Research Center for Accelerator and
Radioisotope Science (RARIS), Tohoku University

Deuteron charge radius by low-energy electron scattering at the ULQ2 facility

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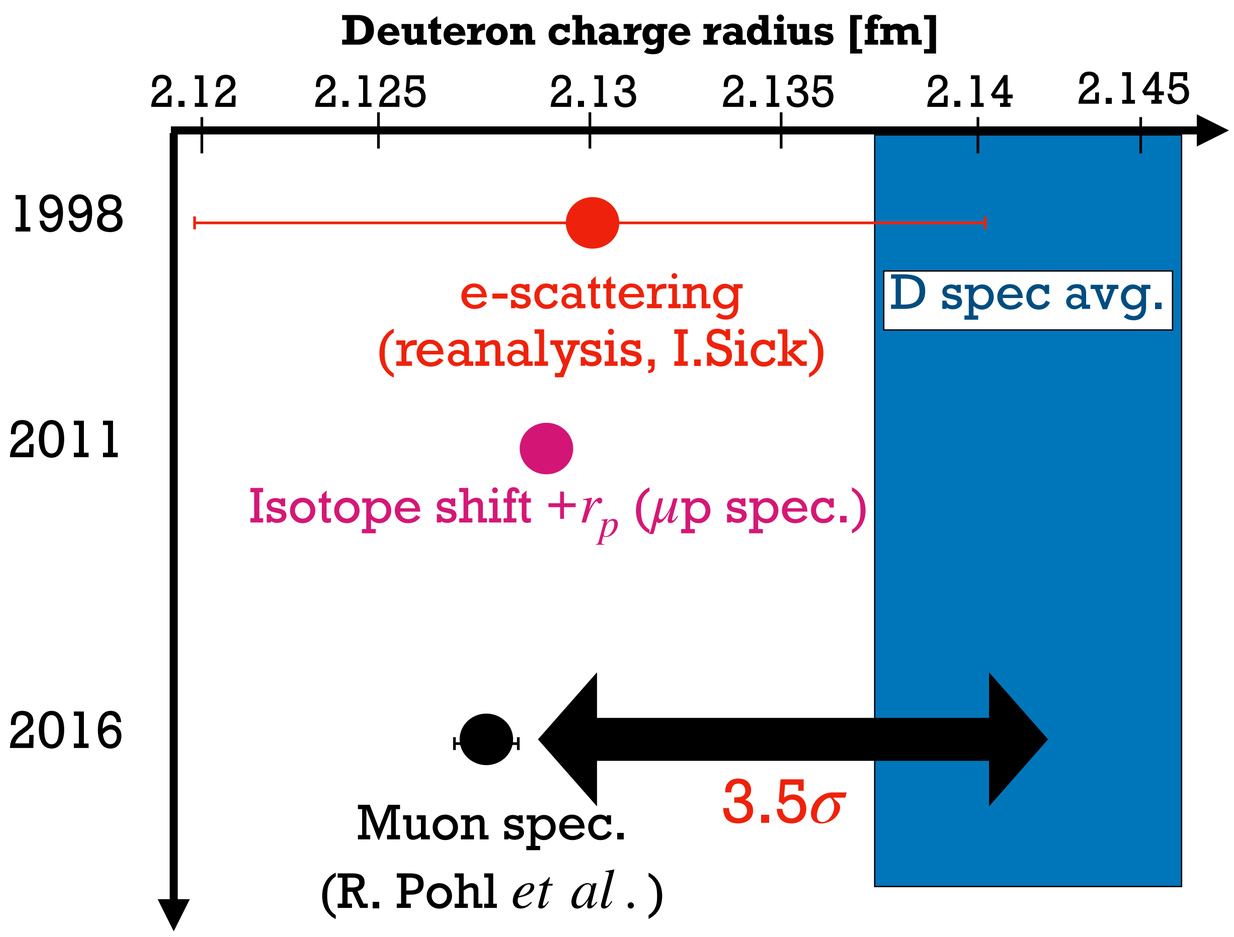
for the ULQ2 collaboration

Outline

1. Physics motivation about deuteron radius
2. ULQ2 (Ultra-Low Q^2) facility
    - Features of ULQ2 for ed scattering
    - Experimental setup
3. Current status of ULQ2 for ed scattering
4. Summary

1.Physics motivation

Deuteron radius puzzle



- 3.5σ discrepancy between r_d from μD spec. and the average of ordinary deuterium spec.
- The discrepancy cannot be discriminated by e-d scattering results
- The most recent e-d scattering experiment was conducted 20 yeas ago
- **New ed scattering experiment is needed (DRad in JLab plans to conduct e-d scattering experiment)**

Little contribution from e-d scattering because of the huge error

Access to the neutron charge radius r_n^2 poorly known

$$r_d^2 = r_n^2 + r_{str}^2 + r_p^2 + r_{corr.}^2$$

r_d: deuteron charge radius (Experiment)
r_n: neutron charge radius (We can access)
r_{str}: deuteron structure radius (computable)
r_p: proton charge radius (Experiment)
$r_{corr.}$: relativistic correction (computable)

