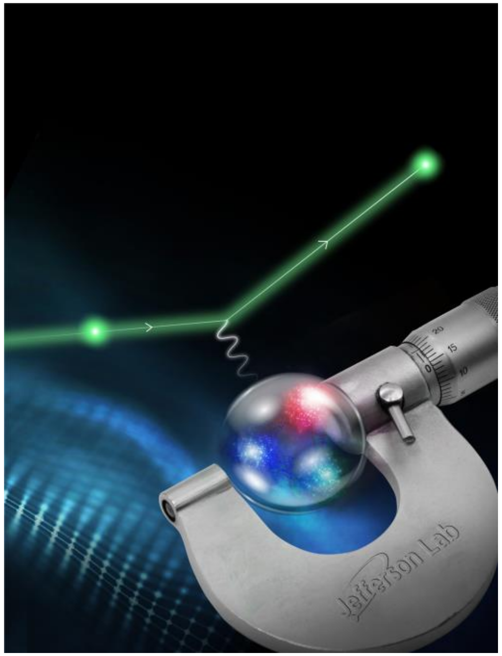
PRadII - DRad Experiments Current Status and Plans



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For the PRad-DRad Collaboration

CLAS Collaboration Meeting July 2023

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Outline

- Proton charge radius and PRad experiment
- PRad-II experiment (E12-20-004)
- Hidden Sector Particles/X17 search experiment (E12-21-003)
- DRad experiment (PR12-23-011)

Jefferson Lab Duke UNIVERSITY

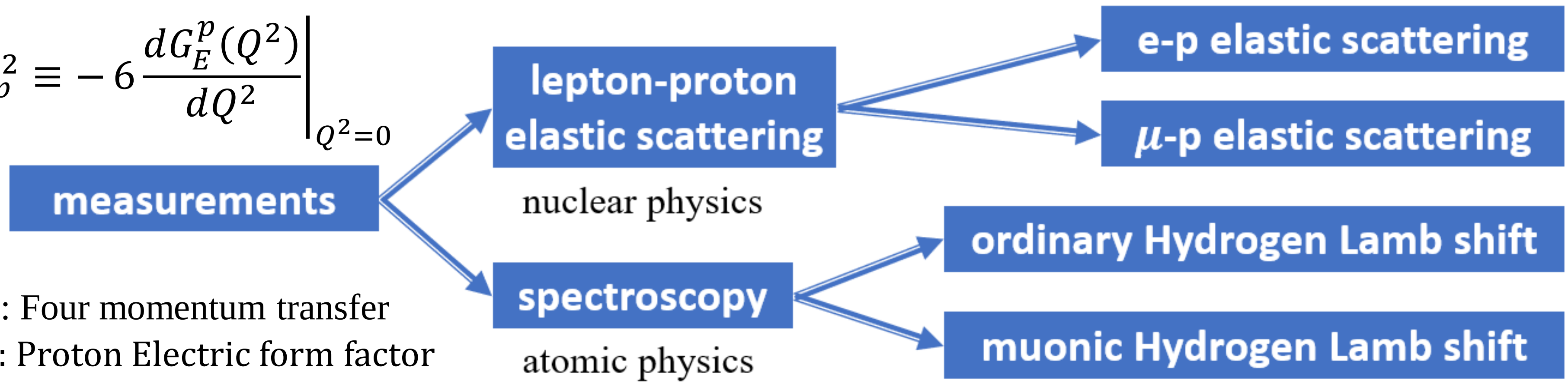
Proton root-mean-square charge radius

- The proton is the primary, stable building block of nearly all visible matter in the Universe.

Proton rms charge radius r_p *— an important quantity of the proton:*

- Understand how QCD works in the non-perturbative region
- Important input to the bound-state QED calculations, the proton finite size contributes to the muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%
- Impacts the determination of the Rydberg constant R_∞

$$r_p^2 \equiv -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$



Q^2 : Four momentum transfer
G_E^p : Proton Electric form factor

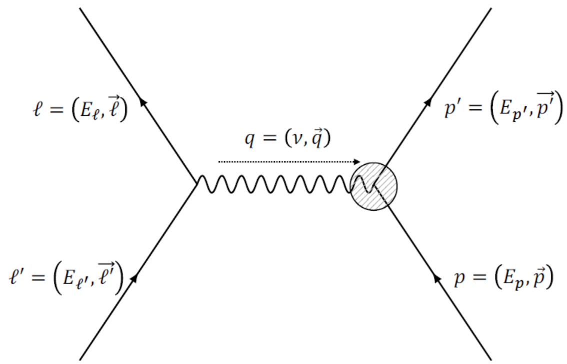
Unpolarized e-p elastic scattering

- In the Born approximation (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2) \right)$$

$$Q^2 = 4EE' \sin^2(\theta/2)$$

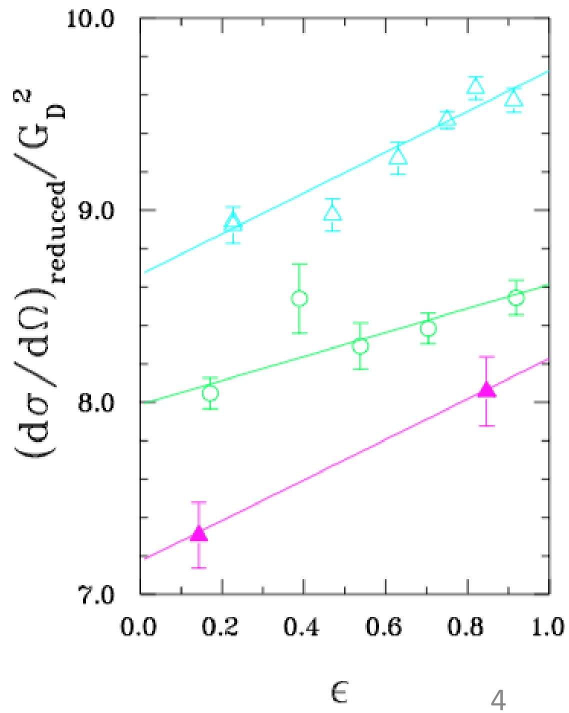
$$\tau = Q^2/(4M_p^2) \quad \varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$$



$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = G_M^{p\,2}(Q^2) + \frac{\varepsilon}{\tau} G_E^{p\,2}(Q^2)$$

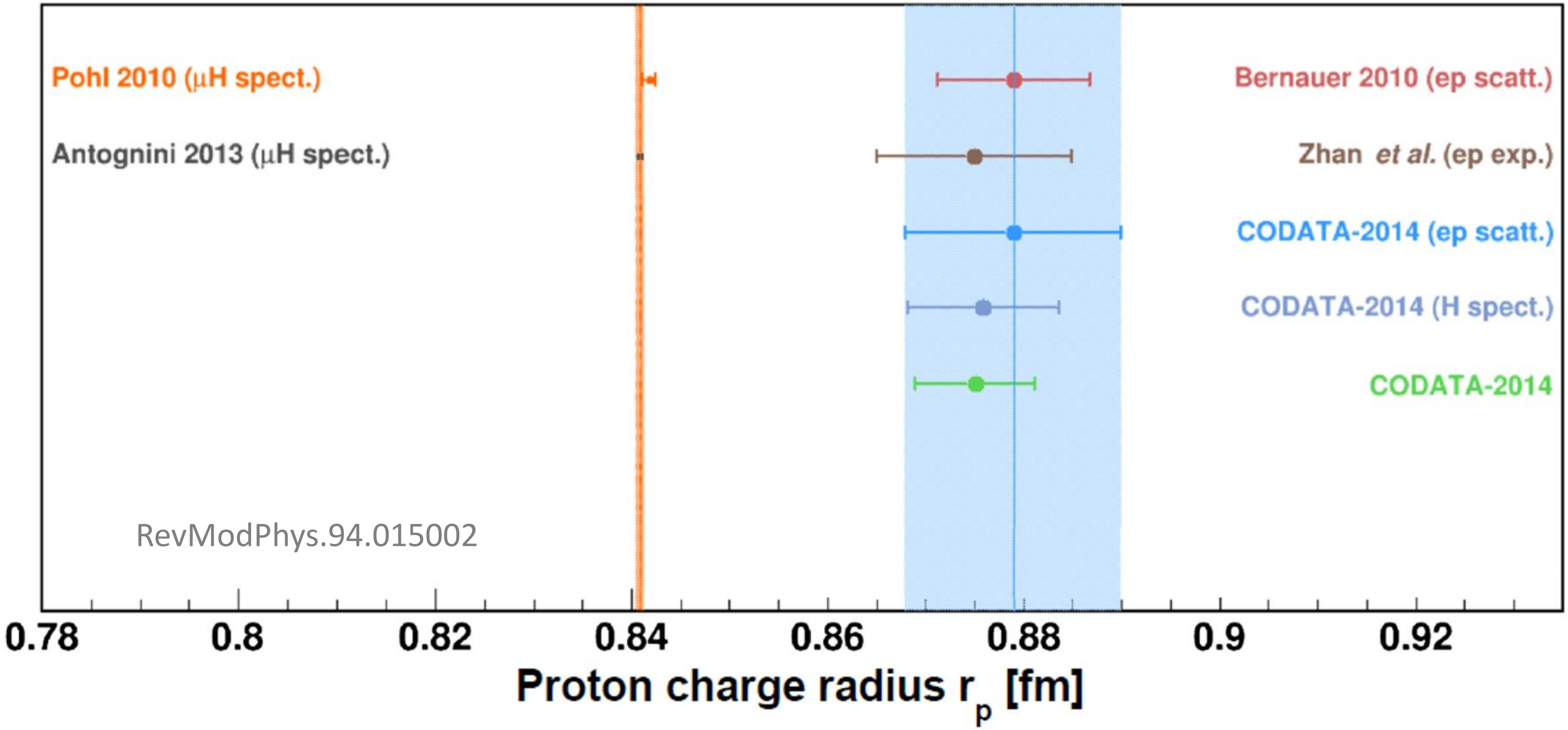
- G_E^p and G_M^p can be extracted using Rosenbluth separation

- At very low Q^2 region, cross section dominated by G_E^p, one may also extract G_E^p assuming G_M^p in certain form.



Proton charge radius puzzle

~ 8σ discrepancy between muon and electron based measurements



Proton rms charge radius measured using

electrons: 0.8770 ± 0.0045 (CODATA2010 + Zhan et al.)

muons: 0.8409 ± 0.0004

The PRad-II experiment

PRad result: $r_p = 0.831 \pm 0.007(\text{stat.}) \pm 0.012(\text{sysm.})\text{fm}$ supports a smaller r_p

→ PRad has not reached its ultimate precision for this experimental technique

→ Possible difference between proton radius from electronic vs. muonic system

→ Need higher precision to investigate the discrepancy between PRad and MAMI form factor

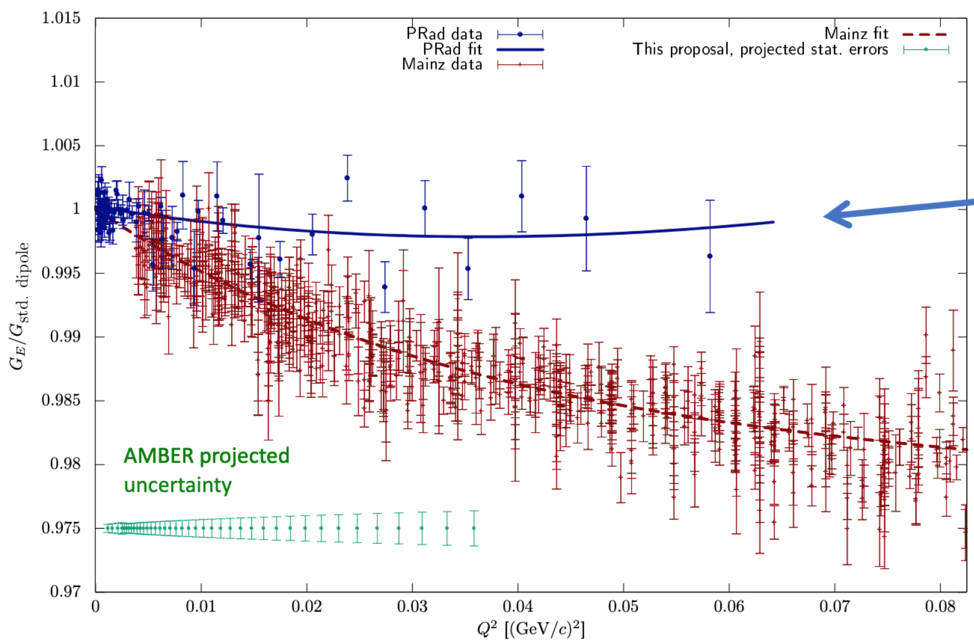
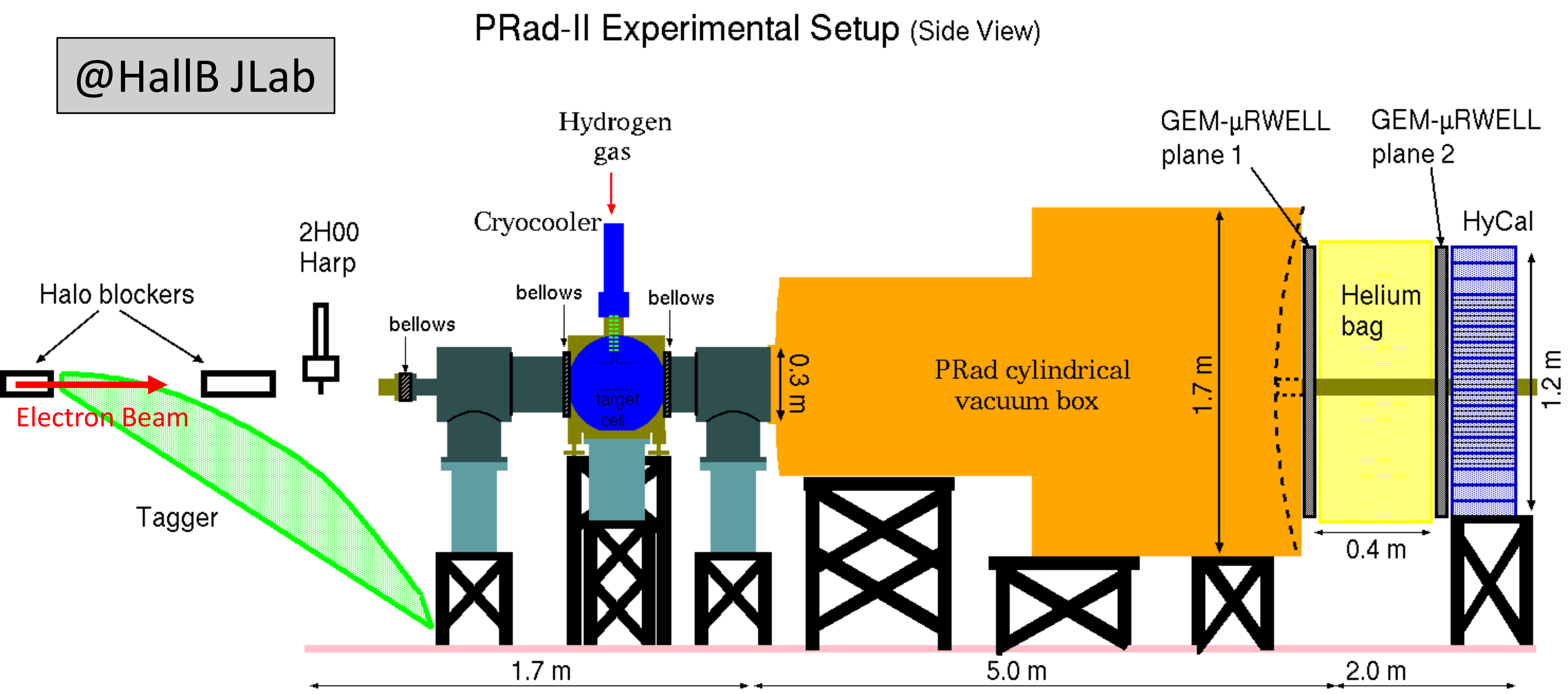


