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

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Outline

- Introduction and the deuteron charge radius puzzle
- Experiment apparatus
- Event selection and PID
- Preliminary uncertainty estimation
- Summary

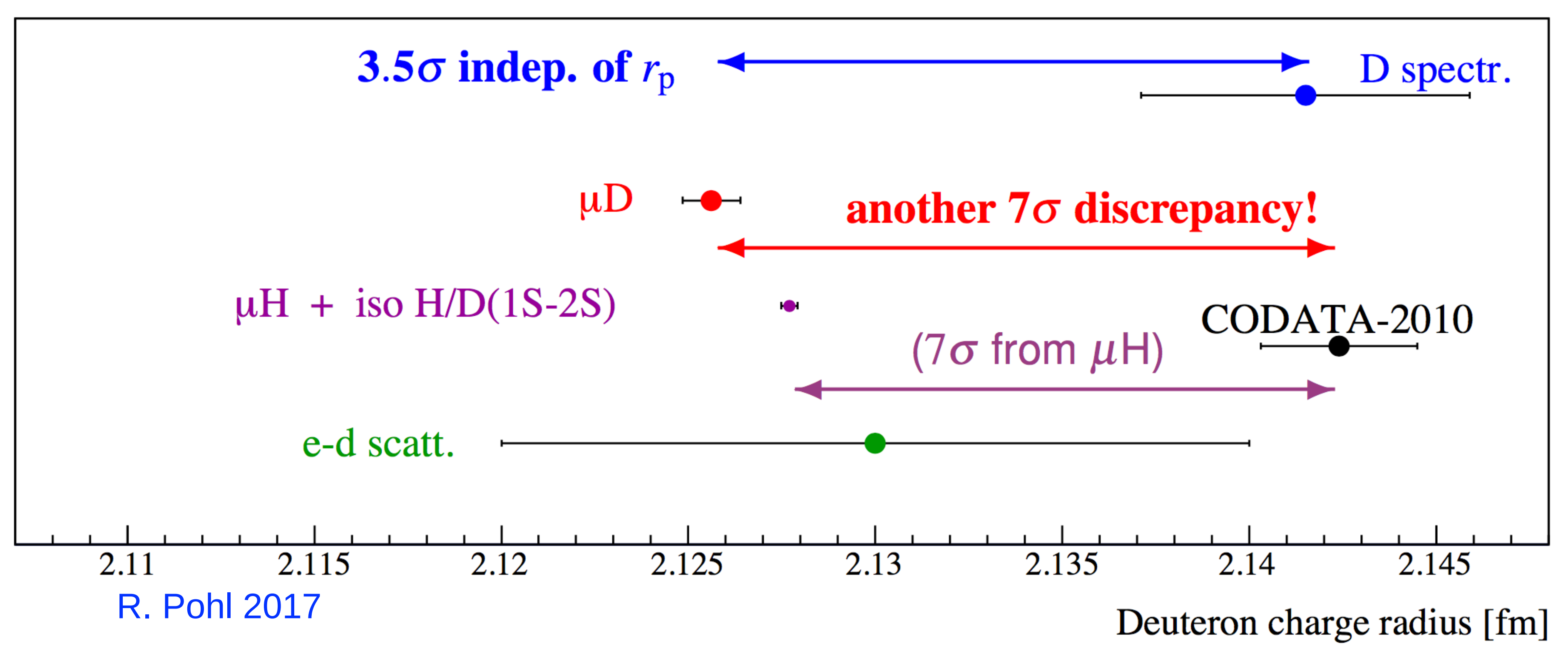
Introduction

- Deuteron: the simplest nuclear system in nature
- A possible third observation in addition to the muon g-2 factor and the proton radius puzzle which is relation to a possible violation of electron-muon universality
- Except for the "*Proton Charge Radius Puzzle*", there is also a *"Deuteron Charge Radius Puzzle"*

Introduction

- Three major methods:

1. Laser spectroscopy; 2. Isotope shift; 3. Electron scattering



- Calls for new independent experiments with highest possible accuracy!

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

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

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

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

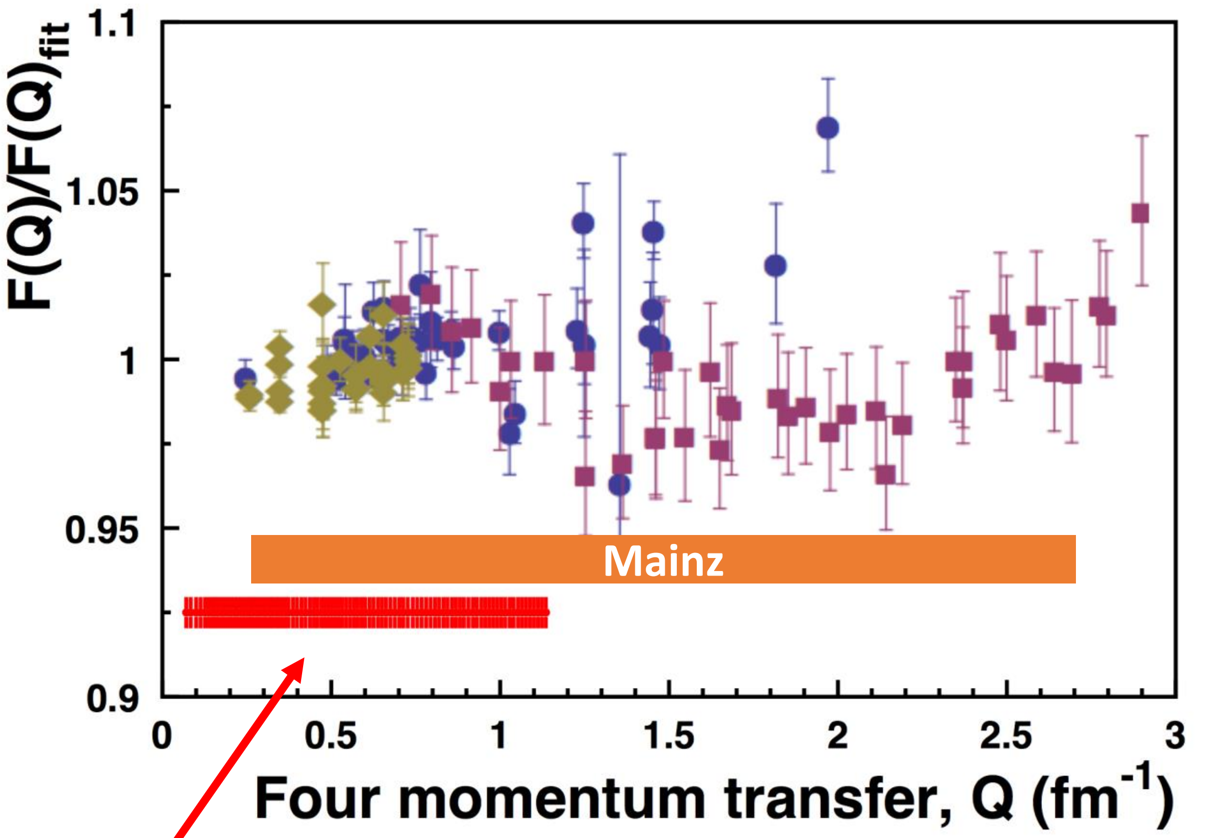
● G.G. Simon et al. Nucl. Phys. A364, 285 (1981):

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

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

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

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



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

Previous experiments used:

- magnetic spectrometer method;
- different type of targets;
- normalized *e-d* to *e-p* cross sections.

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

The highlight of DRad experiment setup

- Measure *e-d* elastic cross sections at very low Q^2 range:

  $$[2 \times 10^{-4} - 5 \times 10^{-2}]\ (GeV/c)^2\ .$$

- Two beam energies, E = 1.1 and 2.2 GeV to increase Q^2 range and control systematics.

- Experimental method based on PRad, with three additions:

• magnetic-spectrometer-free calorimetric experiment;
• windowless deuterium/hydrogen gas flow target to reduce background;
• additional GEM detector for scattered electron tracking (new);
• cylindrical recoil detector for reaction elasticity (new);
• Veto counters for timing (PrimEx veto counters)

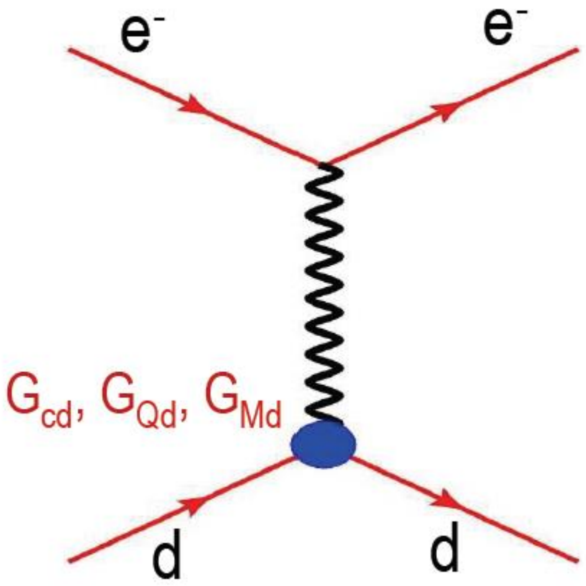
- That will allow:

➢ measure cross sections in one kinematical settings for a large Q^2 range;
➢ simultaneous detection of $ee \to ee$ Moller scattering process;
➢ measure e-d cross section to subprecent precision

The extraction of Deuteron Charge Radius

- In the Born approximation, the cross section for e-d elastic scattering:

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



$\frac{d\sigma}{d\Omega}|_{NS}$ is for elastic scattering from point-like spinless particle.
and B are structure functions related to the deuteron charge(G_{Cd}
electric quadrupole (G_{Qd})and magnetic dipole (G_{Md}) form factor

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

- At low Q^2, the rms charge radius can be obtained from the slope of the charge form factor G_{Cd} :

$$R_d^2 = -6\left[\frac{dG_{Cd}(Q^2)}{dQ^2}\right]_{Q^2=0}$$

Extraction of ed Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the ed cross section will be normalized to the Møller cross section:

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

$$\Downarrow$$

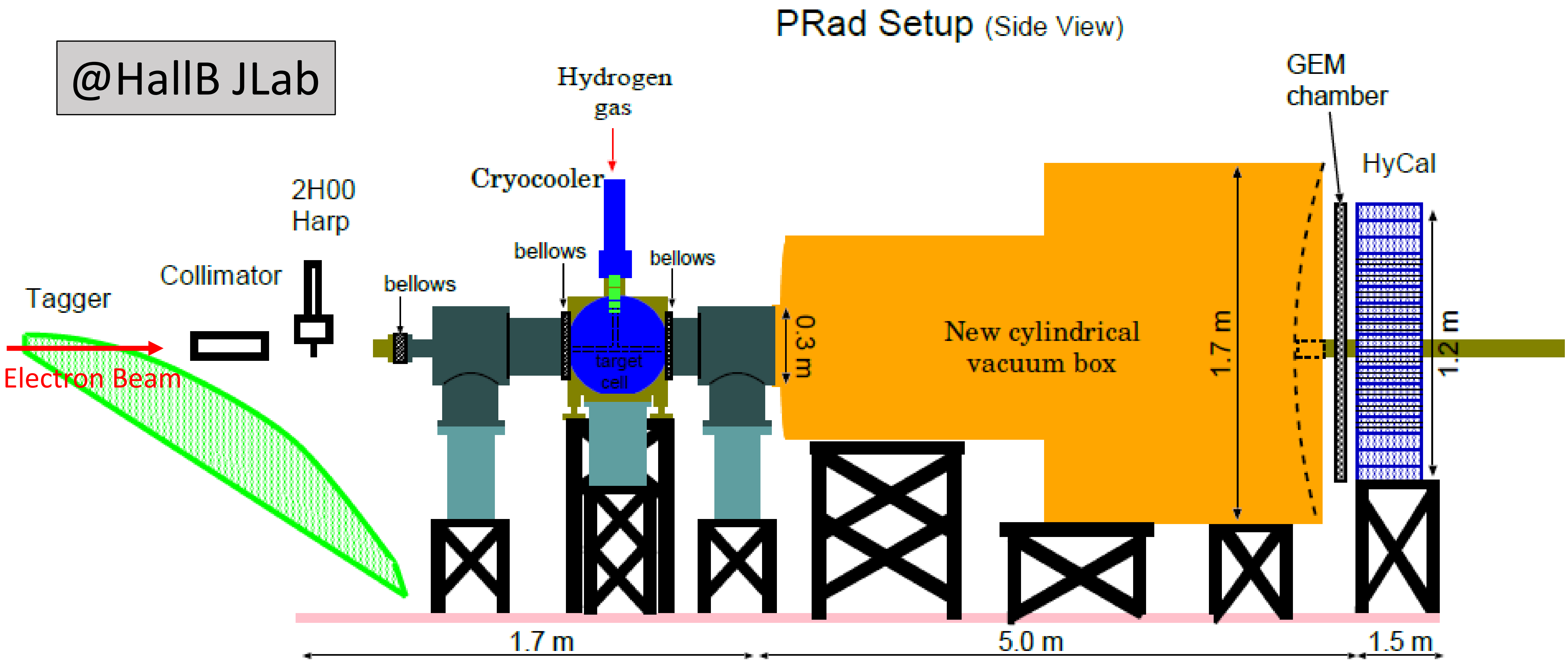
$$\left(\frac{d\sigma}{d\Omega}\right)_{ed}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}(ed \to ed \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{ed}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{ed}}\right]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

- **Luminosity cancelled by taking ed/ee ratio**

- **Method 1: bin by bin method – taking ed/ee counts from the same angulear bin**
  - ➢ Cancel part of the efficiency and acceptance
  - ➢ May introduce Q^2 dependent uncertainty from Moller
  - ➢ Limited converge due to double arm Moller acceptance

