Precision Deuteron Charge Radius Measurement with Elastic Electron-Deuteron Scattering

(**PR12-17-009**)

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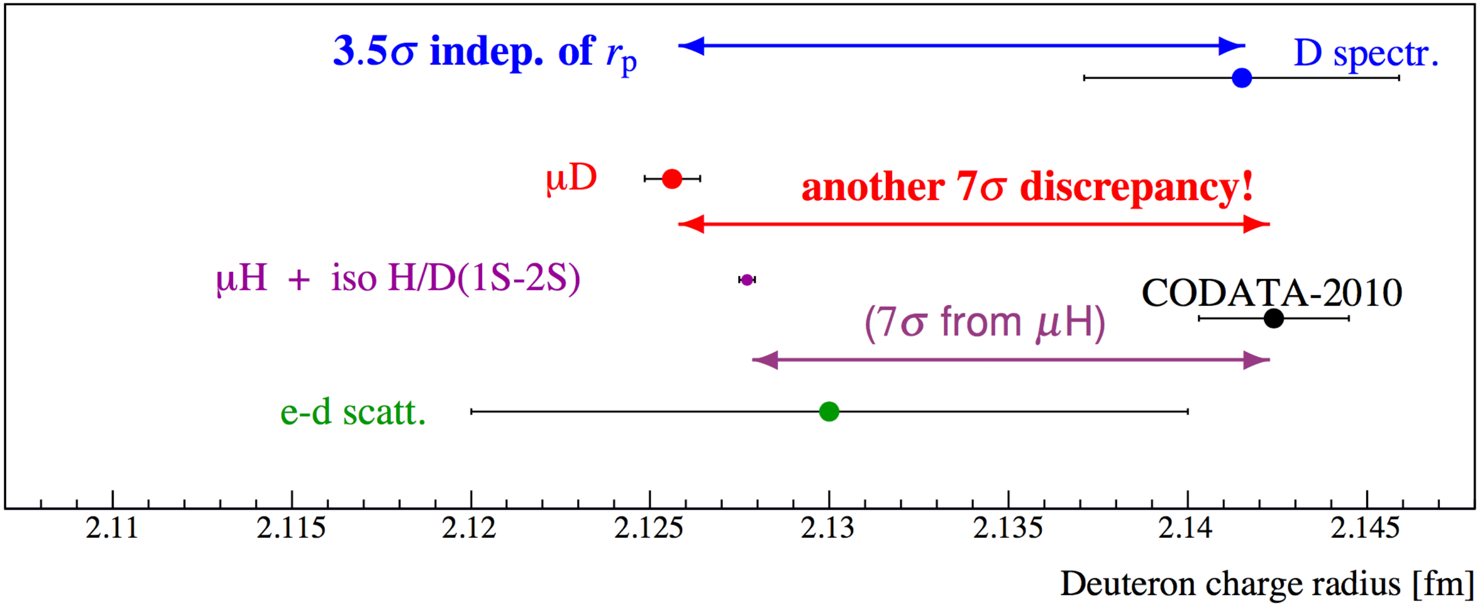
Outline

- Motivation
- Proposed experiment
  - experimental method
  - control of systematic errors
  - PRad short status
- Summary

Motivation of the Experiment

- *"Proton Charge Radius Puzzle"* is still unsolved after seven years.
- There is a newly developing *"Deuteron Charge Radius Puzzle"*

H/D isotope shift:	$r_d^2 - r_p^2 = 3.82007(65)$ fm2
Muonic deuterium:	$r_d = 2.12562(13)_{exp}(77)_{theory}$ fm
Electronic deuterium:	$r_d = 2.14150(450)$ fm



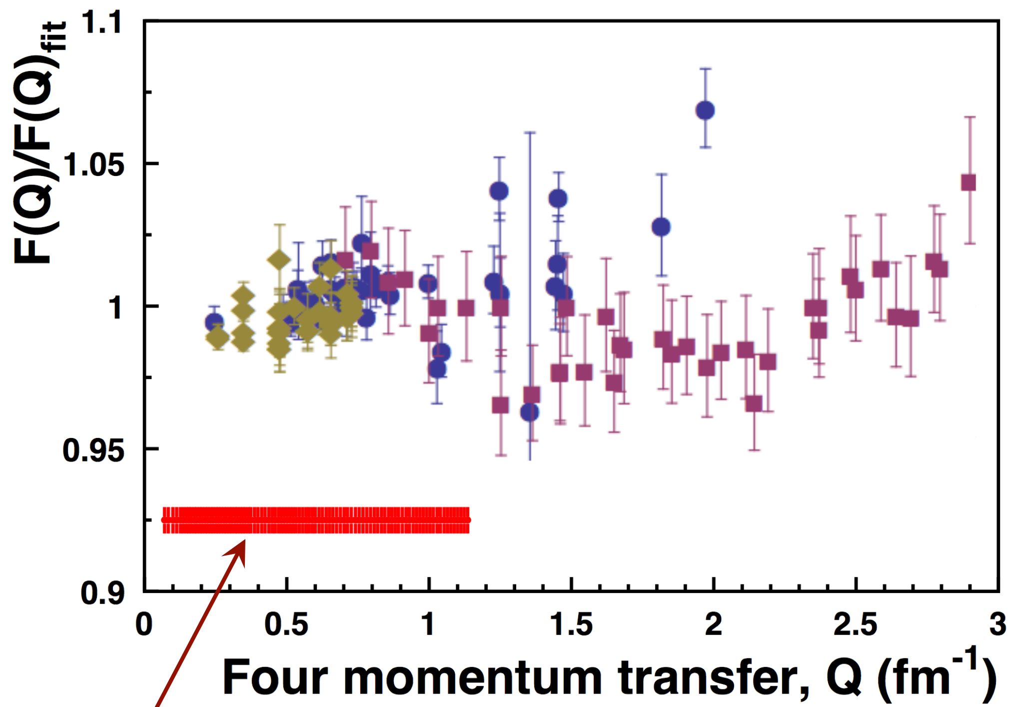
(R. Pohl, 2017)

- Calles for new independent experiments with possible highest accuracy!
- New ed- cross sections at low Q^2 will be a critical input to reduce theory error in r_d extracted from μD spectroscopy.

Previous *ed* → *ed* Experiments at Low Q^2 Range

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

- R.W. Berard et al. Phys. Rev. Lett. B47,355 91973)
  different target: cooled H_2 and D_2 gas
  measured ratio of *ed/ep* cross sections
  Q = [0.2 – 0.7] fm^{-1}
- G.G. Simon et al. Nucl. Phys. A364, 285 1981
  different gas and liquid targets:
  Q = [0.2 – 2.0] fm-1
- S. Platchkov, et al. Nucl. Phys. A510, 740, 1990
  different LH2 and LD2 targets
  Q = [0.7 – 4.5] fm^{-1}



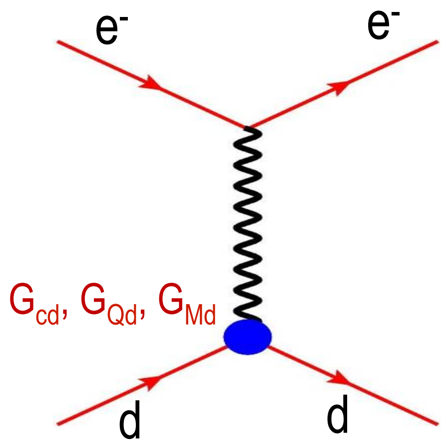
I. Sick and D. Trautmann, NPA 637, 559 (1998)

Previous experiments used:

- ✓ magnetic spectrometer method;
- ✓ different type of targets;
- ✓ normalized *ed-* to *ep-* cross sections.

✓ We propose a new, most optimized method to measure *ed* → *ed* absolute cross sections with high accuracy.

Deuteron Charge Radius from *ed* → *ed* Scattering Experiment



- In the limit of first Born approximation the elastic *ed*- scattering is expressed with A(Q²) and B(Q²) 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:

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

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

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

- At low Q^2 contribution from G_{Qd} and G_{Md} are small (they can be ignored or included from other experiments). Then, the deuteron rms charge radius:

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

Proposed Experiment

- Measure *ed* → *ed* elastic cross sections at very low Q^2 range: $[2\times10^{-4} – 5\times10^{-2}]$ $(GeV/c)^2$.

- Experimental method based on PRad, with two additions:
  - ✓ magnetic-spectrometer-free calorimetric experiment;
  - ✓ windowless deuterium/hydrogen gas flow target;
  - ✓ cylindrical recoil detector for reaction elasticity (new);
  - ✓ additional GEM detector for scattered electron tracking (new).

- That will allow:
  - reach very low Q^2 range, (~ 10^{-4} GeV^2) for the first time;
  - simultaneous detection of *ee* → *ee* Moller scattering process;
  - providing best control of systematic errors;
  - measuring cross sections in one kinematical settings for a large Q^2 range;
  - low background experiment;
  - essentially model independent r_d extraction.

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

Control of Systematic Errors

- Major improvements over previous experiments:
  1) Simultaneous detection of two processes
     - *ed* → *ed*
     - *ee* → *ee* Moller scattering → Tight control of systematic errors
  2) Windowless D_2 gas target → Low beam background
  3) Very low Q^2 range: [$2\text{x}10^{-4}$ – $5\text{x}10^{-2}$] $(\text{GeV/c})^2$ → practically, model independent r_d extraction

- Extracted yield for *ed* → *ed*

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

- … and for *ee* → *ee*, Moller

$$\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-} = \frac{N_{\text{exp}}^{\text{yield}}\,(e^-e^- \to e^-e^-)}{N_{\text{beam}}^{e^-} \cdot N_{\text{tgt}}^{\text{D}} \cdot \varepsilon_{\text{geom}}^{e^-e^-} \cdot \varepsilon_{\text{det}}^{e^-e^-}} \,,$$

- Then, *ed*- cross section is related to Moller:

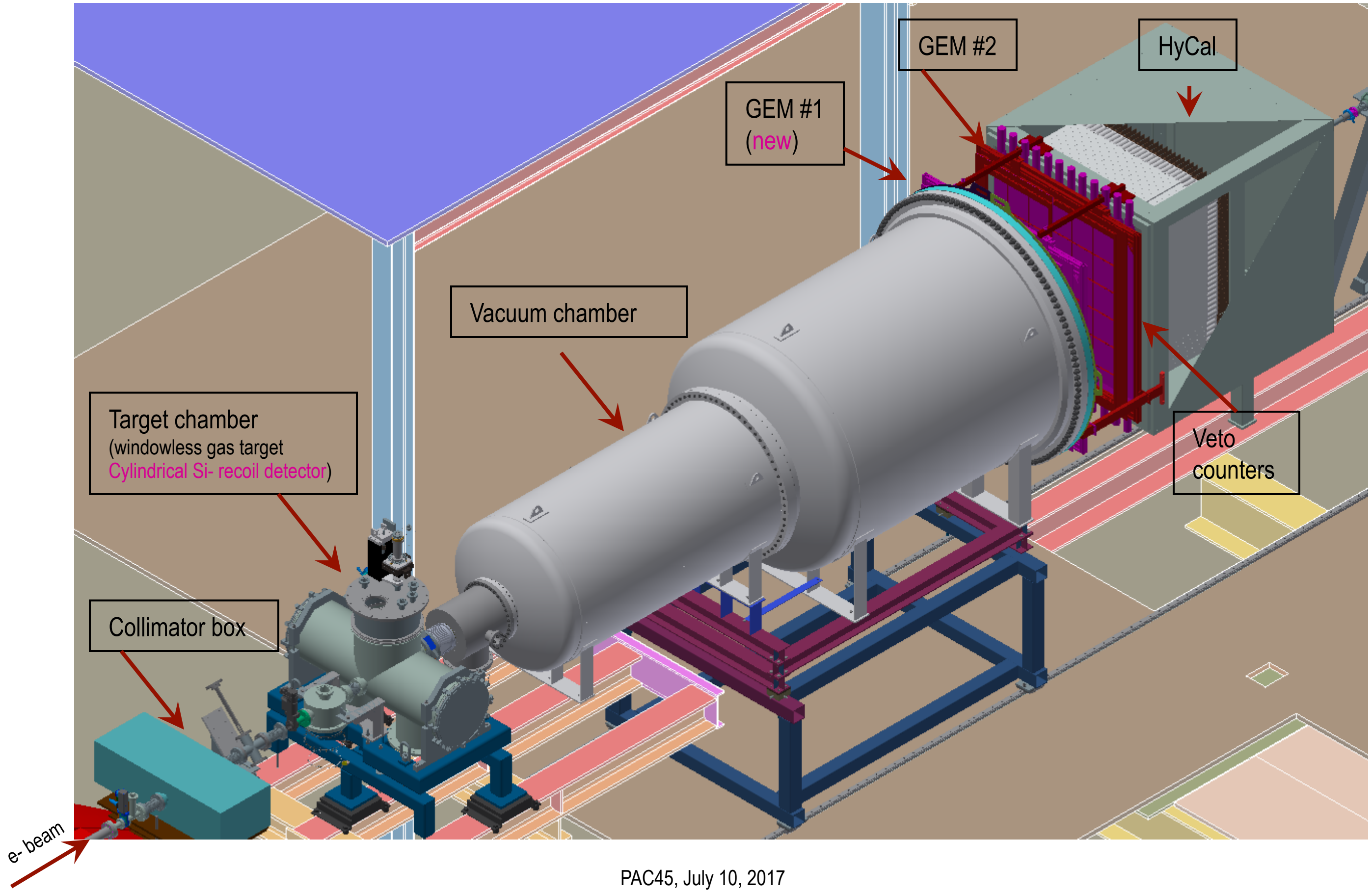
$$\left(\frac{d\sigma}{d\Omega}\right)_{ed}(Q_i^2) = \left[\frac{N_{\text{exp}}^{\text{yield}}\,(ed \to ed \text{ in } \theta_i \pm \Delta\theta)}{N_{\text{exp}}^{\text{yield}}\,(e^-e^- \to e^-e^-)} \cdot \frac{\varepsilon_{\text{geom}}^{e^-e^-}}{\varepsilon_{\text{geom}}^{ed}} \cdot \frac{\varepsilon_{\text{det}}^{e^-e^-}}{\varepsilon_{\text{det}}^{ed}}\right]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

- Two major sources of systematic errors, N_e and N_{tgt}, typical for all previous experiments, cancel out.
- Geom. acceptances and detection efficiencies will be extracted during *ep* → *ep* calibration run with hydrogen gas in target cell.
- Moller scattering will be detected in double-arm and single-arm modes in HyCal acceptance.

Proposed Experimental Setup

- Based on the PRad method and experimental setup, three additions:

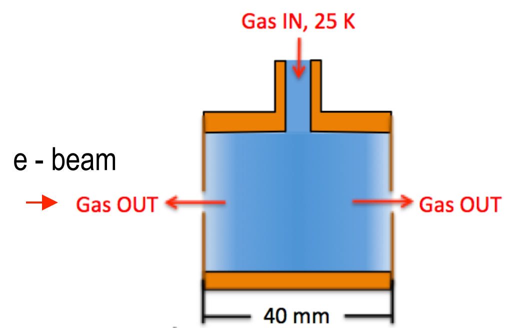
  - ✓ cylindrical recoil detector for reaction elasticity (new);
  - ✓ additional GEM detector for scattered electron tracking (new)
  - ✓ veto counters for timing (PrimEx veto counters).



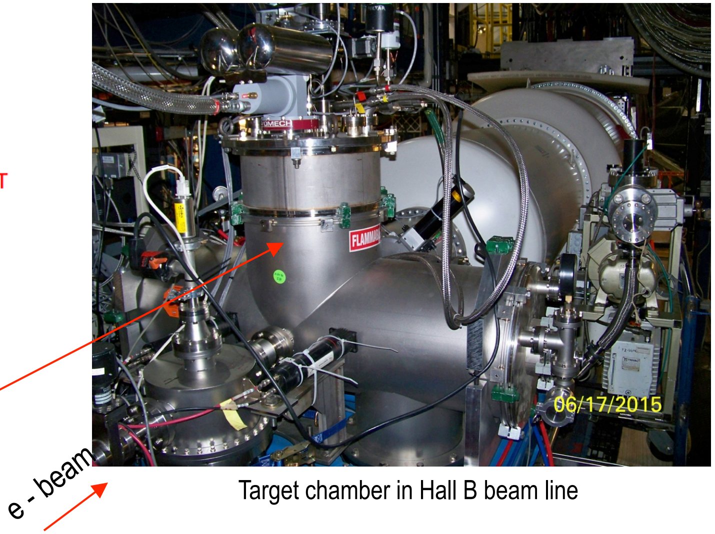
Windowless Target and Si-strip Cylindrical Recoil Detector

- Detection of recoiled deuterons: elasticity in *ep* → *ep* scattering
- Based on PRad windowless gas flow target and CLAS12 Barrel Silicon Tracker (SVT):
  - consist of 20 panels of twin, single-sided Si-strip detectors (size; 42x52mm^2);
  - thicknesses: lower, ≈ 200 μm, upper ≈ 300 μm (to be optimized);
  - do-decagon arrangement with R=13 cm radius;
  - 256 strops on each sensor, angular resolution: $\delta\varphi \leq 5$ mrad, $\delta\theta \leq 20$ mrad

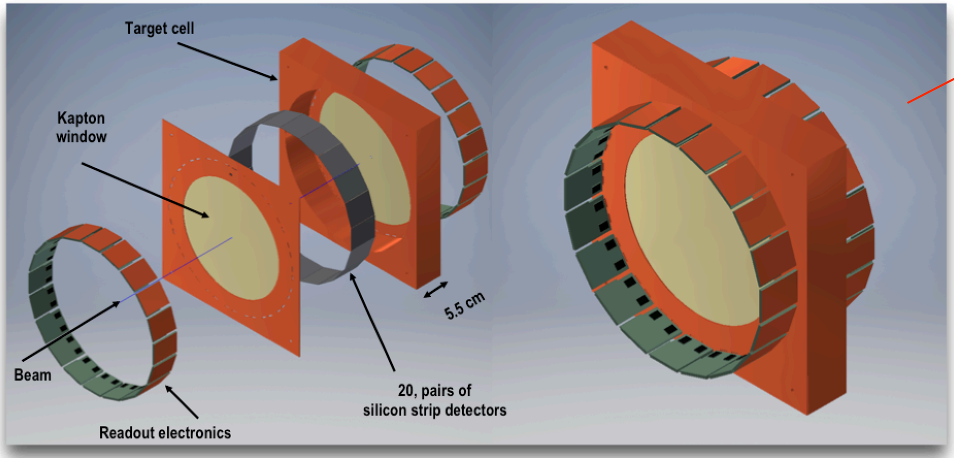
- Windowless deuterium gas flow target:
  - areal density: ~2 x10^{18} D /cm^2
  - crycooled to ~20 K



