Proton and deuteron radius measurements with ultra-low energy electron scattering

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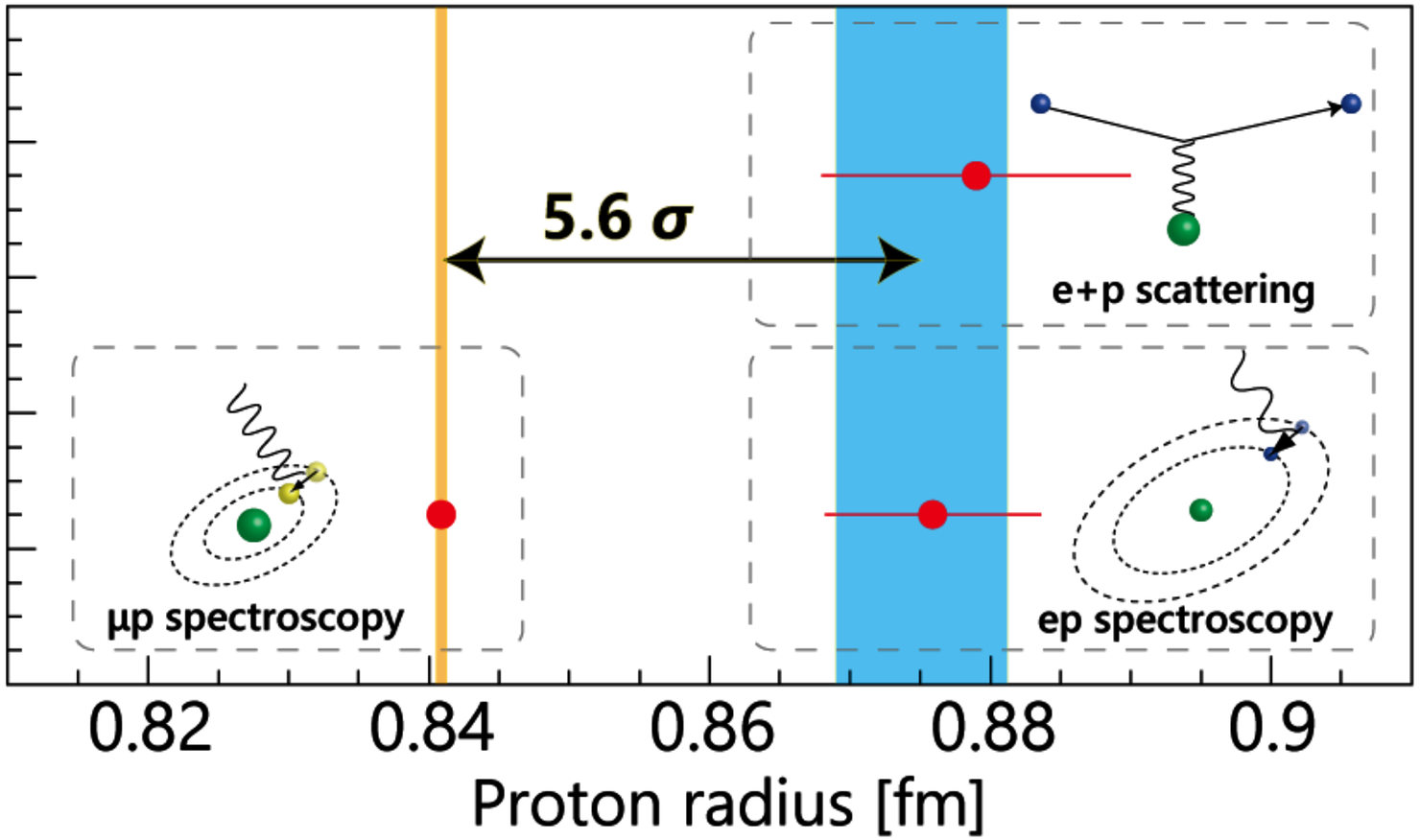
and ULQ2 collaboration