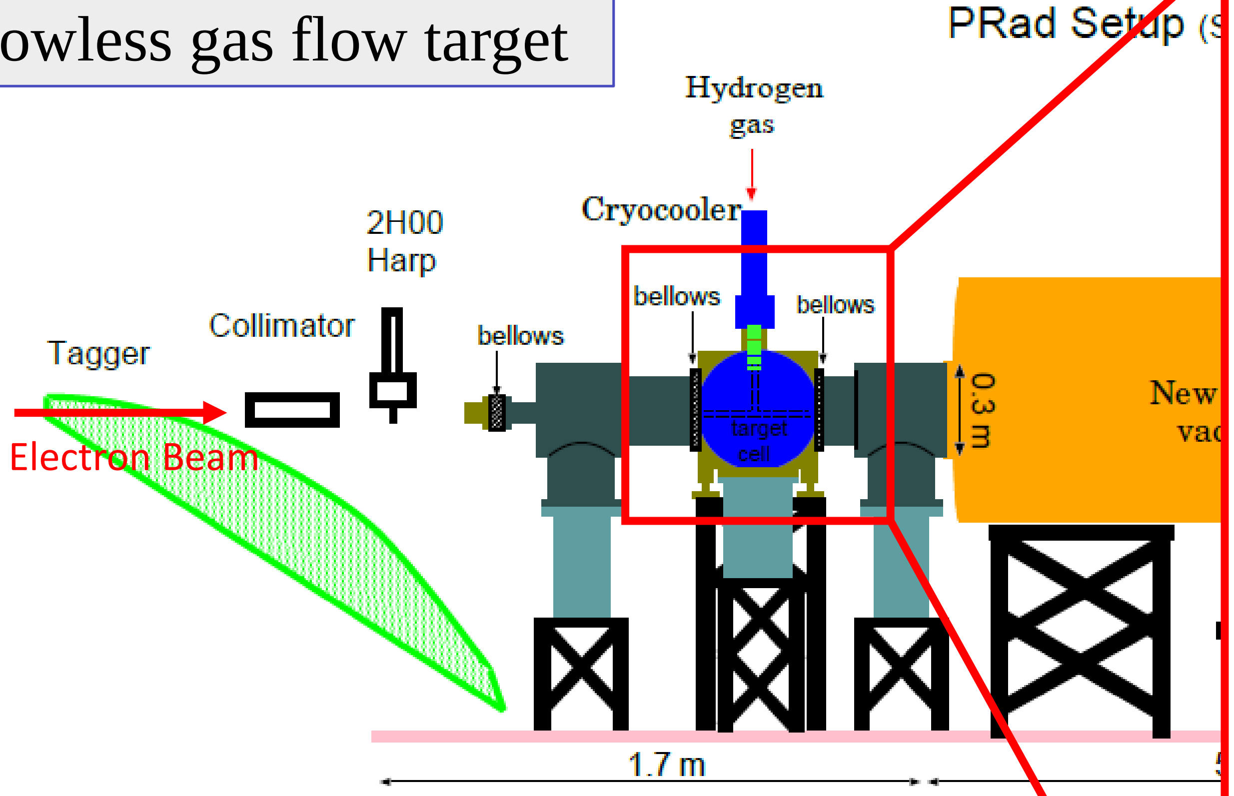
- **Method 2: integrated Moller method – integrate Møller in a fixed angle range and use it as common normalization for all angular bins**
  - ➢ Moller uncertainty only affects normalization
  - ➢ Need correction for GEM efficiency

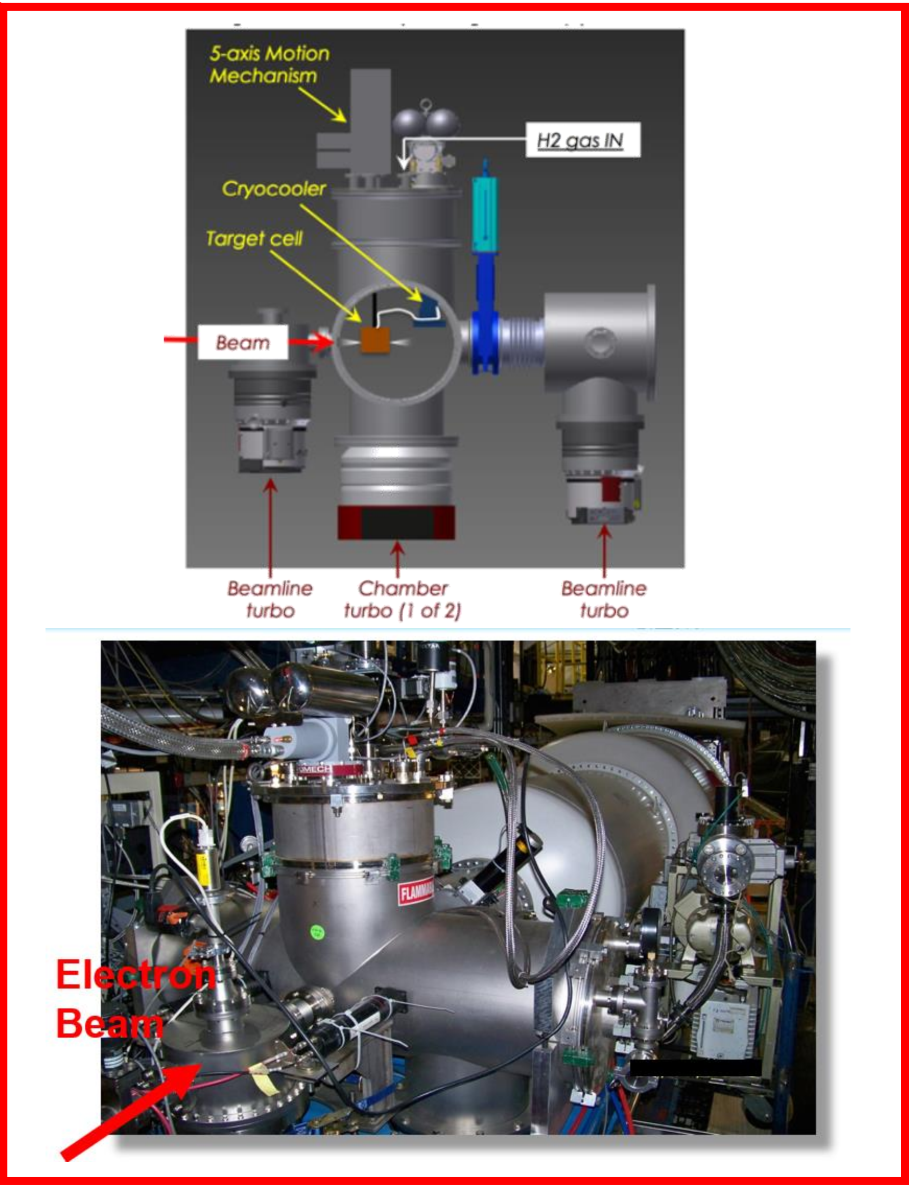
PRad experimental appratus



PRad experimental appratus

Windowless gas flow target

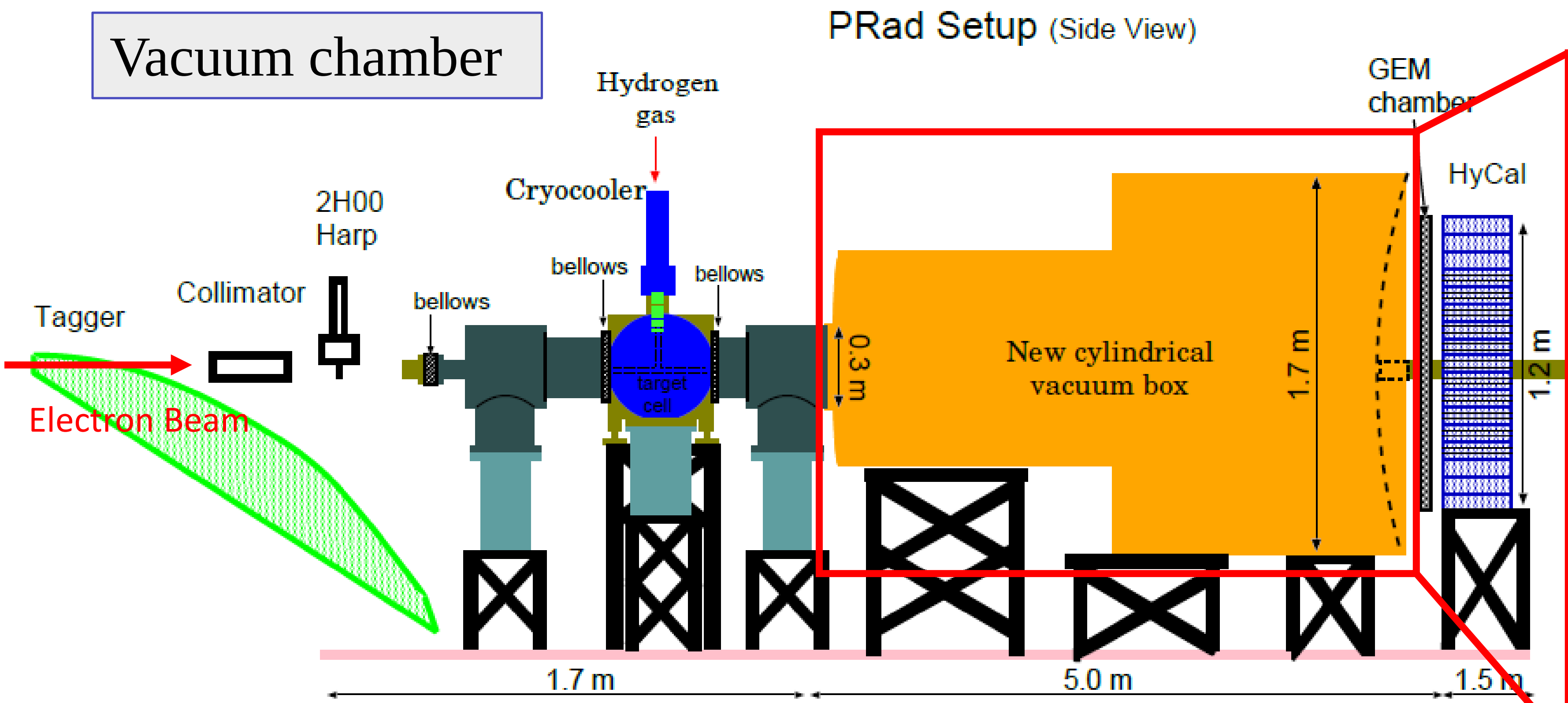




- 8 cm diam x 4 cm long target cell
- 4 mm diam holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2
- remove major background source

PRad experimental appratus

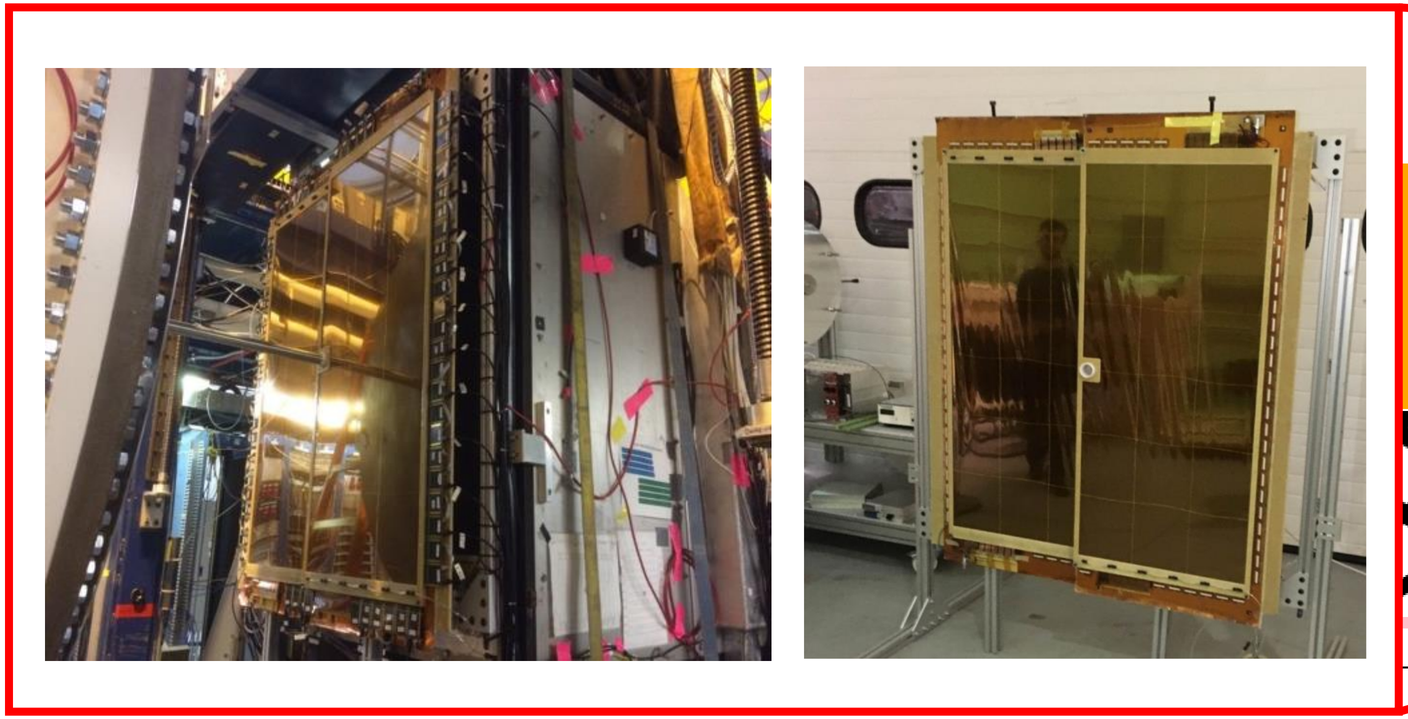
Vacuum chamber

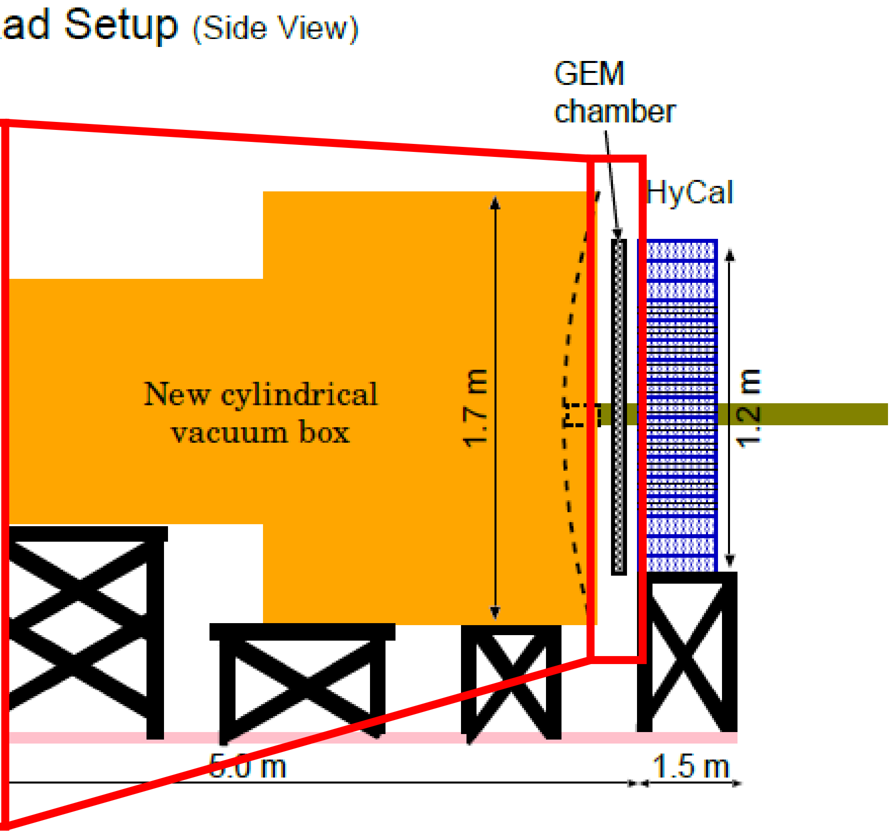


- 5 m long two stage vacuum chamber, further remove possible background source from the electron multiple scattering
- vacuum chamber pressure: 0.3 mTorr