figure: J. Bernauer

- Based on the PRad experimental technique
- Three beam energies, E = 0.7, 1.4 and 2.1 GeV to increase Q^2 range
- Even lower $Q^2 \sim 10^{-5}(\text{GeV/c})^2$
- Upgrades to the original detectors, new detectors, new calculations…
- Overall uncertainty reduced by **3.8** times compared to PRad

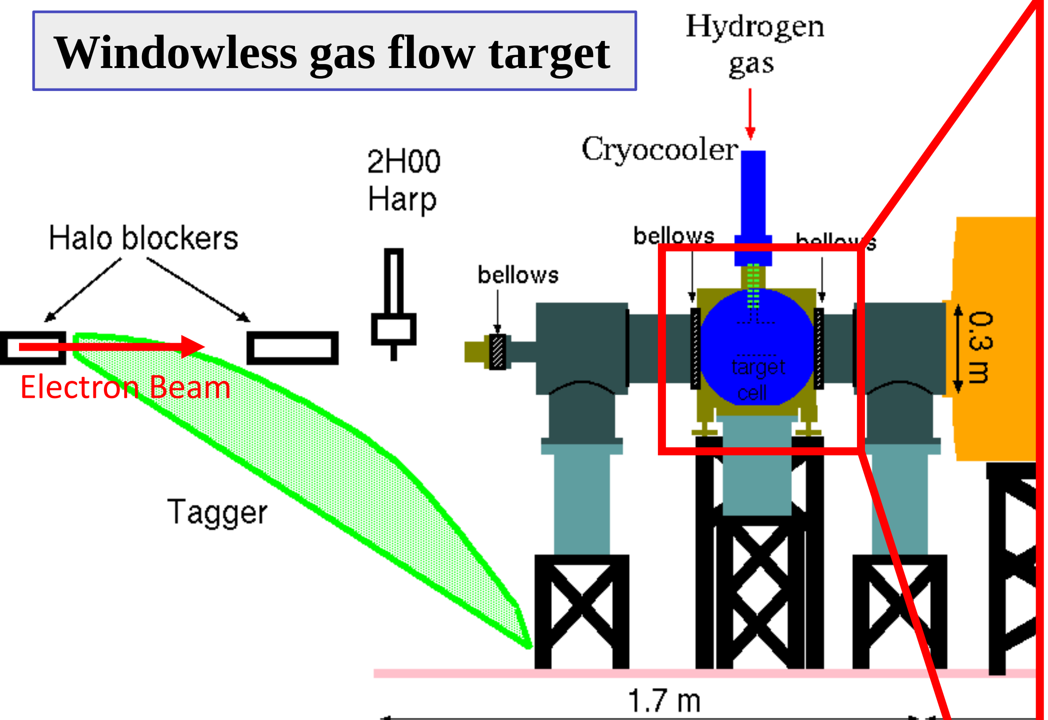
PRad-II experimental apparatus

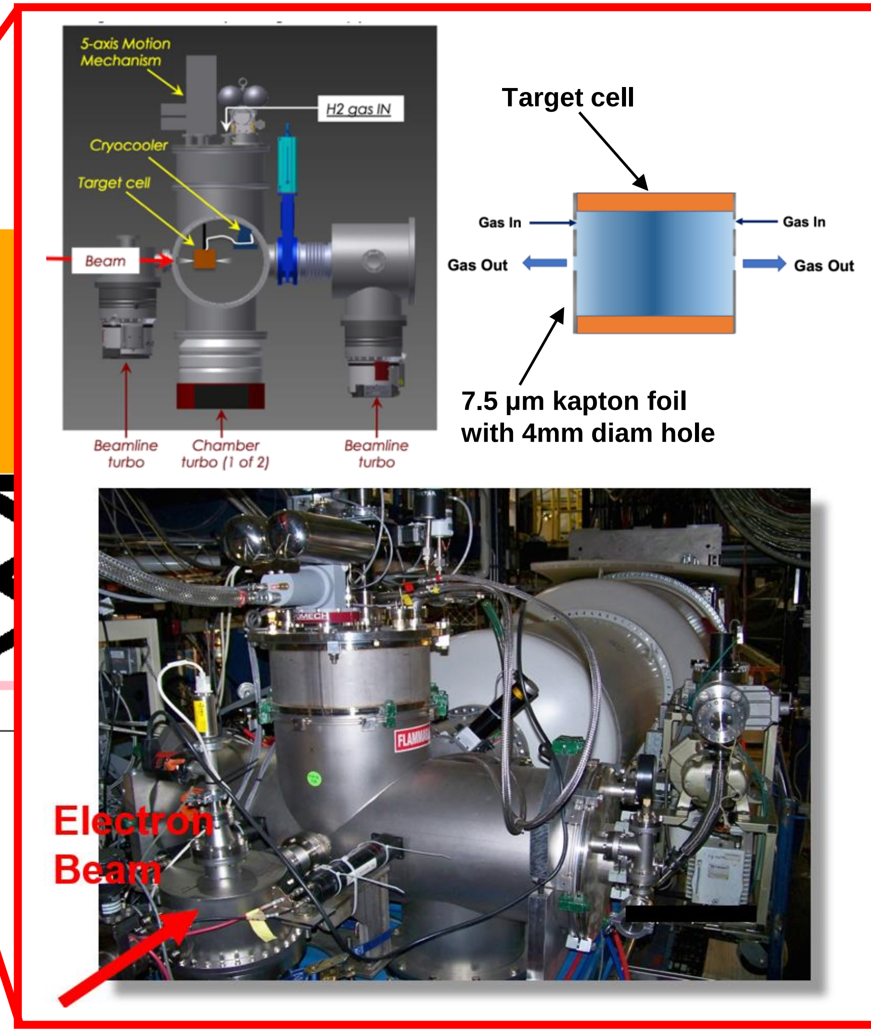
- PRad-II experiment (E12-20-004), approved with highest "A" scientific rating among all proposals submitted in June 2020



PRad-II experimental apparatus

Windowless gas flow target



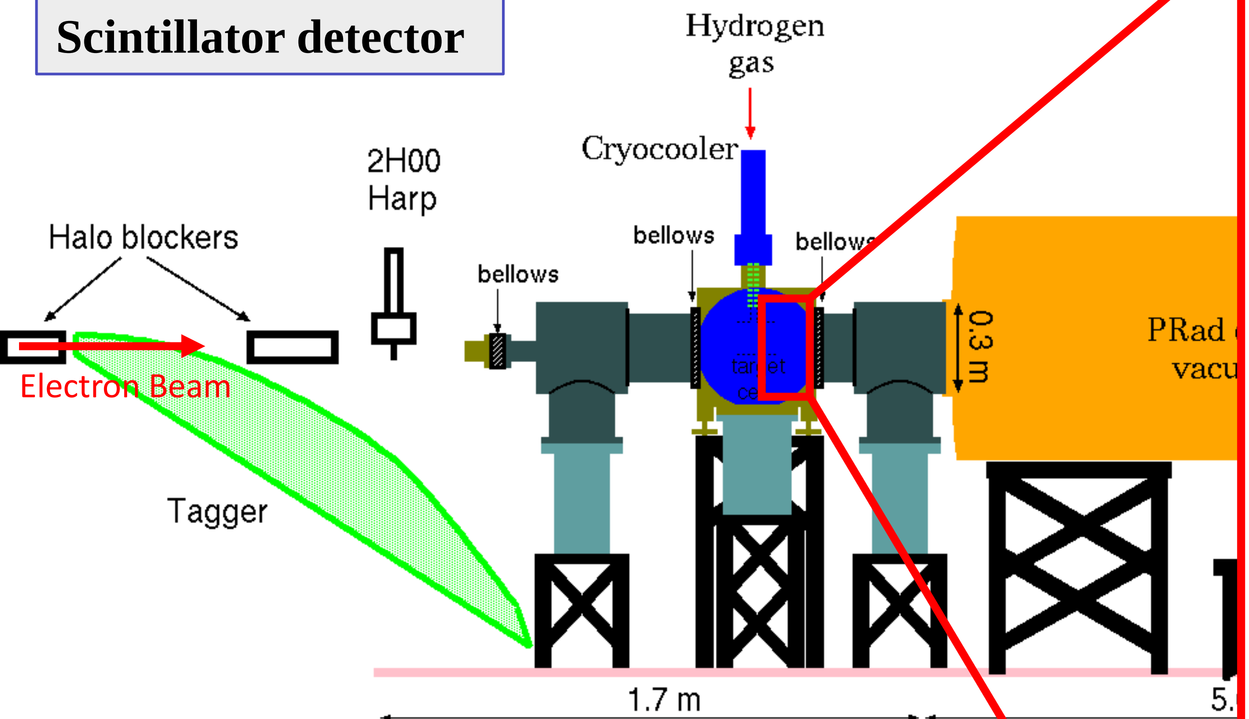


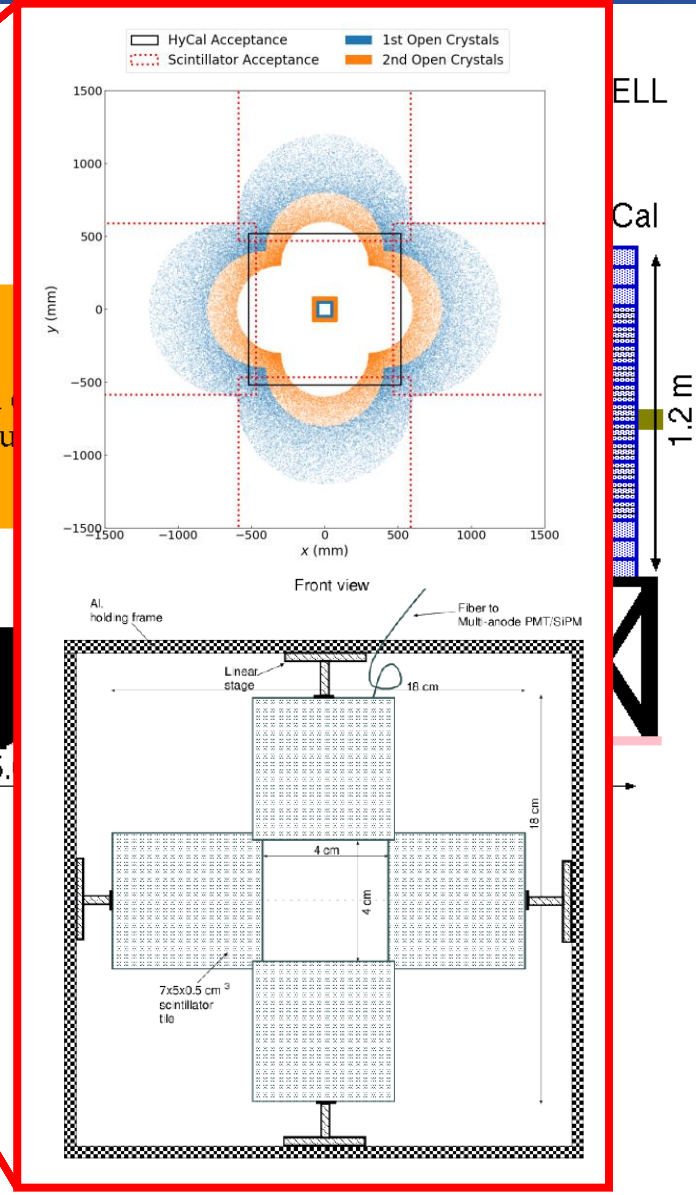
- 29 cm diam x 5.5 cm long target cell
- 4 mm diam holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} atoms / cm^2
- remove major background source