Outline

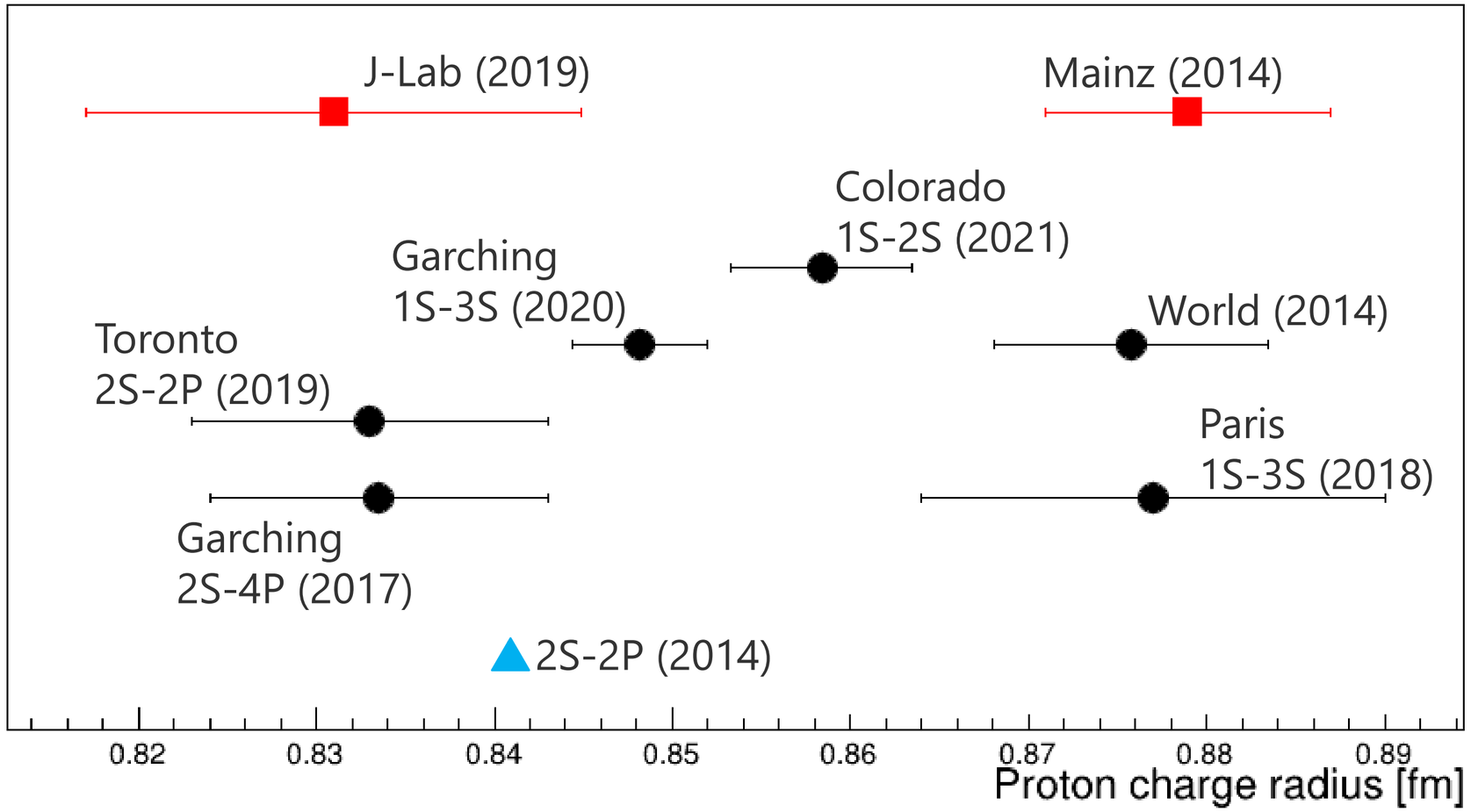
- Proton radius puzzle
- Deuteron radius puzzle
- RARiS : Low energy electron scattering facility
- Summary