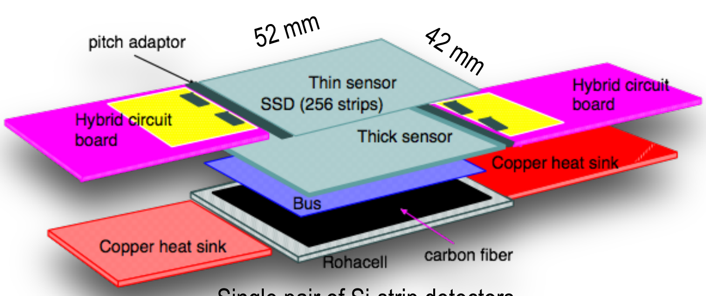
Windowless gas target concept



Target chamber in Hall B beam line



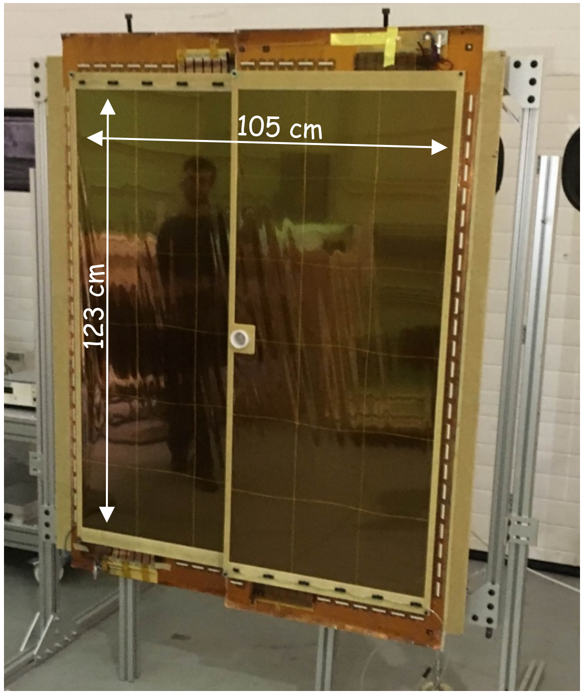
Si-strip recoil detector parts

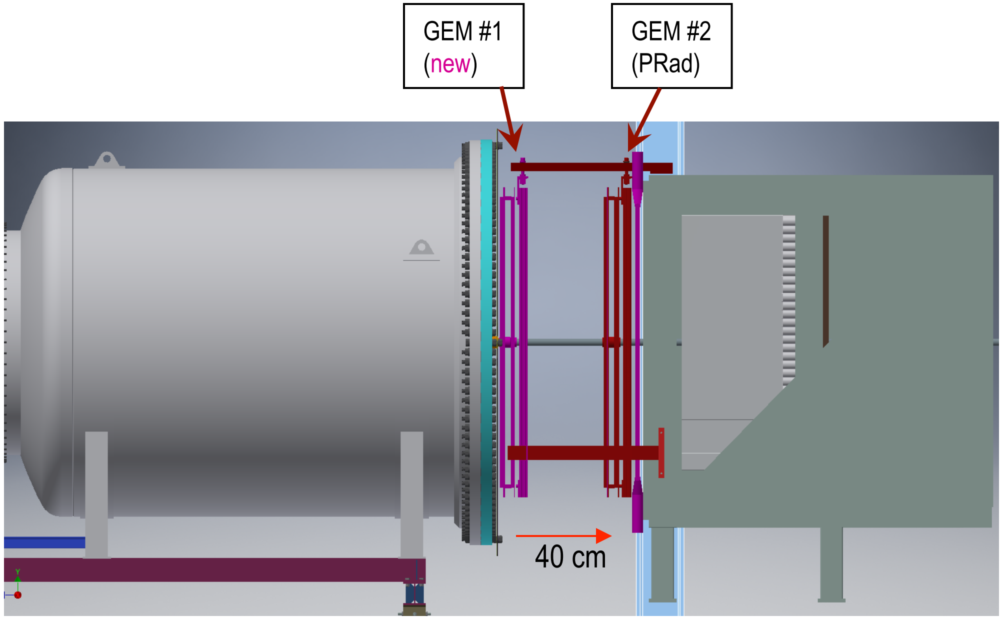


Single pair of Si-strip detectors

Second GEM for Scattered Electron Tracking

- Based on PRad GEM detector (UVa group), twice less material (0.25% r.l. vs. 0.5% r.l.):
  - twice less material than previous GEM (0.25% r.l. vs. 0.5% r.l.);
  - located at 40 cm distance from the first;
  - will provide tracking for the scattered electrons;
  - better control of beam line background, especially at very small angles ($\theta_e \approx 1^0$)

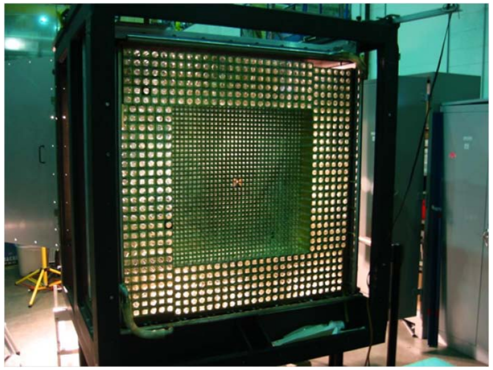


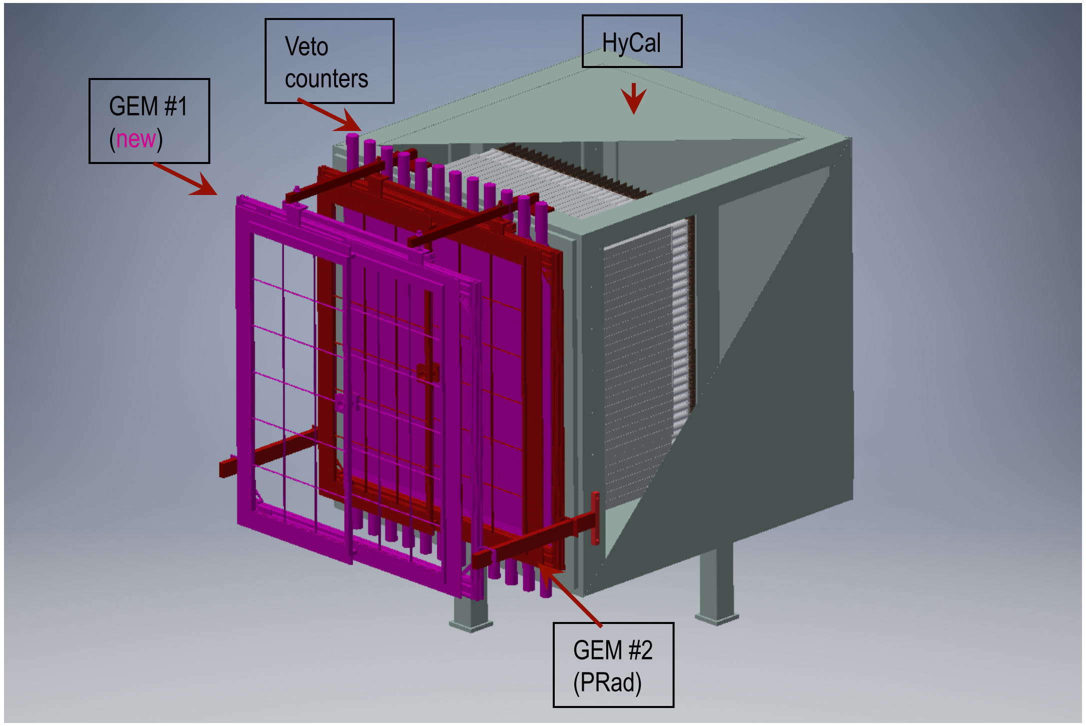


Electromagnetic Calorimeter and Veto Scintillators

- PrimEx (also PRad) hybrid electromagnetic calorimeter, HyCal:
  - energy and position of scattered electrons;
  - provides trigger in experiment;
  - large acceptance, high resolution.

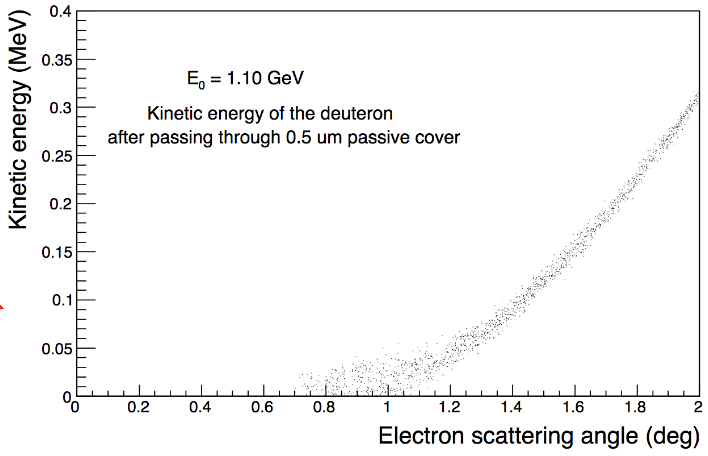
- PrimEx veto counters for timing in scattered electrons (< 1 ns time resolution).



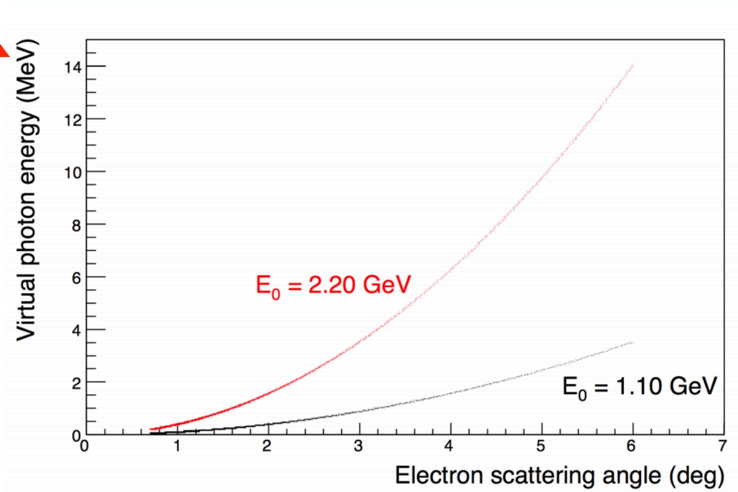


Kinematics and Q^2 Coverage
(ITAC question/comment #1)

- Full GEANT4 simulation code has been developed, including all detectors.
  - ✓ for these beam energies deuterons will recoil at large polar angles: $\theta_d = [83^0 \div 89^0]$;
  - ✓ and detected in the Si-detectors ("*dead layer*" ~ 0.5 µm);
  - ✓ for 1.1 GeV: $\theta_d > 1.1^0$ will be detected; with $Q^2 \geq 4\text{x}10^{-4}$ $(GeV/c)^2$



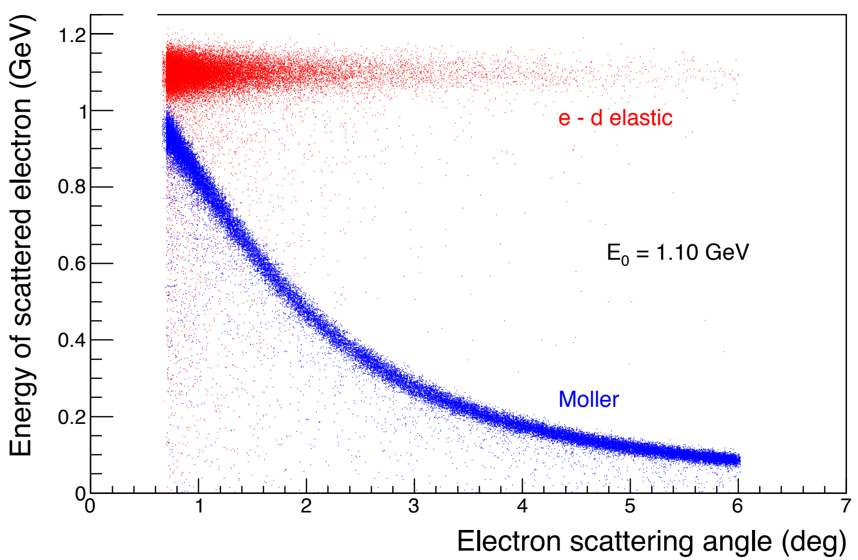
- Also, at this very small angles, the virtual photon energy: $E_{\gamma^*} < 2.2$ MeV (deuteron electro-disintegration threshold).
  Trigger in experiment: $E_{HyCal} > 0.2\ E_{beam}$;
  - ➢ These events will be detected without recoil deuterons In Si-strip detector;

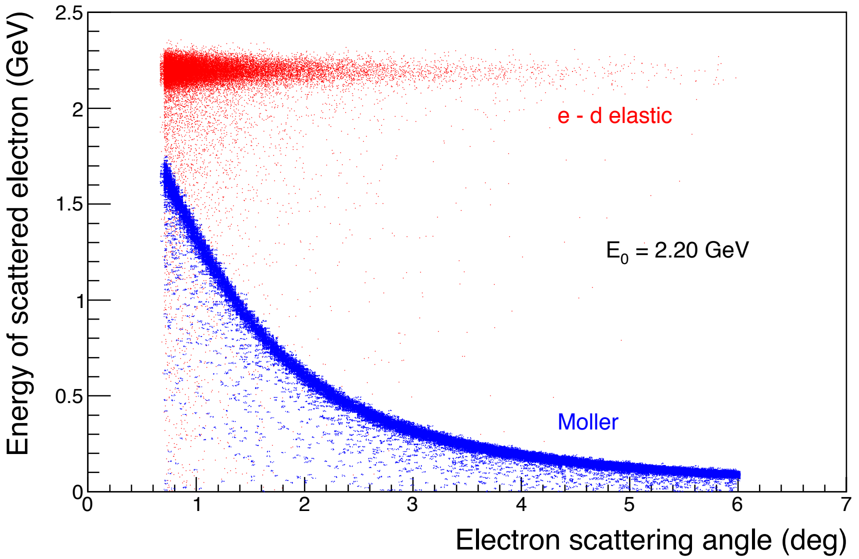


- In summary, the proposed experiment will cover the $Q^2 = [2\text{x}10^{-4} \div 5\text{x}10^{-2}]$ $(GeV/c)^2$ range, as it is stated in the proposal.

