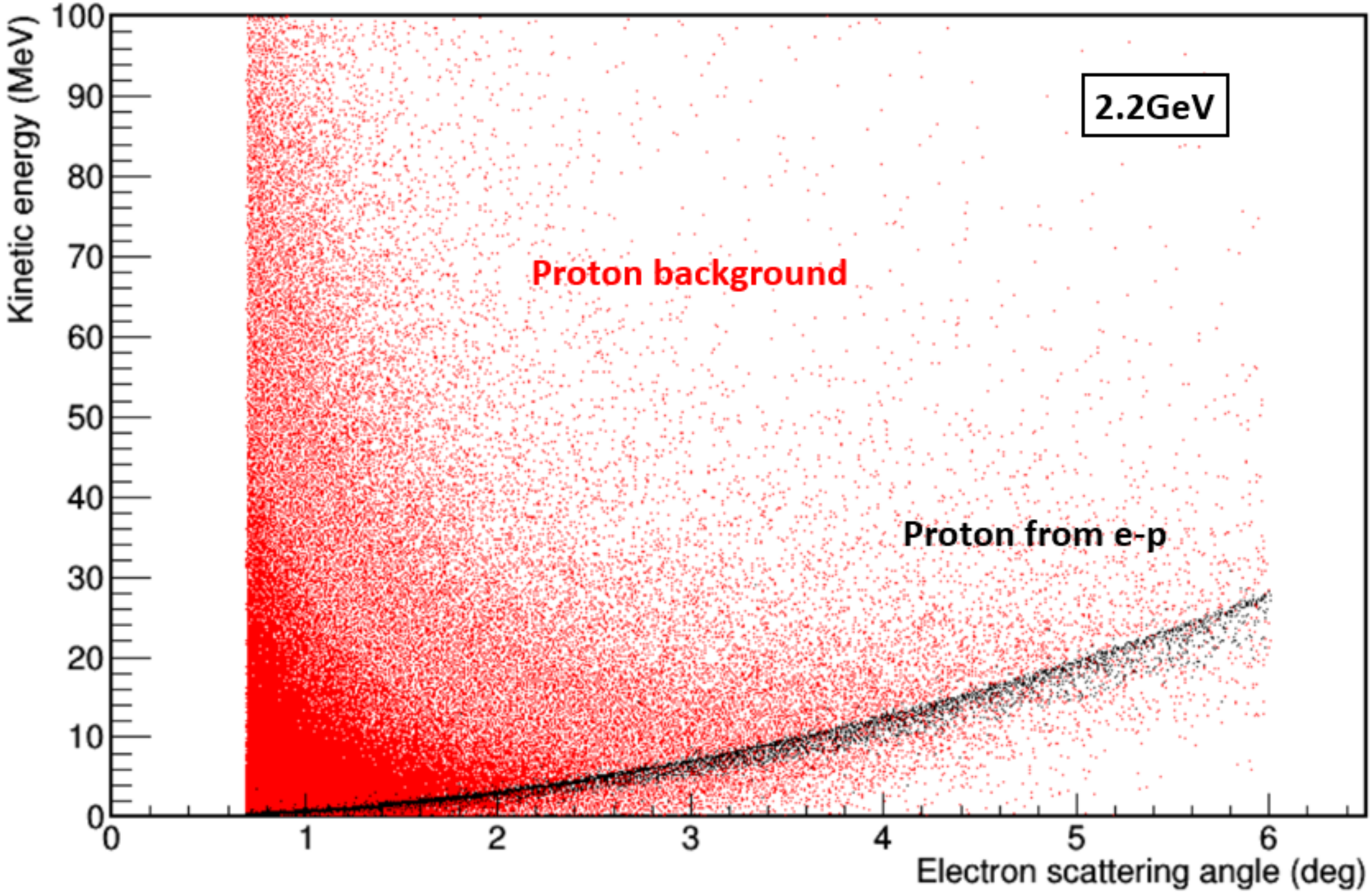


The projected cross sections and form factor

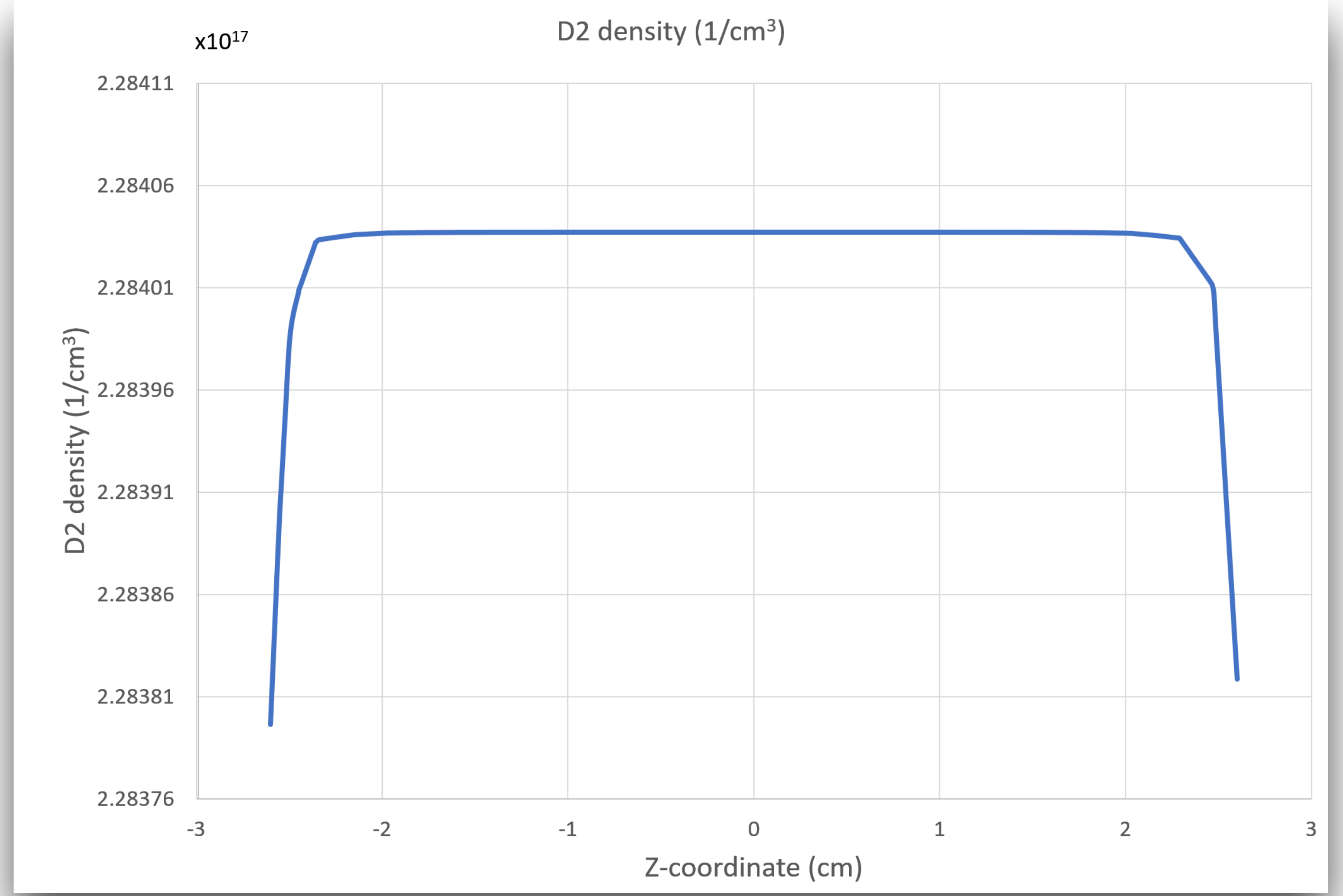




Simulated *ep* elastic and *eD* quasi-elastic scattering



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)