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

PRad-II experimental apparatus

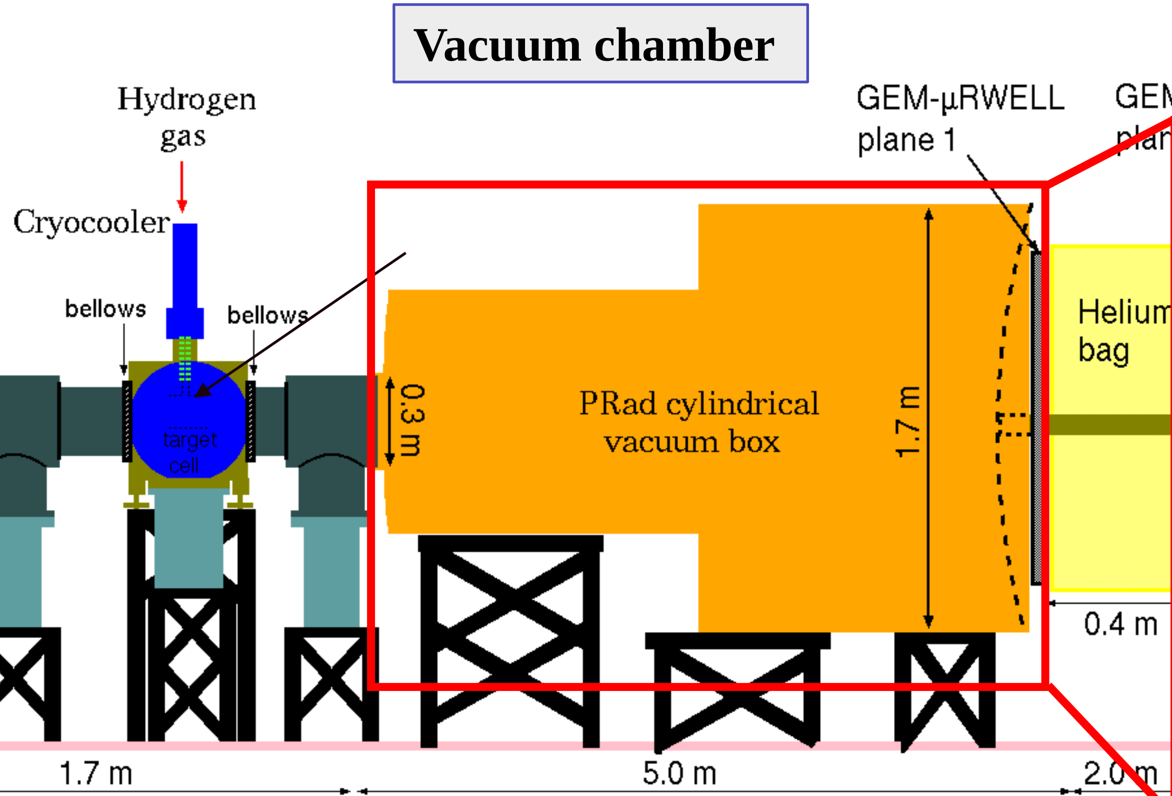
Scintillator detector





- 25 cm downstream from the target center
- Four $7 \times 5 \times 0.5\ \mathrm{cm}^3$ tiles of plastic scintillators
- Each tile attached to a linear stage in x/y direction
- Identify e-p elastic events and Møller events at 0.5~0.8 degrees

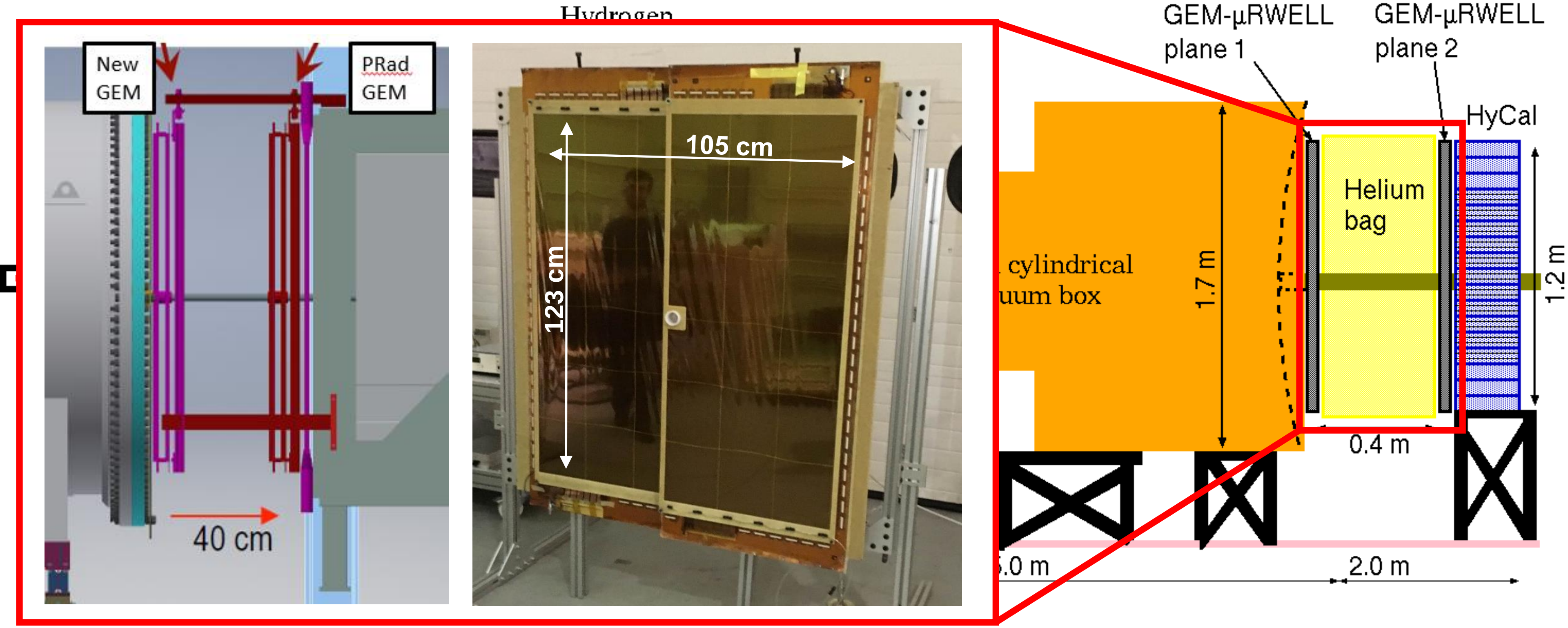
PRad-II experimental apparatus



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

PRad-II experimental apparatus

Tracking detectors



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

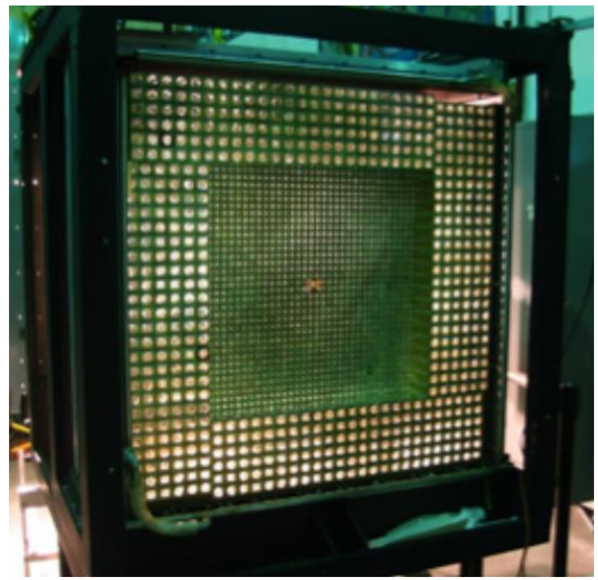
PRad-II experimental apparatus

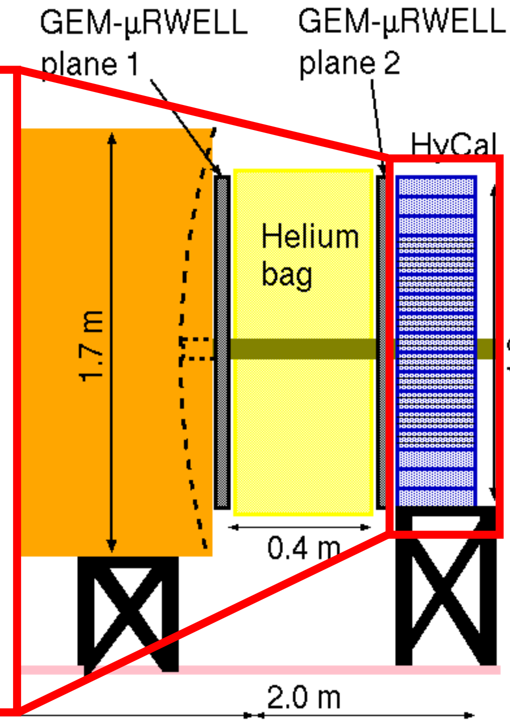
Upgraded Hybrid Calorimeter (HyCal)

- High resolution and efficiency
- 5.5 m from the target
- Scattering angle coverage:
  ~ 0.6° to 7.5°
- Full azimuthal angle coverage

PRad HyCal:

- Inner 1156 $PbWO_4$ modules
- Outer 576 lead-glass modules



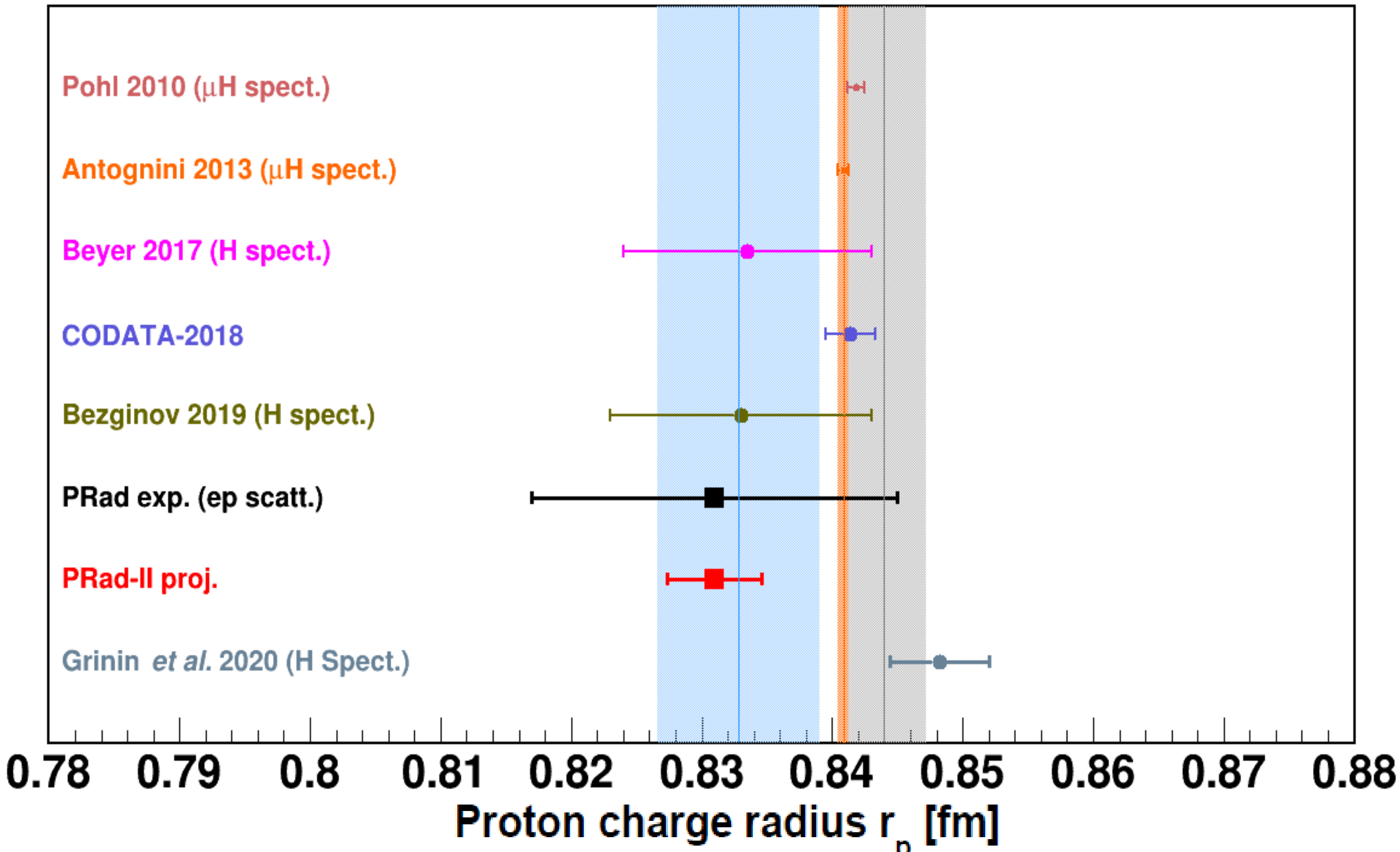


Upgraded HyCal:

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

PRad-II Projection

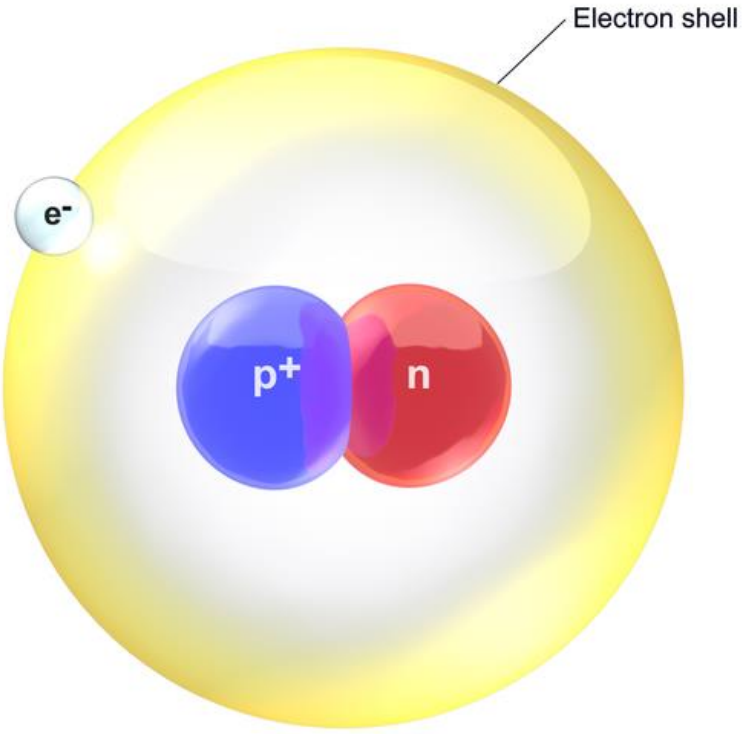
- The mentioned upgrades in hardware combines with the planned NNLO radiative correction calculations reduces the overall uncertainty by a factor of **3.8** compared to PRad
- Form factor measurements reach even lower $Q^2 \sim 10^{-5}(\mathrm{GeV/c})^2$