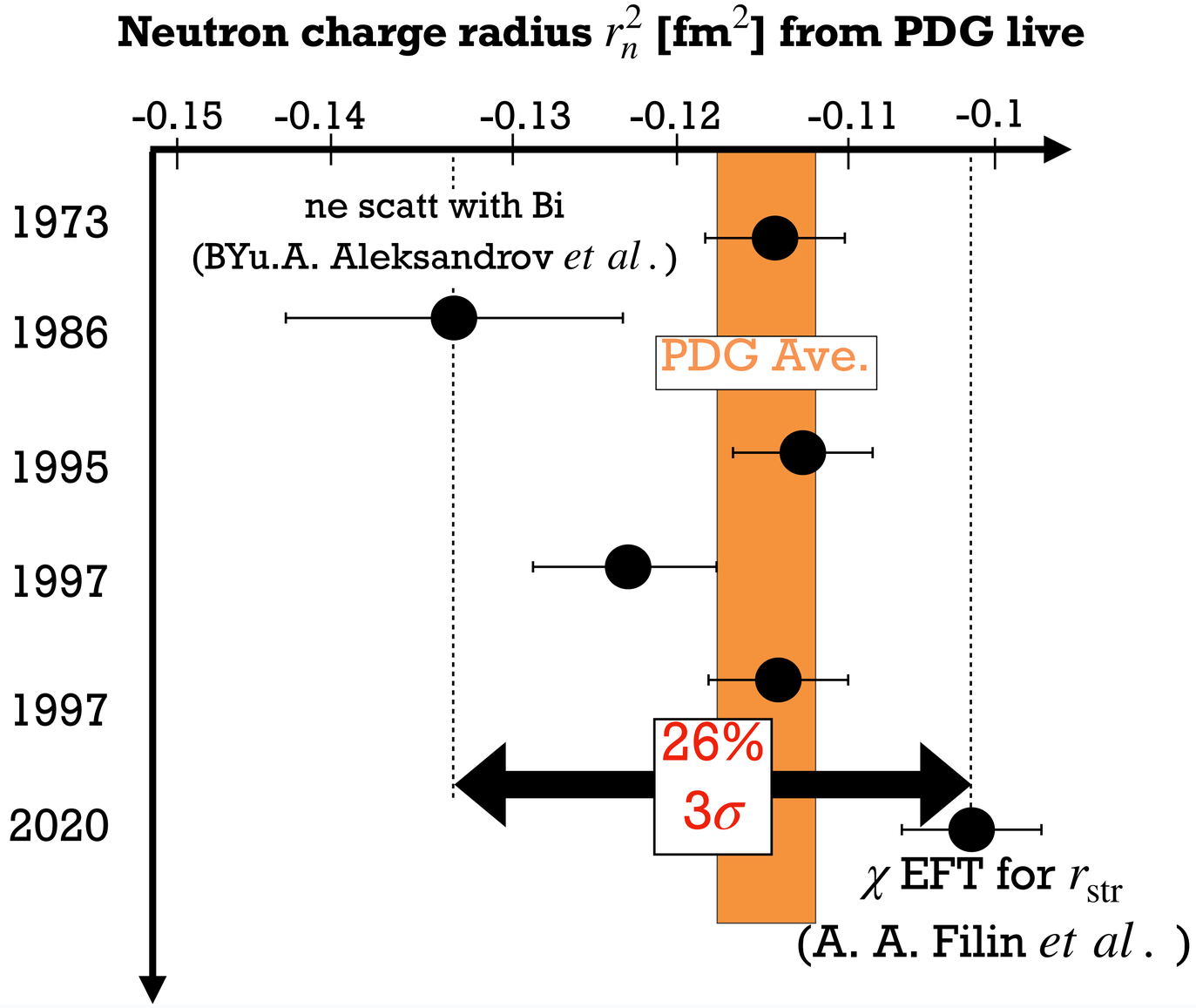
4th moment

$$r_d^4 = r_{\mathrm{str}}^4 + \frac{10}{3} r_{\mathrm{str}}^2 \left(r_p^2 + r_n^2 \right) + \text{corrections}$$

Appear in 4th moment too

$$G_E(Q^2) = 1 - \frac{r^2}{6}Q^2 + \frac{r^4}{120}Q^4 + \frac{r^6}{5040}Q^6 + \cdots$$

$$r^2 = -6 \frac{dG_E(Q^2)}{d(Q^2)}\bigg|_{Q^2=0} \qquad r^4 = 30 \frac{d^2G_E(Q^2)}{d(Q^2)^2}\bigg|_{Q^2=0}$$