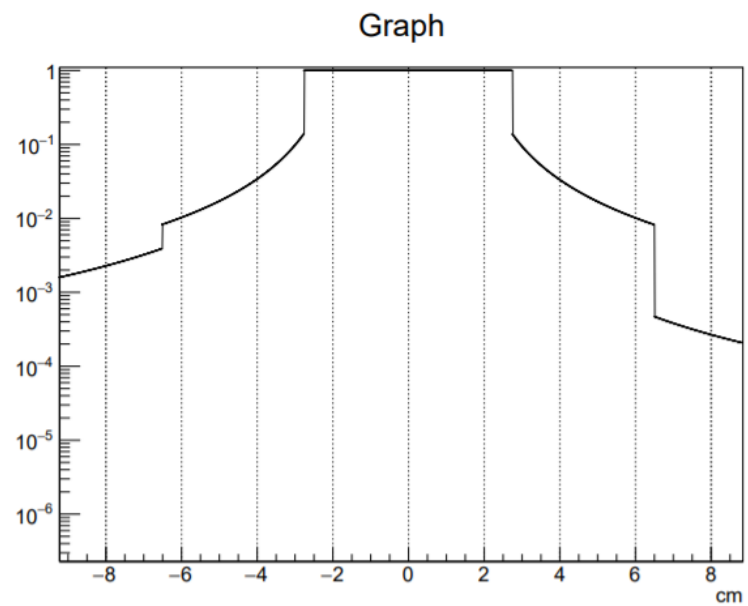
$$\frac{d\sigma}{d\Omega} \propto N_{yield} \qquad \frac{d\sigma/d\Omega|_{\text{uniform}}}{d\sigma/d\Omega|_{\text{tail}}} = \frac{N_{uniform}}{N_{tail}}$$

Relative uncertainty of cross section:

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

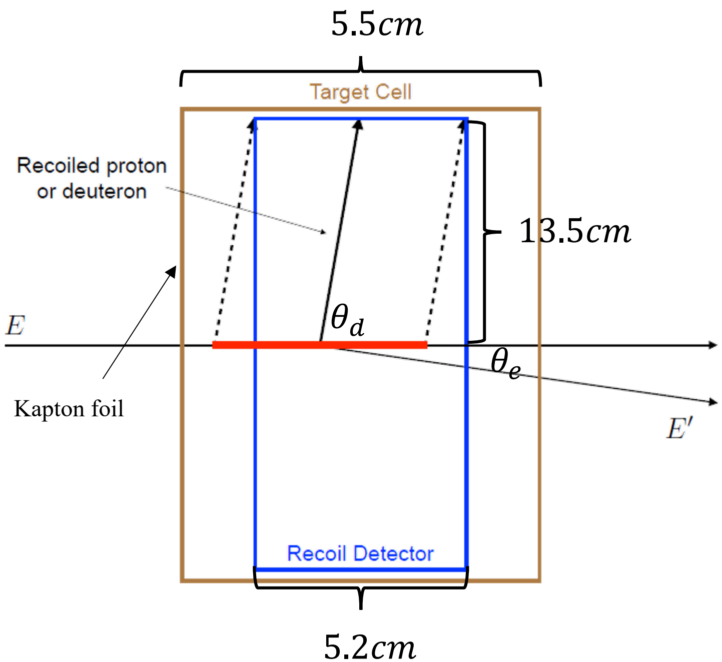
Relative uncertainty of the radius: $\Delta R = \dfrac{|R_{uniform} - R_{tail}|}{R_{uniform}}$

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.

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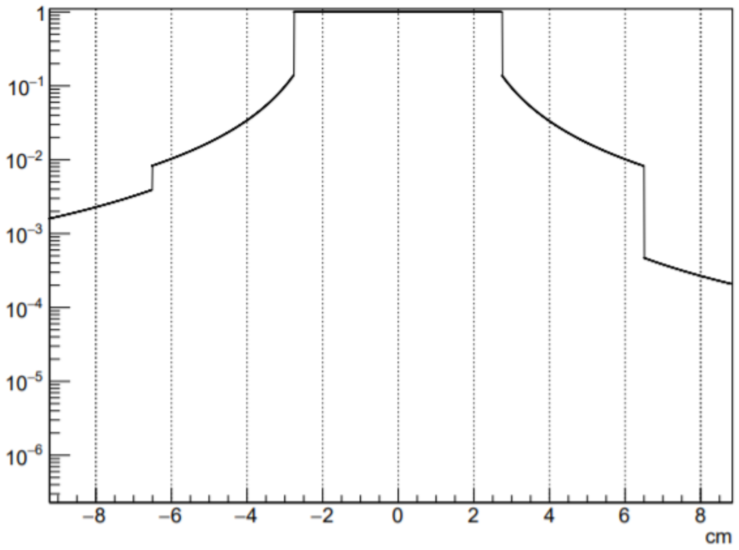
Optimization for the Recoil Detector acceptance

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.

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)

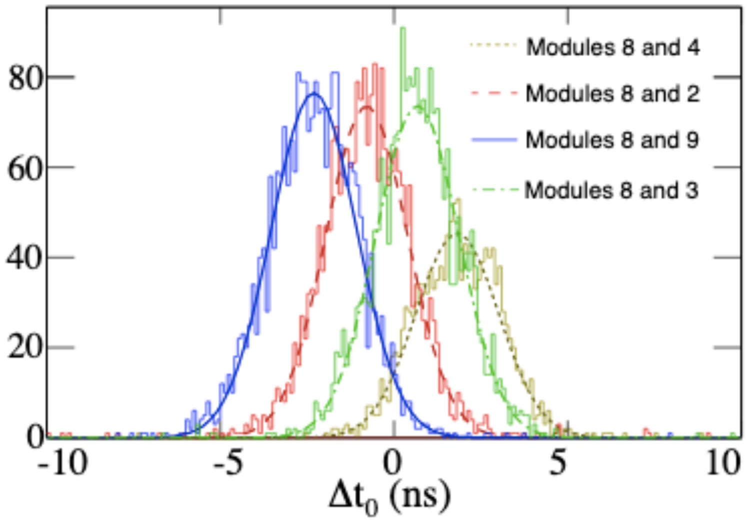


Figure 9: Distribution of $\Delta t_{0,ij}$ for a single module and four of its adjacent modules when all modules had $1000 < S_p < 2000$ ADC counts, together with Gaussian fit curves.