PRad experimental appratus

Gas Electron Multiplier (GEM)



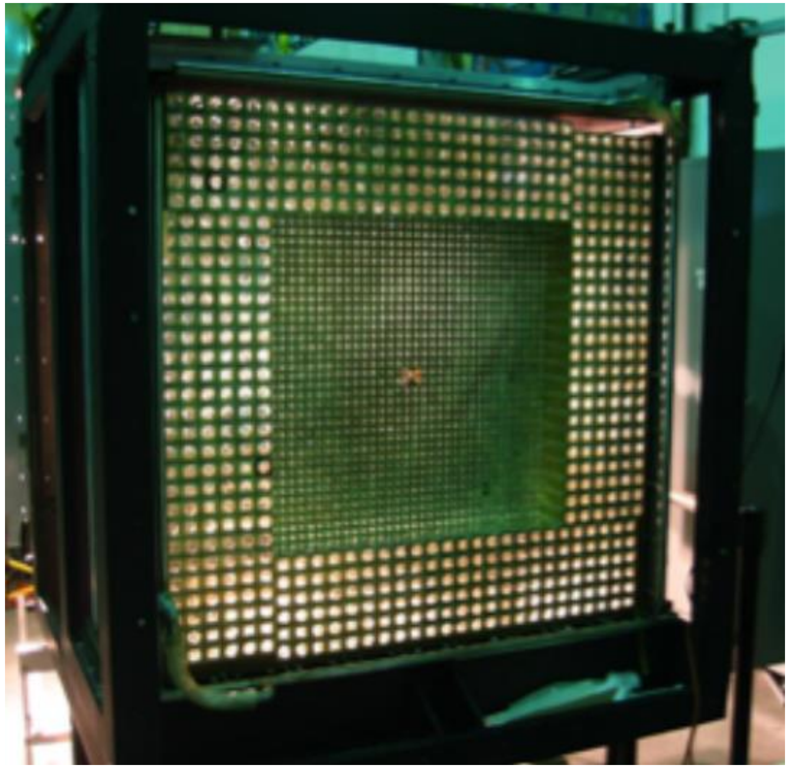


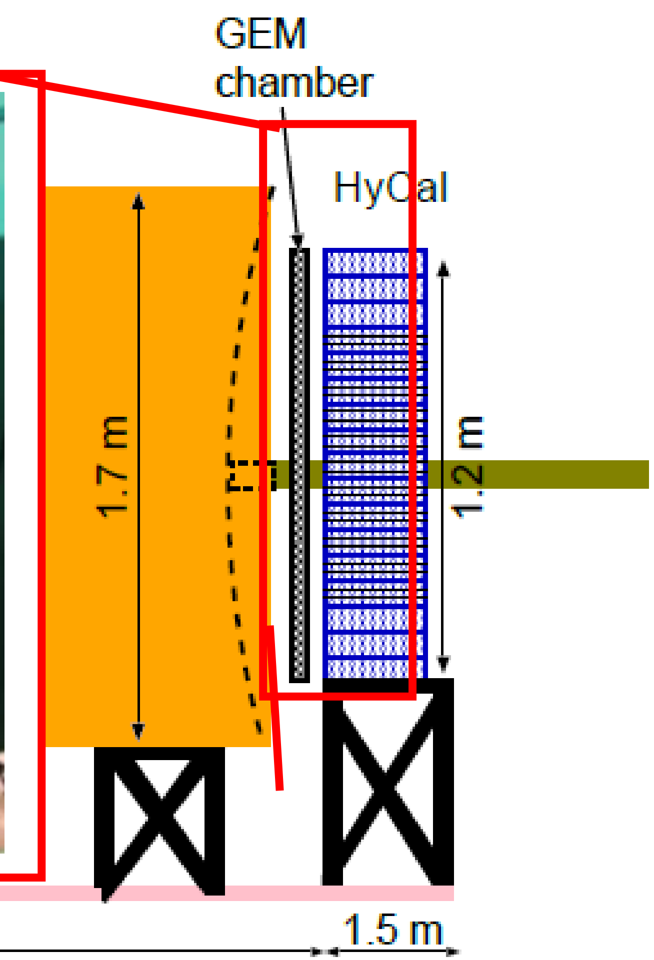
- Two large area GEM chambers
- Small overlap region in the middle
- Excellent position resolution (72 μm)

PRad experimental appratus

Hybrid Calorimeter (HyCal)

- Hybrid EM calorimeter (HyCal)
- High resolution and efficiency
- 5.8 m from the target
  - Inner 1156 $PbWO_4$ modules
  - Outer 576 lead-glass modules
- Scattering angle coverage:
  ~ 0.6° to 7.5°
- Full azimuthal angle coverage

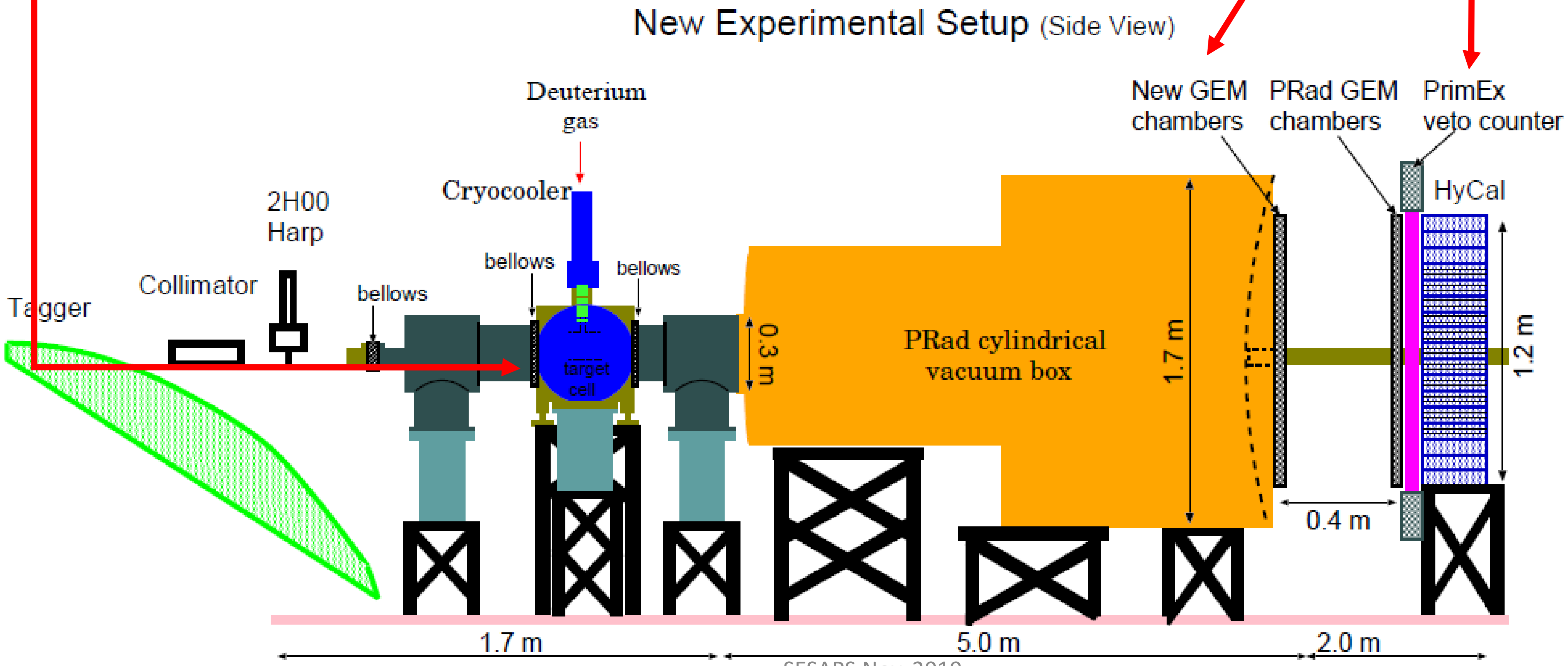


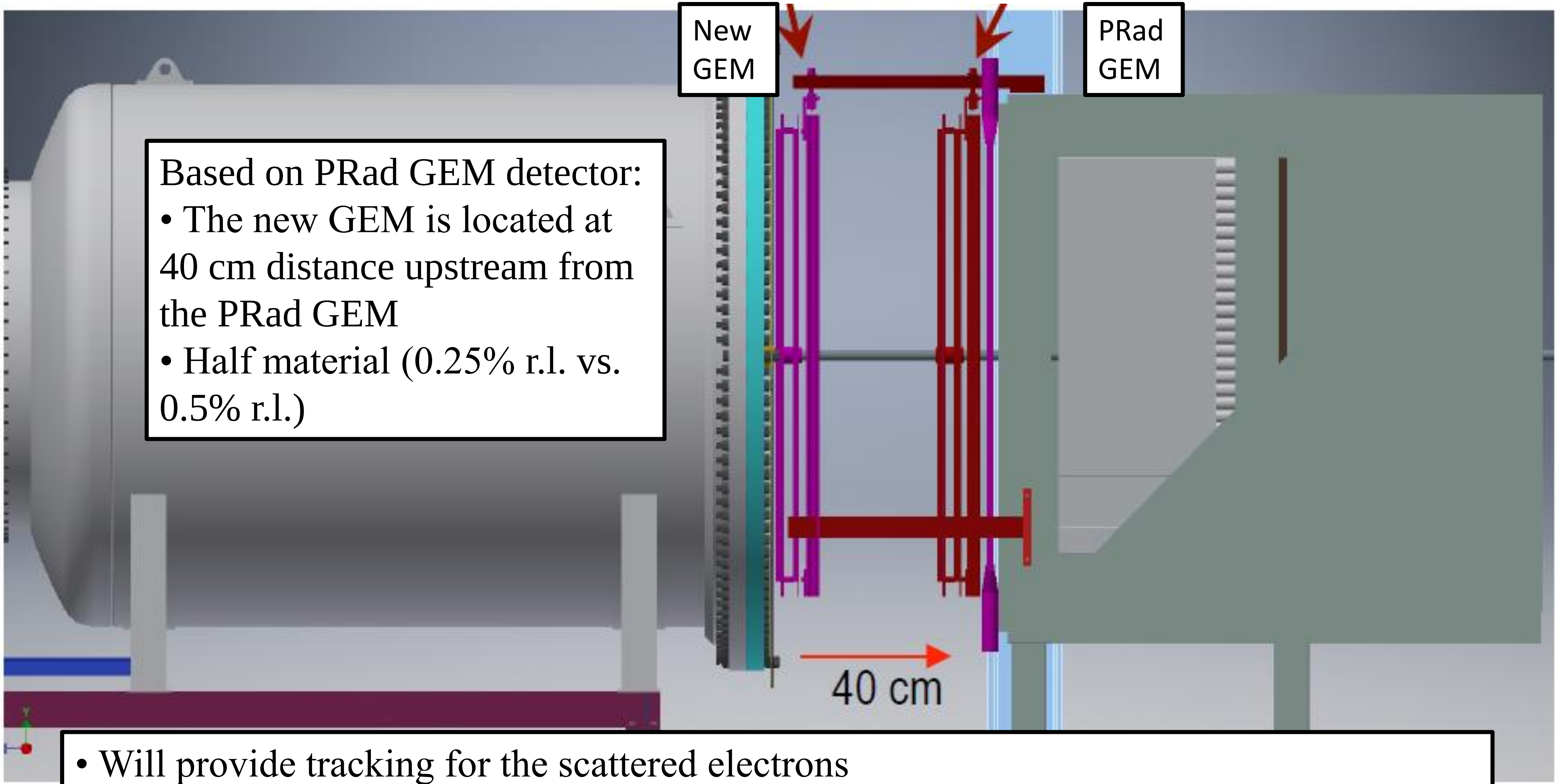


Proposed DRad experiment setup

The PRad experiment successfully extracted the radius with precision from subpercent cross section measurement. Based on PRad experiment setup, three additions:

- Additional GEM detector for scattered electron tracking (new)
- Cylindrical recoil detector for reaction elasticity (new)
- Veto counters for timing (PrimEx veto counters)