Proton radius puzzle

$$r_p^2 \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$$



Present status of the proton radius puzzle

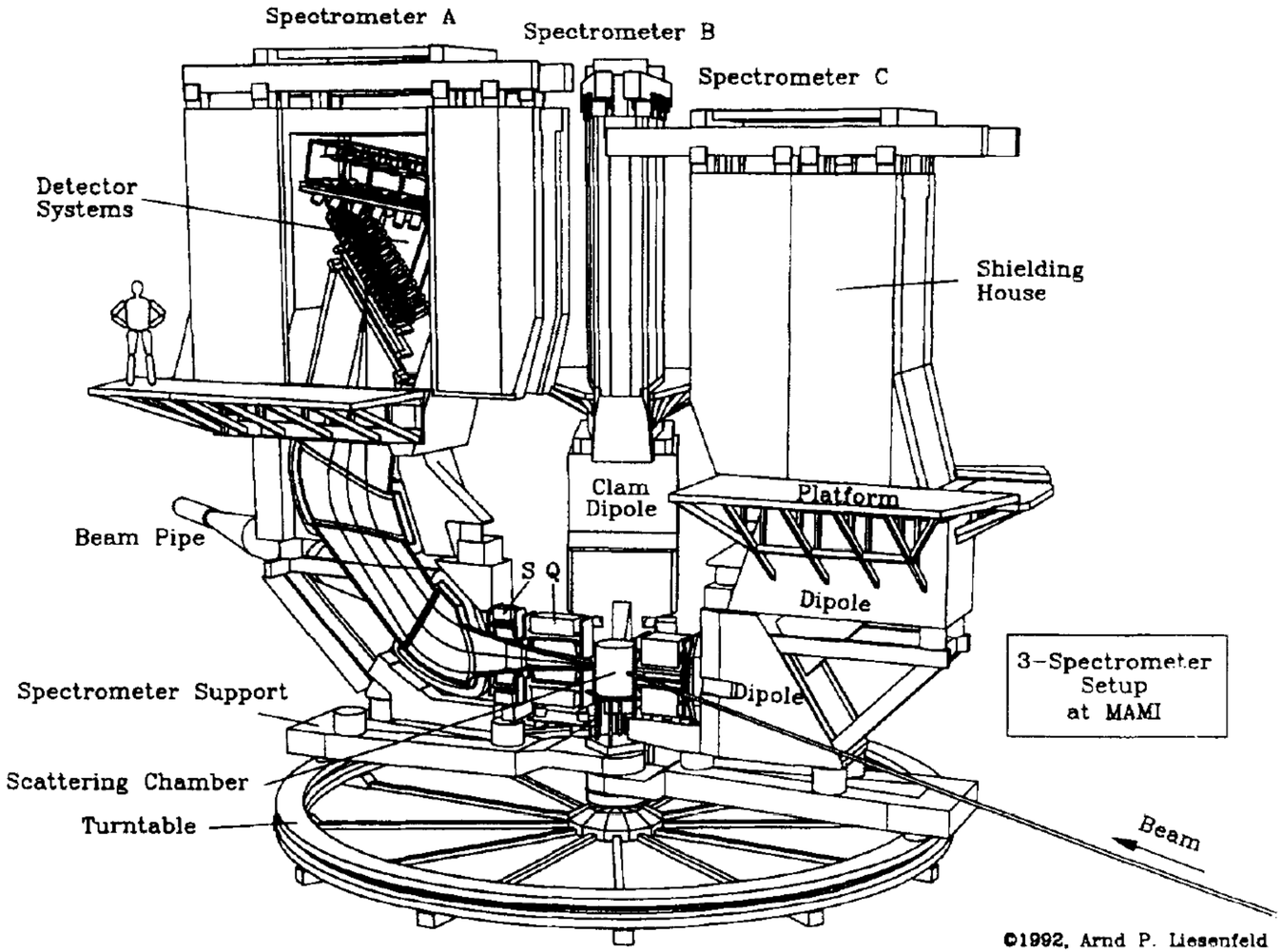


electron scattering
hydrogen spec.
μ-hydrogen spec.

What makes the difference?

QED calculation?
Undiscovered systematic effects?
Model dependencies?

Mainz experiment



Blomqvist *et.al.*, NIMA 403 (1998) 263-301

- Three electromagnetic spectrometers
- Middle energy and wide angle
  - $E_e = 180, 315, 450, 585, 720, 855$ MeV
  - $\theta = 15.5° - 130°$
- $Q^2 = 0.003 - 1\ [\mathrm{GeV}^2/c^2]$
- 1422 points measurement
- 31 normalize parameters
- Absolute cross section accuracy ~ few %
- Larger r_p (0.879 ± 0.008 fm)

Large systematic error have been pointed out due to inaccuracy of the absolute CS.

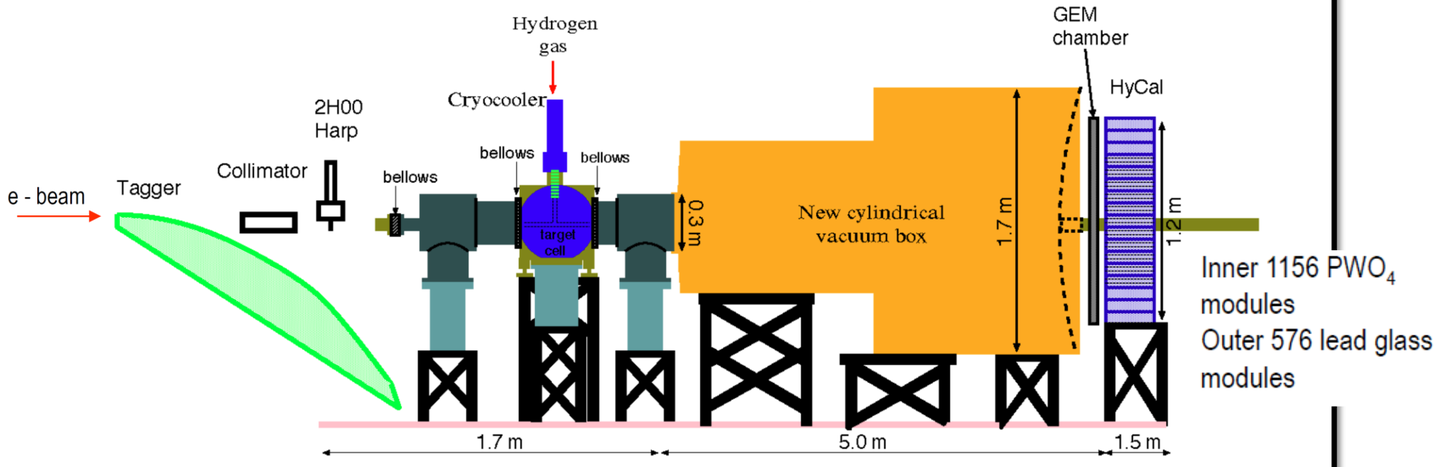
Magix exp. is planed with MESA.