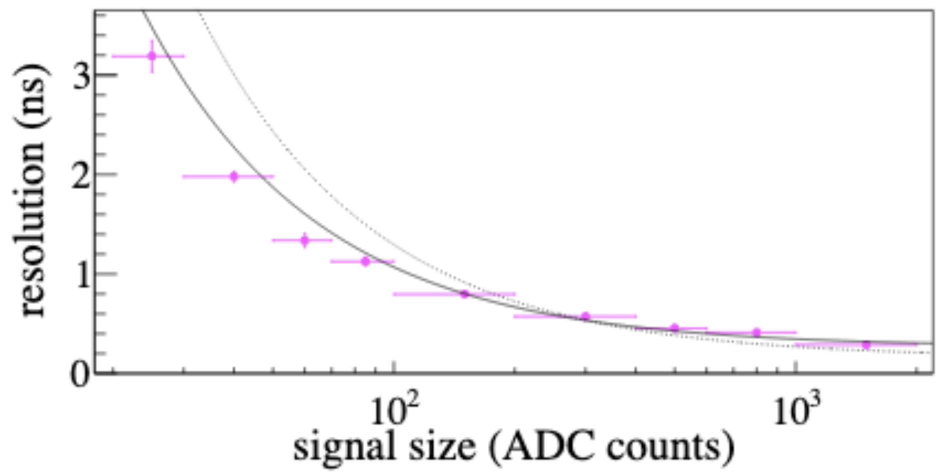


Figure 11: Final timing resolution for one module. The solid

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

Uncertainty with upgraded HyCal

Item	$d\sigma/d\Omega$ (%)	G_c (%)
Event Selection	0.005~0.06	0.003~0.03
Radiative correction	0.06~0.15	0.03~0.08
GEM efficiency	negligible	negligible
HyCal response	negligible ~ 0.48	negligible ~ 0.24
Acceptance	0.03~0.04	0.01~0.02
Beam energy	0.008~0.24	0.004 ~ 0.12
Inelastic ed	negligible ~ 0.02	negligible ~ 0.01
Efficiency of recoil detector	0.13	0.06
Bias from the fitter	-	-
Total Systematic	**0.16~0.58**	**0.08~0.29**
Statistical	**0.02~0.29**	**0.01~0.14**
Total uncertainty	**0.16~0.65**	**0.08~0.33**

Uncertainty with upgraded HyCal

PRad HyCal

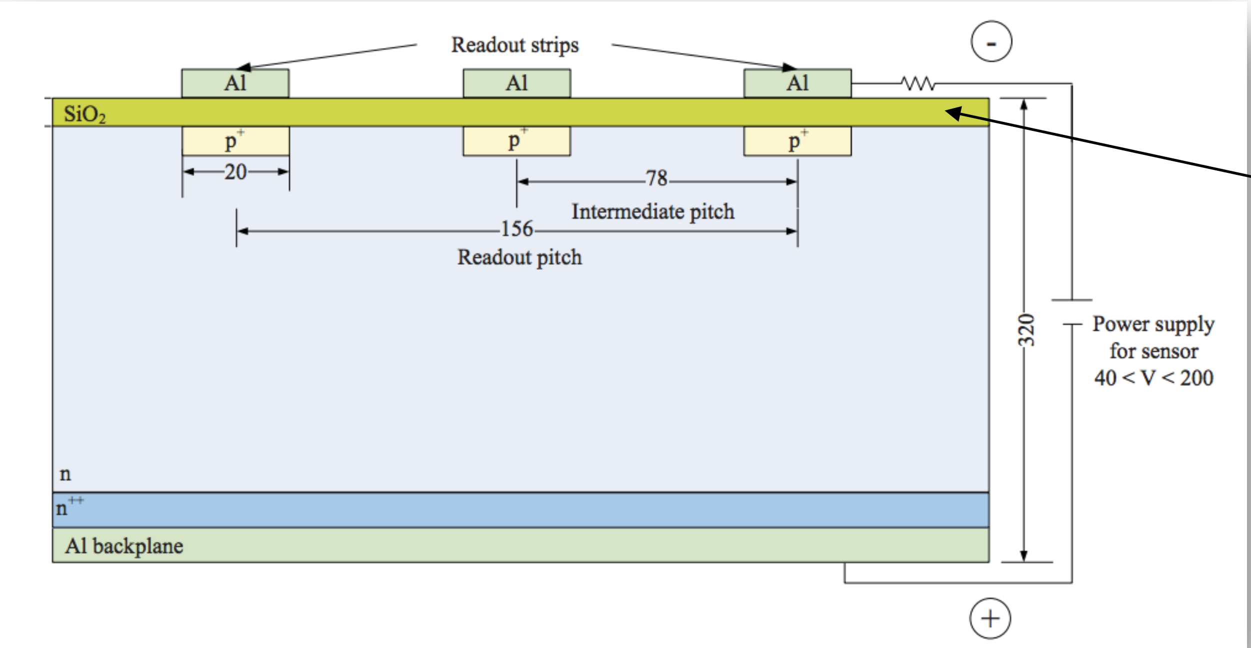
Item	Rd uncertainty (%)
Event Selection	**0.110%**
Radiative correction	0.045%
HyCal response	**0.090%**
Geometric acceptance	0.022%
Beam energy	0.008%