Event Selection and Radiative Corrections

- Event generators for both $ed \rightarrow ed$ and $ee \rightarrow ee$ have been developed and implemented in GEANT4 simulation code
- ed- elastic events can be safely selected from Moller events for : $\theta_e \geq 0.7^0$





Physics Background

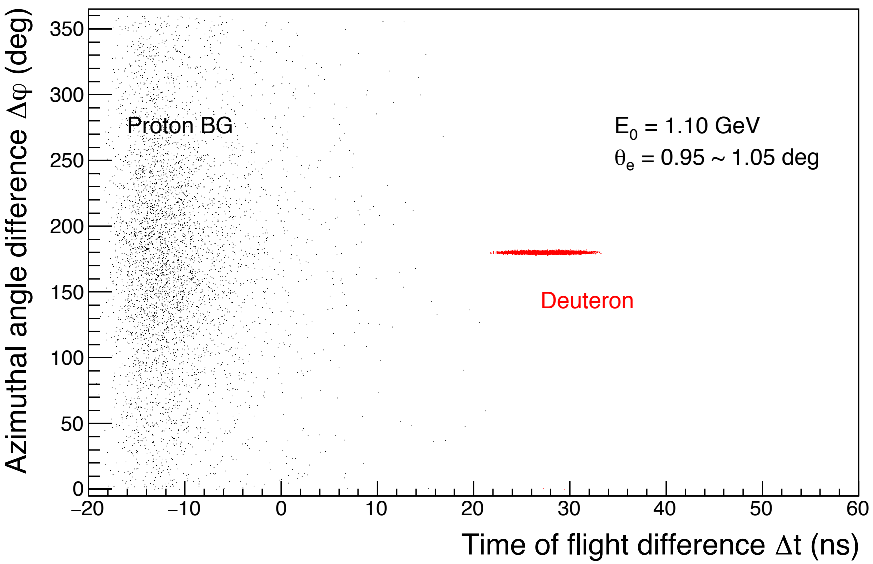
(deuteron electro-disintegration, Reader question/comment #1(a))

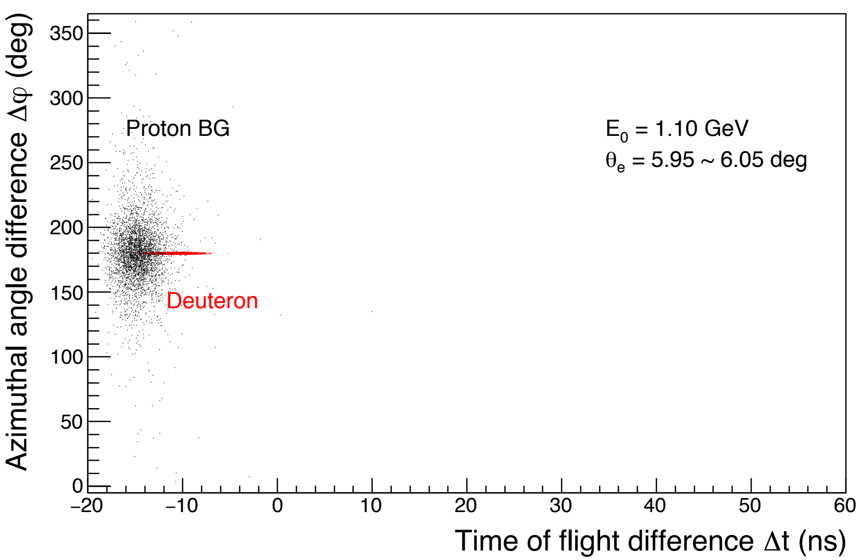
- Elastic *ed* → *ed* events *vs.* *ed* → *e+p+n* will be selected by:

  - ✓ time-of-flight (Δt) *vs.* co-planarity (Δφ) between scattered electron and recoiled deuteron;
  - ✓ dE/dx *vs.* total energy in both Si-strip detectors (ΔE).

- Complete simulation of deuteron electro-disintegration process, including Fermi-motion and realistic models:

(QUEEG Monte Carlo event generator for CLAS6)

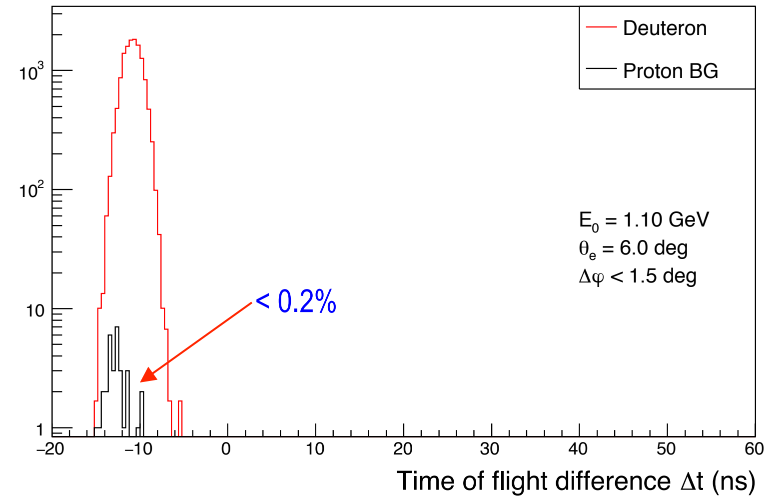




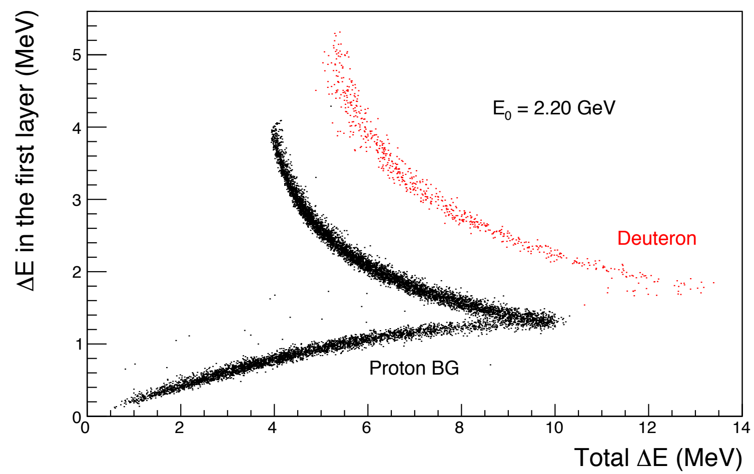
Physics Background (Cont'd)

(deuteron electro-disintegration, Reader question/comment #1(a))

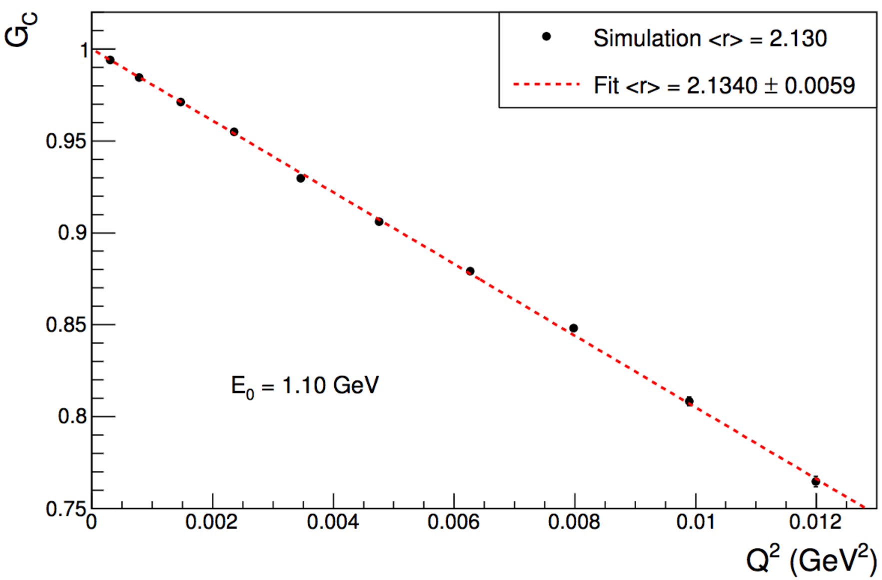
- Applying [Δφ *vs.* Δt] and [dE/dx *vs.* ΔE] cuts removes the physics background for most angles for 1.1 GeV beam energy. Except for $\theta_e \approx 6^0$, where the background level is ≤ 0.2%.

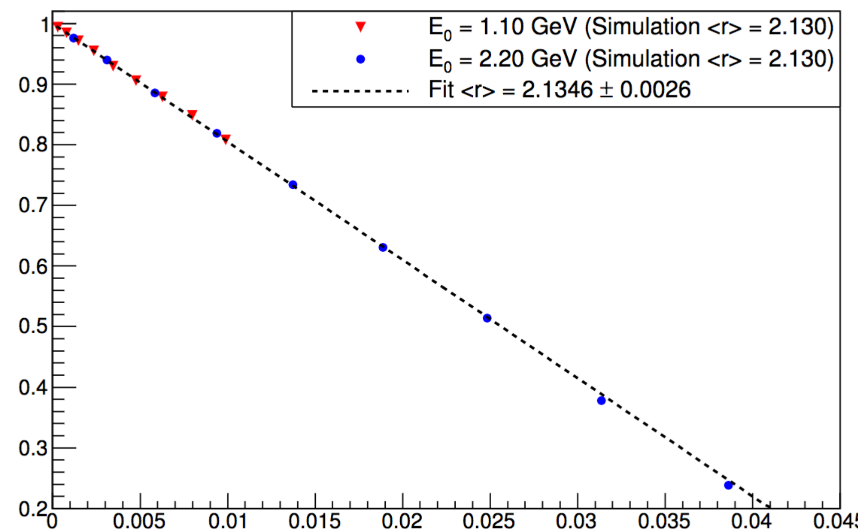


- For 2.2 GeV the [dE/dx *vs.* ΔE] cut alone is very effective for elastic event selection.



Extraction of Deuteron Charge Radius





- Extraction of r_d from MC simulations with radiative corrections.
- Estimated systematic uncertainty < 0.2%

Responses to TAC, ITAC and Readers Comments/questions

- Our responses to TAC, ITAC and Readers comments/questions had been prepared and submitted some days ago.
- Some of them are addressed in this talk above.
- We will try to address any questions still left open.
- Those comments and questions had been very helpful and constructive.
    - Thank you!