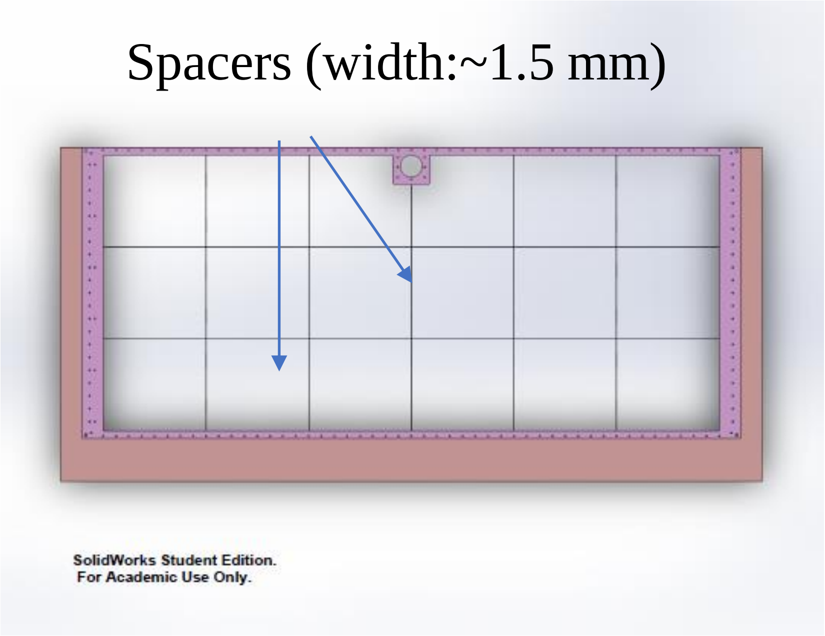


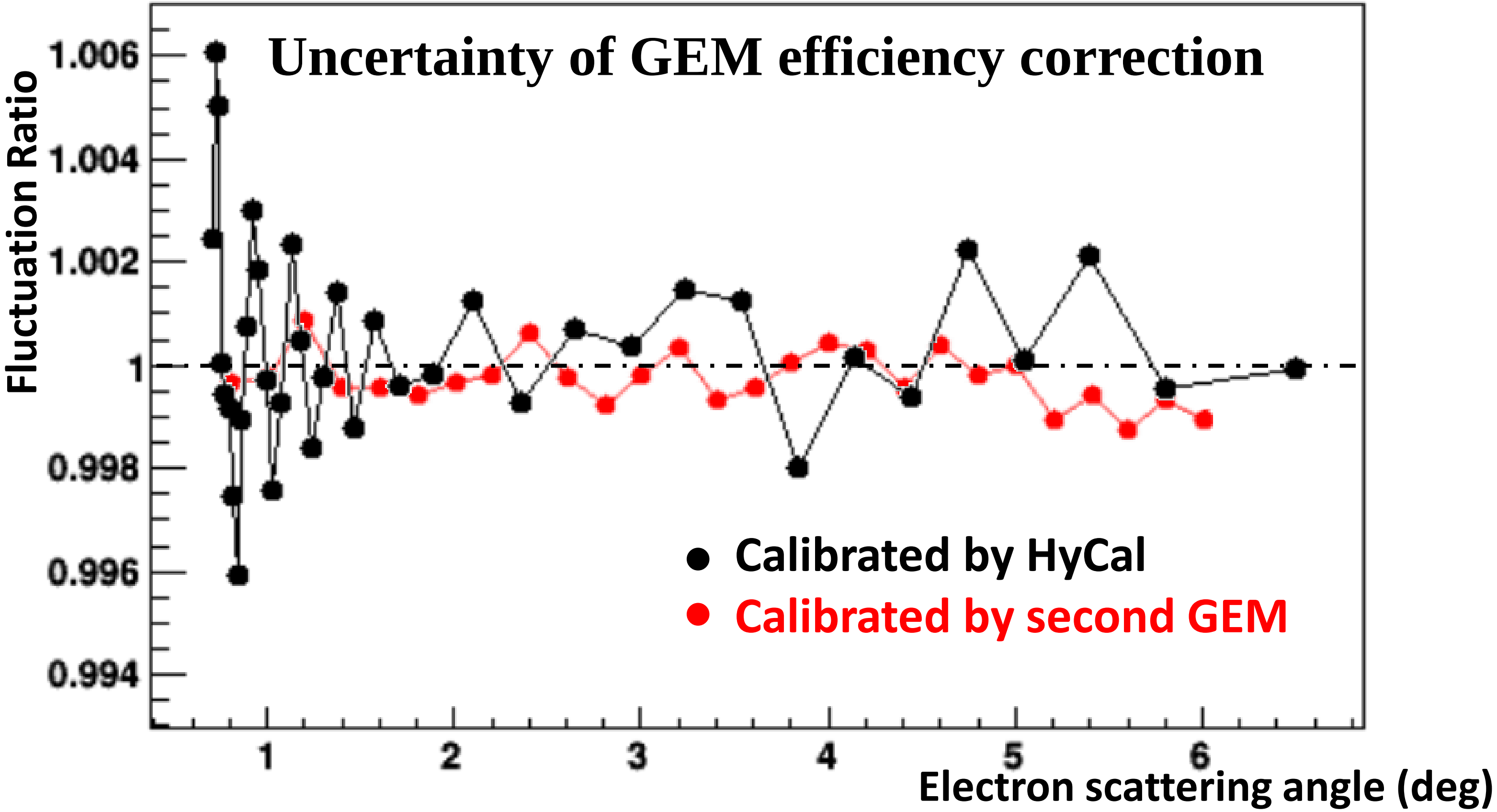
Based on PRad GEM detector:
- The new GEM is located at 40 cm distance upstream from the PRad GEM
- Half material (0.25% r.l. vs. 0.5% r.l.)

- Will provide 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)

The improvement after adding the second GEM

- PRad GEM efficiency calibrated by HyCal, the precision limited by HyCal finite resolution
- The precision greatly improved if calibrated by a second GEM
- Integrated Moller method applicable for full angular range with high precision GEM efficiency measurement.



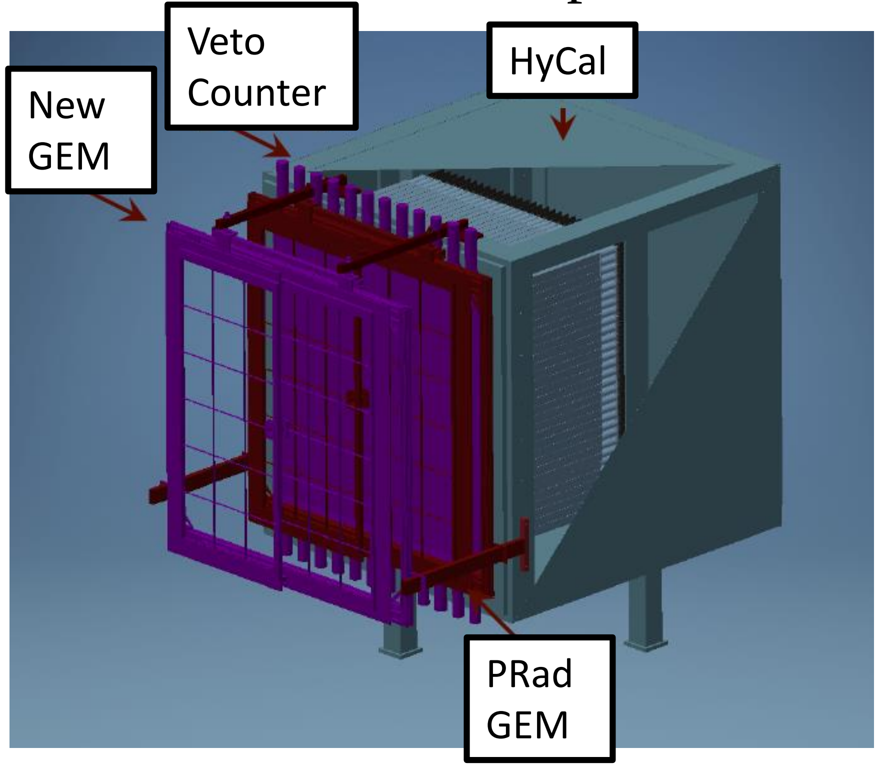


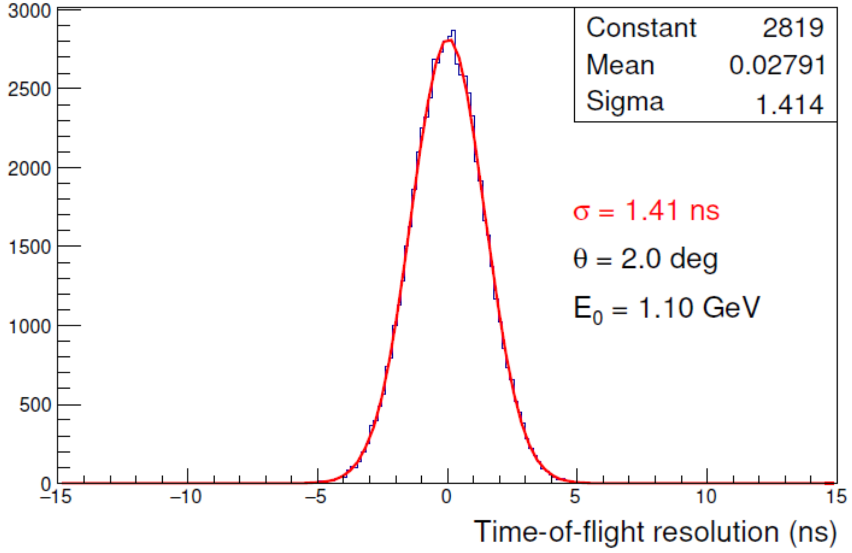
Veto Scintillators

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

$$e+d \rightarrow e+p+n$$

- Measure the time-of-flight difference between the recoil detector and the HyCal Calorimeter for particle identification between deuteron and proton from the deuteron inelastic scattering.

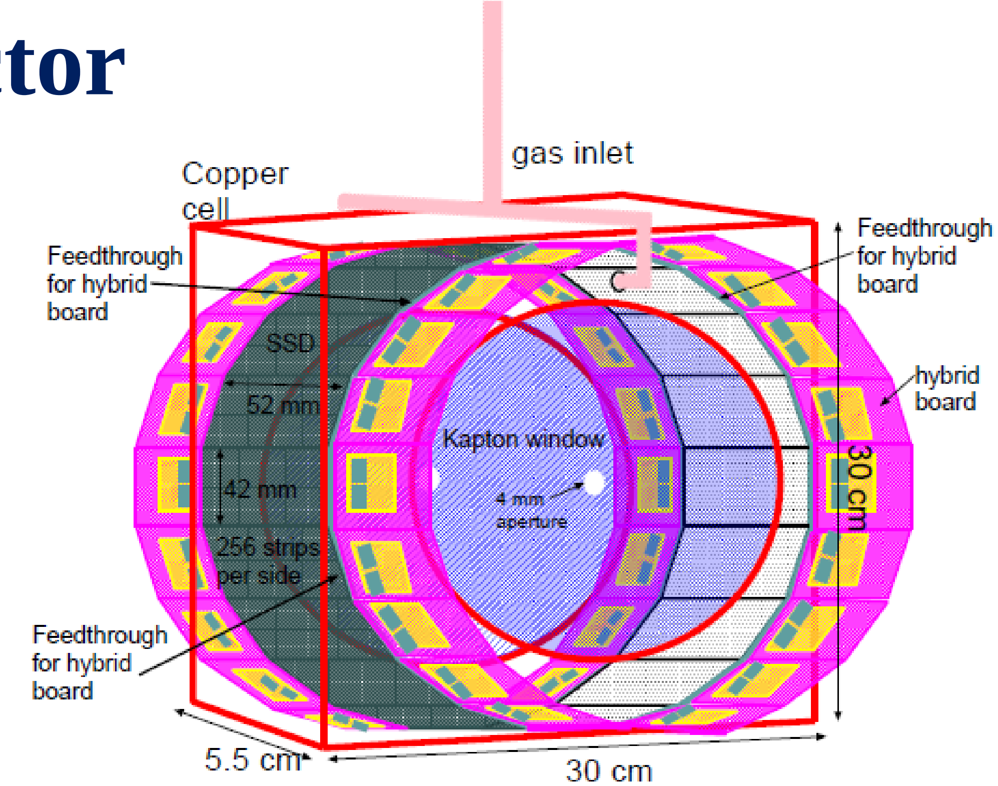




Si-strip Cylindrical Recoil Detector

Detect recoil particles, provide two major information:

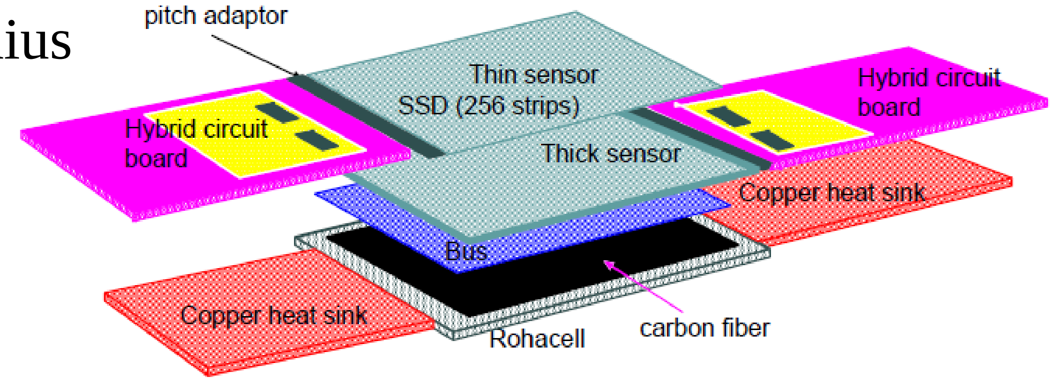
- Timing
- Azimuthal angle



Based on the CLAS12 Barrel Silicon Tracker(SVT)