Upgrade HyCal

Item	Rd uncertainty (%)
Event Selection	0.070%
Radiative correction	0.045%
HyCal response	0.043%
Geometric acceptance	0.022%
Beam energy	0.008%

Item	Rd uncertainty (%)
Total correlated	**0.15%/0.10%**
GEM efficiency	0.03%
Inelastic e-d	0.024%
Efficiency of recoil detector	0.15%
Statistical	0.05%
Total Rd uncertainty	**0.22%/0.19%**

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/cm^2
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

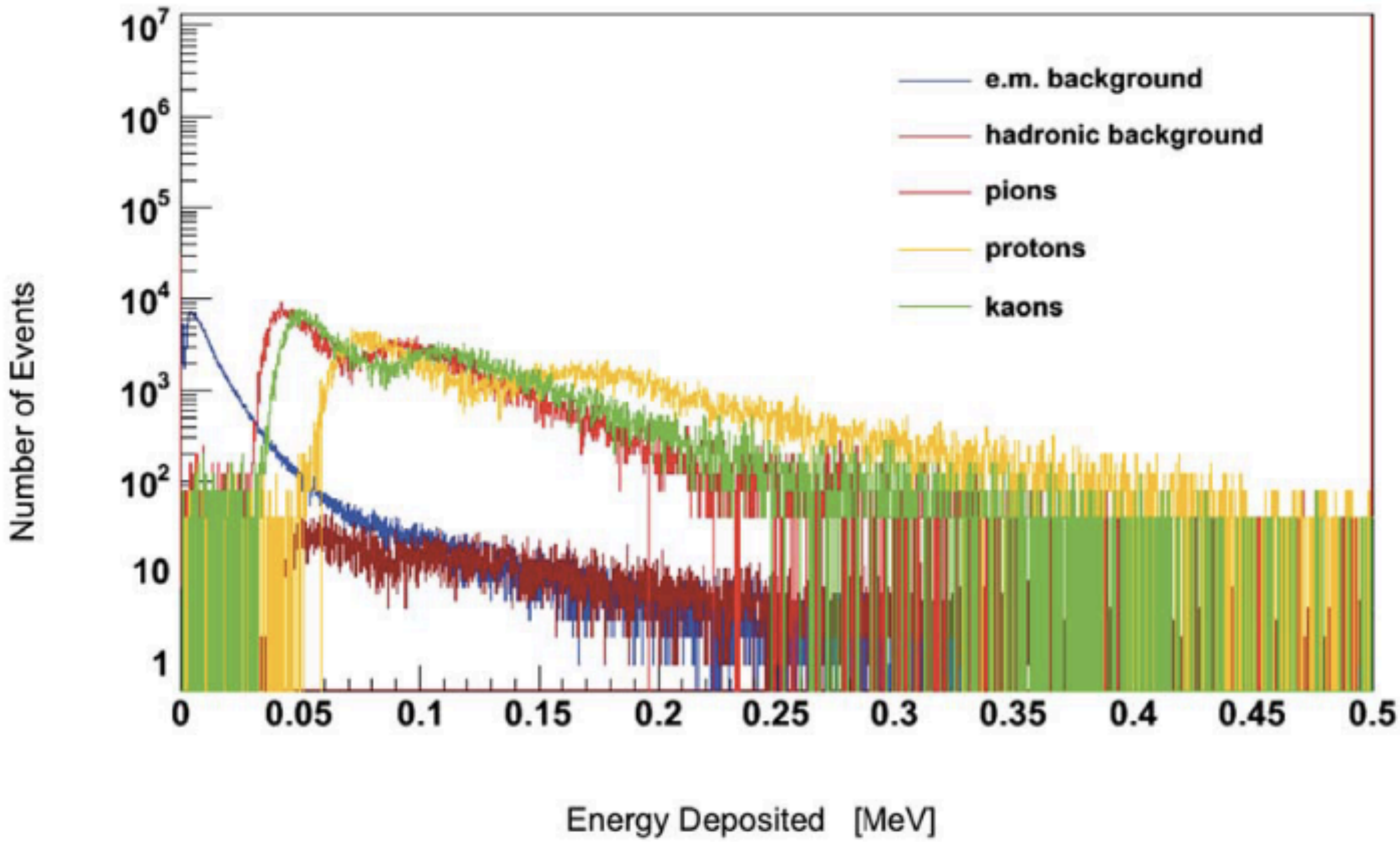


FIG. 3.2.4. The energy deposited for pion, proton, and kaon tracks, plus electromagnetic and hadronic backgrounds; signal $800 < p < 1000$ MeV.