PRad experiment

PRad Experimental Setup in Hall B at JLab (schematics)

- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal
- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam 12.7 mm for e^- beam halo "cleanup")
  - Harp 2H00
  - pipe connecting Vacuum Window through HyCal

PRad Setup (Side View)



A. Gasparian PRP–2018 10

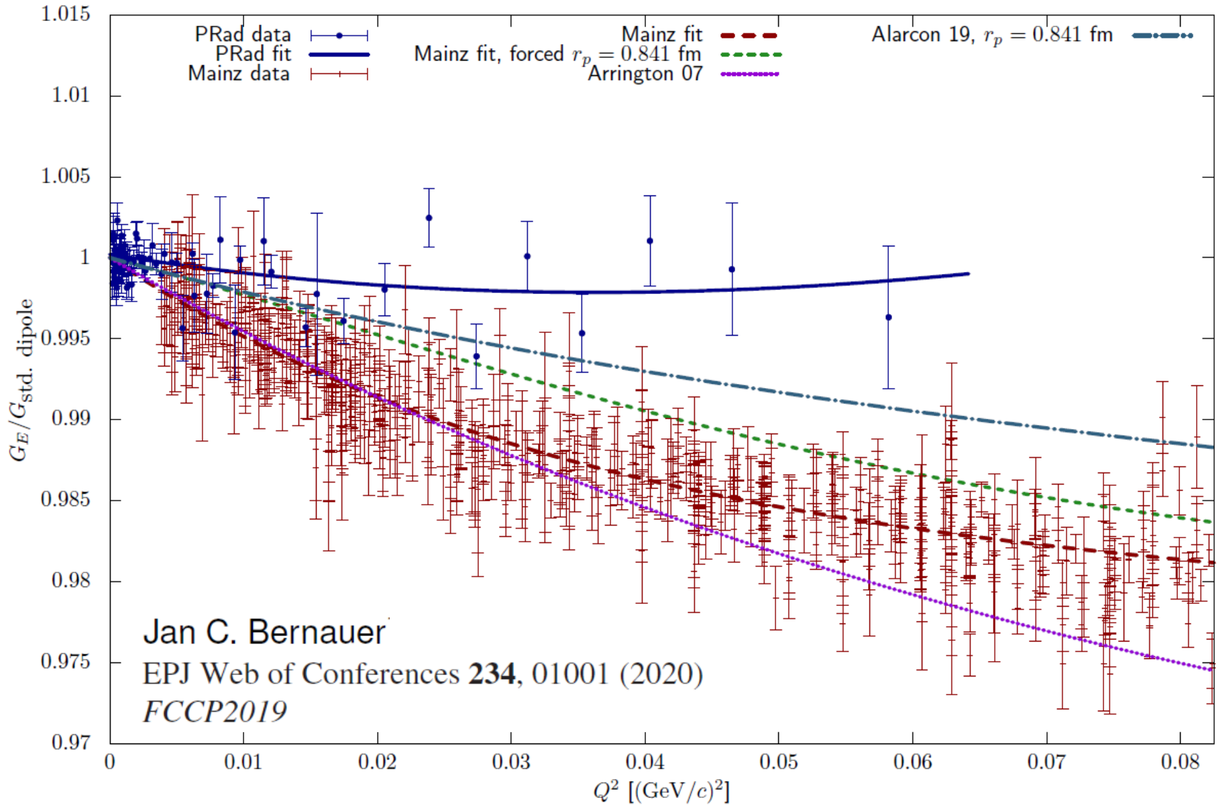
A. Gasparian PRP2018 slide

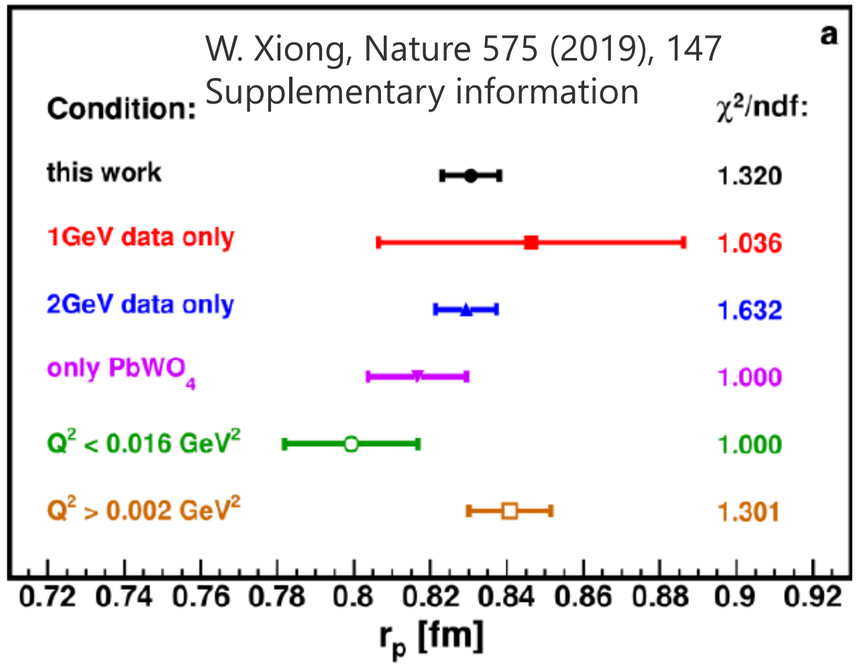
- Calorimeter and position detector
- High energy and very forward angle
  - $E_e = 1.1, 2.2$ GeV
  - $\theta = 0.7° - 7°$
- $Q^2 = 0.0002 - 0.06\ [\mathrm{GeV}^2/c^2]$
- Absolute cross section with ee→ee
- Smaller r_p (0.83 ± 0.01 fm)

Problems have been pointed out about background subtraction due to poor energy resolution (~ several %).