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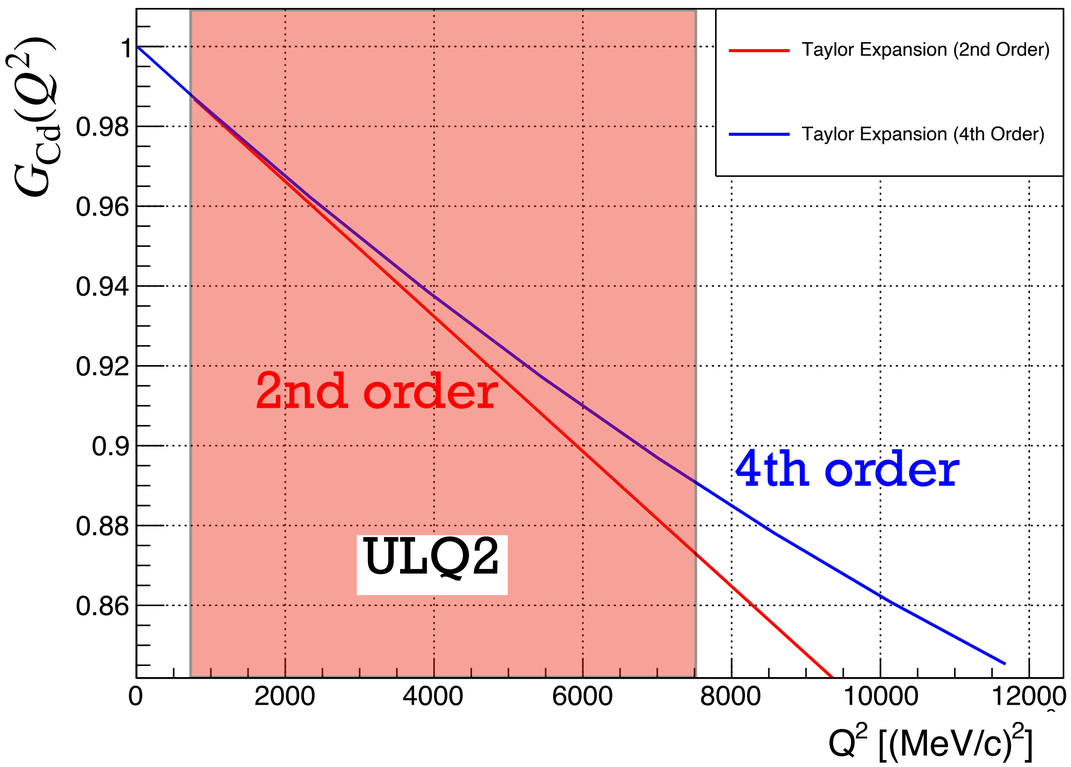
4th moment

$$r_d^4 = r_{\mathrm{str}}^4 + \frac{10}{3} r_{\mathrm{str}}^2 \left(r_p^2 + r_n^2 \right) + \text{corrections}$$

$$G_{Cd}(Q^2) = 1 - \frac{r^2}{6}Q^2 + \frac{r^4}{120}Q^4 + \frac{r^6}{5040}Q^6 + \cdots$$

$$r^2 = -6 \frac{dG_E(Q^2)}{d(Q^2)}\bigg|_{Q^2=0} \qquad r^4 = 30 \frac{d^2G_E(Q^2)}{d(Q^2)^2}\bigg|_{Q^2=0}$$

Taylor expansion of deuteron form factor



4th moment may extract r_n^2 too

2. ULQ2 (Ultra-Low Q^2) facility

Determine the absolute value of e-d cross section

Cross section

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

Very low contribution($< 10^{-3}$) in low Q

Charge form factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-d} \propto G_{Cd}^2(Q^2) + \alpha(\theta)\cdot G_{Md}^2(Q^2) + G_{Qd}^2(Q^2)$$

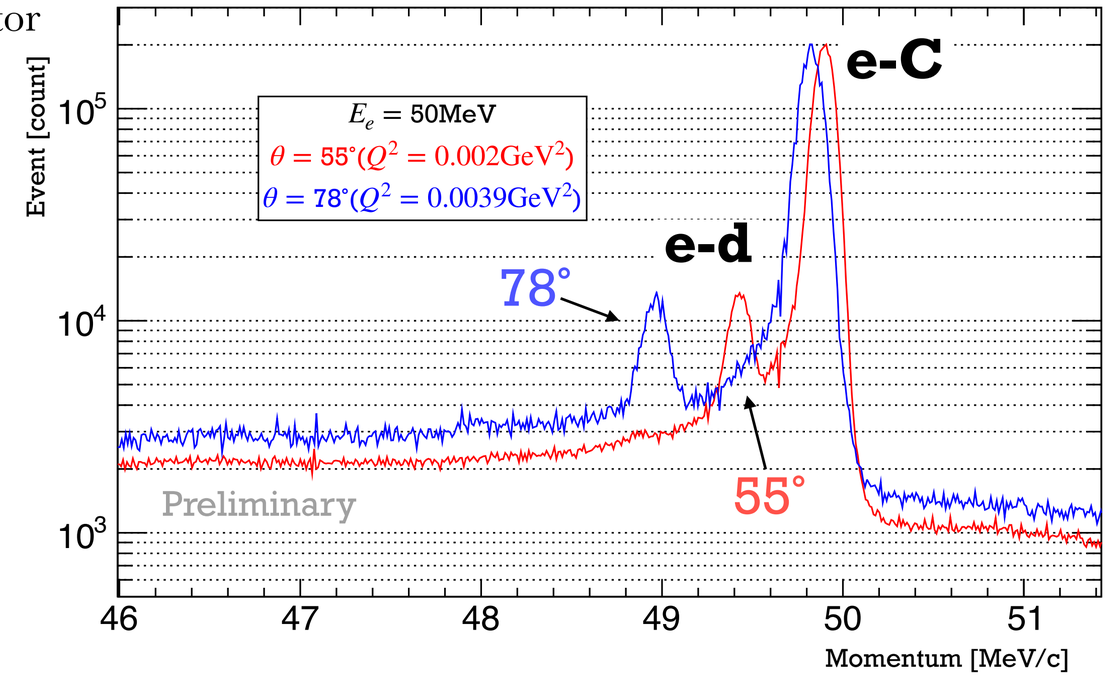
Magnetic form factor Quadrupole form factor