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

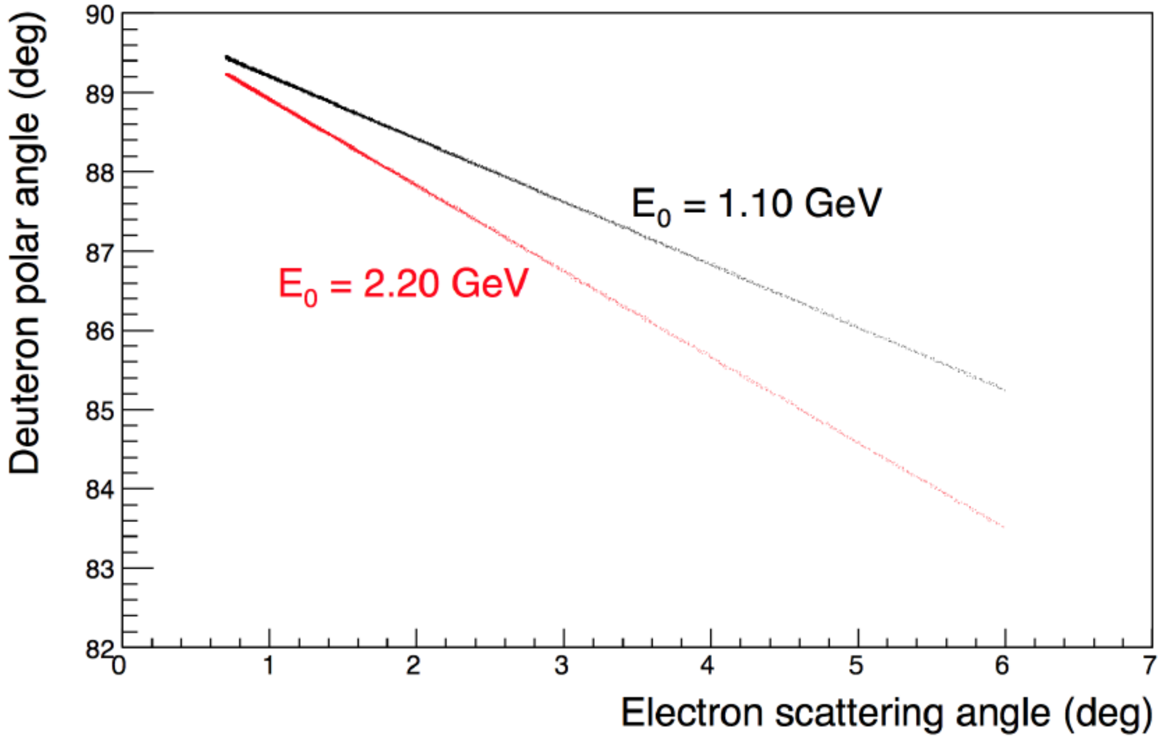
Single pair of Si-strip detectors

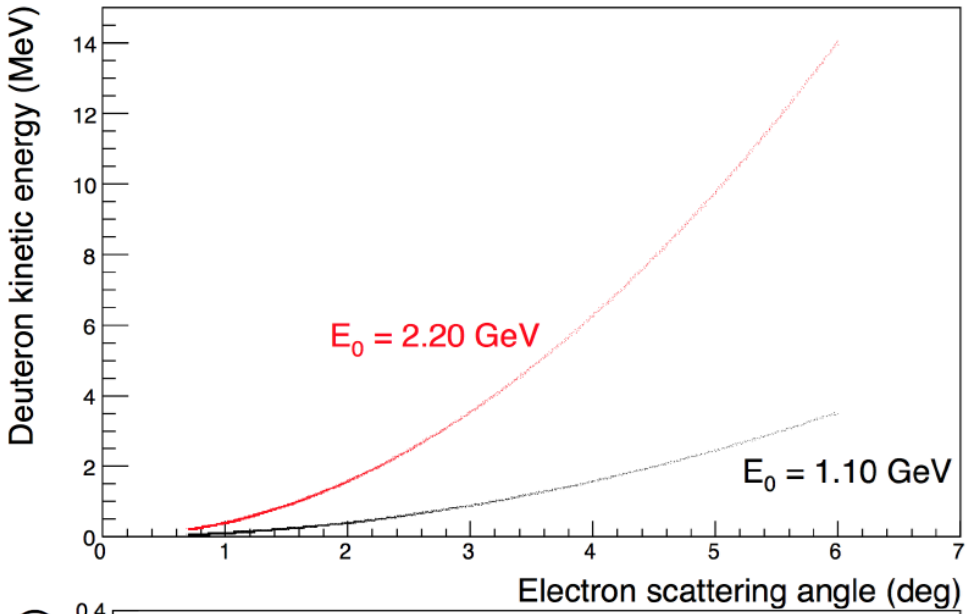


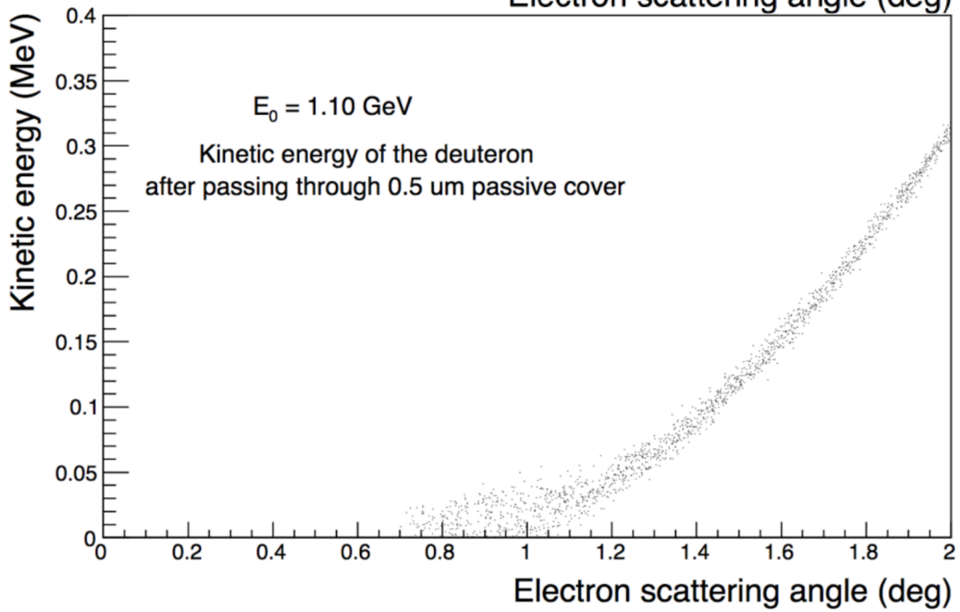
Kinematics and Q^2 Coverage

Full GEANT4 simulation code has been developed, including all detectors.

- For 1.1GeV and 2.2 GeV beam energies, deuterons will recoil at large polar angles: $\theta_d = 83° - 89°$





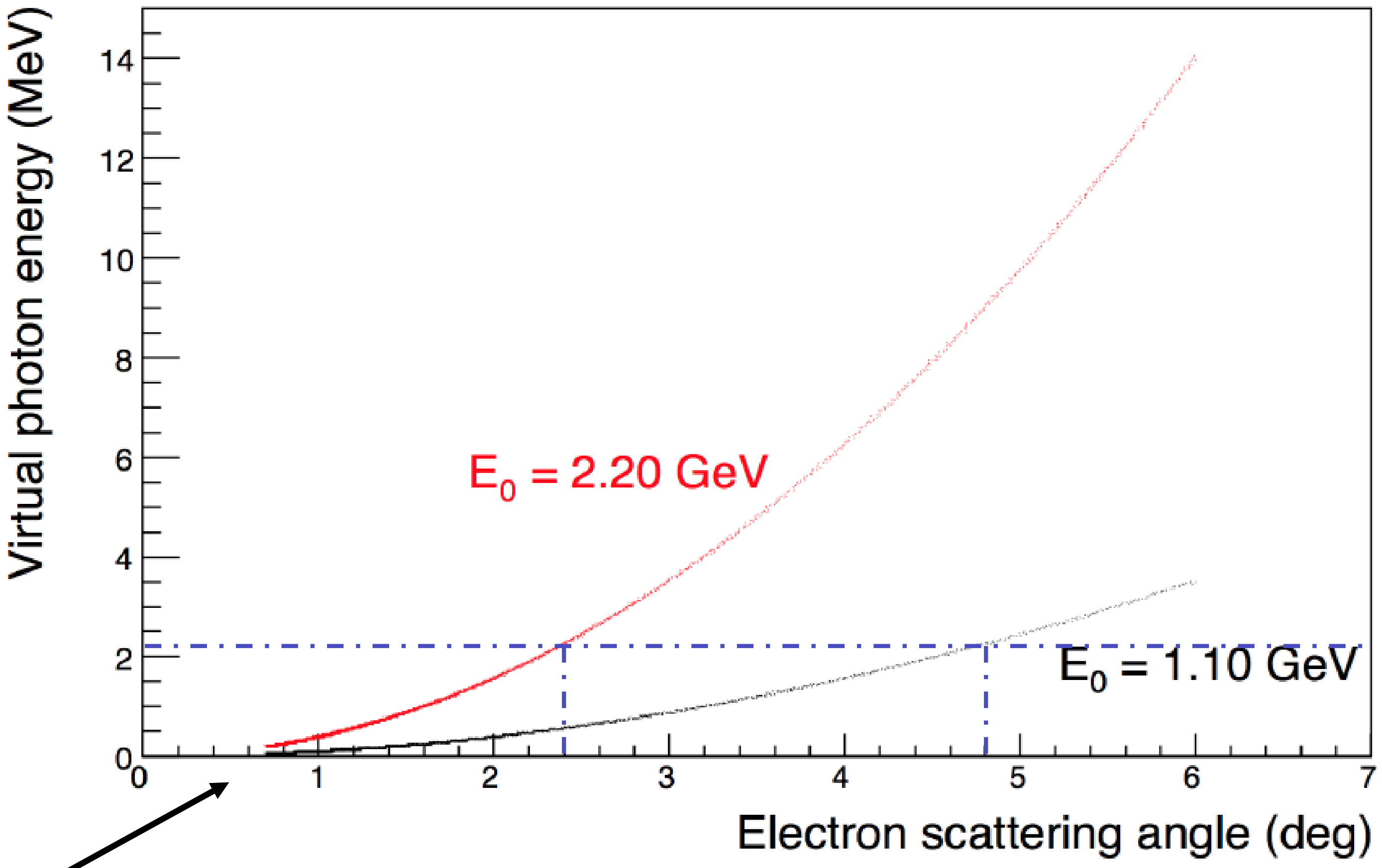


For 1.1 GeV: $\theta_e > 1.1°$ will be detected, with $Q^2 \geq 4 \times 10^{-4} (\mathrm{GeV/c})^2$

PID for recoil particles

- To select the deuteron from the proton background, we will use the following information:

1. Deuteron breakup threshold
2. Energy deposition in the Recoil Detector
3. Time of flight and co-planarity



Eγ* < 2.2 MeV (deuteron electro-disintegration threshold)

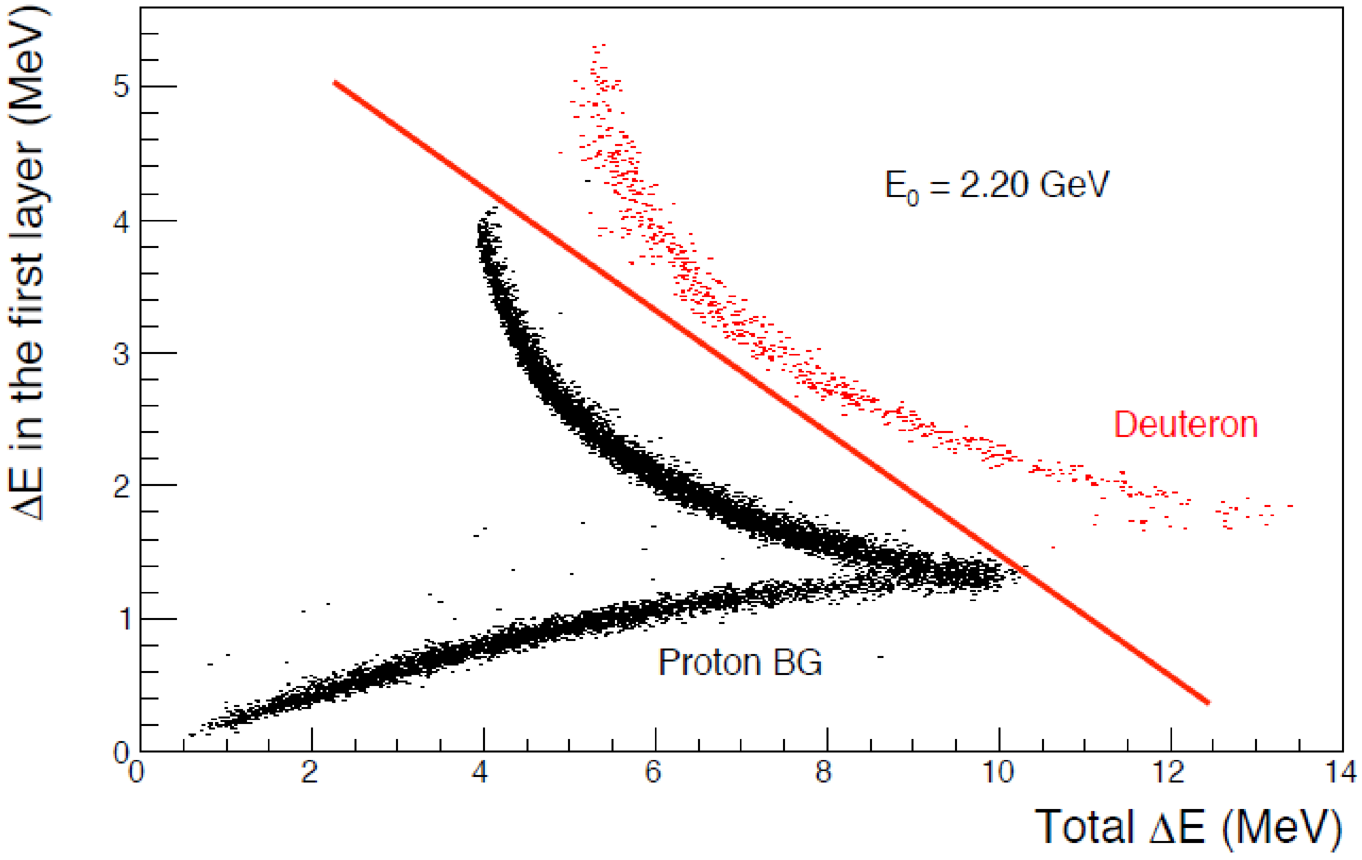
The e-d elastic event can be detected without using the recoil detector, when:

$\theta_e < 2.4°$ (2.2GeV), $\theta_e < 4.8°$(1.1GeV)

PID for recoil particles

- Complete simulation of deuteron electro-disintegration process, including Fermi-motion and realistic models is developed. (QUEEG Monte Carlo event generator for CLAS6)