PRad2 is planed with new high resolution detectors.

PRad solve the puzzle ?





The radius from PRad mainly was determined by higher Q2 data (1.1 GeV data never contribute)

However, there are serious inconsistency at larger Q2 b/w PRad and Mainz.

Ultra Low Q^2 (ULQ2) experiment

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(Q^2)|^2$$

$$|F(Q^2)|^2 \propto G_E^2(Q^2) + \alpha(\theta) G_M^2(Q^2)$$

$$< r_p^2 > \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$$

ULQ2 experiment

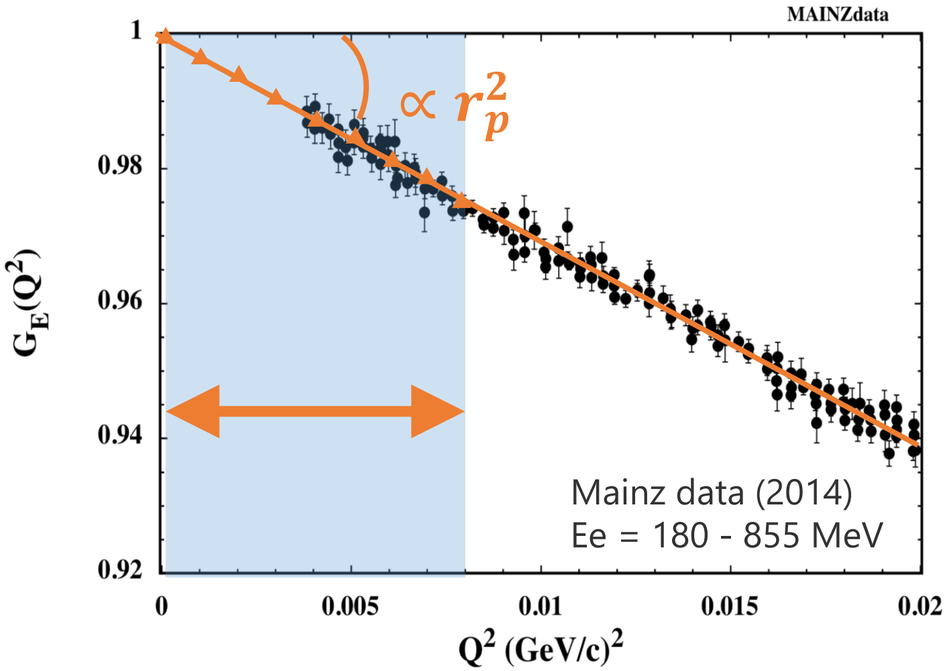
- Determine the proton radius with 1% accuracy by electron scattering

to achieve

① Extreme low Q^2 : $\mathbf{0.0003 \leq Q^2 \leq 0.008}$ $(\mathrm{GeV}/c)^2$.