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

SVT design and performance from CLAS12 data

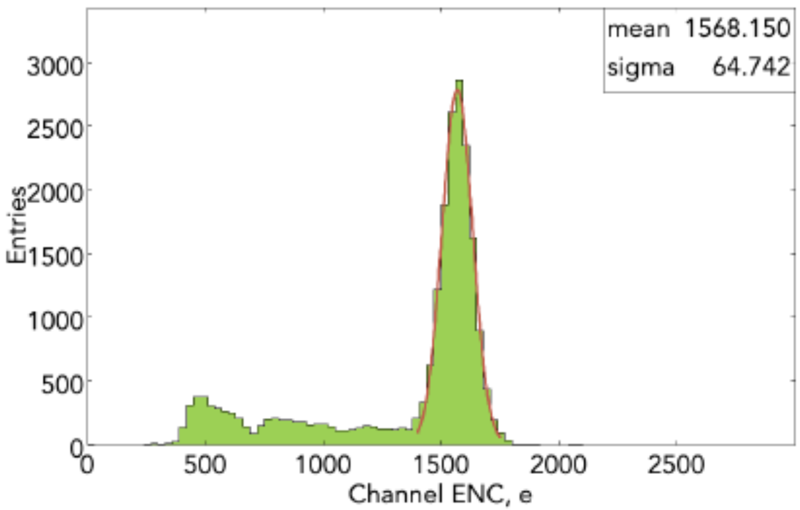


Figure 79: SVT ENC for all channels. The main peak corresponds to the full length strips (33 cm). The shoulder on the left side is related to the shorter strips.

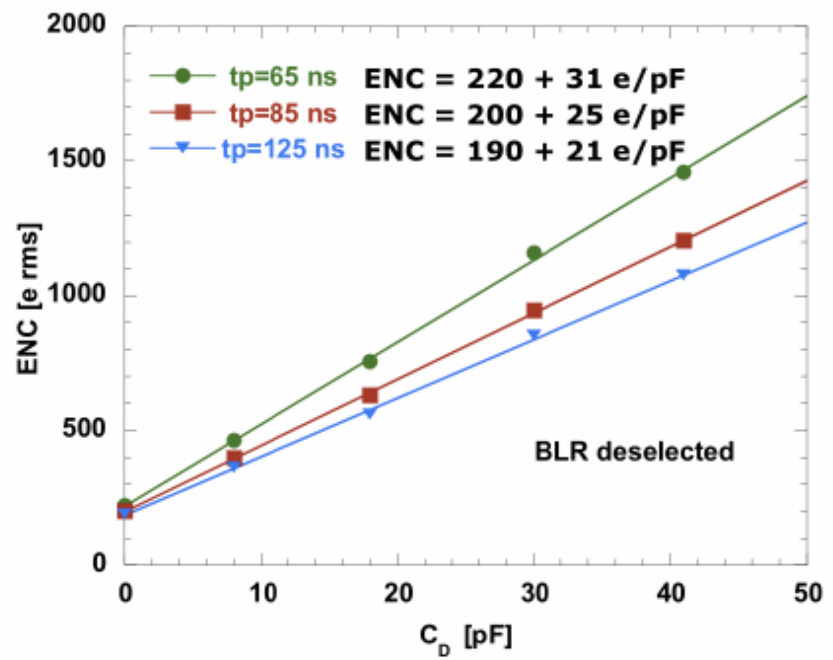


Figure 59: FSSR2 ENC vs. detector capacitance at different shaping time settings.