Beam Time Request

- Target thickness: $N_{tgt} = 2x10^{18}$ D atoms/cm^2
  Beam intensity: I_e ~10 nA ($N_e = 6.25x10^{10}$ e^-/s)

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

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

$\approx$ 170 events/s $\approx$ 14.9 M events/day

Rates are high, however,
for 0.8% stat. error for the last Q^2= $1.3x10^{-2}$ $(GeV/c)^2$ bin
8 days are needed.

2) for E_0= 2.2 GeV, Total rate for *ed → ed*

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

to have ~ 1 % stat. error for the last Q^2 bins
we request 16 days for this energy run.

	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	6
Total	39

- Requested beam time

Estimated Uncertainties

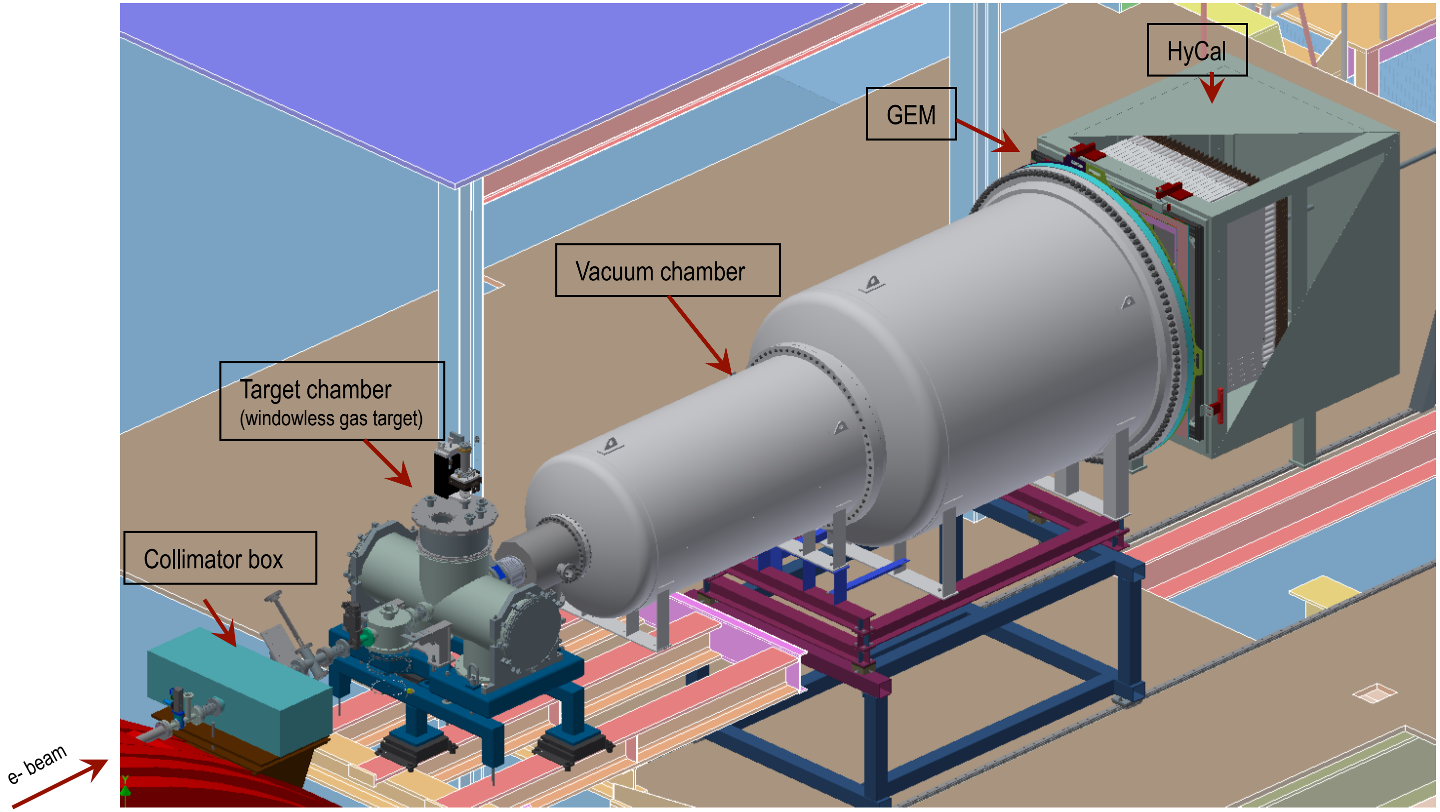
- Estimated error budget (added quadratically)

Contribution	Estimated Error (%)
Statistical error	0.1
Event selection (including rad. Corrections)	0.3
Acceptance in recoil detector	0.3
Ratio in acceptance and detector efficiency	0.2
Fitting procedure	0.2
Total	0.5

- Estimated errors are rather conservative, based on our experience we believe it can be done better.

Status of the PRad Experiment

- PRad was designed to address the *"proton radius puzzle".*
  - Measurement of $ep \rightarrow ep$ elastic cross sections at very low Q^2 range, $[10^{-4} - 10^{-2}]$ $(GeV/c)^2$:
    - non-magnetic-spectrometer, calorimetric method;
    - simultaneous detection of Moller ($ee \rightarrow ee$) process: → control of systematic errors;
    - windowless hydrogen gas flow target → low background experiment



Status of the PRad Experiment (Cont'd)

- Experiment Timeline:

✓ Proposal approved by PAC39 — 2012
✓ Development of funding proposals for H_2 gas flow target (NSF MRI #PHY-1229153) and GEM detector (US DOE grant DE-FG02-03ER41231) — 2013
✓ Development and construction of the target and GEM — 2015
✓ Experimental data taking — May/June 2016

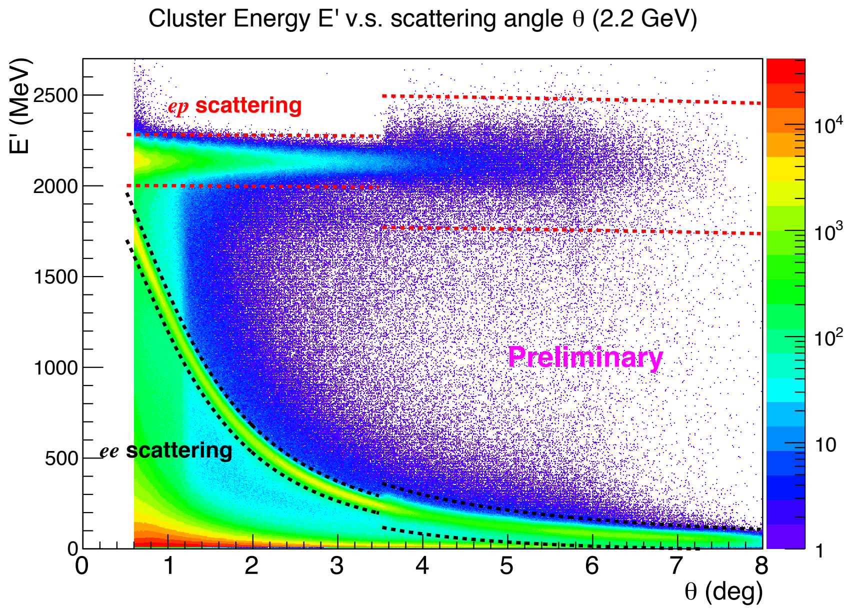
- Experimental Data Collected:

❖ with E_e = 1.1 GeV beam:

✓ 4.2 mC (target areal density: $2\text{x}10^{+18}$ H /cm^2)
✓ 604 M events with target;
✓ 53 M events with "empty" target;
✓ 25 M events with ^{12}C target for calibration.

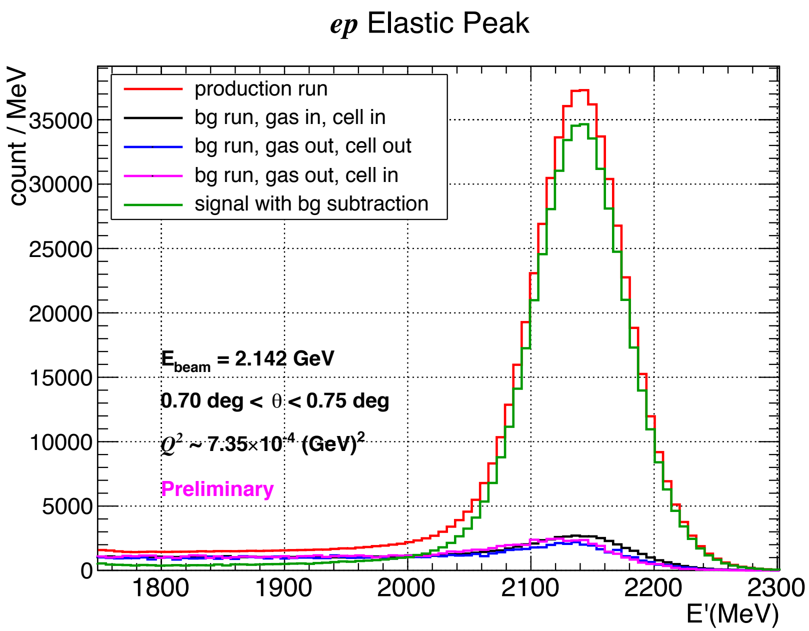
❖ with E_e = 2.2 GeV beam:

✓ 14.3 mC (target areal density: $2\text{x}10^{+18}$ H /cm^2)
✓ 756 M events with target;
✓ 38 M events with "empty" target;
✓ 10.5 M events with ^{12}C target for calibration.