RevModPhys.94.015002

Deuteron

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



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

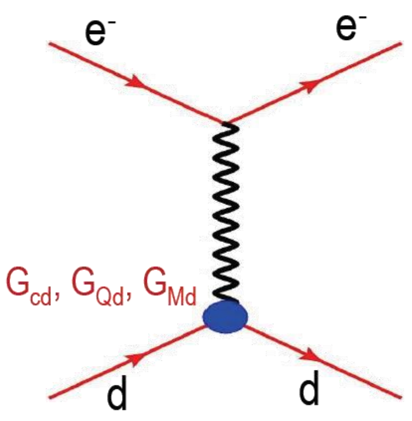
$$r_d^2 \equiv -6 \frac{dG_C^d(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

Q^2 : Four momentum transfer
$\mathrm{G_C^d}$: Deuteron charge form factor

Unpolarized e-d elastic scattering

- In the Born approximation (one photon exchange):

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



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

$$A(Q^2) = {\mathrm{G}_\mathrm{C}^d}^2(Q^2) + \frac{2}{3}\tau {\mathrm{G}_\mathrm{M}^d}^2(Q^2) + \frac{8}{9}\tau^2 {\mathrm{G}_\mathrm{Q}^d}^2(Q^2)$$

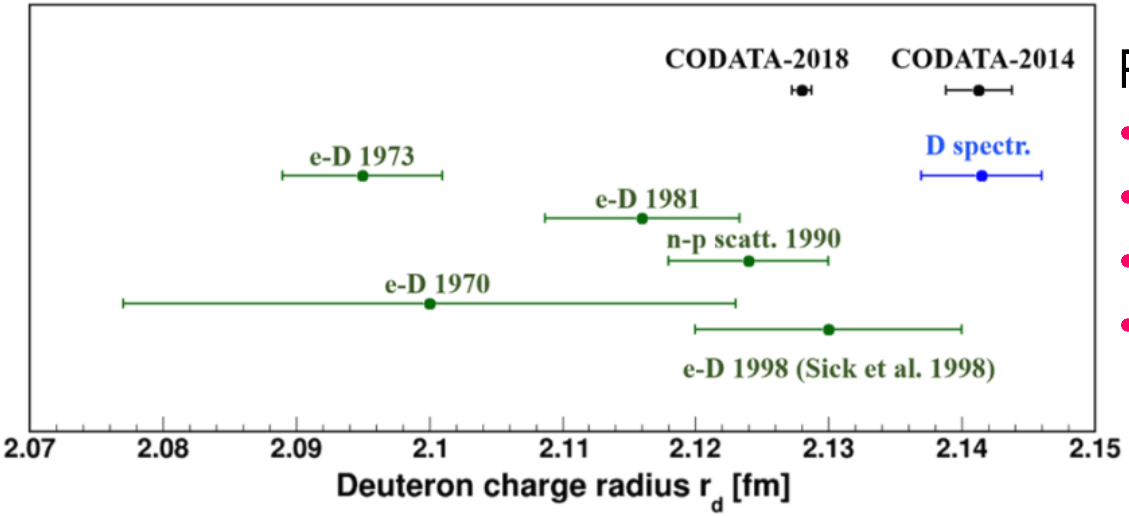
$$B(Q^2) = \frac{4}{3}\tau(1+\tau){\mathrm{G}_\mathrm{M}^d}^2(Q^2) \qquad \tau = Q^2/(4M_d^2)$$

- At very low Q^2(DRad), cross section dominated by $\mathrm{G_C^d}$, one may extract $\mathrm{G_C^d}$ by assuming $\mathrm{G_M^d}$ and $\mathrm{G_Q^d}$ in certain forms from parametrizations based on the data.

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

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

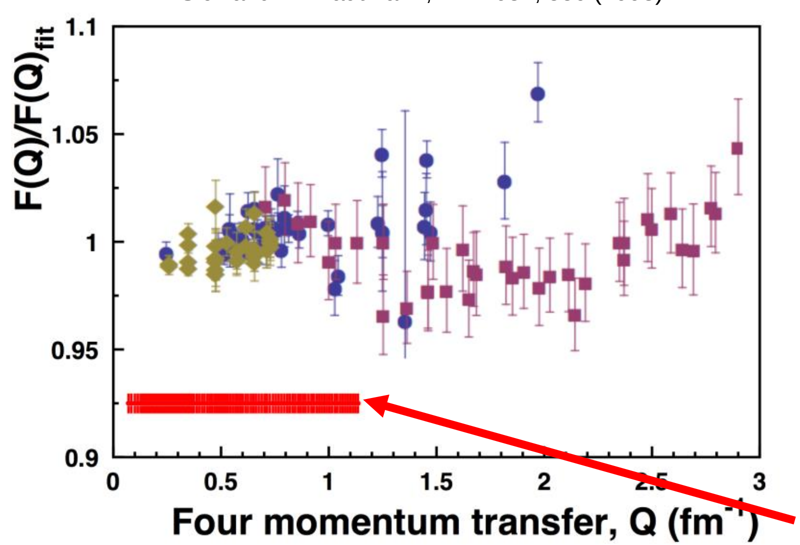
The deuteron charge radius from e-d scattering



Previous e-d scattering experiments:

- magnetic spectrometer method
- different types of targets
- normalized to *e-p* cross sections
- the most recent result in 1998 is a reanalysis of old data

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



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

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

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

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

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

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

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

The highlight of DRad proposal

- DRad proposal(PR12-23-011): calorimetric method with windowless gas flow target based on PRad-II experiment(E12-20-004)
- Measure *e-d* elastic cross sections at very low Q^2 range:

$$[5 \times 10^{-3} - 1.3]\mathrm{fm}^{-2} \,/\, [2 \times 10^{-4} - 5 \times 10^{-2}]\,\mathrm{GeV}^2$$

- Two beam energies, E = 1.1 and 2.2 GeV to increase Q^2 range
- A new two-layer cylindrical recoil detector for reaction elasticity
- Veto counters for timing (PrimEx veto counters)
- Simultaneous detection of $ee \to ee$ Møller scattering process to control systematics

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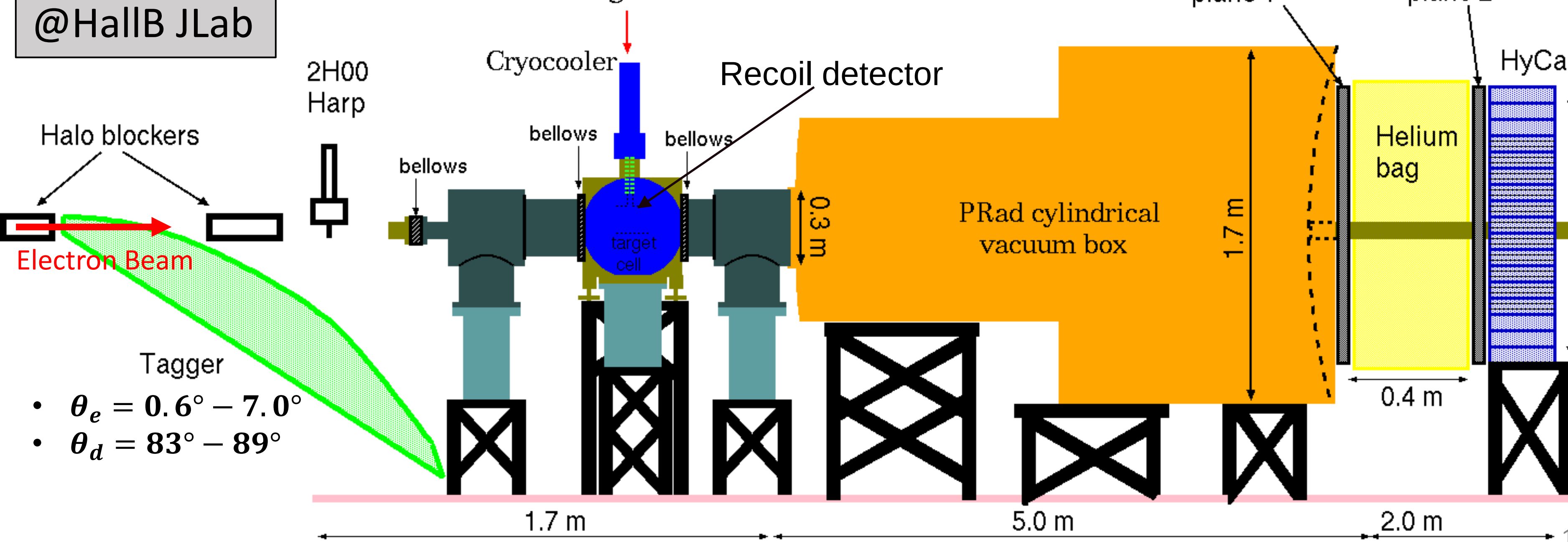


- $\theta_e = 0.6° - 7.0°$
- $\theta_d = 83° - 89°$

Proposed DRad experiment apparatus

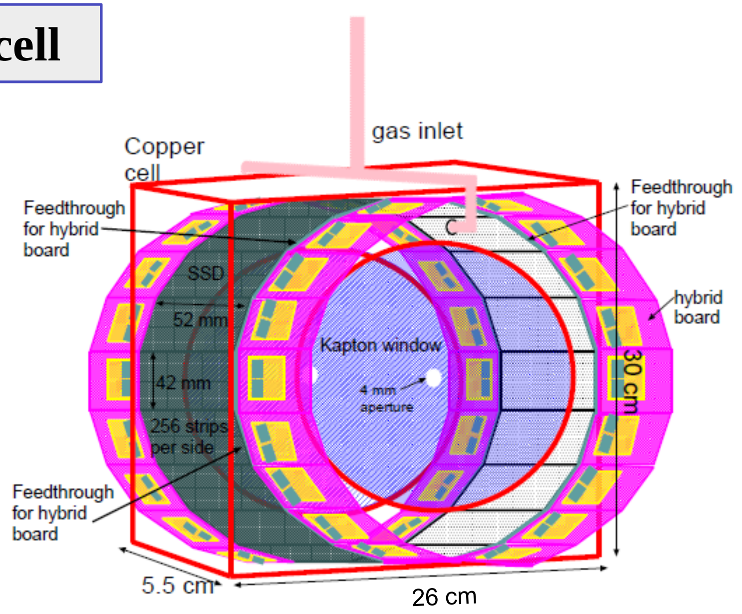
Si-strip Cylindrical Recoil Detector inside the target cell

Detect recoil deuteron, proton background, provide information:

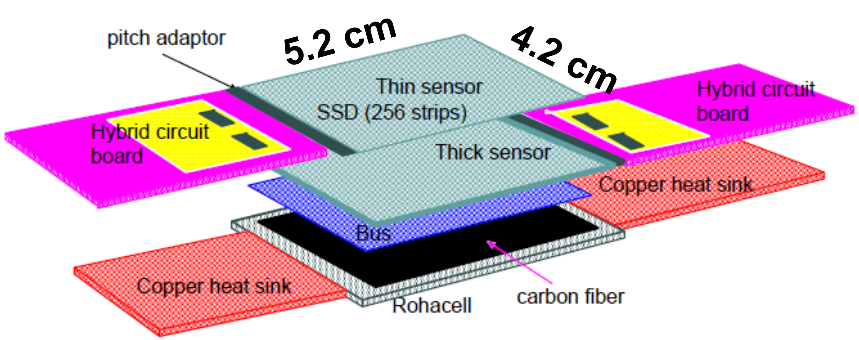
- Timing & Azimuthal angle
- Energy

Based on the CLAS12 Barrel Silicon Tracker (SVT)

- 20 panels of twin, single sided Si-strip detectors (42x52mm²), 20 sided polygon arrangement with around 13 cm radius
- Thicknesses:
  200 μm (inner layer), 300 μm (outer layer)
- 256 strips on each sensor:
  angular resolution 5 mrad (ϕ) 20 mrad (θ)
- Inactive SiO_2 layer can be as thin as 0.5 um



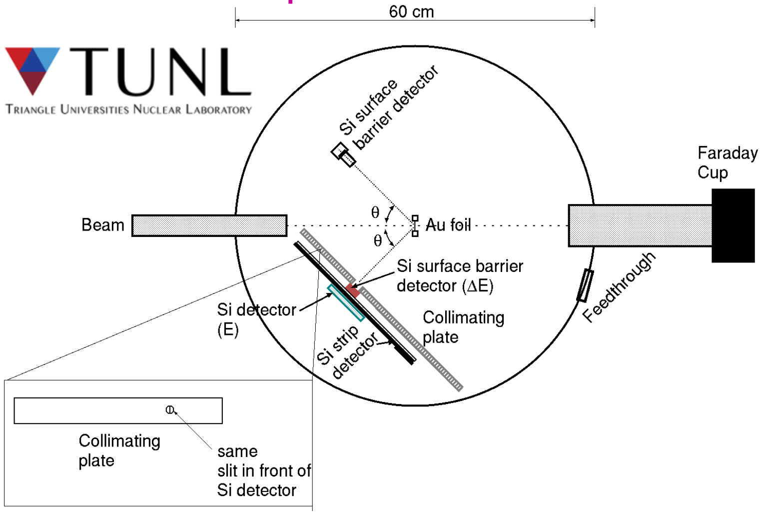
Single pair of Si-strip detectors

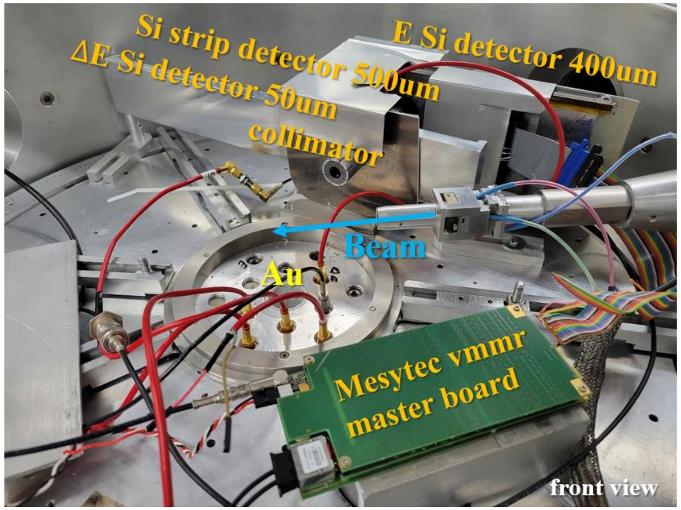


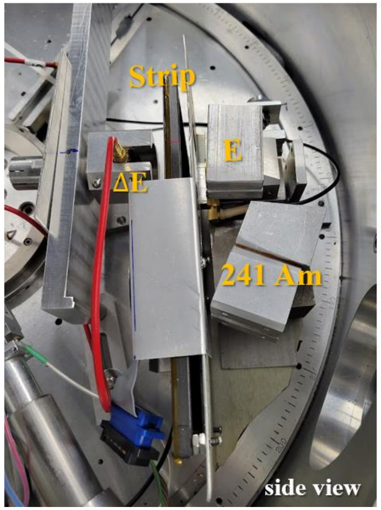
CLAS12 Technical Design Report, 2008 (`https://www.jlab.org/Hall-B/clas12_tdr.pdf`); CLAS12 Detector documentation (`http://clasweb.jlab.org/clas12offline/docs/detectors/html/svt/introduction.html`)