We measure…

Cross section = **Yield ratio** / **Target ratio** × **Well-known**

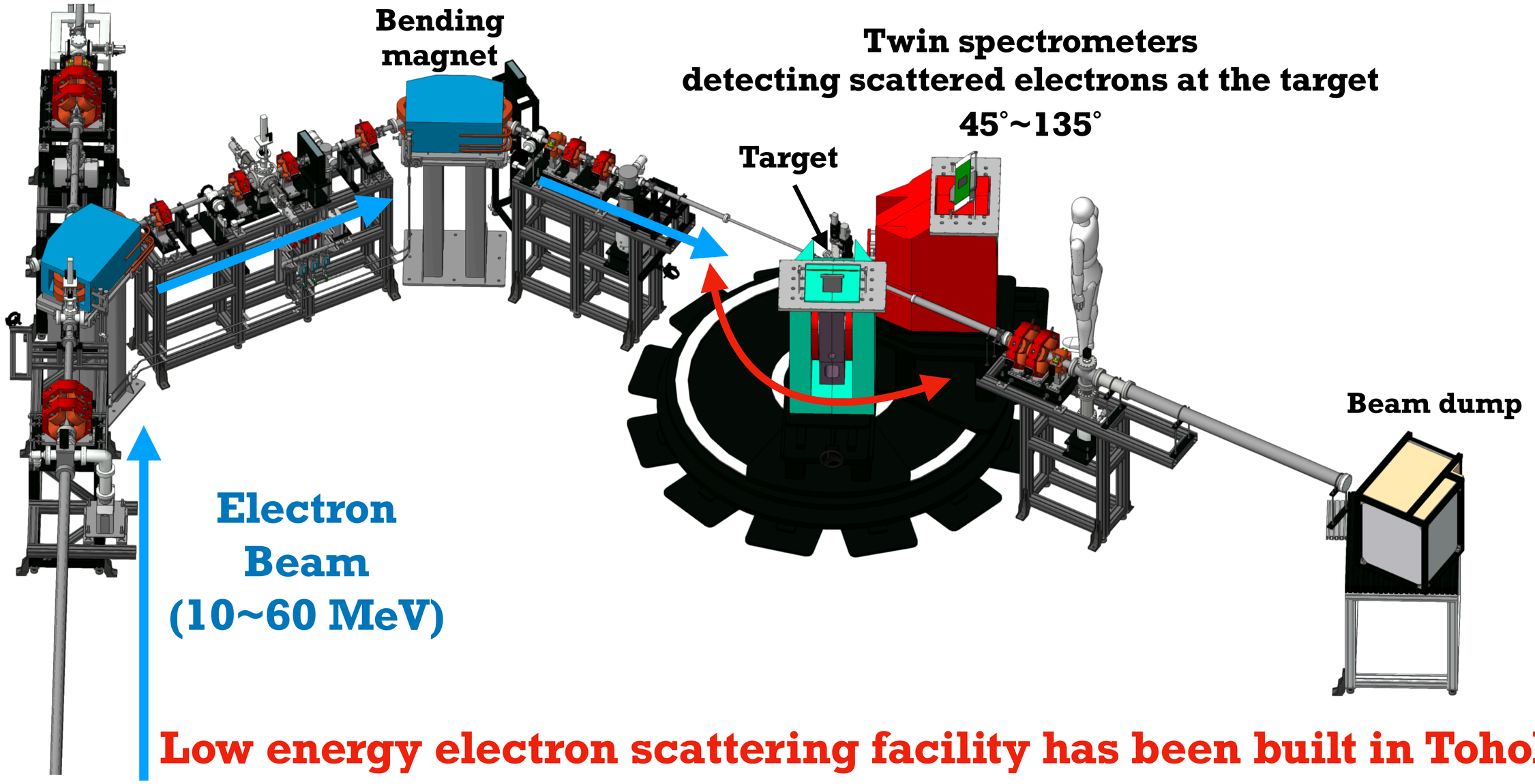
$$\left(\frac{d\sigma}{d\Omega}\right)_{e-d} = \frac{Y_{e-d}/Y_{e-C}}{N_d/N_C}\left(\frac{d\sigma}{d\Omega}\right)_{e-C}$$