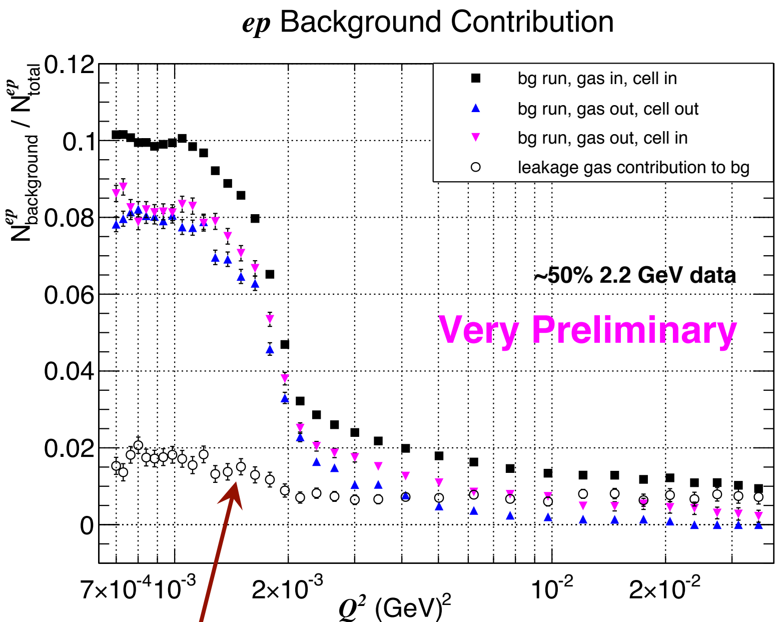
PRad Analysis Status: ep- data quality

- Current focus is on 2.2 GeV data:



Typical energy distribution for ep- events

(for θ_e ~ 1 - 2 degrees)



Beam line background level for ep- events

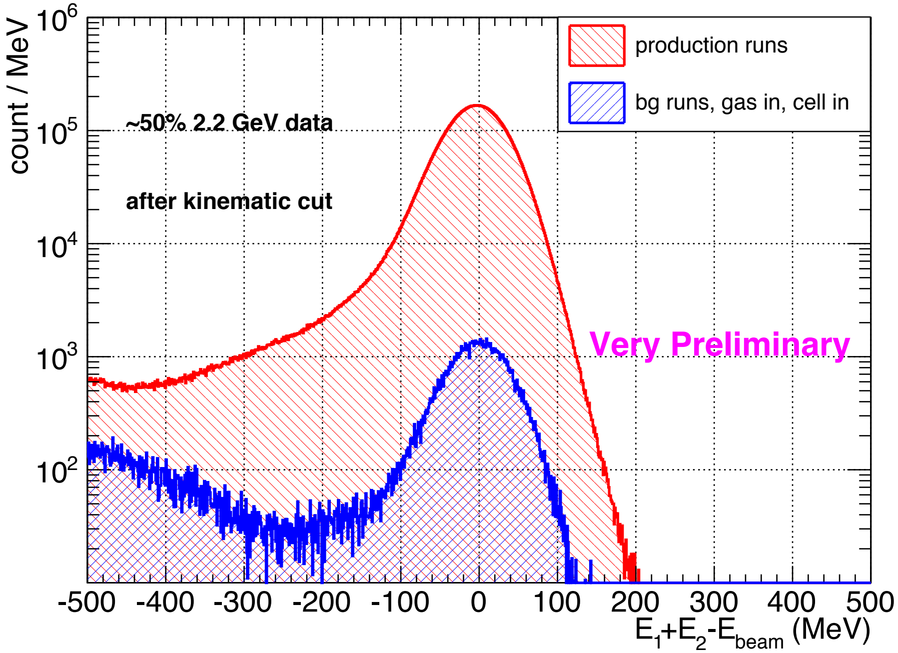
- background level for ep- events is ~ 8 ÷ 10 % for small angles and ~1 ÷ 2 % for relatively larger angles.
- Background from residual gas is ~ 1 ÷ 2 % for all angular range.

- For 1.1 GeV run the background level is factor of 2÷3 higher than for 2.2 GeV run.
- We performed high statistics measurements of background in 3 different ways for both beam energies.

PRad Analysis Status: ee- data quality (Moller)

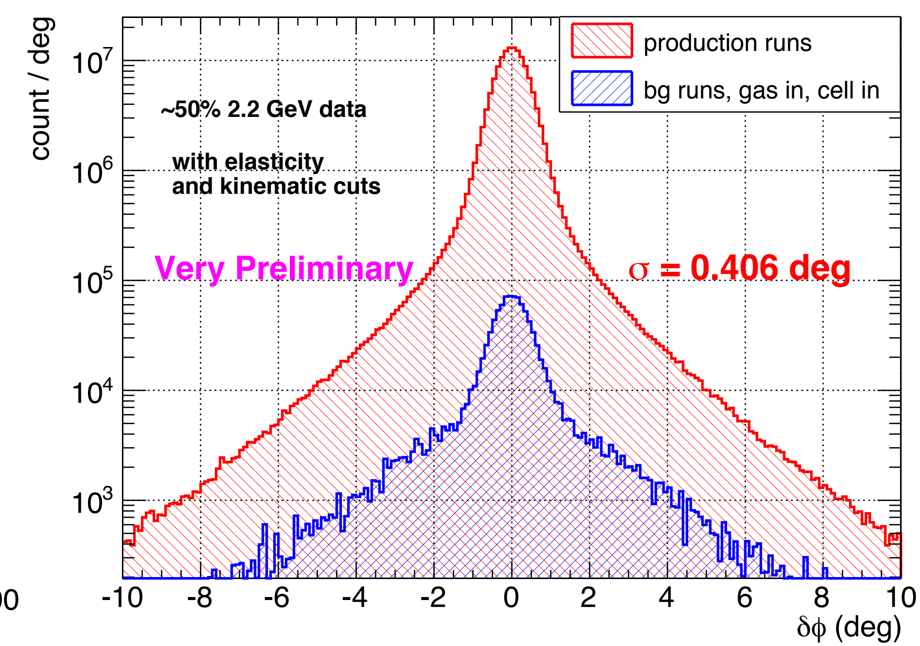
- Moller yield needs to be extracted for ep- normalization.

Elasticity in *ee* scattering



Elasticity distribution for ee- (Moller) events

Co-planarity in *ee* scattering



Co-planarity distribution for ee- (Moller) events

- background level is ≤ 1 % for ee- events (Moller).

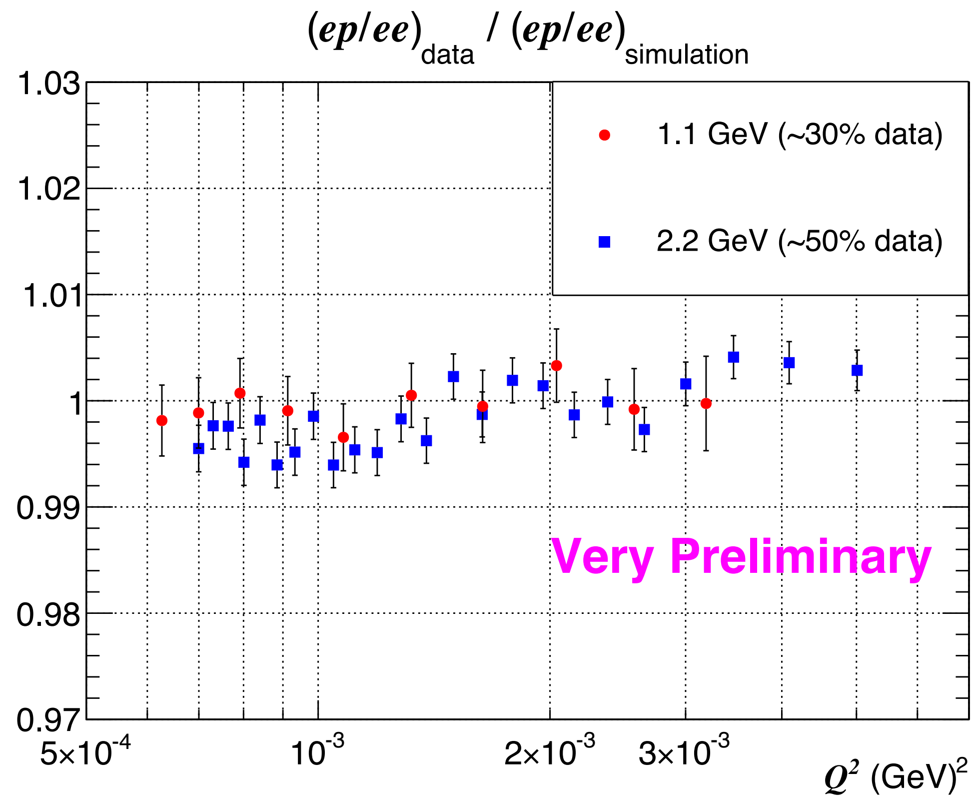
- For 1.1 GeV run the background level is factor of 2÷3 higher than for 2.2 GeV run.
- We performed high statistics measurements of background in 3 different ways for both beam energies.

PRad Analysis Status: Event Selection Quality

(answer to ITAC question #4)

- Control of background in the PRad experiment.
- Consistency of two practically independent measurements (within the ~ 0.2% statistical errors)demonstrates that we control the background, and

PRad will reach its goal of sub-percent extraction of the Proton Radius!!!



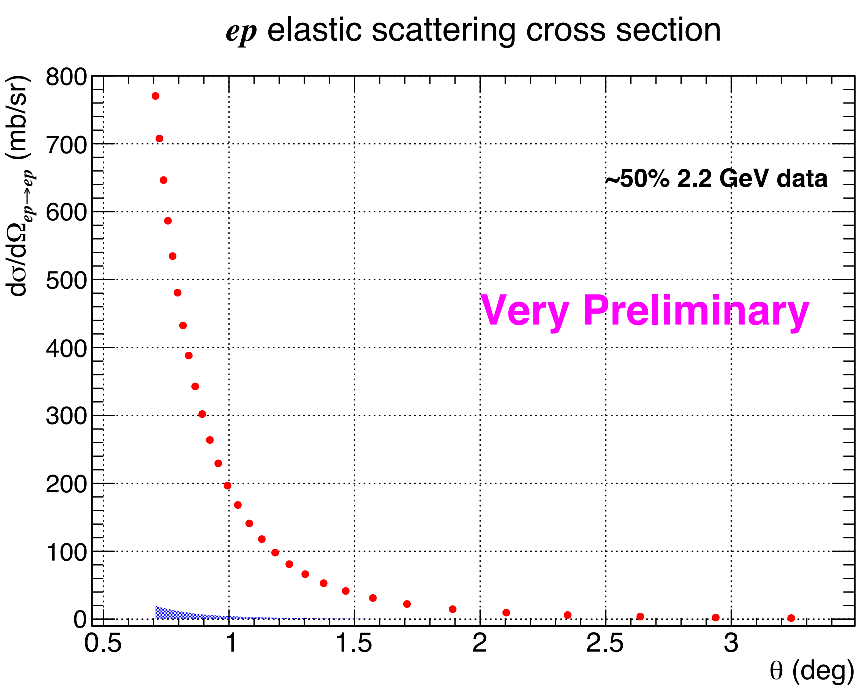
Double ratio of (ep/ee) from experiment and from theory for both 1.1 GeV and 2.2 GeV

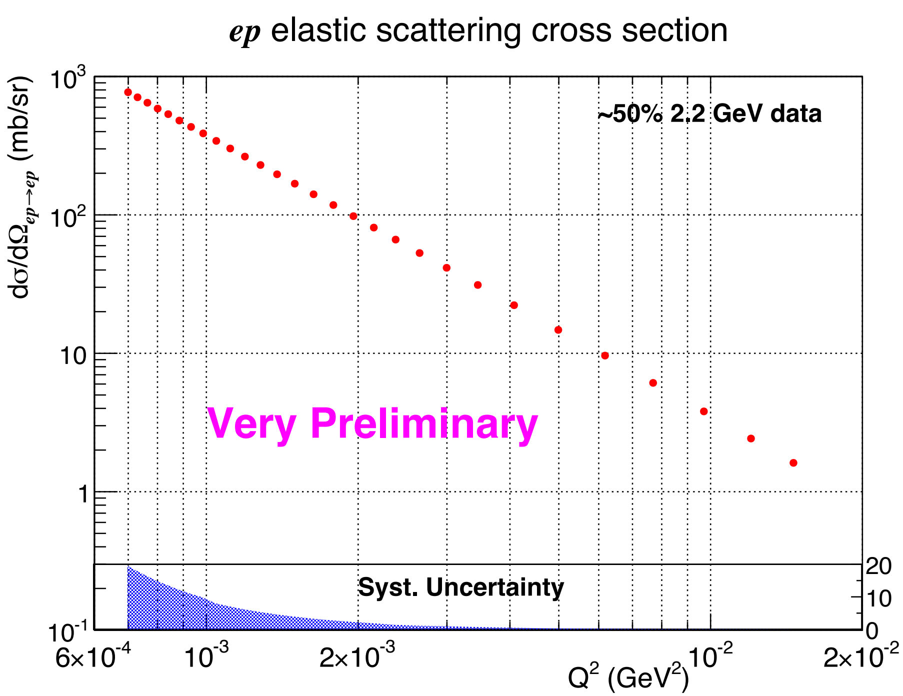
- Tracking would further reduce the background.
- We plan to use second GEM plane in the proposed ed- experiment.