② Rosenbluth separated $\boldsymbol{G_E(Q^2)}$ and $\boldsymbol{G_M(Q^2)}$ (if it necessary).

③ Absolute cross section measurement with $\sim\mathbf{10^{-3}}$ accuracy with simultaneous measurement of e+H and e+C with CH_2 target.



Absolute cross section measurement

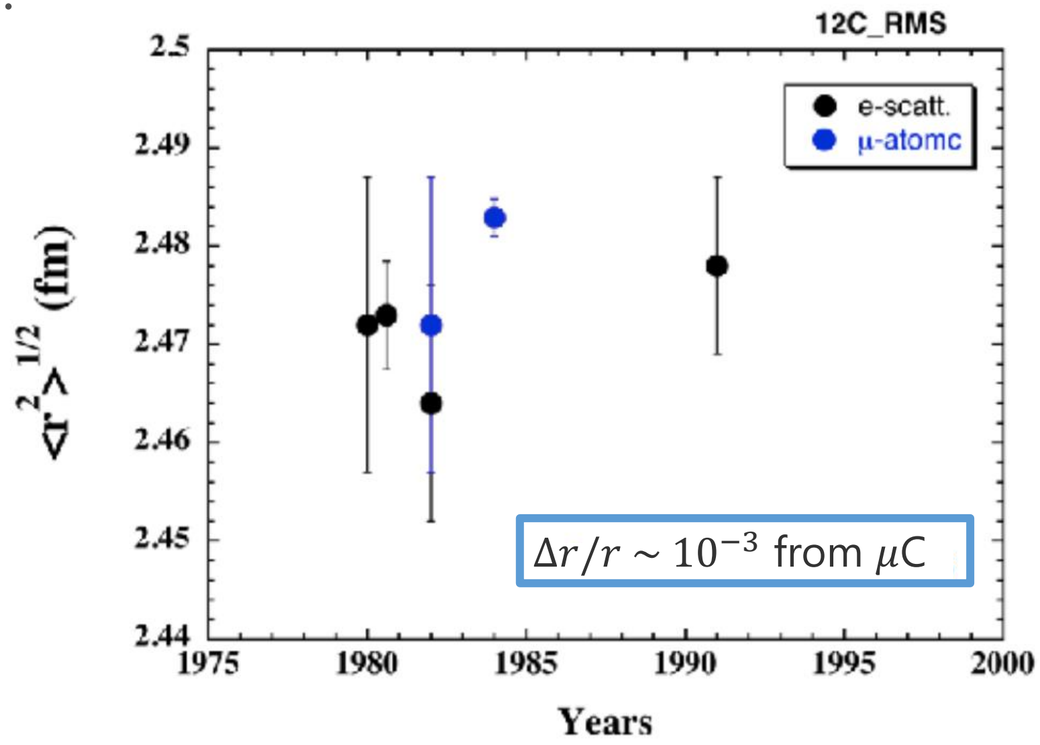
- Absolute cross section with 10^{-3} accuracy.
- Relative measurement to well-known cross section.
  e+p / e+C scattering with CH_2 target

$$\left(\frac{d\sigma}{d\Omega}\right)_{e+p} = \frac{N_{e+p}(\Delta\Omega)}{N_p \quad N_e \quad \Delta\Omega}$$