CD_2 run @E_e=50MeV



We employe CD_2 (polyethylene) target for elastic ed cross section

ULQ2 (Ultra-Low Q^2) facility



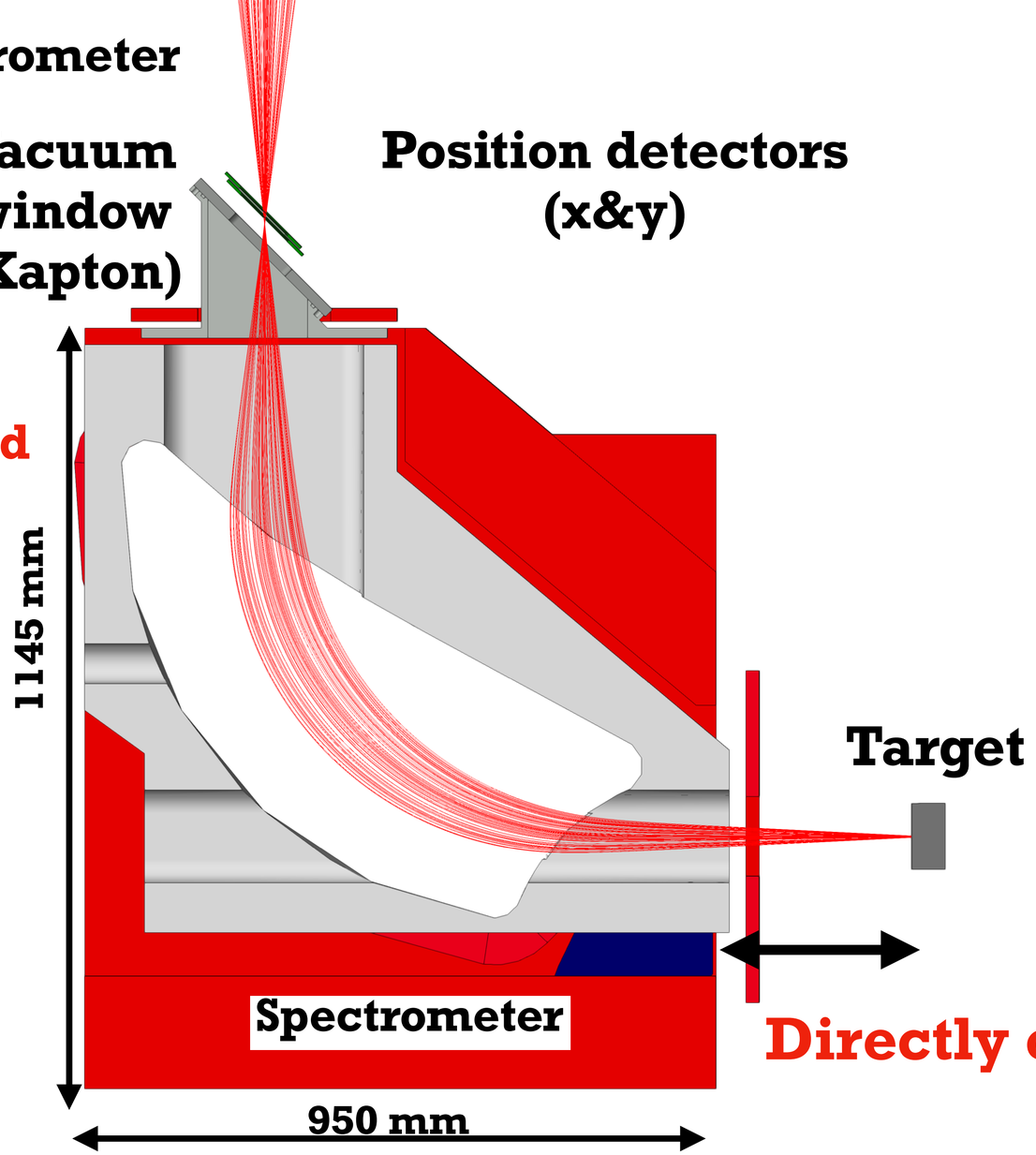
Low energy electron scattering facility has been built in Tohoku

Cross-sectional view of spectrometer

Vacuum window (Kapton)

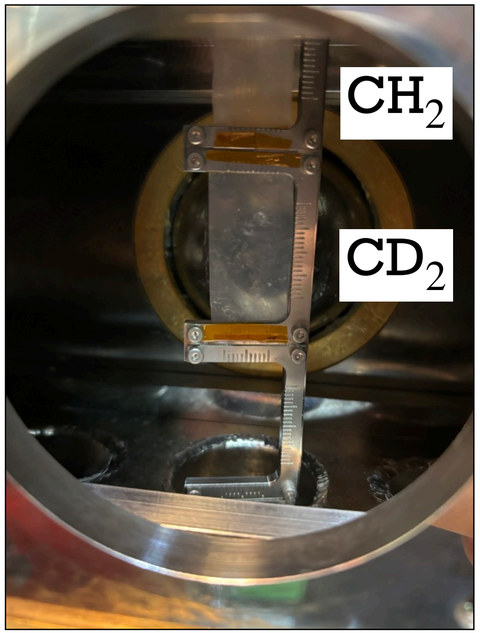
Position detectors (x&y)