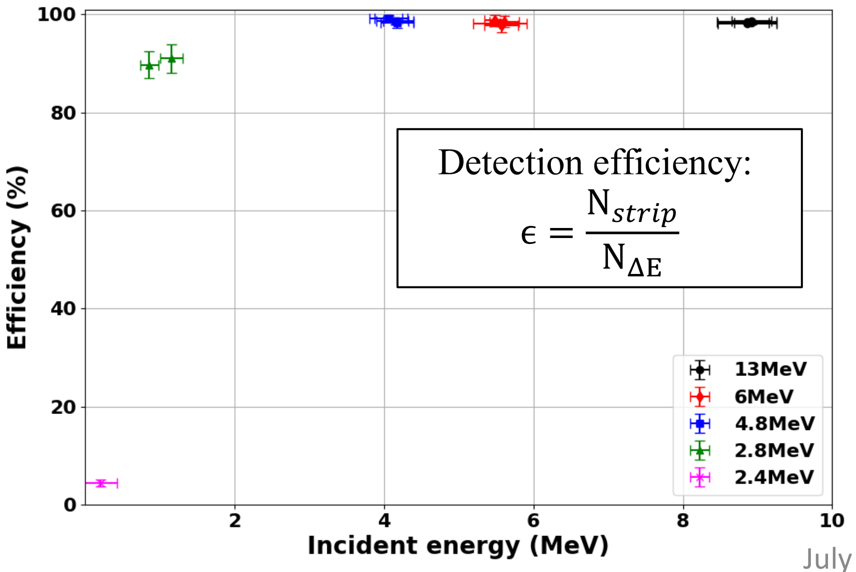
The recoil detector calibration at TUNL

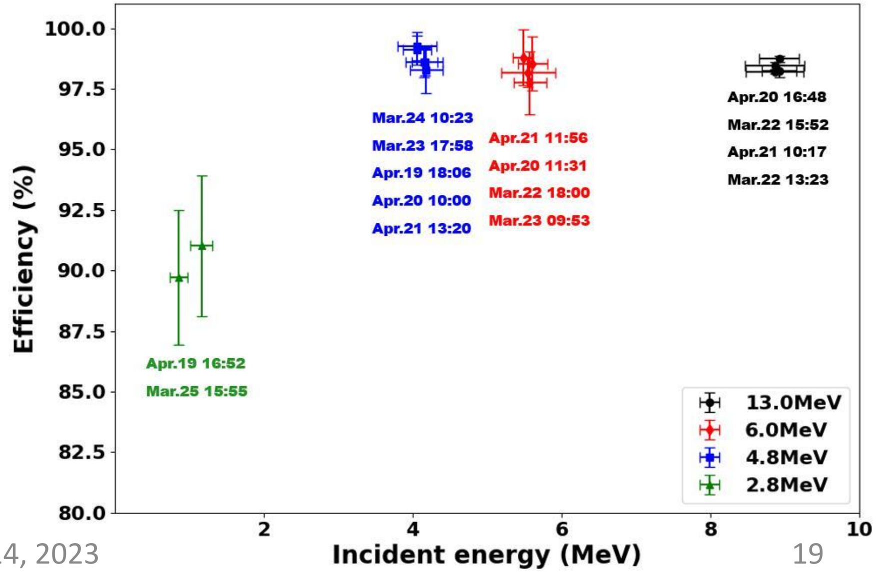
- The Si strip detector (SSD) can be calibrated using e-p elastic run on hydrogen and with the 2.5~13 MeV p/D beam from the Tandem accelerator at TUNL.





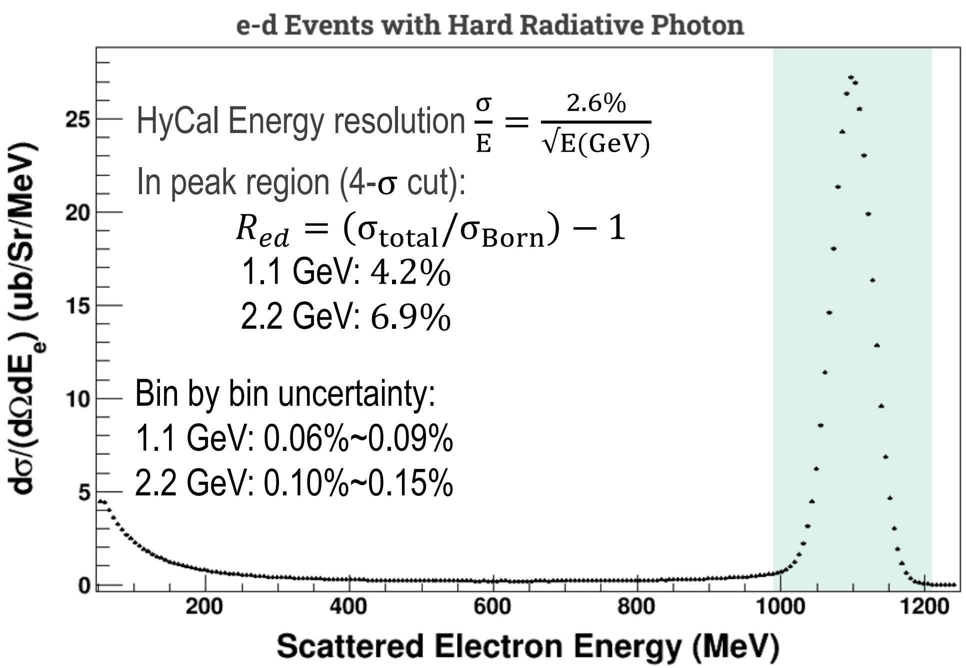






Radiative Correction (RC) Calculations

- 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)]



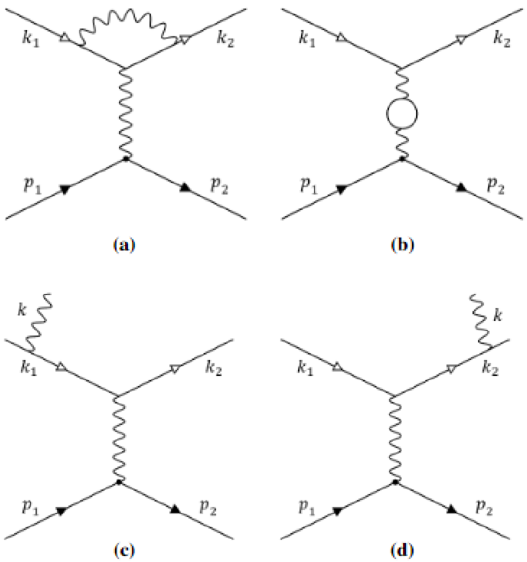


Fig. 2 Feynman diagrams from (a) to (d), describing the lowest-order QED RC contributions to the unpolarized elastic $e + d$ scattering cross section: (a) vertex correction; (b) vacuum polarization; (c), (d) electron-leg bremsstrahlung.

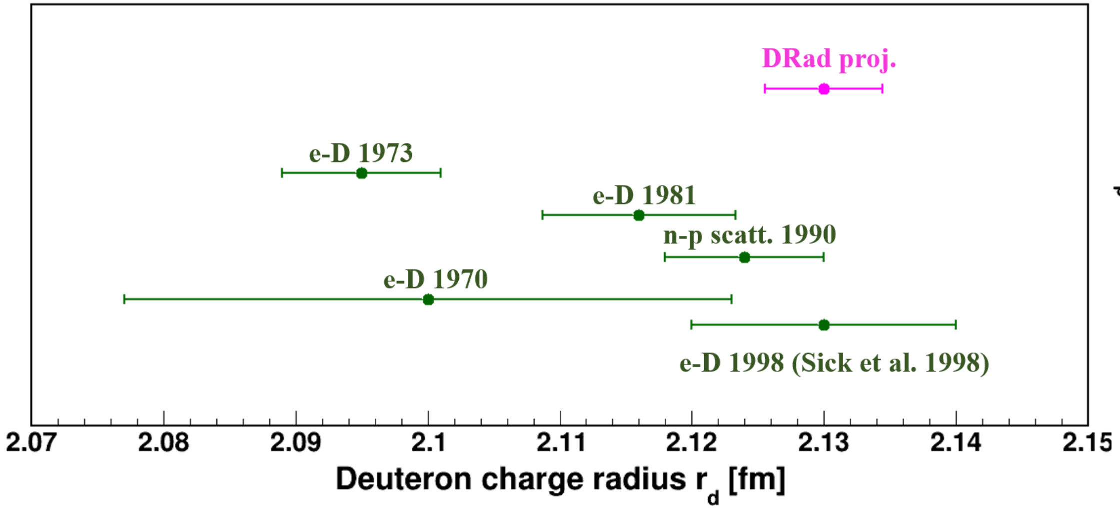
- An event generator is developed and the total correction to the elastic e-d Born cross section in the DRad kinematics is calculated
- The uncertainty of the NLO calculation is estimated, taking into account higher-order contributions, calculation assumptions, and differences between various recipes
- The paper is to be submitted to arXiv and European Physical Journal A

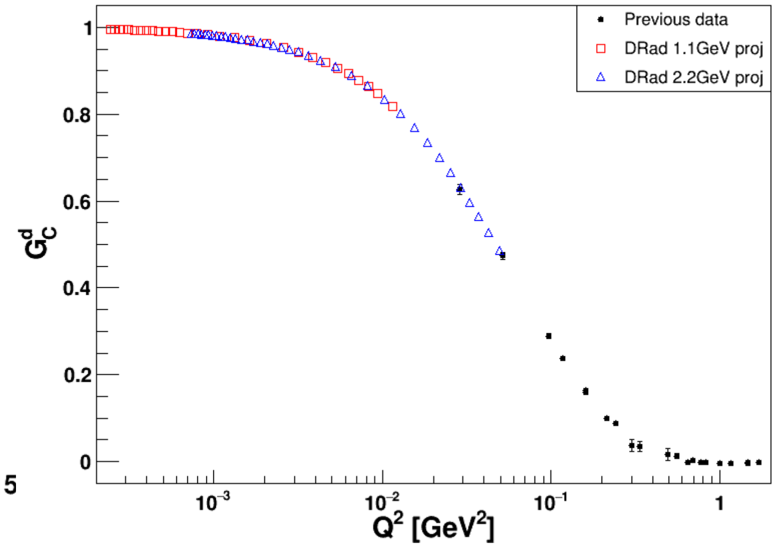
DRad projection

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

Expected R_d uncertainty : 0.2%



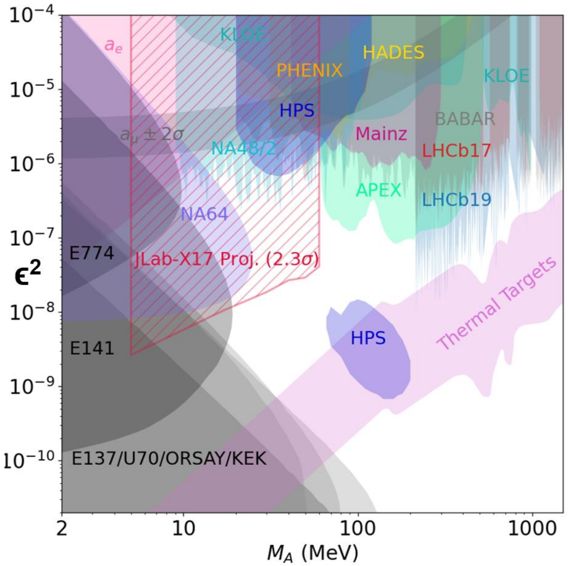


The most precise single measurement from e-d elastic scattering

Hidden Sector Particles/X17 Search Experiment (E12-21-003)

- The experiment has two experimental objectives:
  1) Validate existence or establish an experimental upper limit on the electroproduction of the hypothetical X17 particle claimed in two ATOMKI low-energy proton-nucleus experiments.
  2) Search for "hidden sector" intermediate particles (or fields) in [3 – 60] MeV mass range produced in electron-nucleus collisions and detected in e^+e^- (or $\gamma\gamma$) channels.
- The method:
  "bump hunting" in the invariant mass spectrum over the beam background.
  direct detection of all final state particles (e', e^+e^- and/or $\gamma\gamma$) → full control of kinematics
- Electroproduction on heavy nucleus in forward directions:
  $e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta$, with $X \rightarrow e^+e^-$ (with tracking)
  and $X \rightarrow \gamma\gamma$ (without tracking)

  in mass range of: [3 - 60] MeV,
  target: Tantalum, ($_{73}Ta^{181}$), 1 μm (2.4×10^{-4} r.l.) thick foil.