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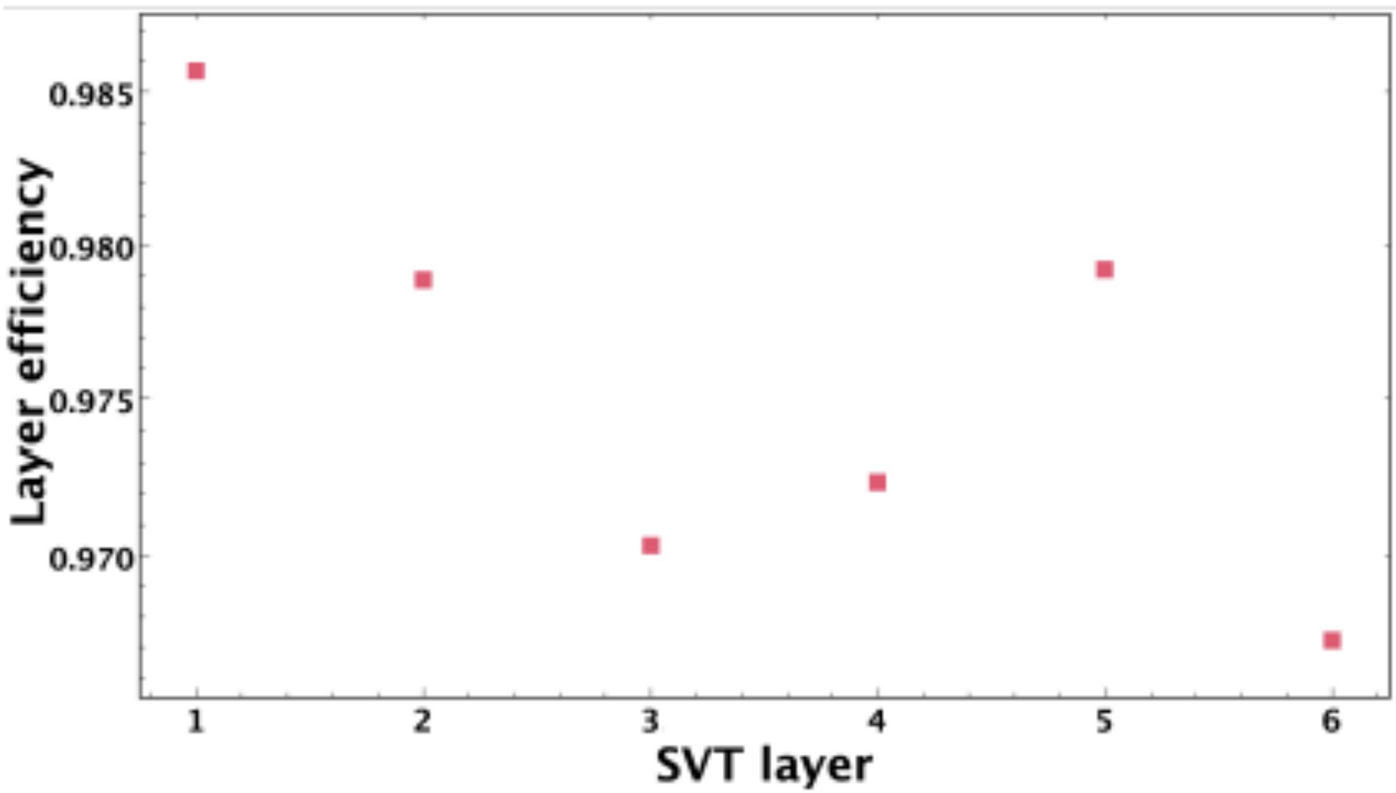
SVT design and performance from CLAS12 data



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SVT design and performance from CLAS12 data

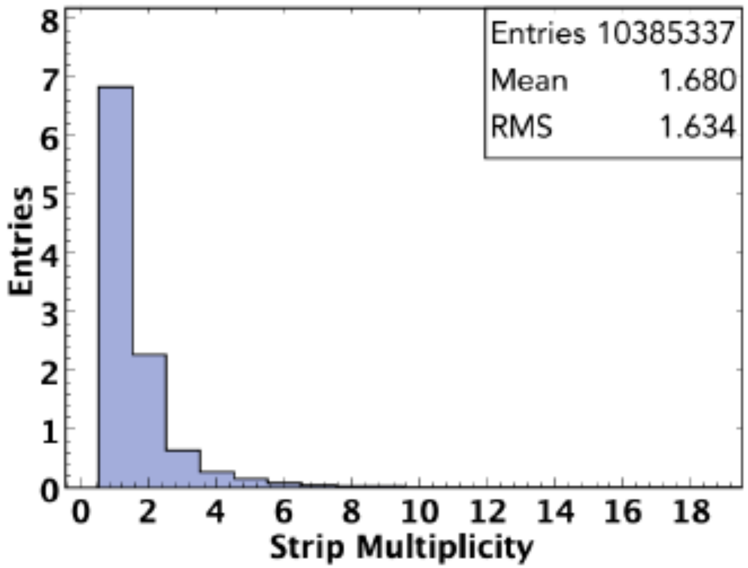


Figure 91: Strip multiplicity of the clusters in the cosmic run. The mean cluster size is in agreement with the simulated data.