N_p: p target number; N_e: Beam dose; $\Delta\Omega$: Solid angle

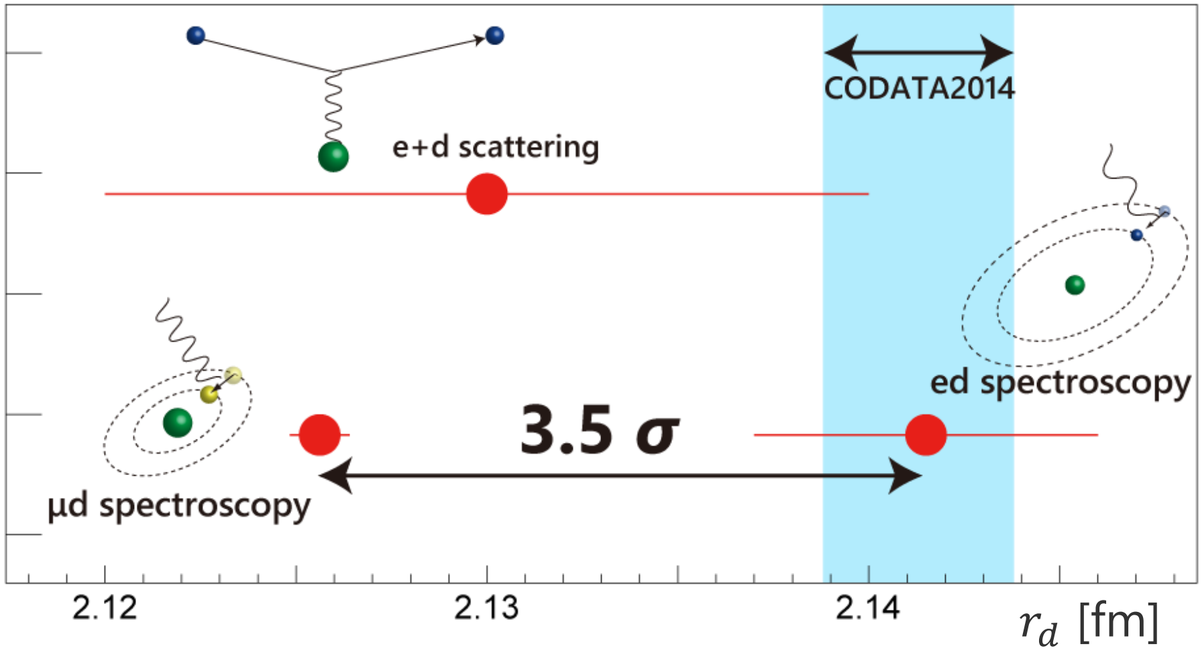
$$\left(\frac{d\sigma}{d\Omega}\right)_{e+p} = \frac{N_{e+p}(\Delta\Omega)/N_{e+C}(\Delta\Omega)}{N_p/N_C}\left(\frac{d\sigma}{d\Omega}\right)_{e+C}$$

N_p/N_C: Ratio of p and C; $\left(\frac{d\sigma}{d\Omega}\right)_{e+C}$: Precisely calculatable



ULQ2-D

Deuteron radius puzzle

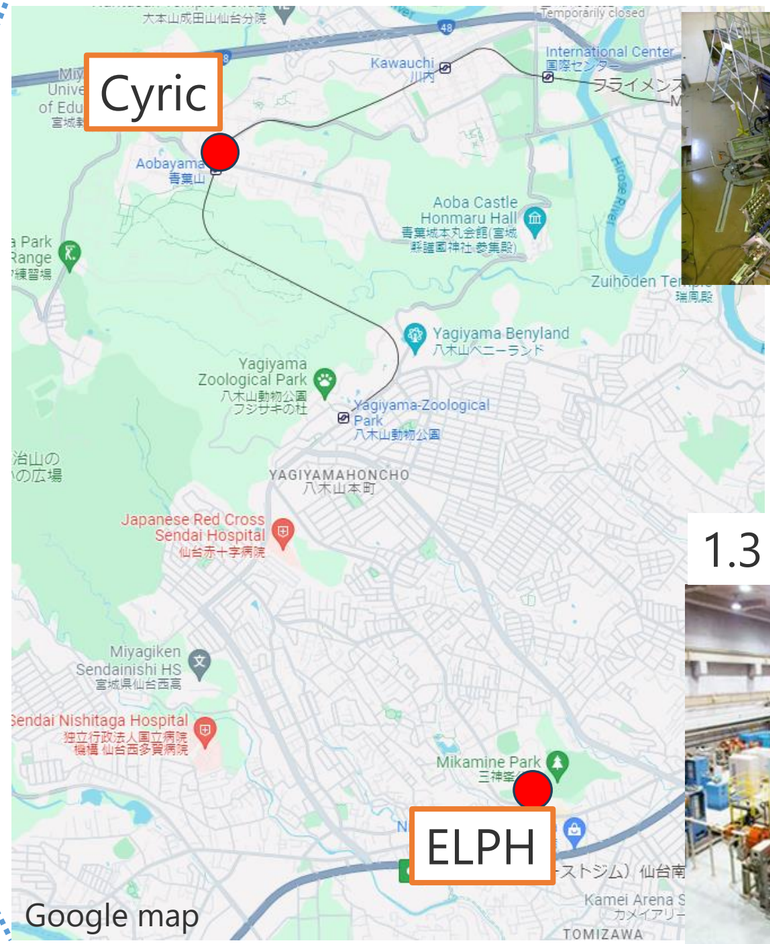


$$r_d^2 = r_{\mathrm{str}}^2 + r_n^2 + r_p^2 + \frac{3}{4m_p^2}$$

r_d : deuteron charge radius
r_{str}: deuteron structure radius
r_n : neutron charge radius
r_p : proton charge radius

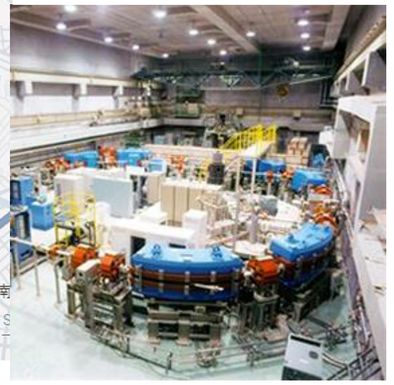
- The deuteron charge radius is also a puzzle.
- The deuteron is the simplest nuclear compound and the radius related to the neutron charge radius.
- Unfortunately, the e+d scattering did not contribute to the puzzle due to the large error.
- We will measure the radius with CD2 target with same technique as the proton.
- The first target accuracy is 0.5%.