- All 3 final state particles will be detected in this experiment:
  - ✓ scattered electrons, e', with 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ decay e+ and e- particles, with 2 GEMs and $PbWO_4$ calorimeter;
  - ✓ or decay $\gamma\gamma$ pairs, with $PbWO_4$ calorimeter (and GEMs for veto).

arXiv:2108.13276

Summary

- PRad-II experiment:
  - Bring the best independent form factor measurement at low Q^2 range
  - Address the FF difference between PRad and MAMI
  - reach lowest Q^2 range $10^{-5}\mathrm{GeV}^2$

- Hidden Sector Particles/X17 search experiment:
  - Uniquely cost effective search for hidden-sector particles in 3~60 MeV mass range
  - Expect to run in 2025

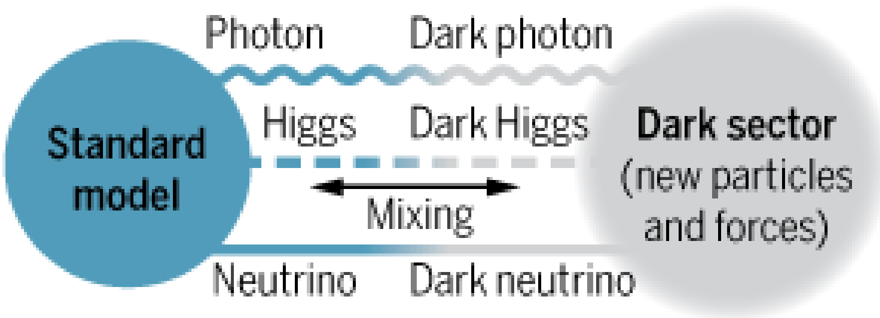
- DRad experiment:
  - Perform the deuteron form factor measurement at very low Q^2 range from cross section independently from the e-p cross section
  - Extract the deuteron charge radius with highest precision in e-d scattering

Acknowledgment: This work is supported in part by the U.S. Department of Energy under Contract No. DE-FG02-03ER41231.

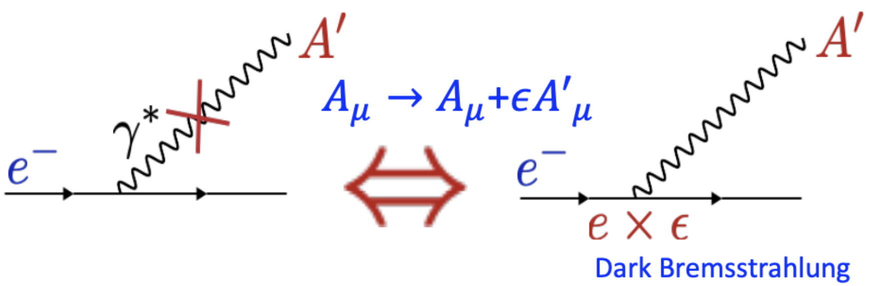
Backup

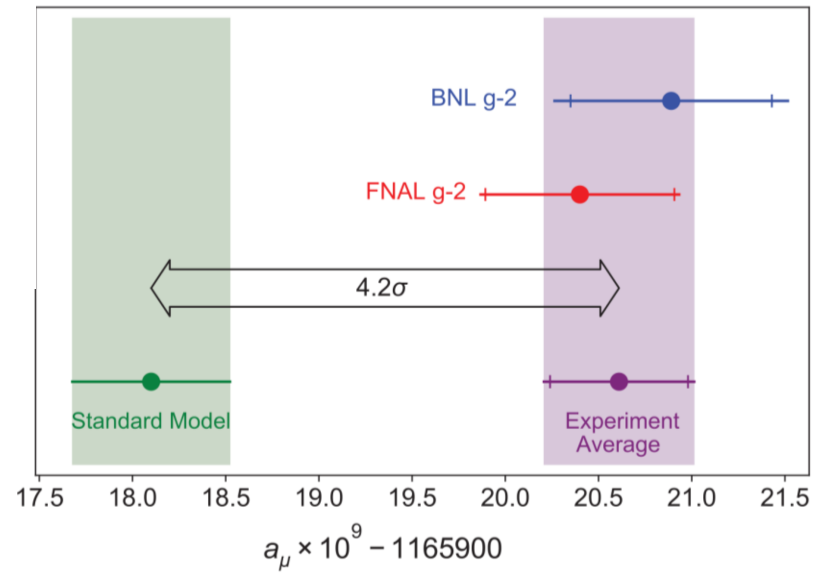
Hidden Sector Particles/X17

- The existence of the dark matter (DM) is well established by astronomical measurements
- No direct information about the DM composition



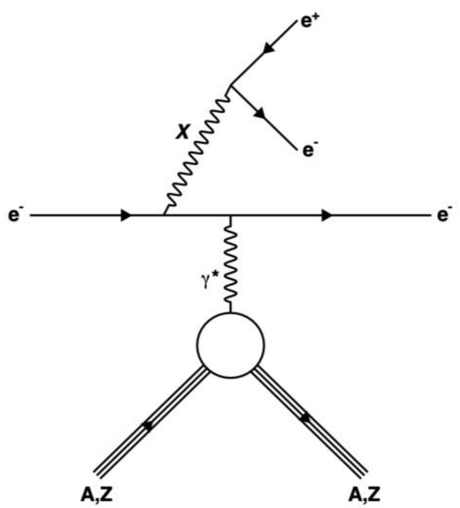
photon - dark photon mixing is equivalent to ordinary matter acquiring a milli-charge **ϵe**





- Small-scale structure in astrophysical observations and the 4.2-σ disagreement between experiments and the standard model prediction for the muon anomalous magnetic moment motivated new DM models and candidates, such as the hidden sector DM (HSDM) models in 1~100 MeV mass region
- ATOMKI Beryllium Anomaly suggests a new particle with a mass of 16.84 MeV, dubbed X17

Hidden Sector Particles/X17 Search Experiment (E12-21-003)

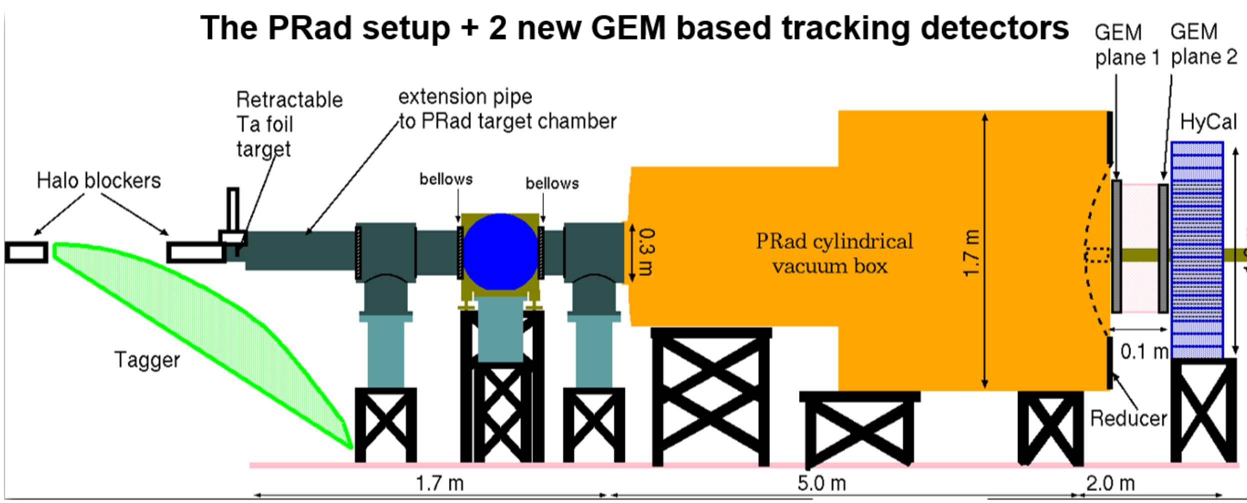


Forward angle electroproduction on a heavy nucleus

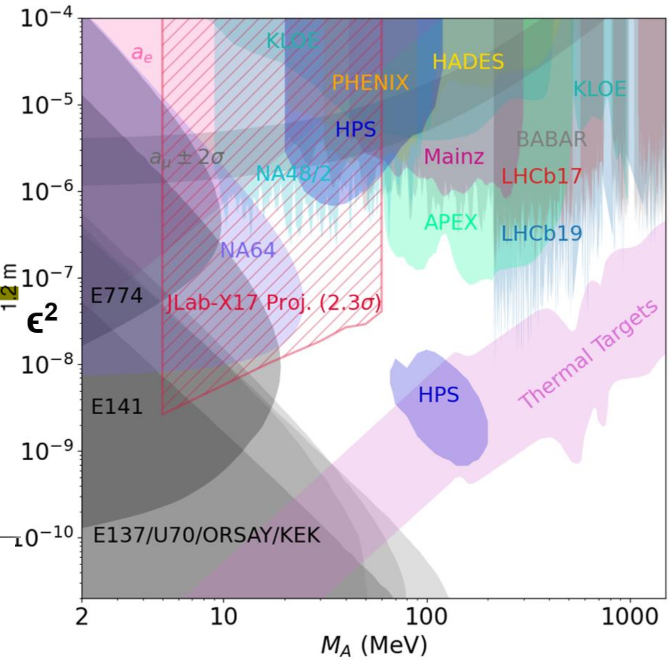
$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta, \quad \text{with} \quad X \rightarrow e^+e^-$$

All 3 final state particles will be detected in this experiment:

- The scattered electron and the pair produced e^+e^- will be detected using a pair of coordinate detectors and high resolution calorimeter
- As the only magnetic spectrometer free experiment at JLab it has an unique technique for background suppression
- Search for hidden-sector particles in 3~60 MeV mass range



Will also be sensitive to the $X \rightarrow \gamma\gamma$ channel but without optimal tracking



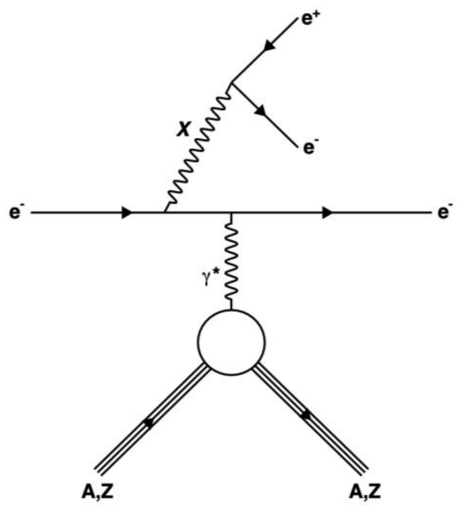
Hidden Sector Particles Search Experiment

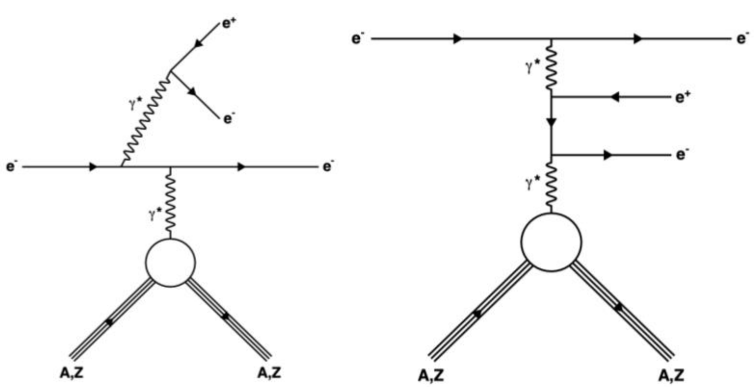
Forward angle electroproduction on a heavy nucleus

$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta$, with $X \rightarrow e^+e^-$

All 3 final state particles will be detected in this experiment:

- The scattered electron and the pair produced $e^+e^- -$ will be detected using a pair of coordinate detectors and high resolution calorimeter
- As the only magnetic spectrometer free experiments the JLab experiment has an unique technique for background suppression