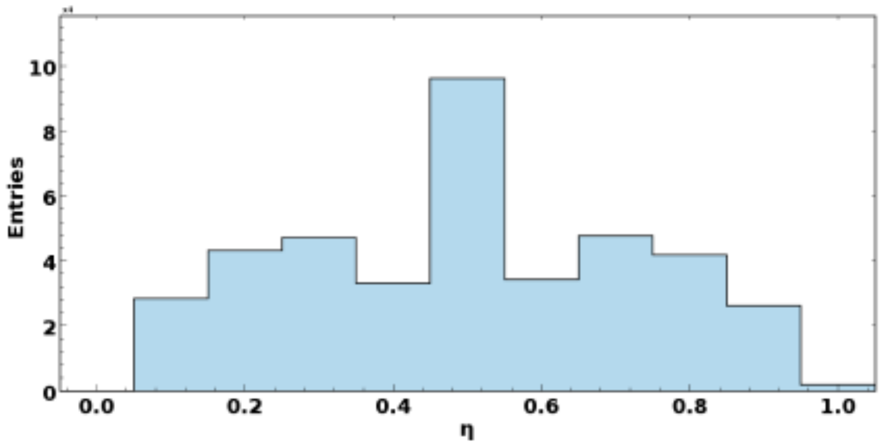


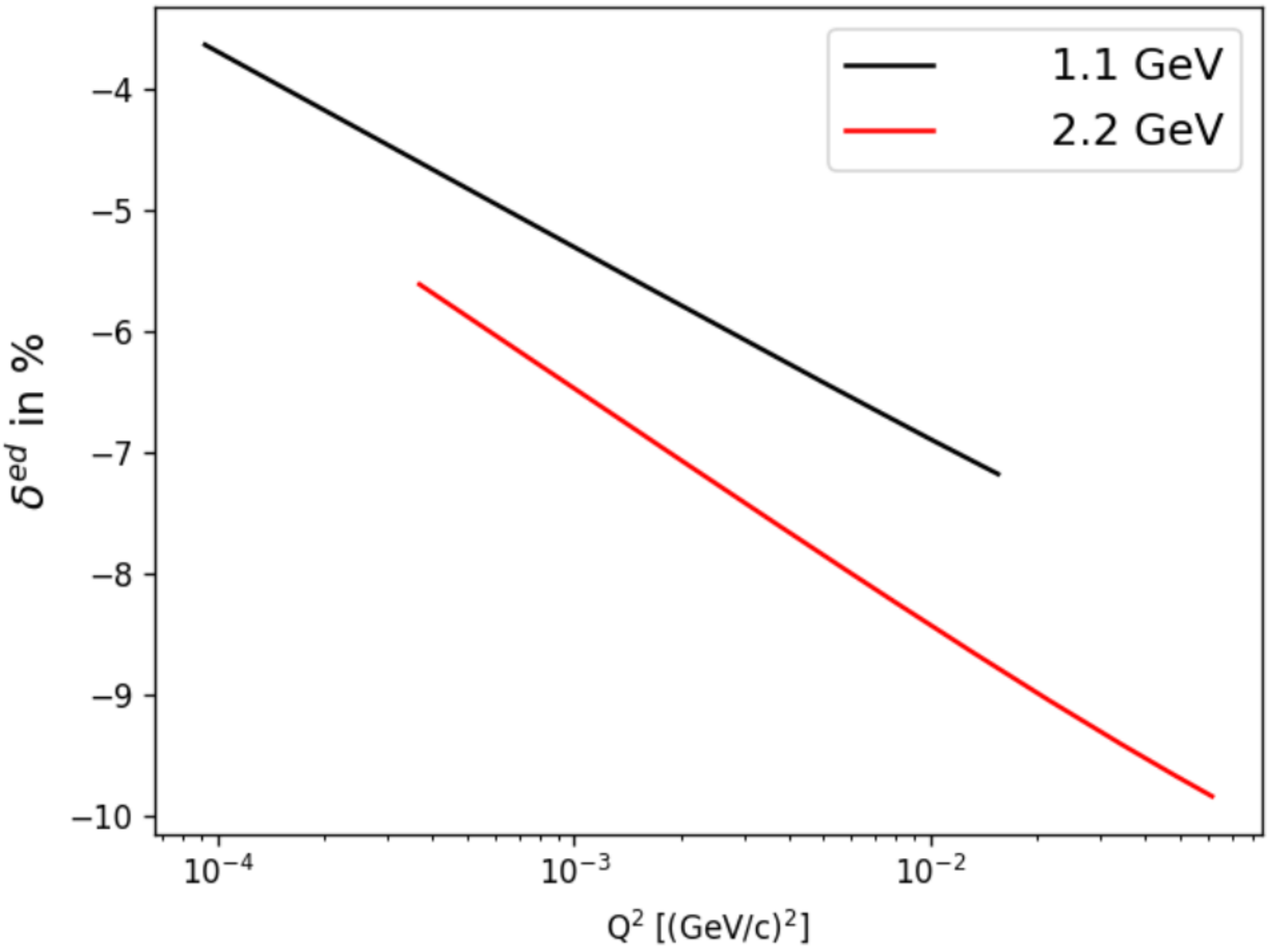
Figure 90: Charge sharing in the SVT sensor: η-function for the two-strip clusters.

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

e-D radiative corrections

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



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**

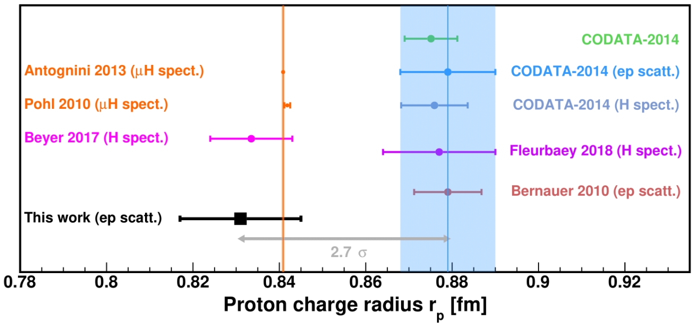
To mimic the bin-by-bin statistical fluctuation of the data, the G_C pseudo-data statistical uncertainty is smeared by adding the G_C in each Q^2 bin with a random number following the Gaussian distribution,

Item	Uncertainty (%)
Event selection	0.110
Radiative correction	0.045
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

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