PRad Analysis Status: Extracted Preliminary Differential Cross Sections

- About half of 2.2 GeV beam energy data have been analyzed:
  - ✓ differential cross sections for *ep* ⟶ *ep* have been extracted;
  - ✓ statistical errors are on the level of ~0.2% at this analysis stage;
  - ✓ systematic errors are estimated to be on the level of ~2% at this analysis stage.

- Physics analysis in progress, extraction of the Proton Radius in 2018.





Summary

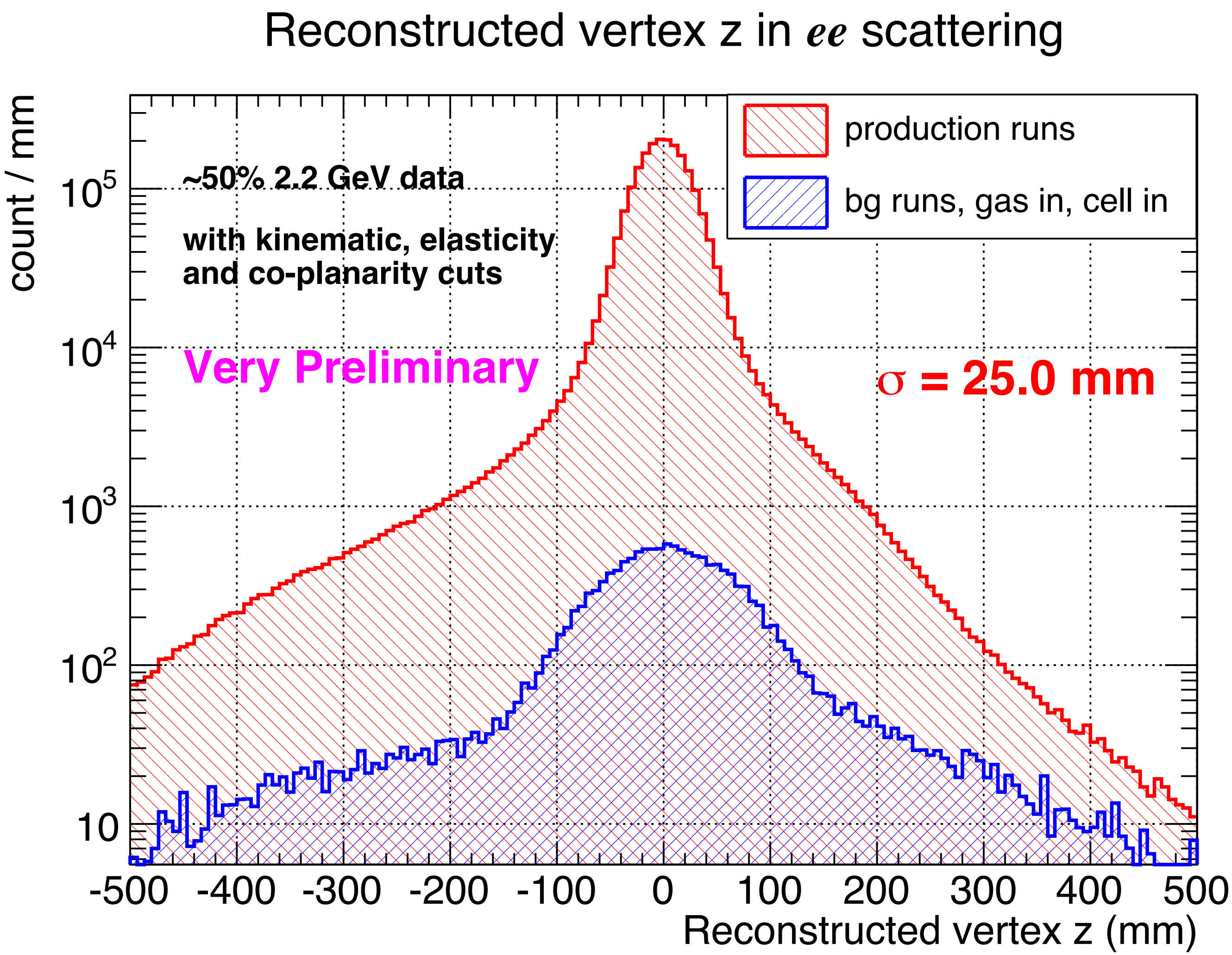
- We propose a new experiment for the deuteron charge radius measurement with a high accuracy to address the newly developing *"deuteron radius puzzle"* in nuclear physics.
- It is based on the PRad experiment for the proton charge radius measurement:
  - ✓ magnetic-spectrometer-free calorimetric experiment;
  - ✓ windowless deuterium/hydrogen gas flow target;
  - ✓ cylindrical recoil detector for reaction elasticity;
  - ✓ additional GEM detector for scattered electron tracking.

  That will allow:
  - ➢ reach very low Q^2 range, [2×10^{-4} – 5×10^{-2}] GeV^2 ;
  - ➢ ed→ed cross sections normalized to well known QED process (Moller scattering);
  - ➢ ensure the elasticity in the extracted ed- cross sections;
  - ➢ measuring cross sections in one kinematical settings for a large Q^2 range;
  - ➢ arguably, it is currently the most optimized ed- measurement to extract the deuteron charge radius with a sub-percent accuracy.
- Requesting 39 days of beam time for this experiment.
- PRad preliminary analysis indicates: backgrounds well understood, proposed uncertainty can be achieved.

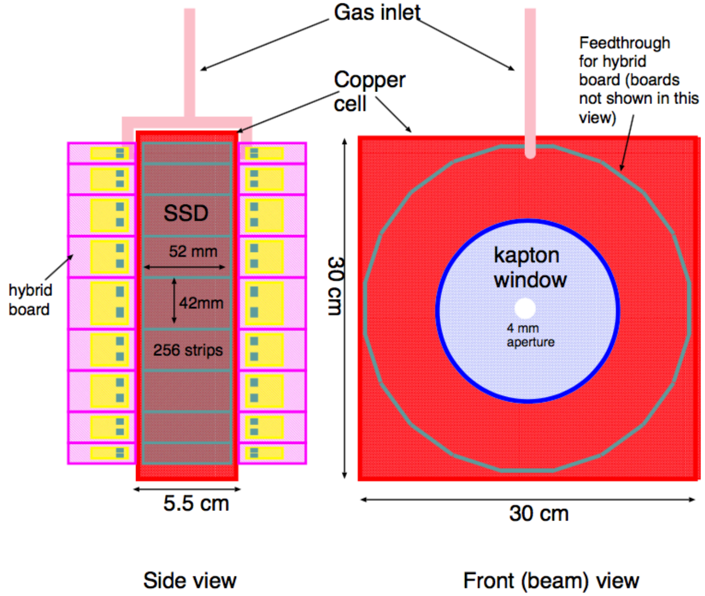
The End

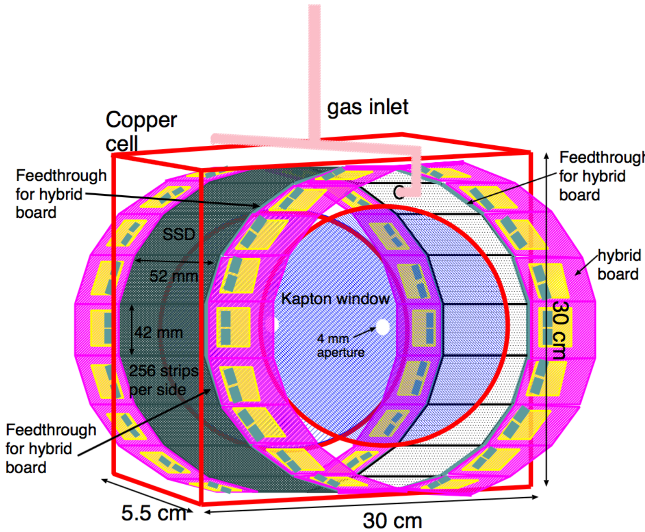
PRad Experiment

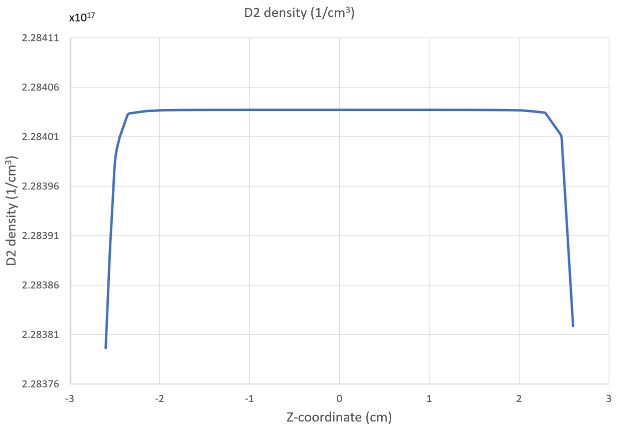
- Proton charge radius puzzle is still unsolved after seven years.