Only one material introduced after the target



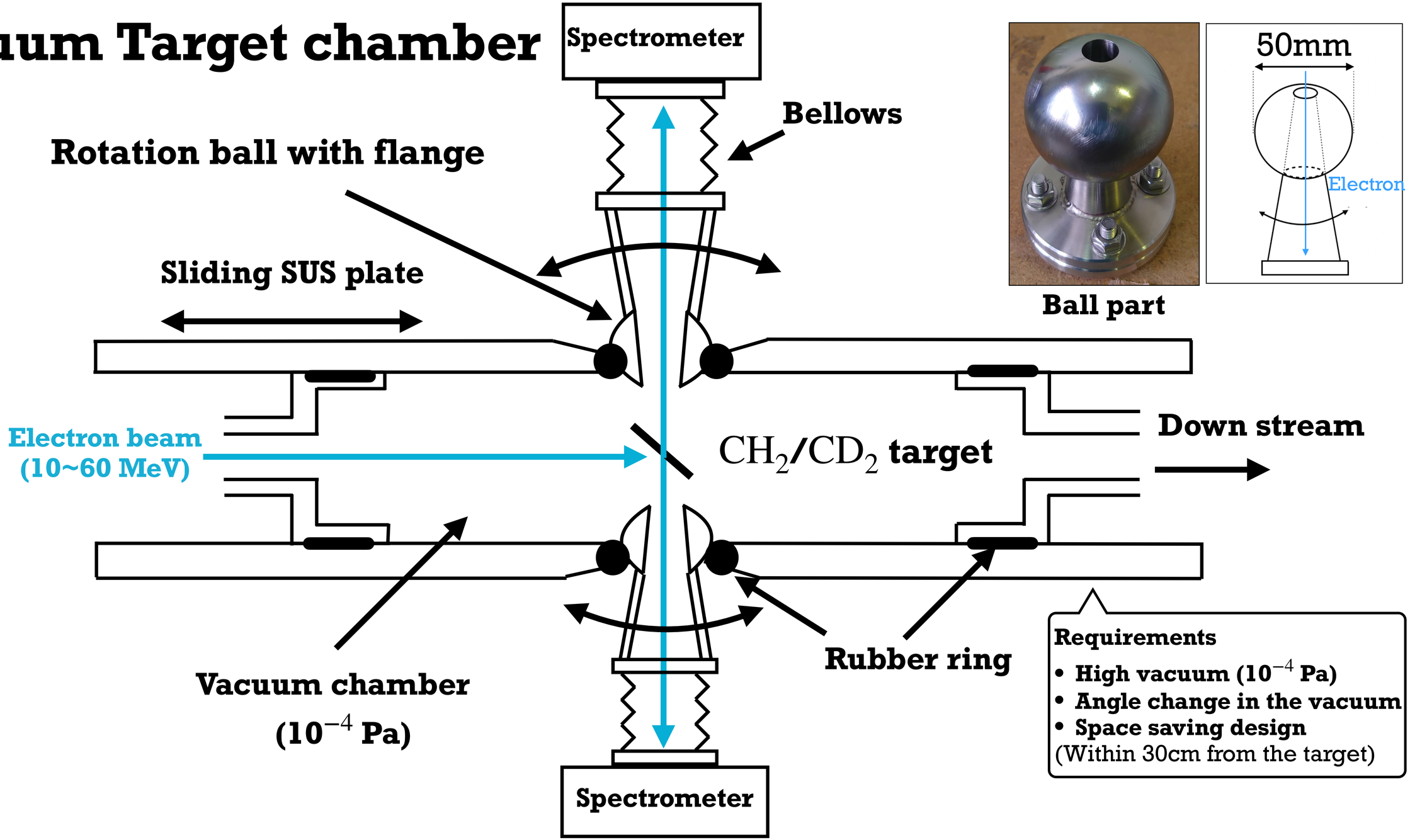
Directly connected to vacuum

Target ladder in target chamber



Vacuum target chamber was newly developed for low energy electron scattering

Vacuum Target chamber



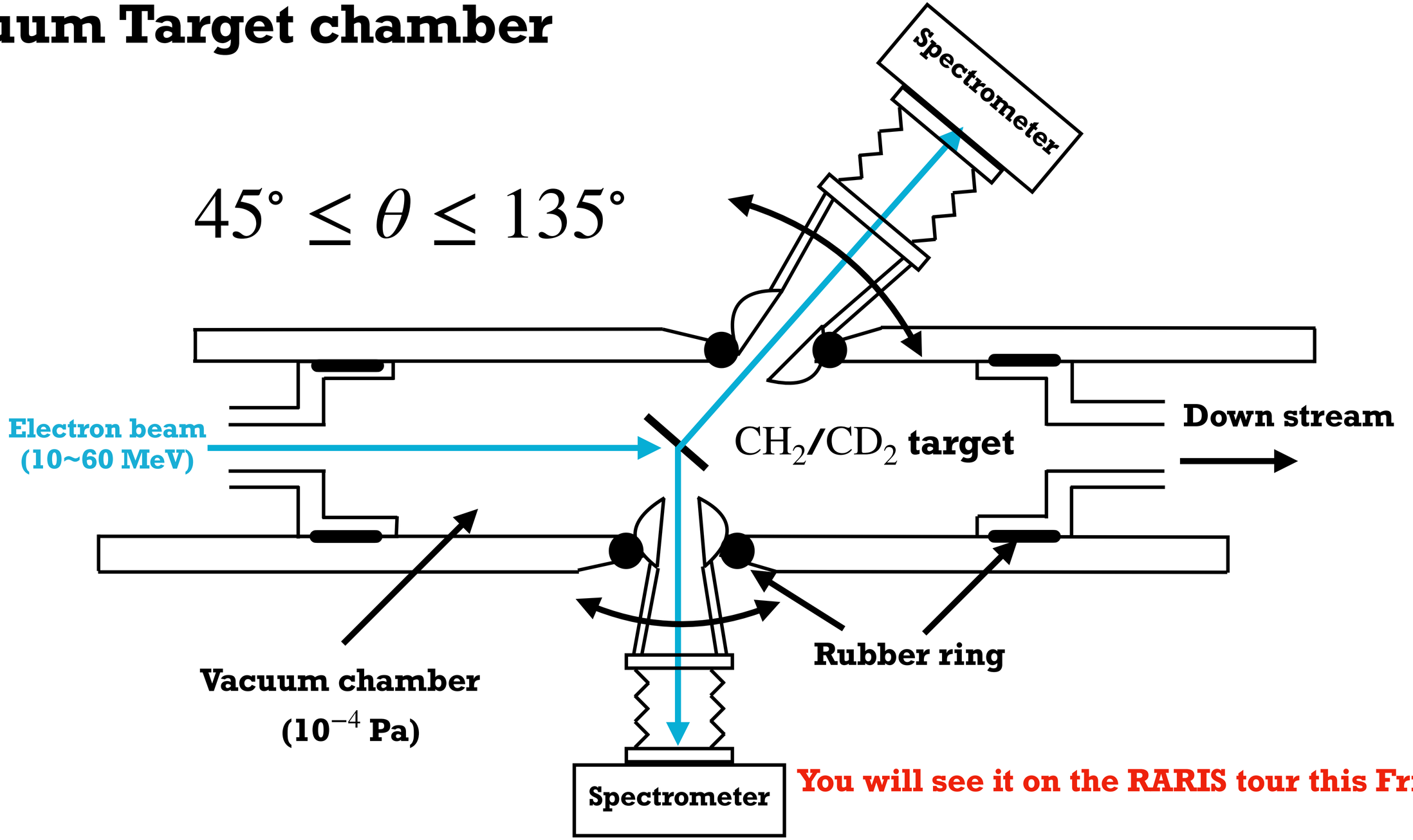
Ball part

Requirements

- **High vacuum (10^{-4} Pa)**
- **Angle change in the vacuum**
- **Space saving design**

(Within 30cm from the target)

Vacuum Target chamber



You will see it on the RARIS tour this Friday!

Comparison with previous precision measurements

They mainly constrain the result of reanalyzing

$$< r_d^2 > \equiv -6\frac{dG_{Cd}(Q^2)}{dQ^2}|_{Q^2\to 0}$$

$$\frac{d\sigma}{d\Omega} \propto G_{Cd}^2(Q^2)$$

	ULQ2 (2023~)	**SLAC (1973)**	**Mainz (1981)**
Q^2 [GeV^2/c^2]	The lowest-ever 0.00075~0.0075	0.0019~0.019	0.0017~0.16
Absolute cross section	Normalization with e-C cross section simultaneously with ed scattering	Normalization with e-p cross section Not simultaneously	Normalization with e-p cross section Not simultaneously
Accuracy of form factors (Stat.)	0.05~0.1%	~0.2%	0.1~0.4%