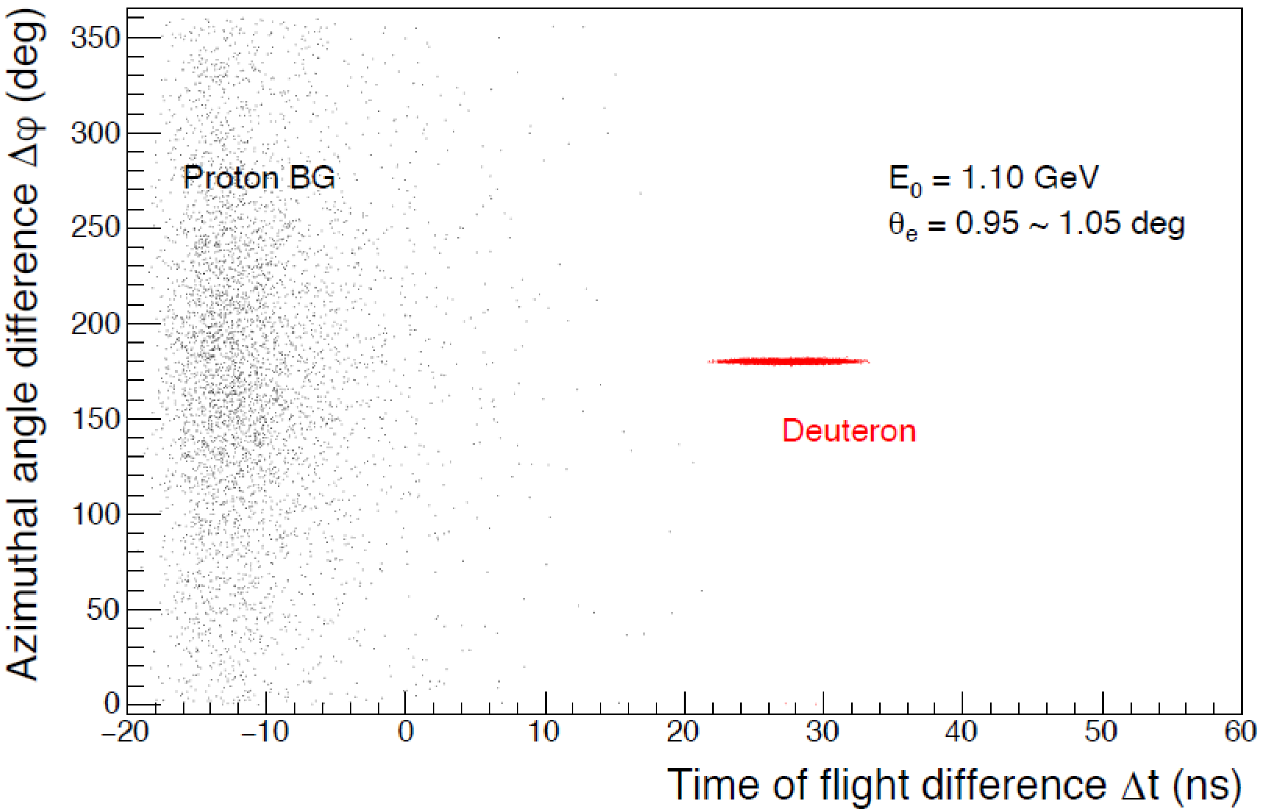
1. dE/dx *vs.* ΔE

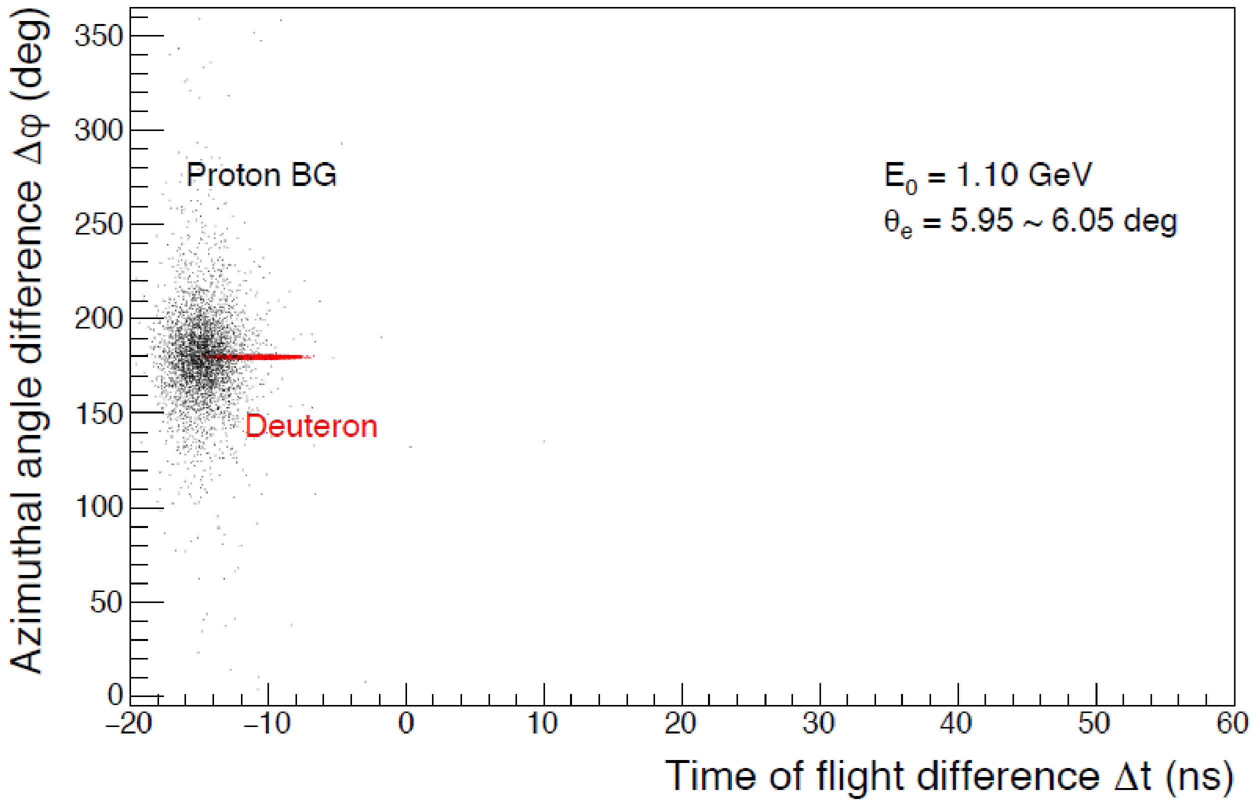


For 2.2 GeV, a 2D cut alone on dE in the first layer vs. total dE in the Si-strip detectors is very effective for PID

PID for recoil particles

- **2. time-of-flight (Δt) vs. co-planarity (Δφ) :**





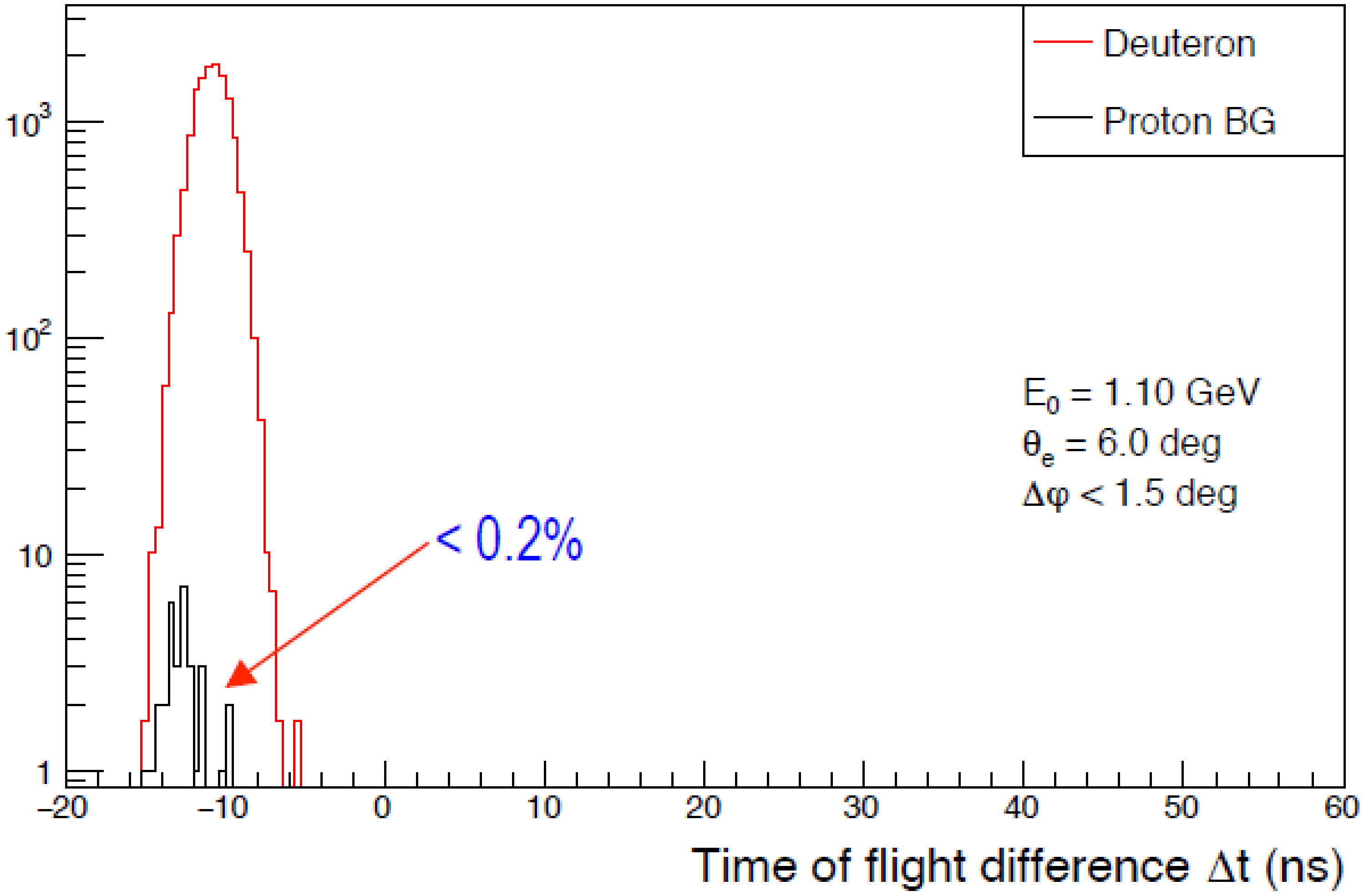
For 1.1 GeV beam energy, the time-of-flight (Δt) vs. co-planarity (Δφ) between scattered electron and recoiled deuteron can be used to separate the Deuteron signal from the Proton background in most of the angular range, except for θe ≈ 6°

PID for recoil particles

- **2. time-of-flight (Δt) vs. co-planarity (Δφ) between scattered electron and recoil deuteron:**

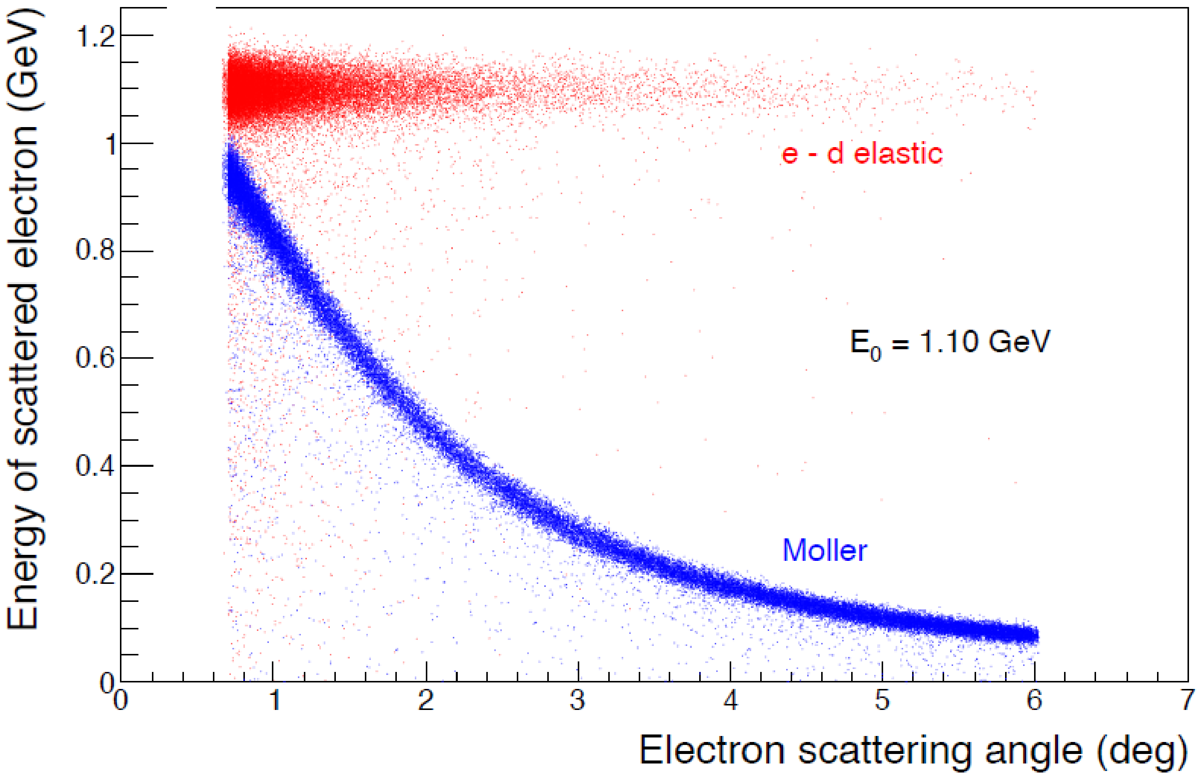
For 1.1 GeV beam energy:

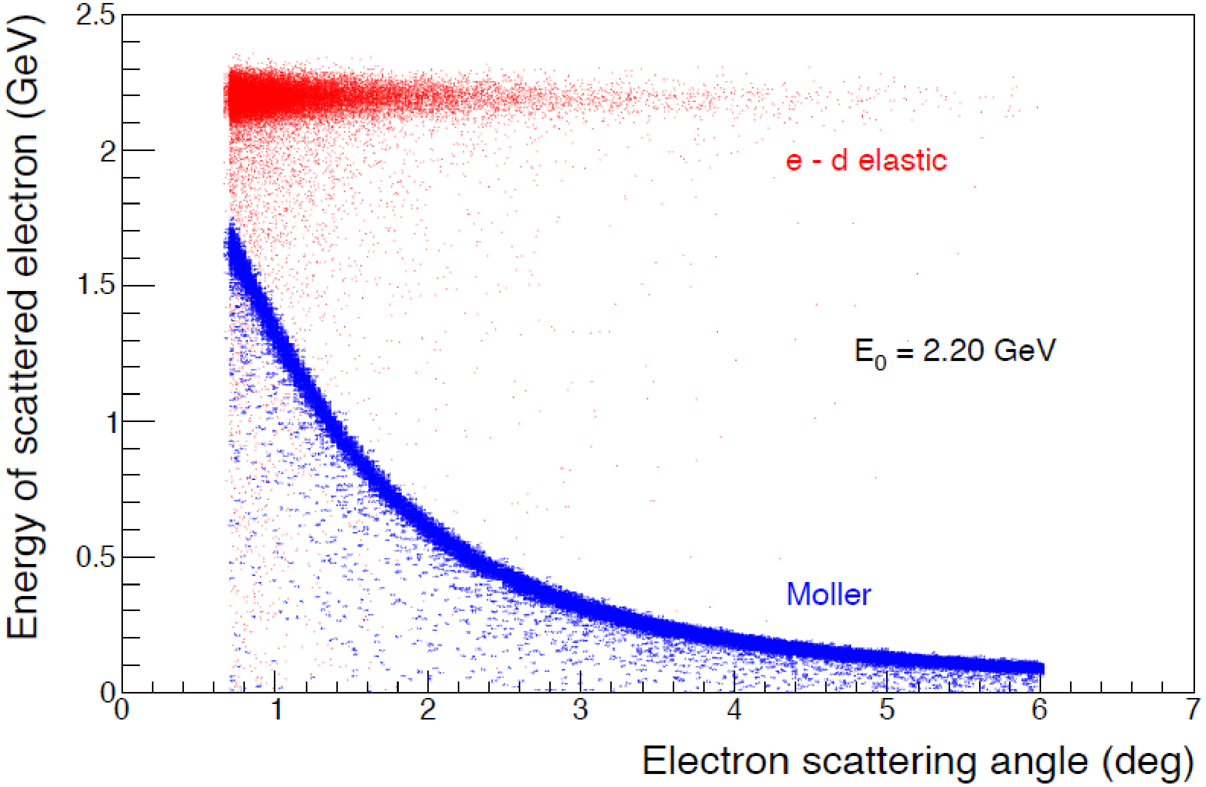
- Applying [Δφ *vs.* Δt] and [dE/dx *vs.* ΔE] cuts removes the proton background for most angles.
- When θe ≈ 6° , where the background level is ≤ 0.2%.