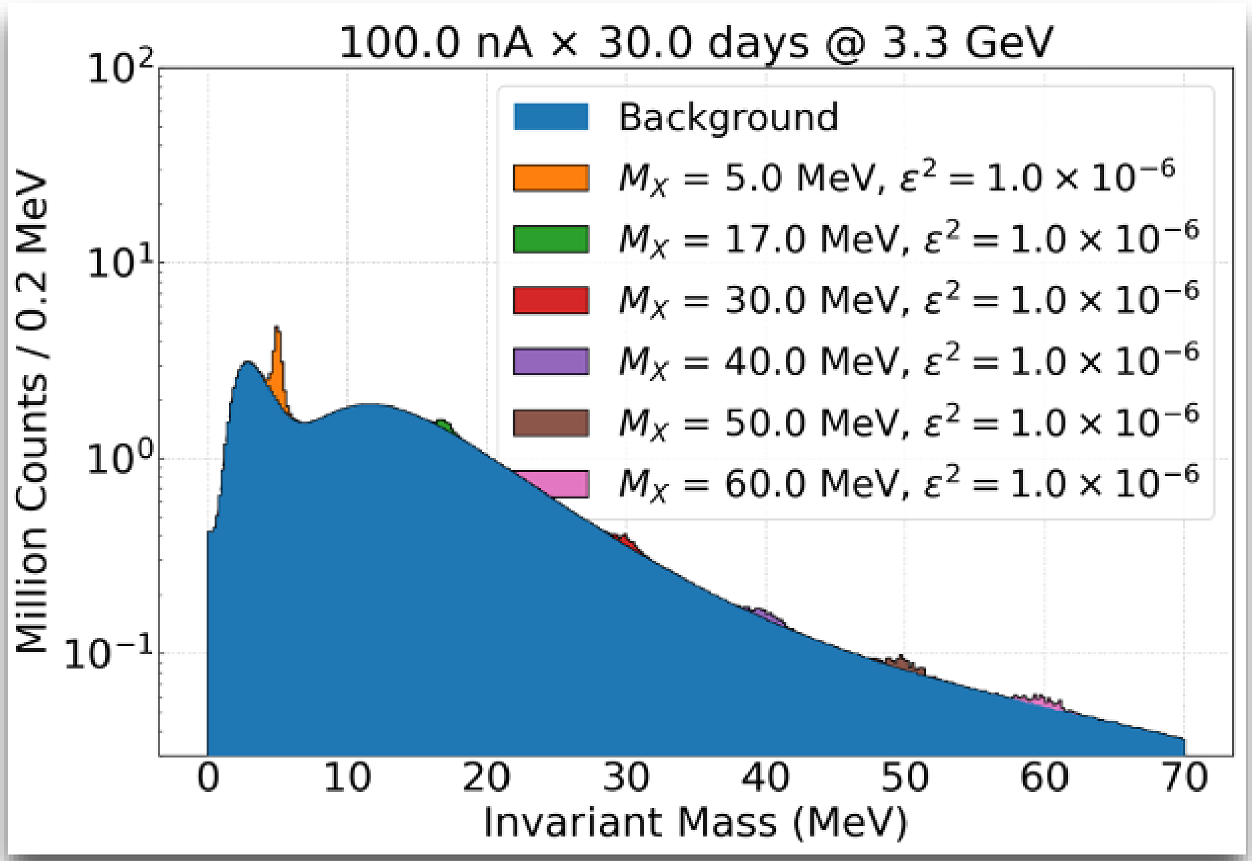




Background: radiative pair production (Trident) and Bethe-Heitler process

Signal: Bremsstrahlung production of X

Hidden Sector Particles Search Experiment



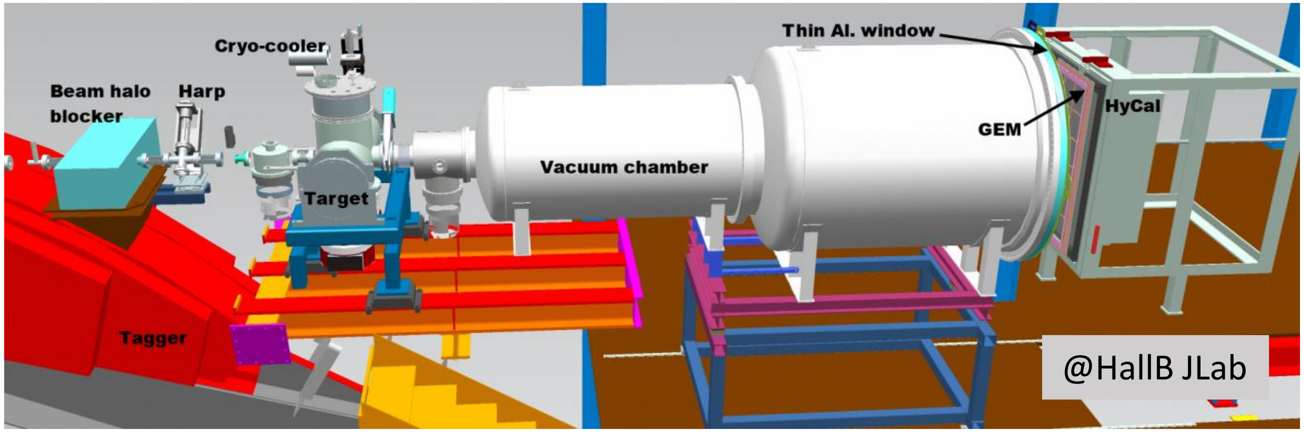
simulated background was scaled to 30 days of beam time

projected signal events with ε^2 = 1.0x10^{-6}

arXiv:2108.13276

The PRad experiment overview

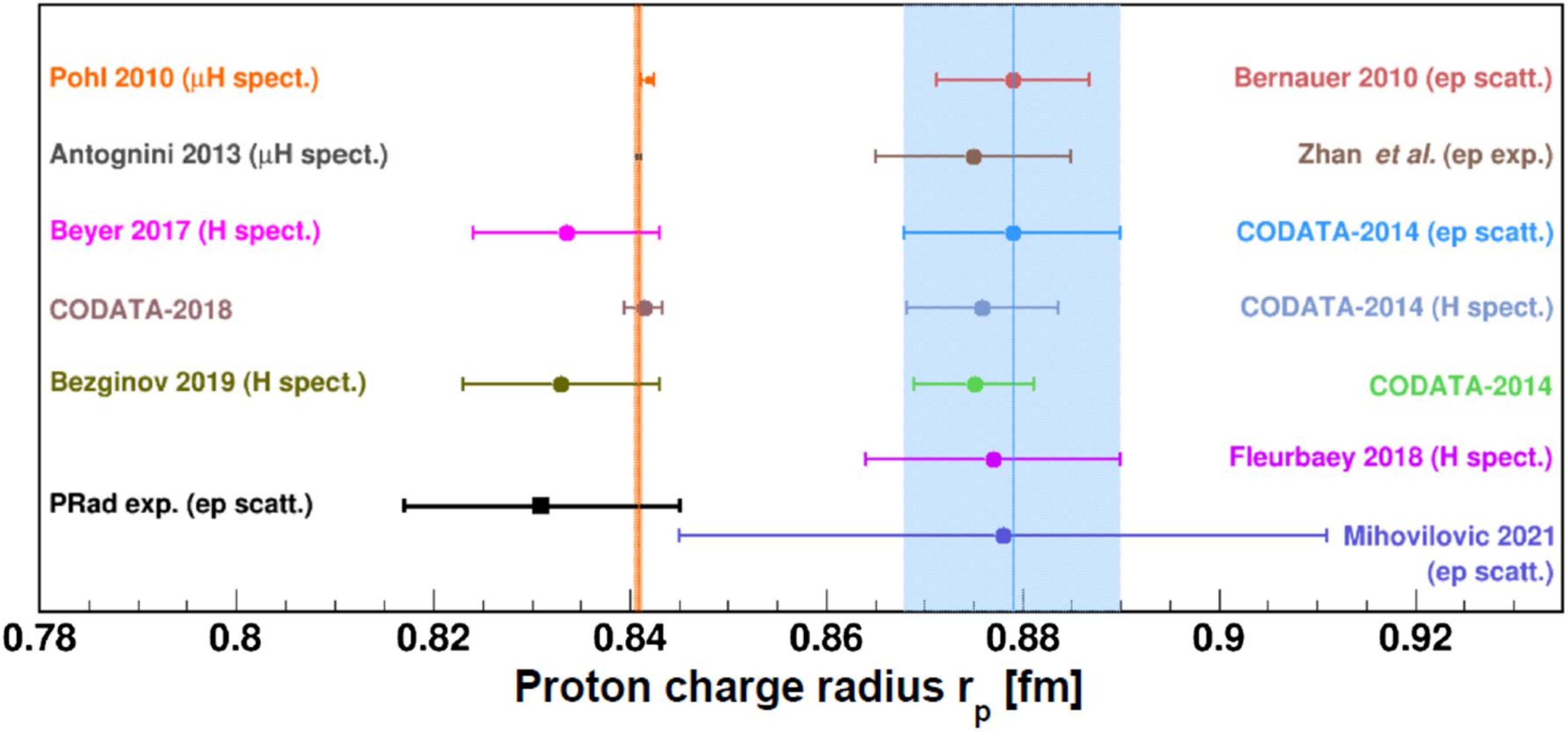
- Magnetic-spectrometer-free calorimetric method
- E_{beam} =1.1, 2.2 GeV, $\theta' = 0.7^o \sim 7.0^o$
- Covers two orders of magnitude in low Q^2 range in one fixed setting: $[2 \times 10^{-4} \sim 6 \times 10^{-2}]\ (GeV/c)^2$



Xiong, W., et al., 2019, "A small proton charge radius from an electron-proton scattering experiment," Nature (London) 575, 147–150

- Unprecedented low Q^2 (~ $2 \times 10^{-4} (GeV/c)^2$)
- A windowless H_2 gas flow target removes major background source
- High resolution, large acceptance hybrid calorimeter detect and measure the electron energy
- Large area GEM detector for position measurement
- Simultaneous detection of $ee \to ee$ Møller scattering process for normalization
- Extract the radius with precision from sub-percent cross section measurement

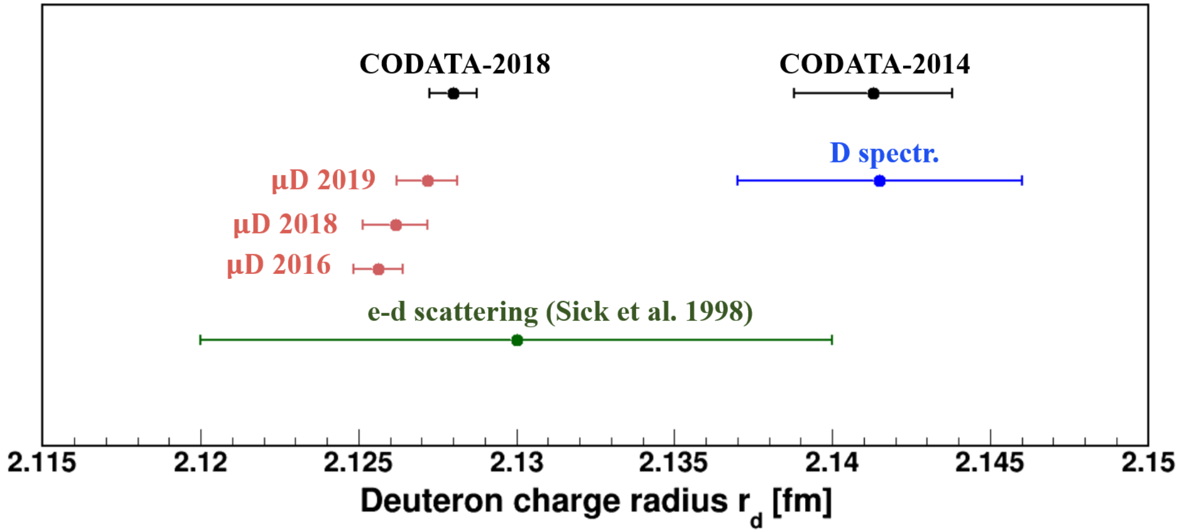
The PRad-II experiment

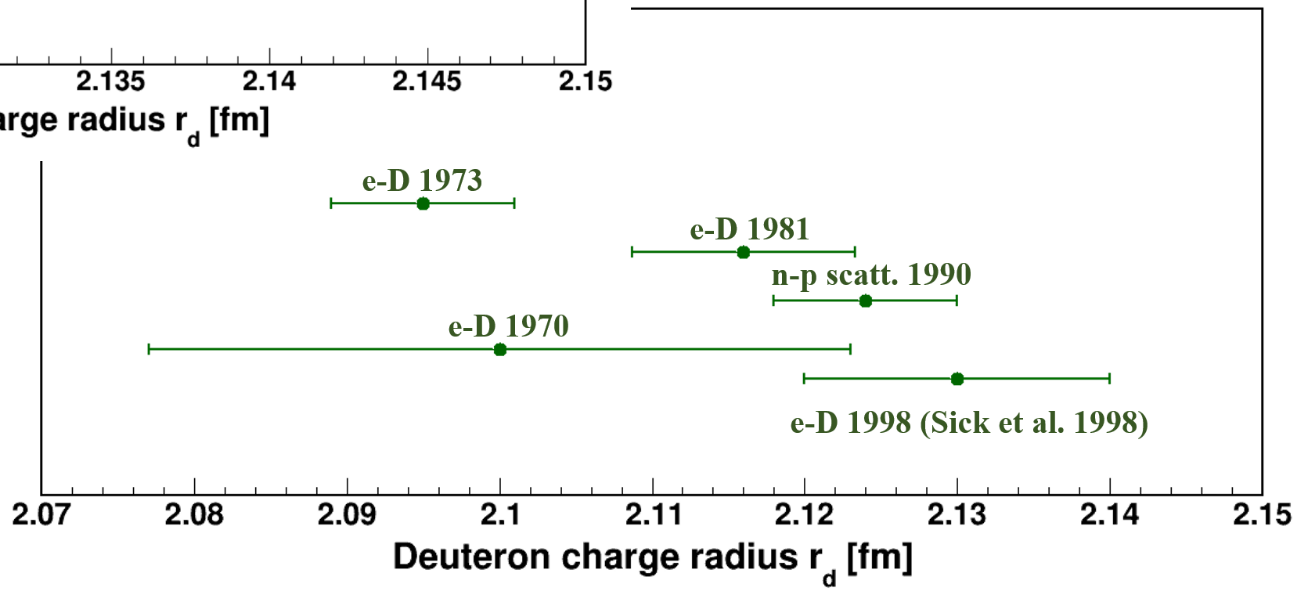


RevModPhys.94.015002

The deuteron charge radius puzzle

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

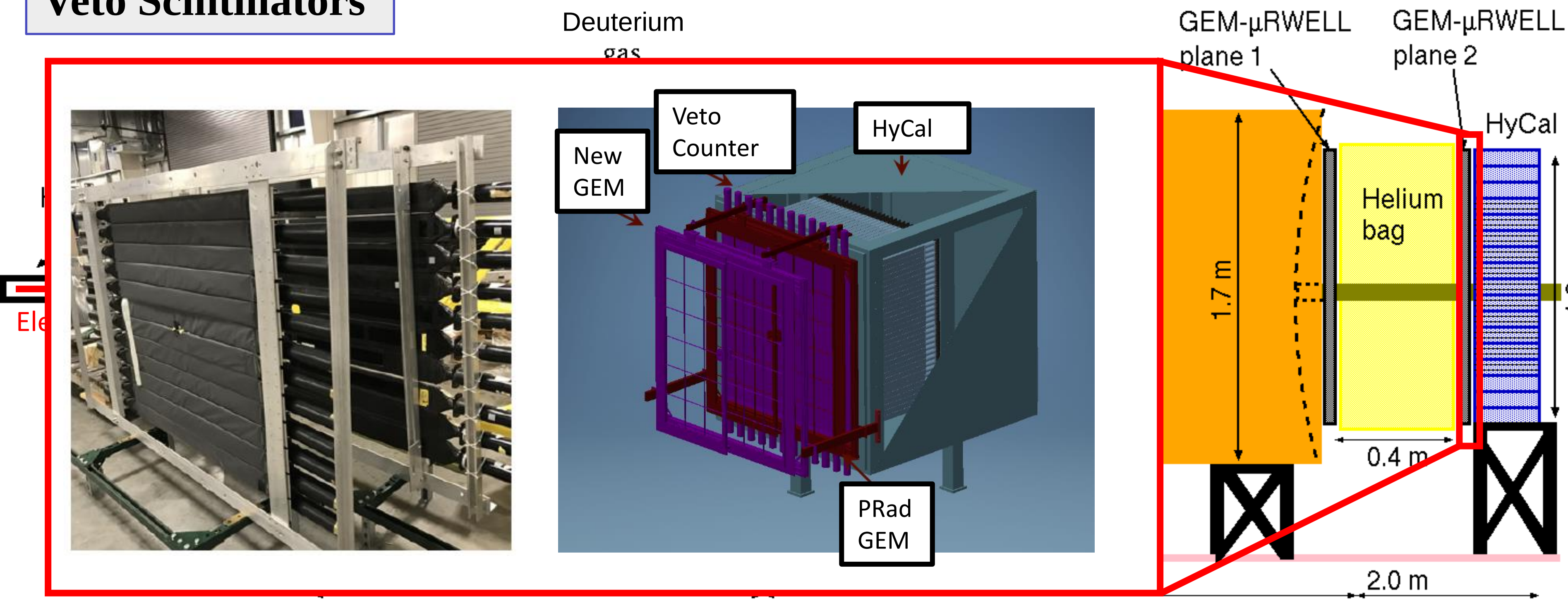




- ~6σ discrepancy between μD spectroscopy results and CODATA-2014 value
- Uncertainties in previous e-d experiments are too large to resolve the puzzle