Accurate form factors can be measured at low Q in the ULQ2

3. Current status of ULQ2 for ed scattering

Current status

2019 The ULQ2 beam line construction was started

2020 The 1st beam for the ULQ2 was provided

2021 Twin spectrometers and the target chamber were installed

2022 The commissioning completed

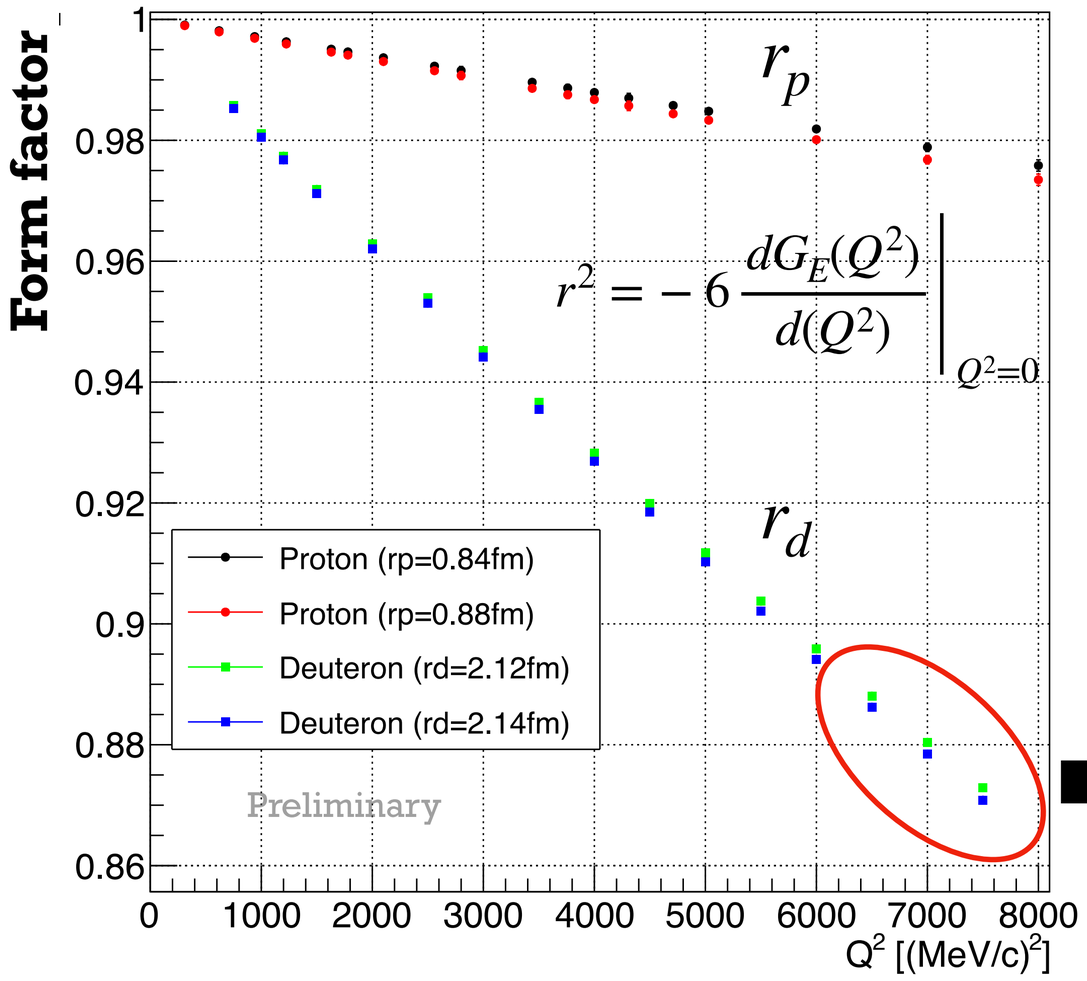
2023 Physics run started

2024 Oct. Data-taking finished←

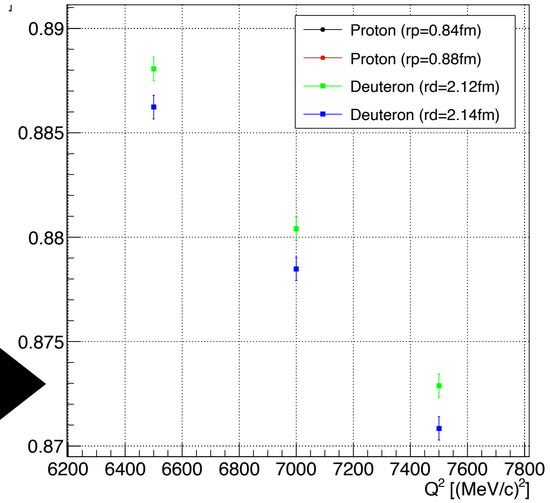
2024~2025 Determination of r_p and r_d

Form factors taken in ULQ2

ULQ2 region and model calculation



- Q^2_{Proton} = 300-8000 $(\mathrm{MeV/c})^2$
- Q^2_{Deuteron} = 750-7500 $(\mathrm{MeV/c})^2$
- E_e = 10-60 MeV
- θ = 45 -135°
- Target: CH_2 or CD_2 (t~100μm)



Difference can be discriminated

Data-taking finished, analysis ongoing

Future ed scattering experiment @JLab

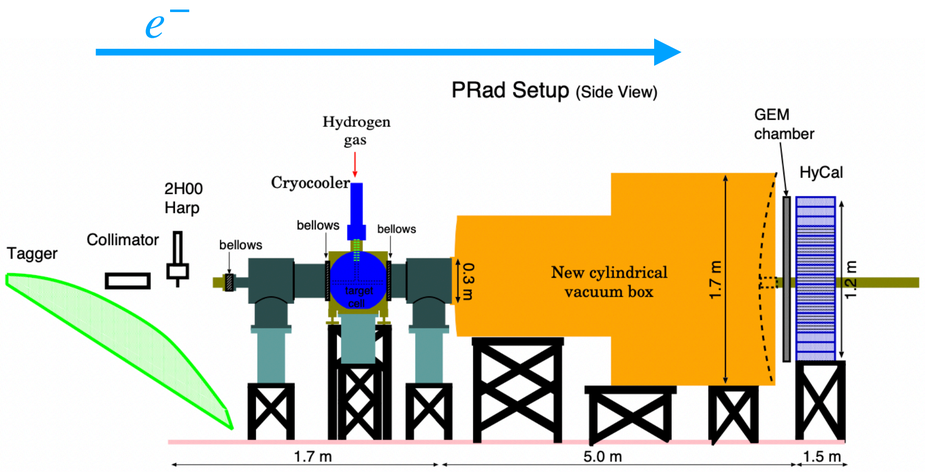


Figure 11: A schematic of the experimental setup used during the PRad experiment.

They plan to measure r_p with same setup(PRadII)

- E=1.1, 2.2GeV
- $Q^2 = 2 \times 10^{-4} \sim 5 \times 10^{-2}$ (GeV/c)^2, 7.5×10^{-4} in ULQ2
- $\theta = 0.7\sim6.0^\circ$ ($45\sim135^\circ$ in ULQ2)
- Windowless Gas target
- Spectrometer less system
- e-d cross section will be measured relative to Møller ($e^-e^- \rightarrow e^-e^-$) QED process
- The proposed experiment will aim a high precision (0.22%) , from Proposal in JLab, A. Gasparian *et al* .

Summary

- New elastic ed scattering experiments are needed to understand the deuteron radius puzzle
- 2nd and 4th moment of deuteron allow us to access to the neutron charge radius poorly known
- Absolute values of form factor will be determined with the CD_2 target in ULQ2
- Form factors in the lowest-ever Q^2 region were taken with the lowest-ever energy electron beam
- Analysis underway to determine r_d

Thank you for your attention!
and
See you in RARIS tour!!