Moller event selection

- Compared to PRad, the Moller event selection method is the same:





e-d elastic process and the Møller process can be separated by a 2D cut.

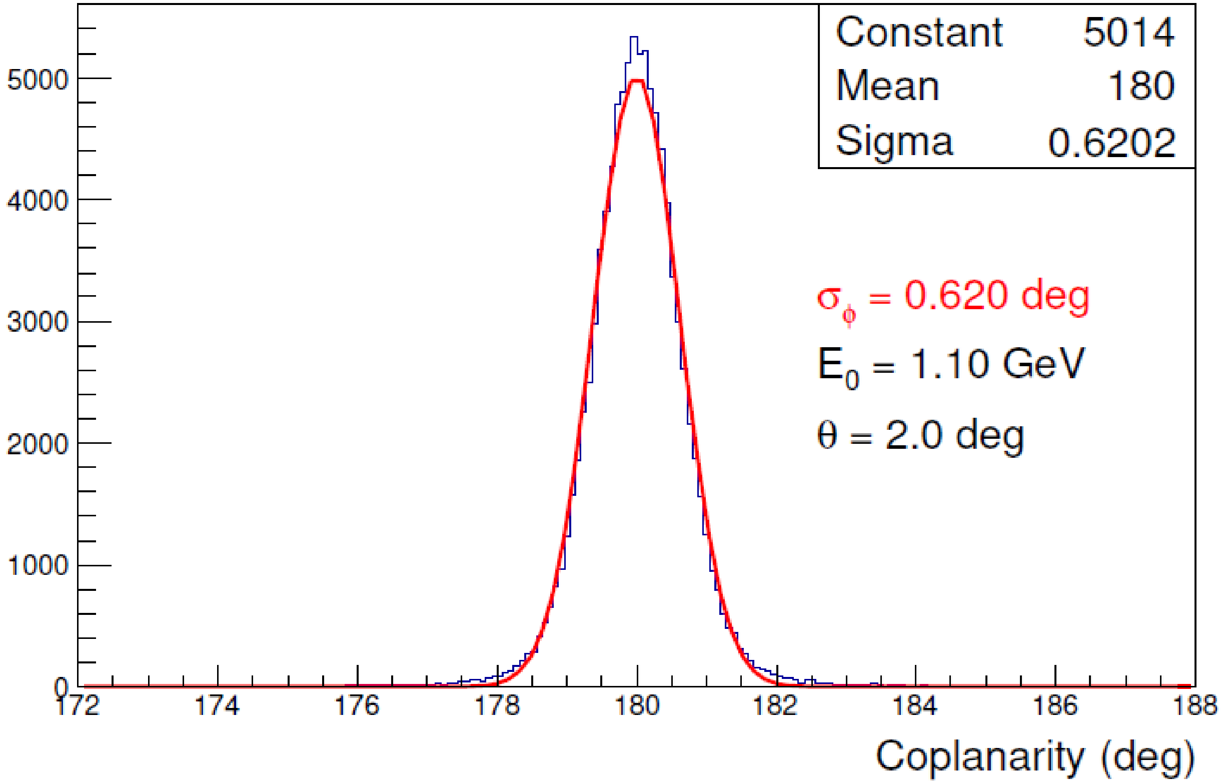
Moller event selection

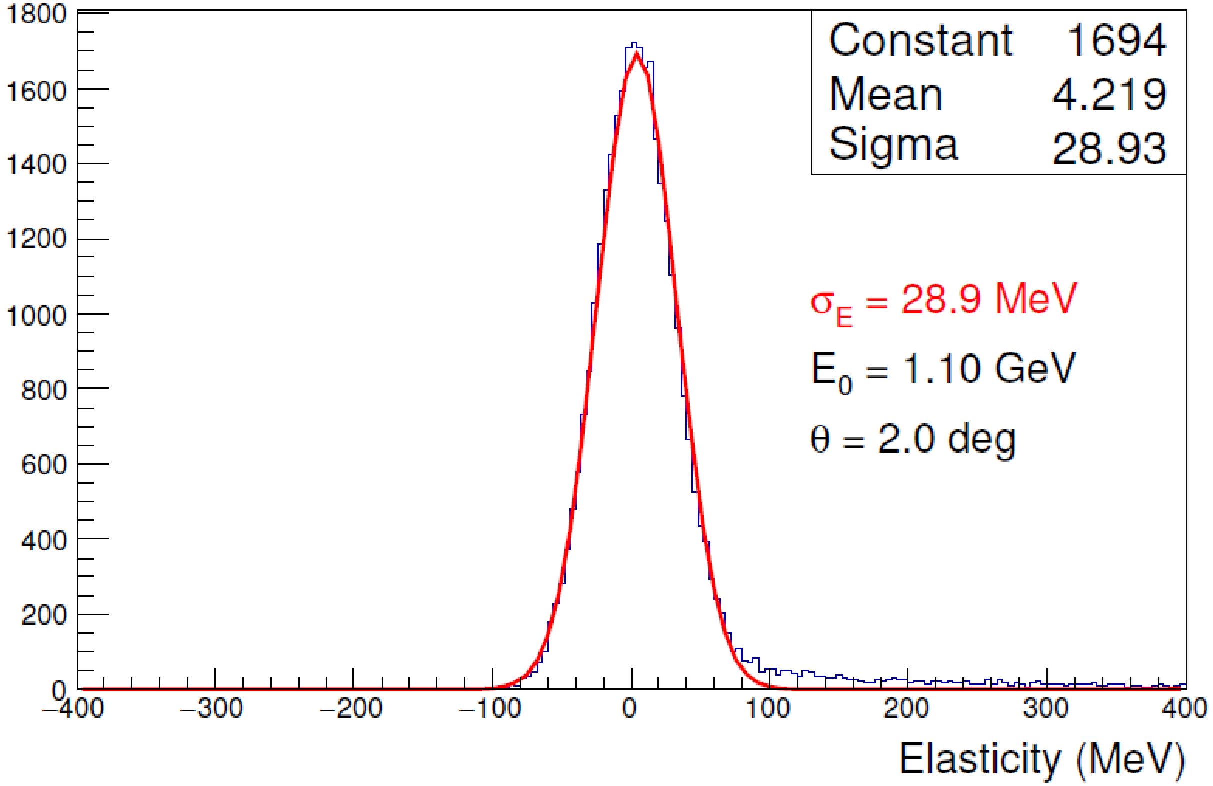
- $e^{-}e^{-}$ co-planarity

$$\phi_{e1} - \phi_{e2} = \pi$$

- $e^{-}e^{-}$ elastic scattering

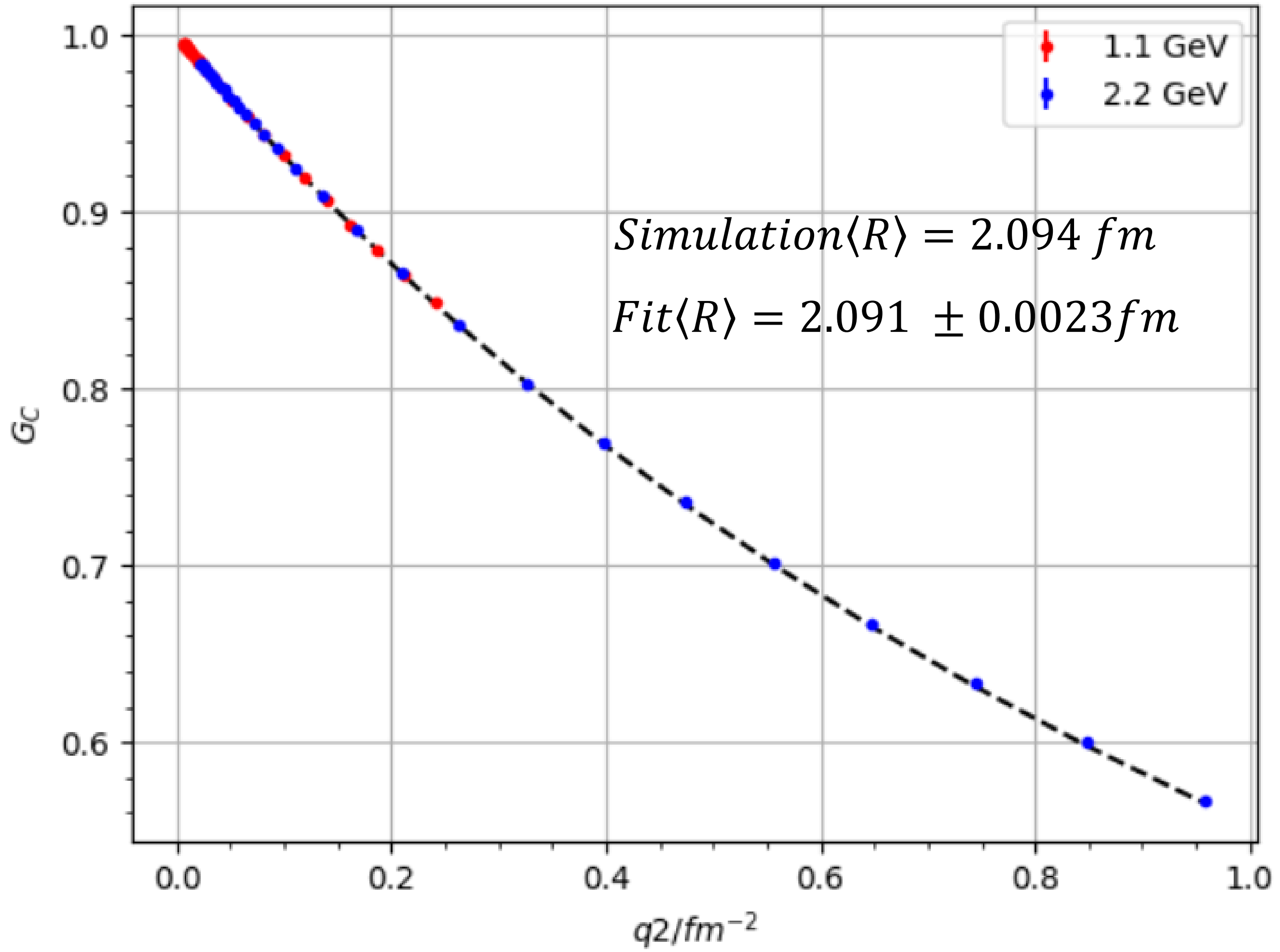
$$Elasticity = E_o - (E_{e1} + E_{e2})$$





- The two GEMs can provide an excellent resolution in the co-planarity.
- The Hycal can provide a high resolution to select the elastic events.

Extraction of Deuteron Charge Radius



Rational(1,1) function

$$f_{rational\_1\_1}(Q^2) = p_0 \frac{1 + p_1^a Q^2}{1 + p_1^b Q^2}$$

$$\mathrm{R} = \sqrt{6(p_1^a - p_1^b)}$$

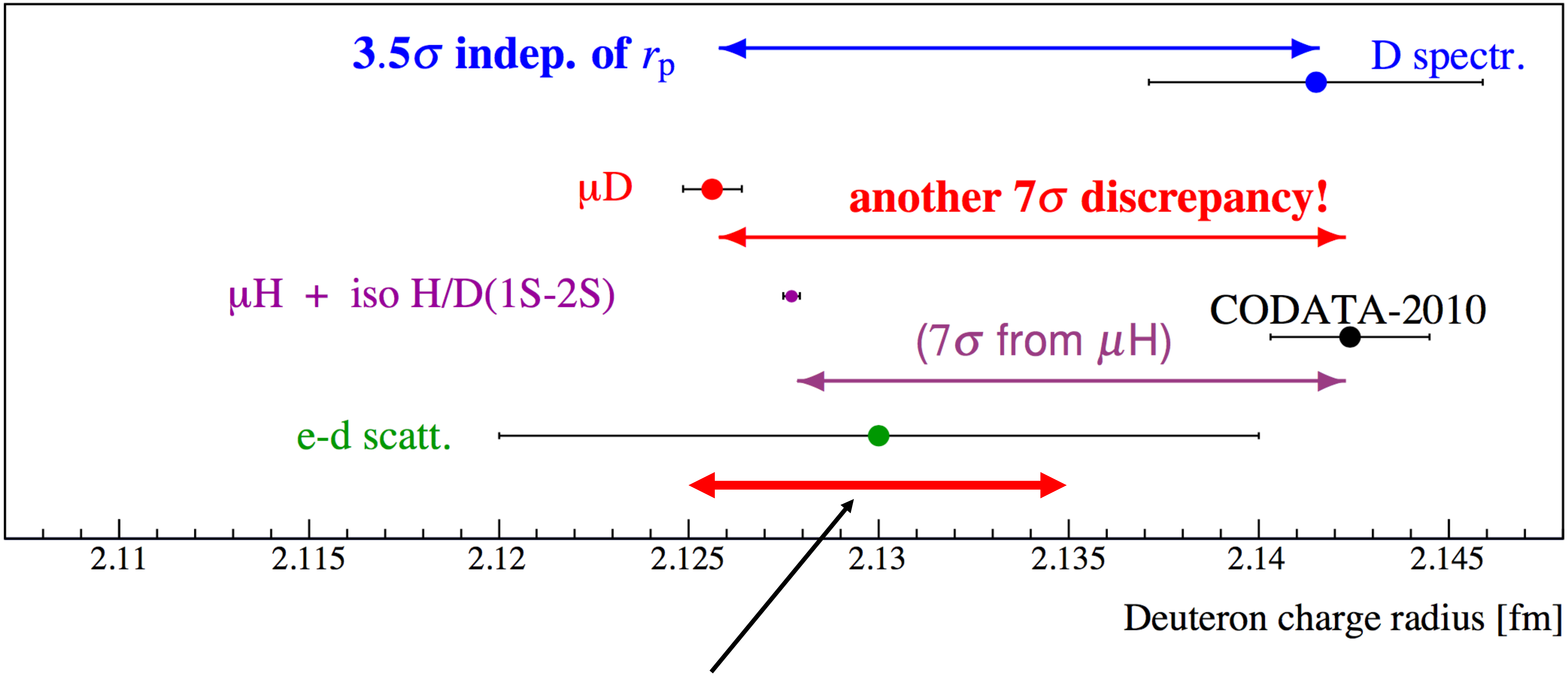
- Three different deuteron parameterizations models to extract R_d from MC simulations with radiative corrections.
- Choose Rational(1,1) to do the fitting.