DRad experiment apparatus

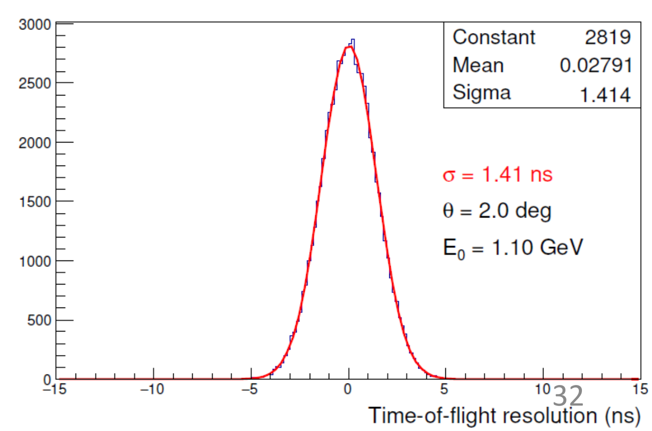
Veto Scintillators



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

  e+d → e+p+n

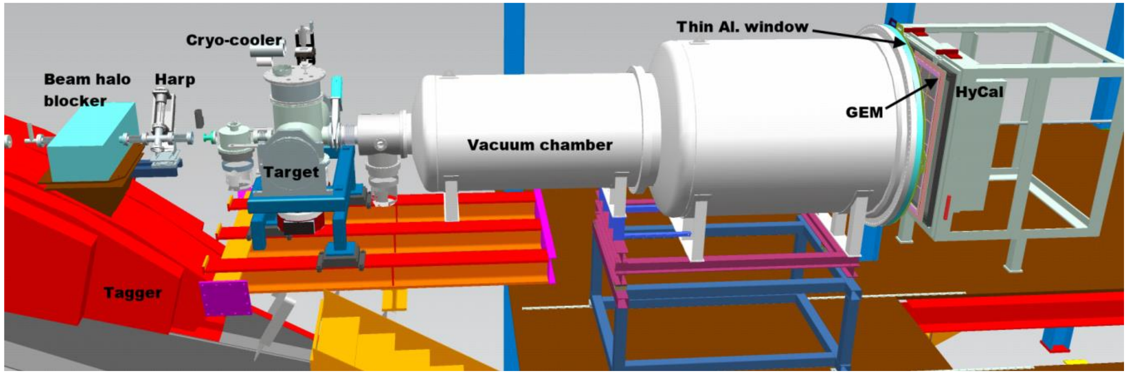
- Particle identification between deuteron and proton: measure the time-of-flight difference between the recoil detector and the HyCal



The highlight of DRad experiment

DRad proposal: PR12-23-011

- Measure *e-d* elastic cross sections at very low Q^2 range:
  $[5 \times 10^{-3} - 1.3]\text{fm}^{-2}$
  $[2 \times 10^{-4} - 5 \times 10^{-2}]\ \text{GeV}^2$
- Two beam energies, E = 1.1 and 2.2 GeV to increase Q^2 range and control systematics.



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

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

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

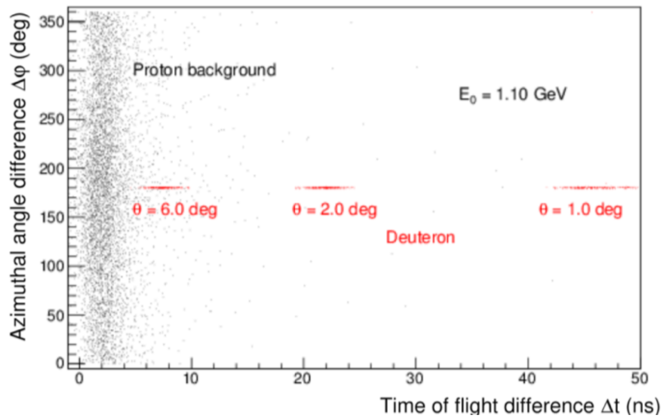
- That will allow:

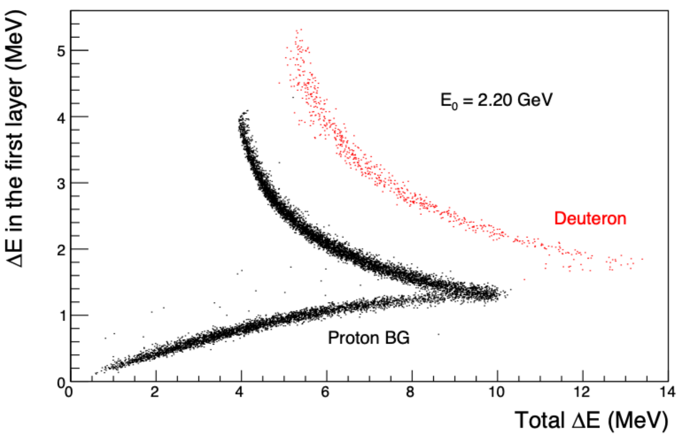
➢ Measure cross sections in one kinematical settings for a large Q^2 range;
➢ Simultaneous detection of $ee \rightarrow ee$ Møller scattering process to control systematics;
➢ Measure e-d elastic cross section to subpercent precision

PID and Event selection

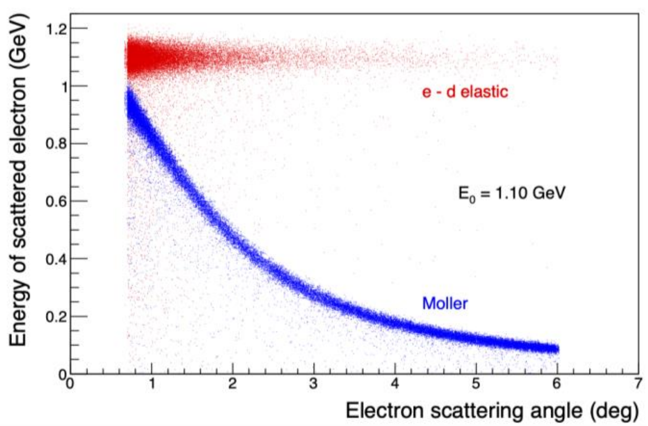
Comprehensive Geant4 simulation of the experiment was developed and used for studying the detection thresholds and backgrounds.

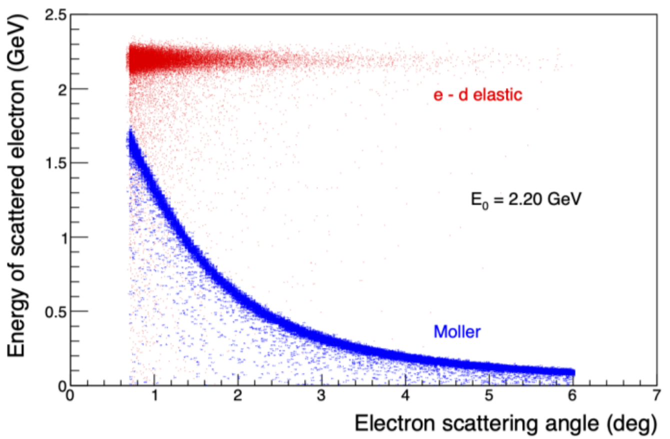
- ❑ Proton from breakup vs elastic recoil deuteron (Electro-disintegration rates are < 6% of the elastic rates)



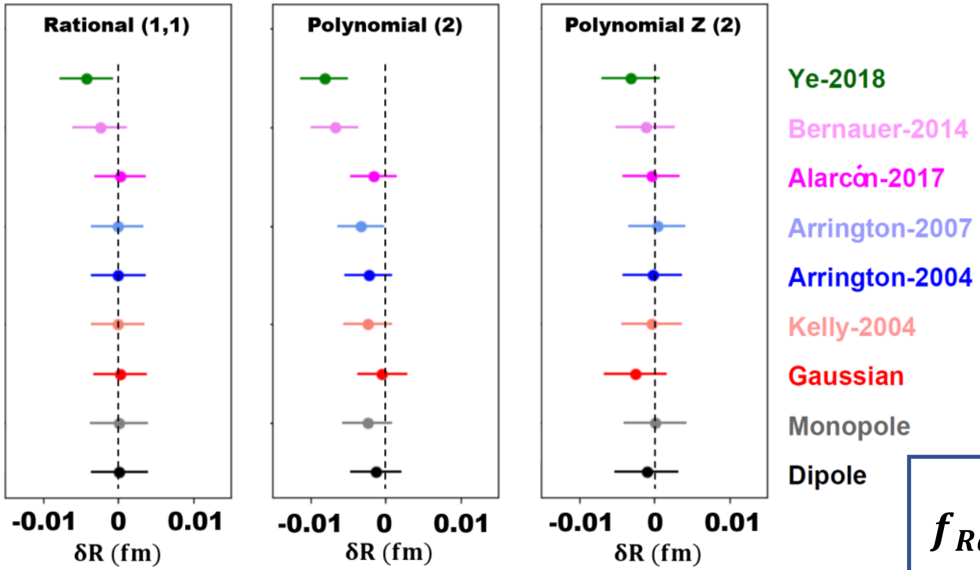


- ❑ Møller event vs e-d elastic event





The robust fitter study for PRad vs DRad



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

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

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

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

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

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

Abbott II:

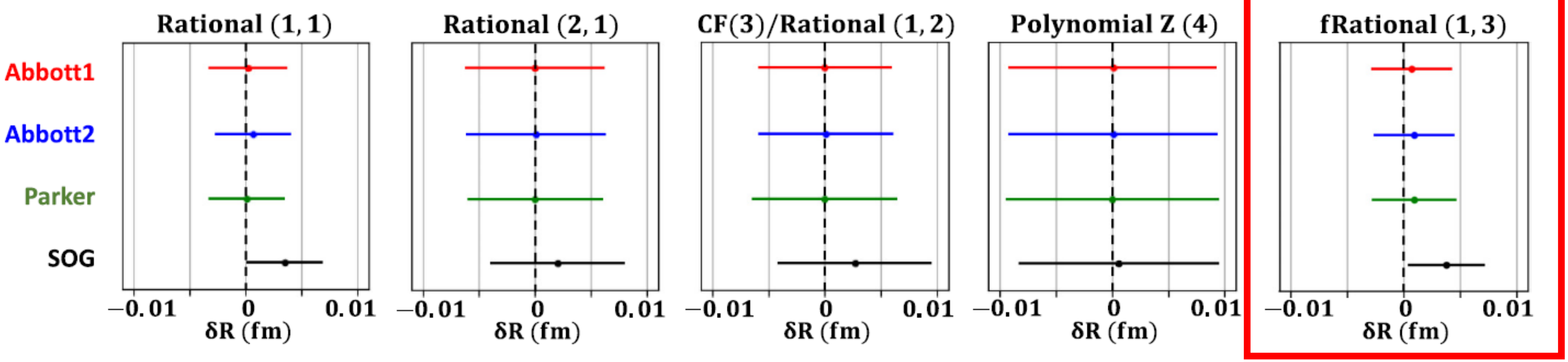
$$G_C^d(Q^2) = \frac{G^2(Q^2)}{(2\tau + 1)} \cdot \left[\left(1 - \frac{2}{3}\tau\right) g_{00}^+ + \frac{8}{3}\sqrt{2\tau} g_{+0}^+ + \frac{2}{3}(2\tau - 1) g_{+-}^+\right]$$

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

Sum-of-Gaussian(SOG):

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

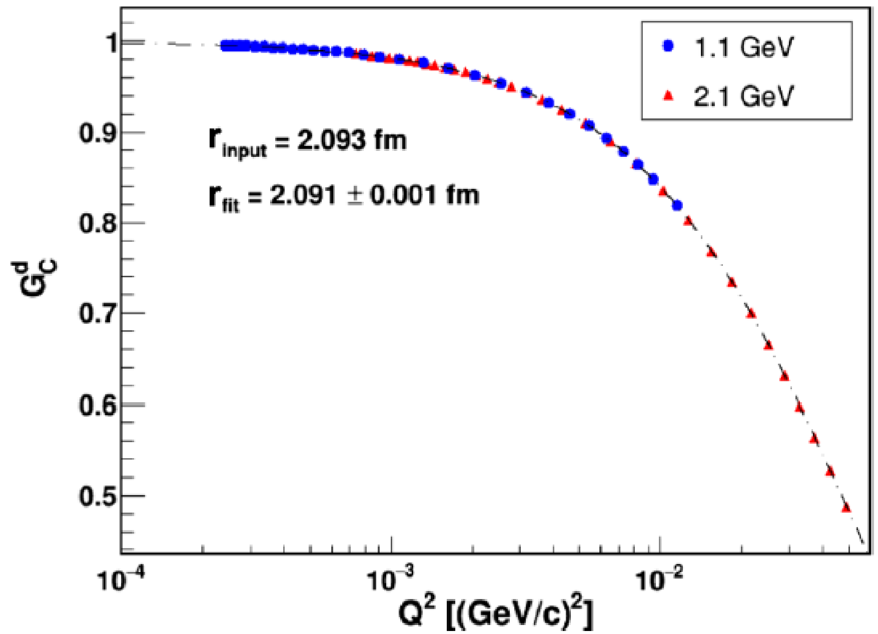
Model dependent study in r_d extraction



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

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

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



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

Radiative Correction (RC) Calculations