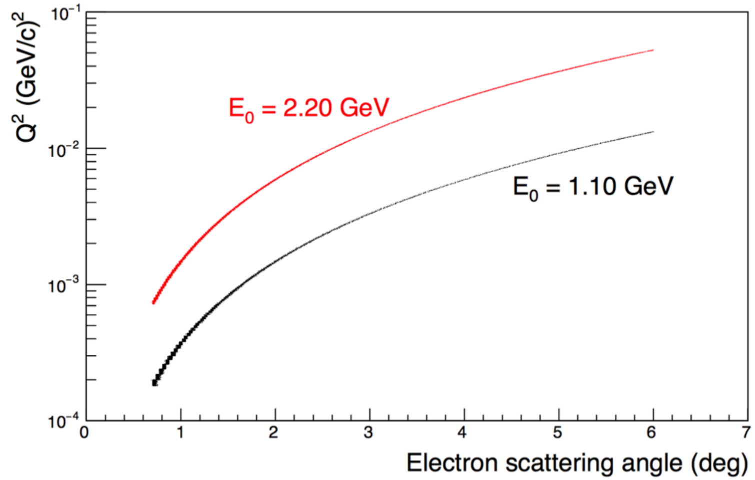
Si-strip Detector

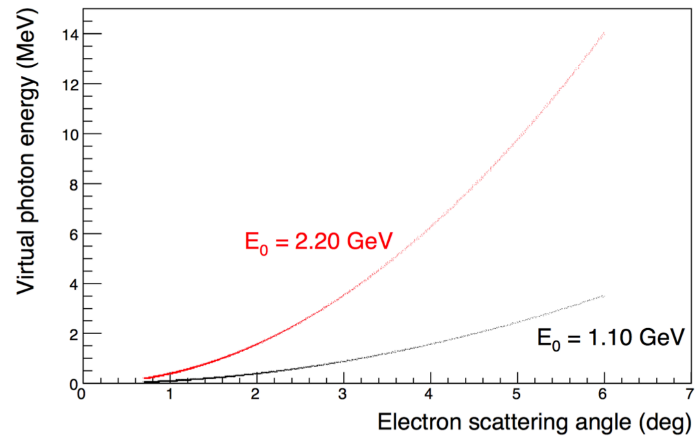


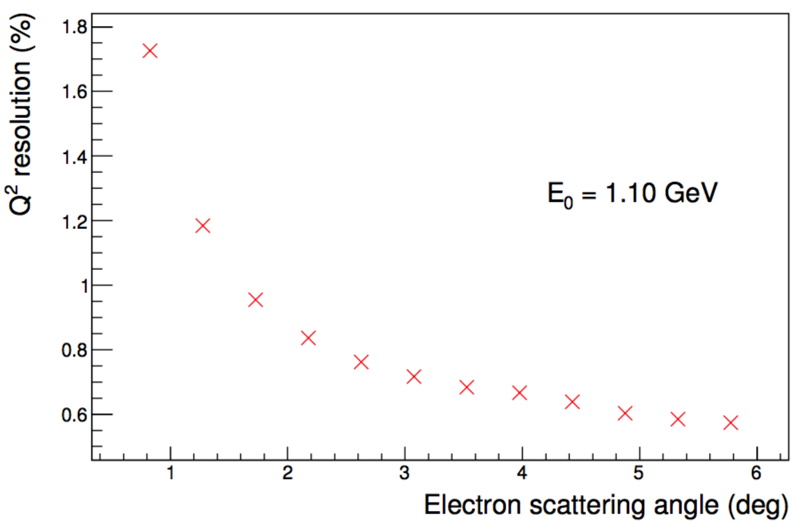


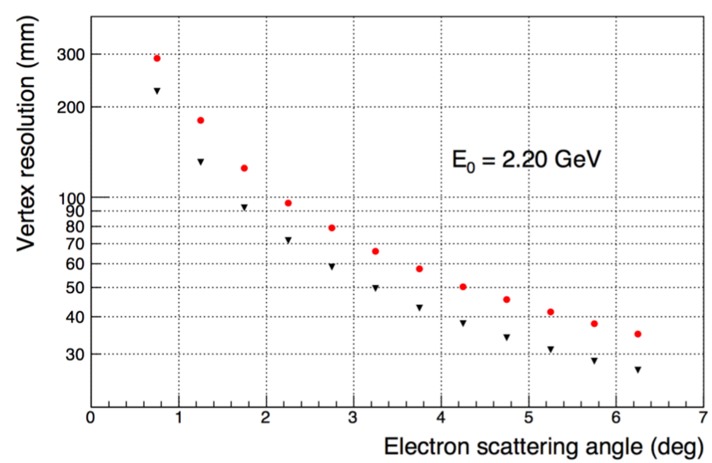


Kinematics and Resolutions

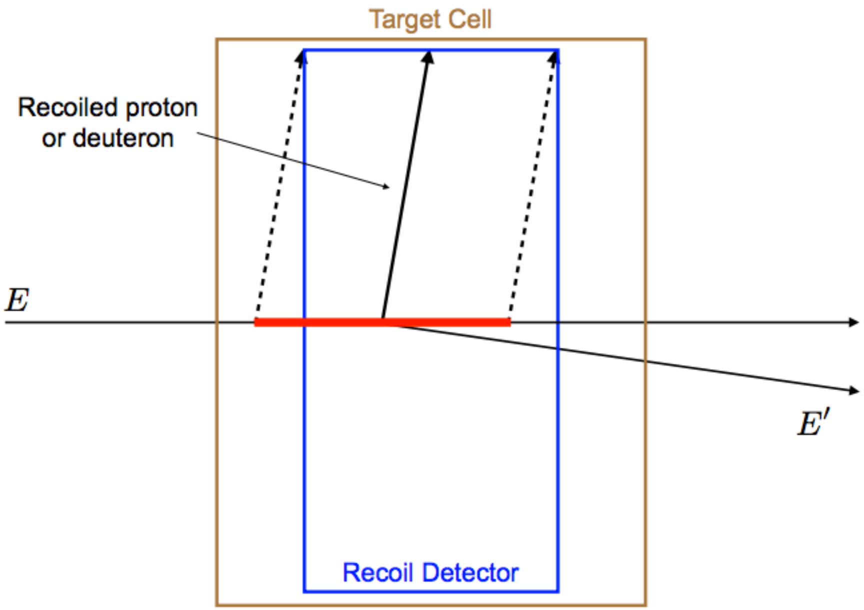


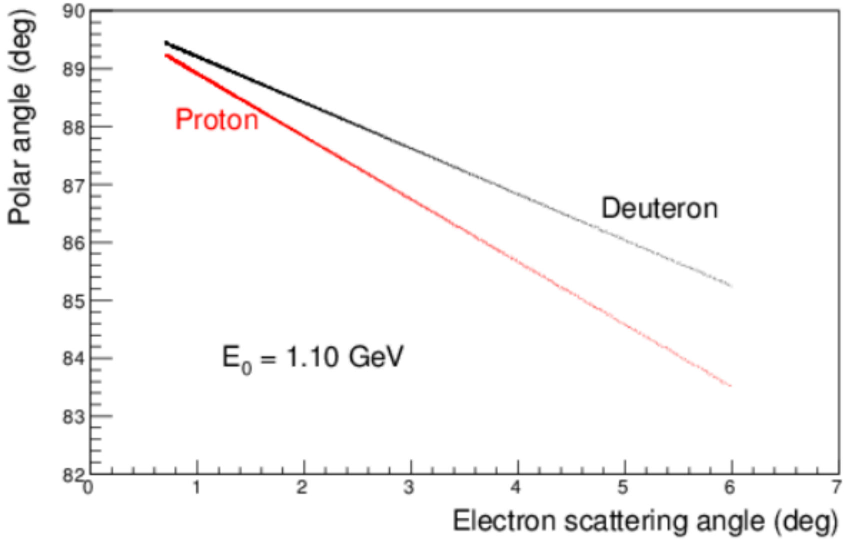


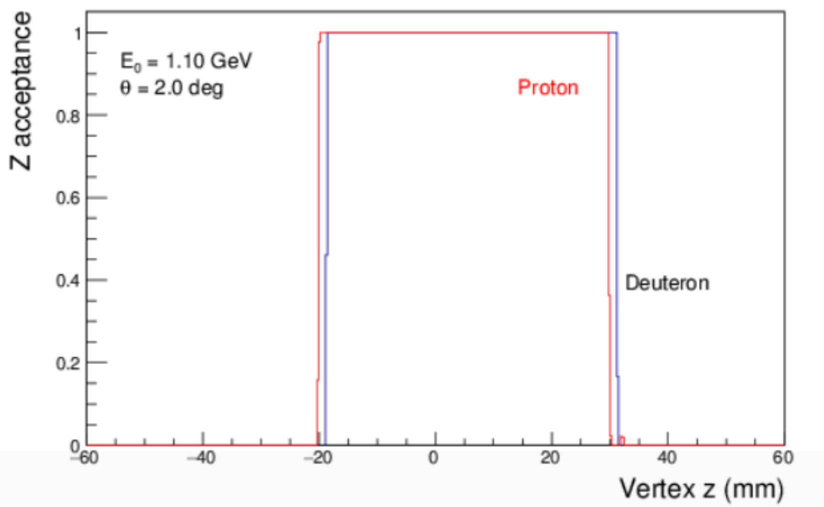




Calibration of Recoil Detector







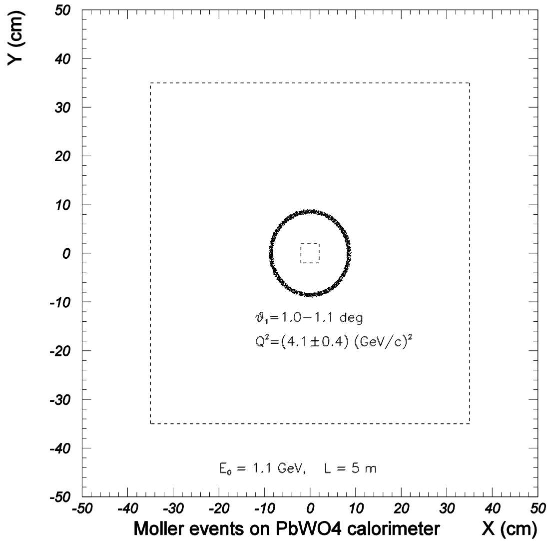
Control of Systematic Errors
(Moller event selection)

Will analyze Moller events in 3 different ways:

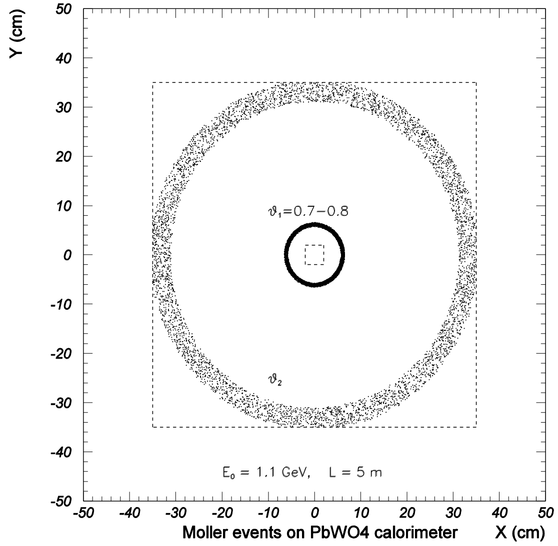
1) Single-arm method: one Moller e^- is in the same Q^2 range

ε_{det} will be measured for [0.7 – 6.0] GeV range

Relative ε_{det} are needed for this experiment



2) Coincident Method



3) Integrated over HyCal acceptance

Relative ε_{det} will be measured with high precision.

Contribution of ε_{det} and ε_{geom} in cross sections will be on second order only.