Systematic uncertainties from

1. Event selection (elasticity cuts, co-planarity cuts…)
2. Radiative correction
3. Detector efficiencies (GEM, HyCal, Recoil Detector…)
4. Beam-line background (Halo hitting collimator, residual gas…)
5. HyCal energy calibration
6. Detector position
7. Beam energy
8. Inelastic contributions
9. Assumed magnetic and quadrupole form factors during the GC extraction
10. The choice of the fitter
11. Detector acceptance

…

Uncertainty budget of the radius



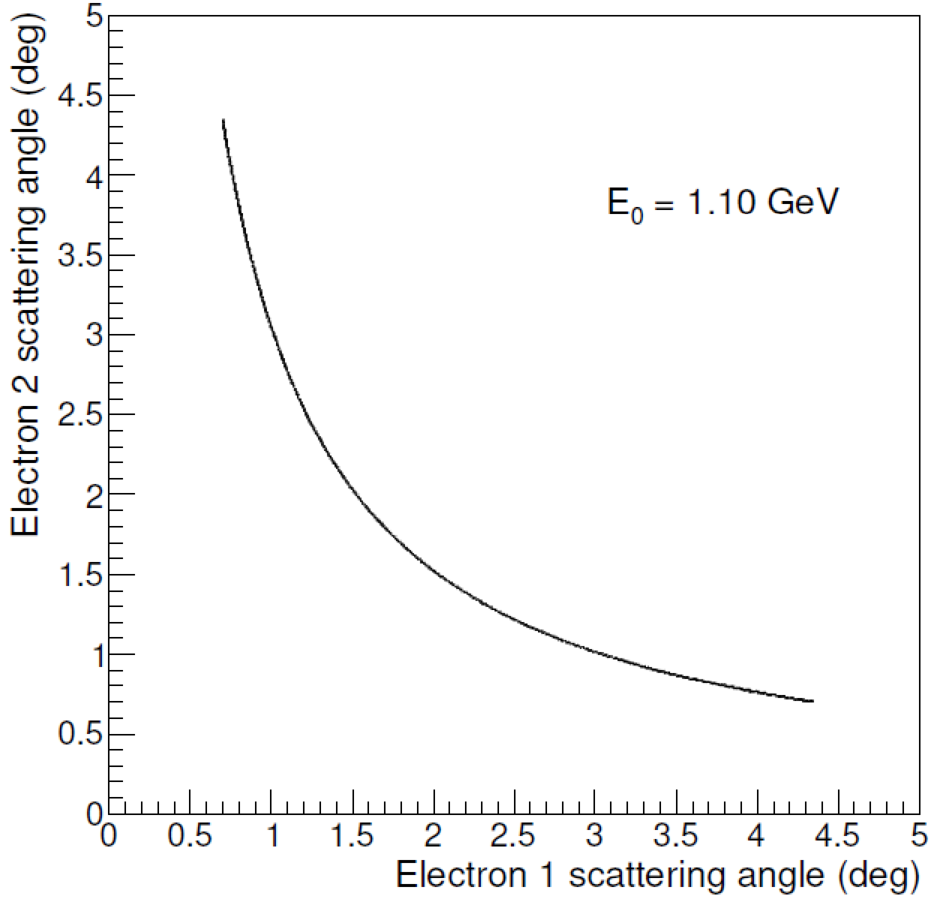
The uncertainty in this proposed experiment is expected to be 0.25%

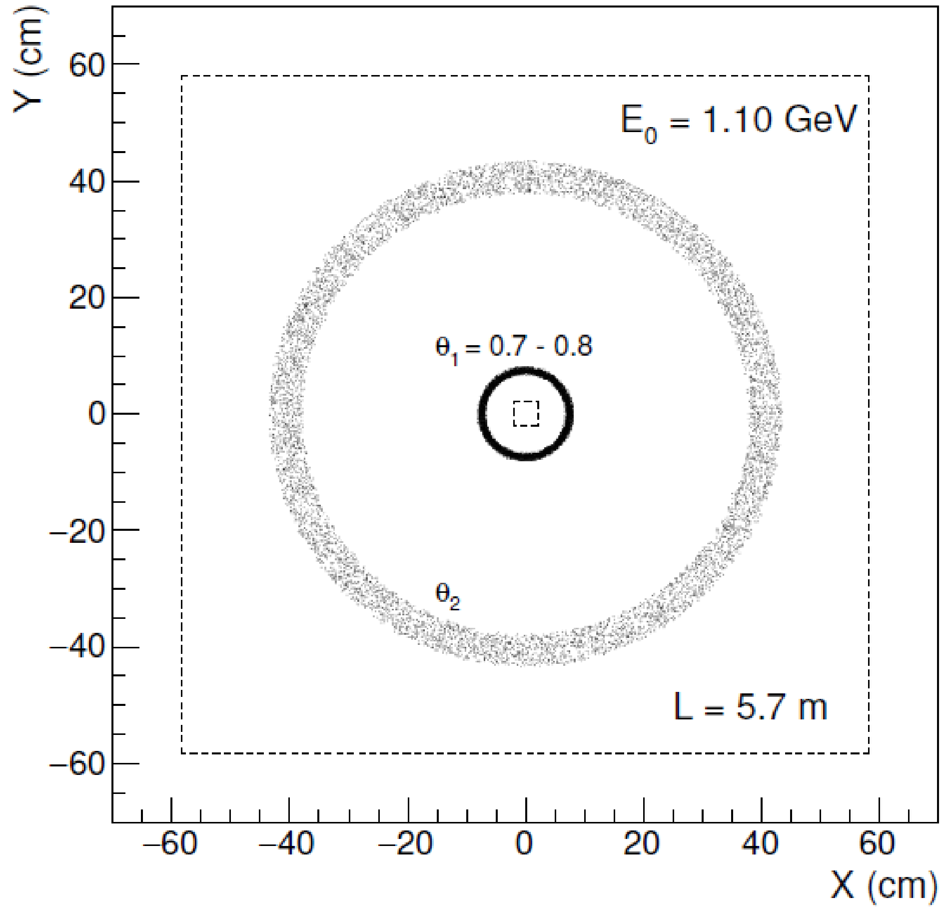
Summary

- We propose a new experiment for the deuteron charge radius measurement with a high accuracy to address the *"deuteron radius puzzle"* in nuclear physics.
- It is based on the PRad experiment for the proton charge radius measurement:
  - magnetic-spectrometer-free calorimetric experiment;
  - windowless deuterium/hydrogen gas flow target to reduce background;
  - cylindrical recoil detector for reaction elasticity;
  - additional GEM detector for scattered electron tracking.
- That will allow:
  - measure cross sections in one kinematical settings for a large Q^2 range $[2 \times 10^{-4} - 5 \times 10^{-2}]\ (GeV/c)^2$;
  - simultaneous detection of $ee \to ee$ Moller scattering process;
  - measure e-d cross section to subprecent precision
- Expected R_d uncertainty : 0.25% (preliminary)
- PRad analysis indicates: backgrounds well understood, proposed uncertainty can be achieved.

Back up

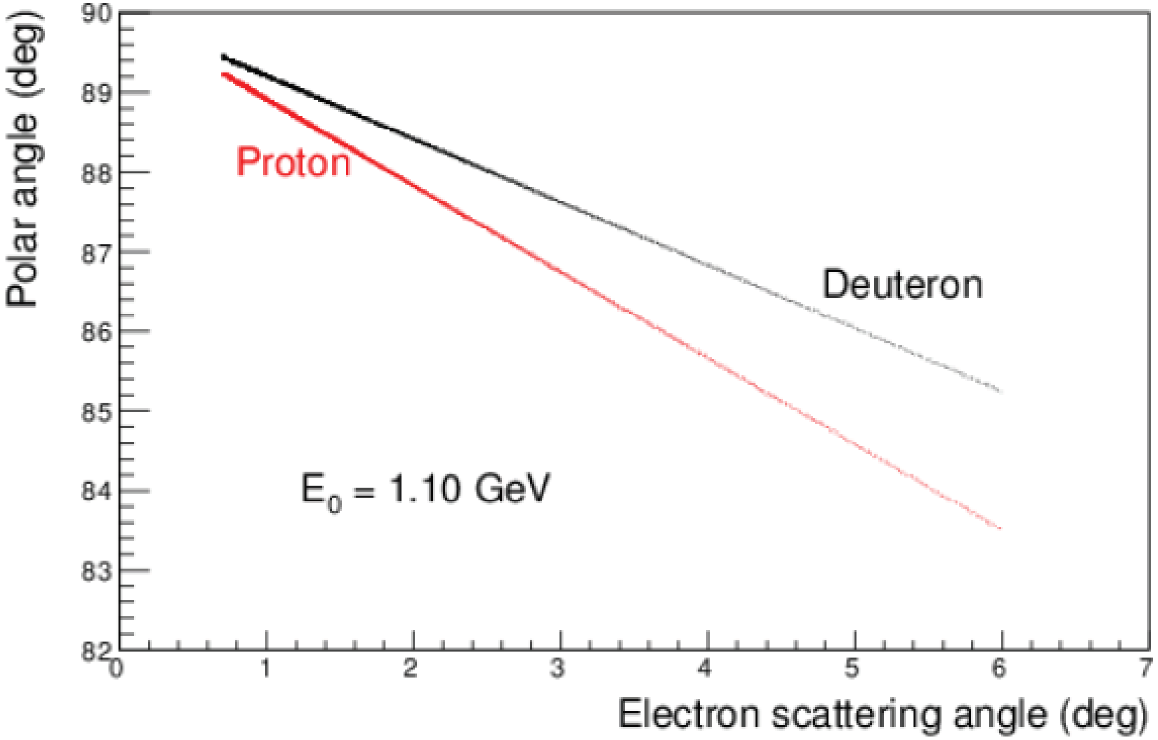
Moller Selection Method

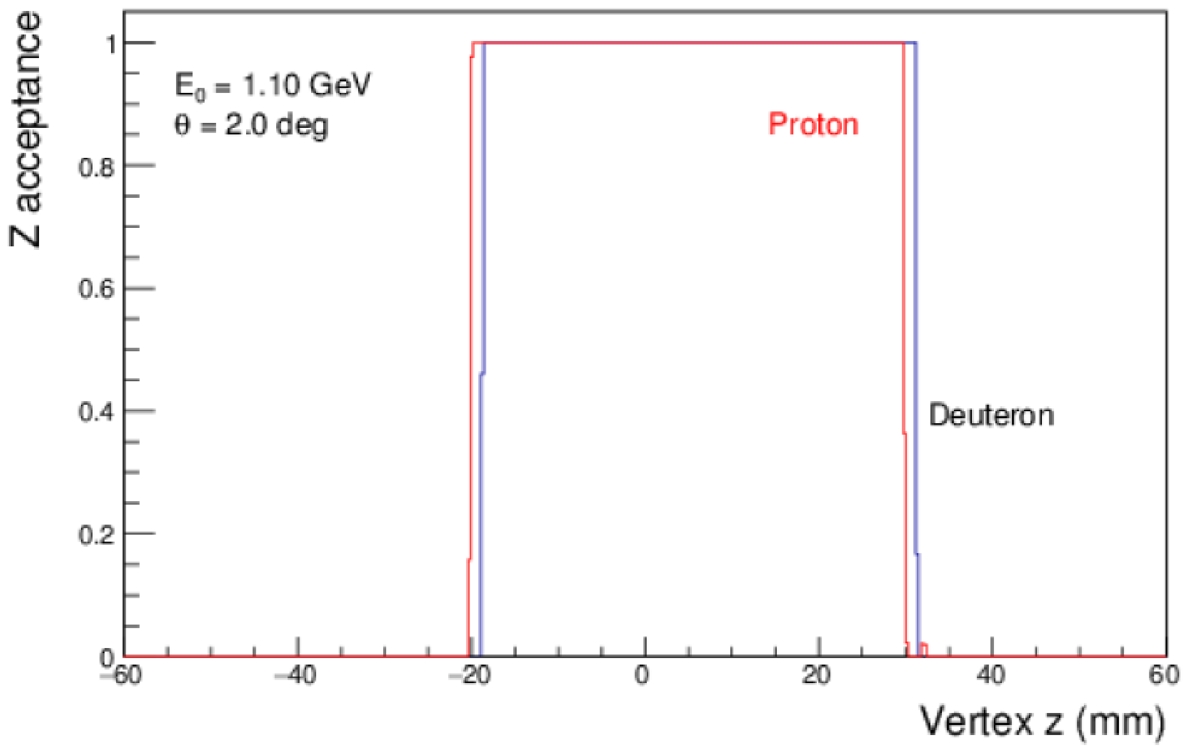




- **Single-arm Moller method**: one Moller e- is in the same Q2 range
- **Double-arm Moller method**: require the two Moller e^- to be detected at the same time, the angular coverage is limites by the acceptance of HyCal

Calibration of the Recoil Detector





- The kinematics of e-p is very similar to the e-d elastic process
- Both detection efficiency ϵ_{det}^{ed} and geometrical acceptance ϵ_{geom}^{ed} of the recoil detector will be measured during special runs with hydrogen gas