Research Center for Accelerator and Radioisotope Science (RARiS)



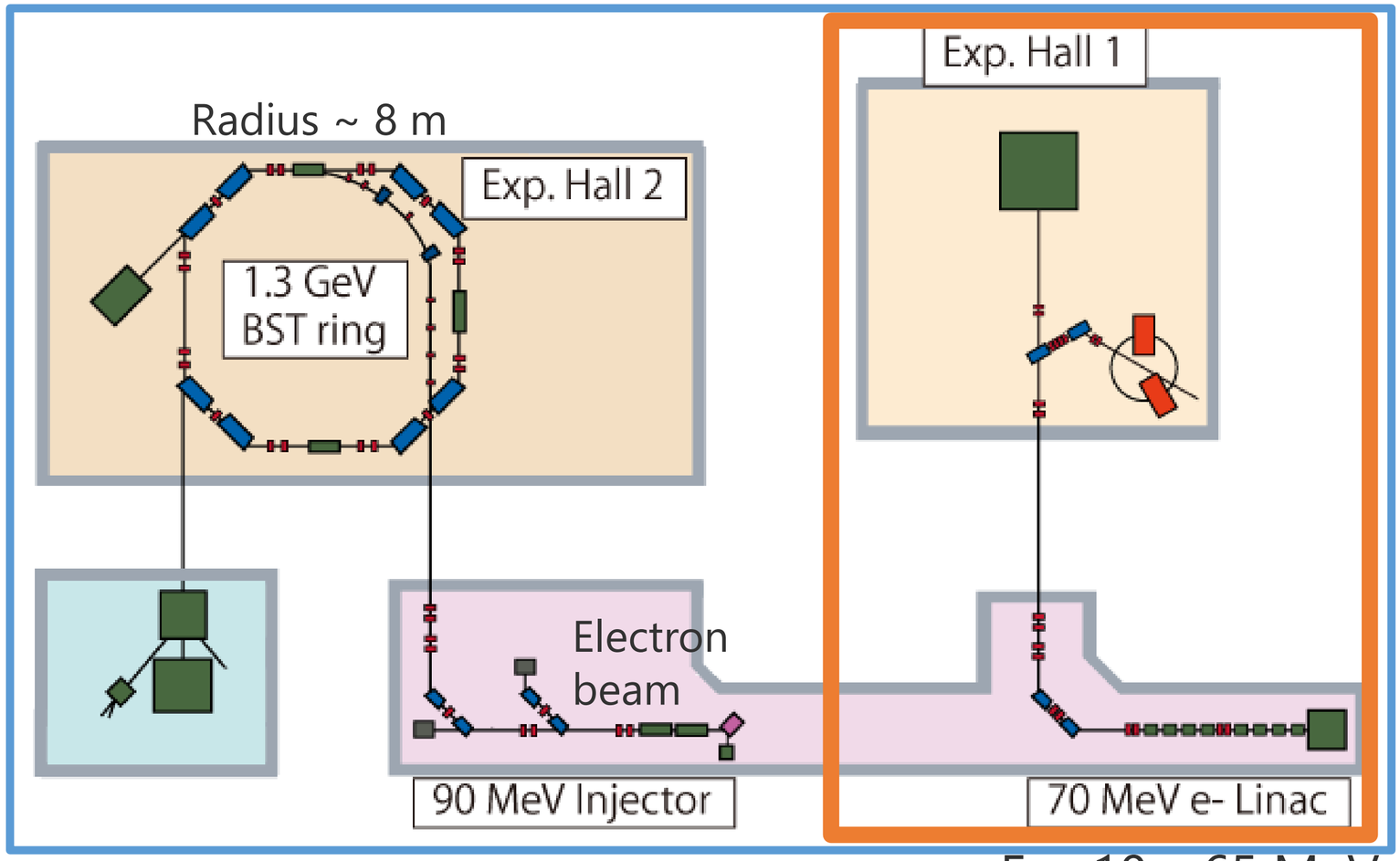
AVF cyclotron

1.3 GeV BST ring



70 MeV e- Linac

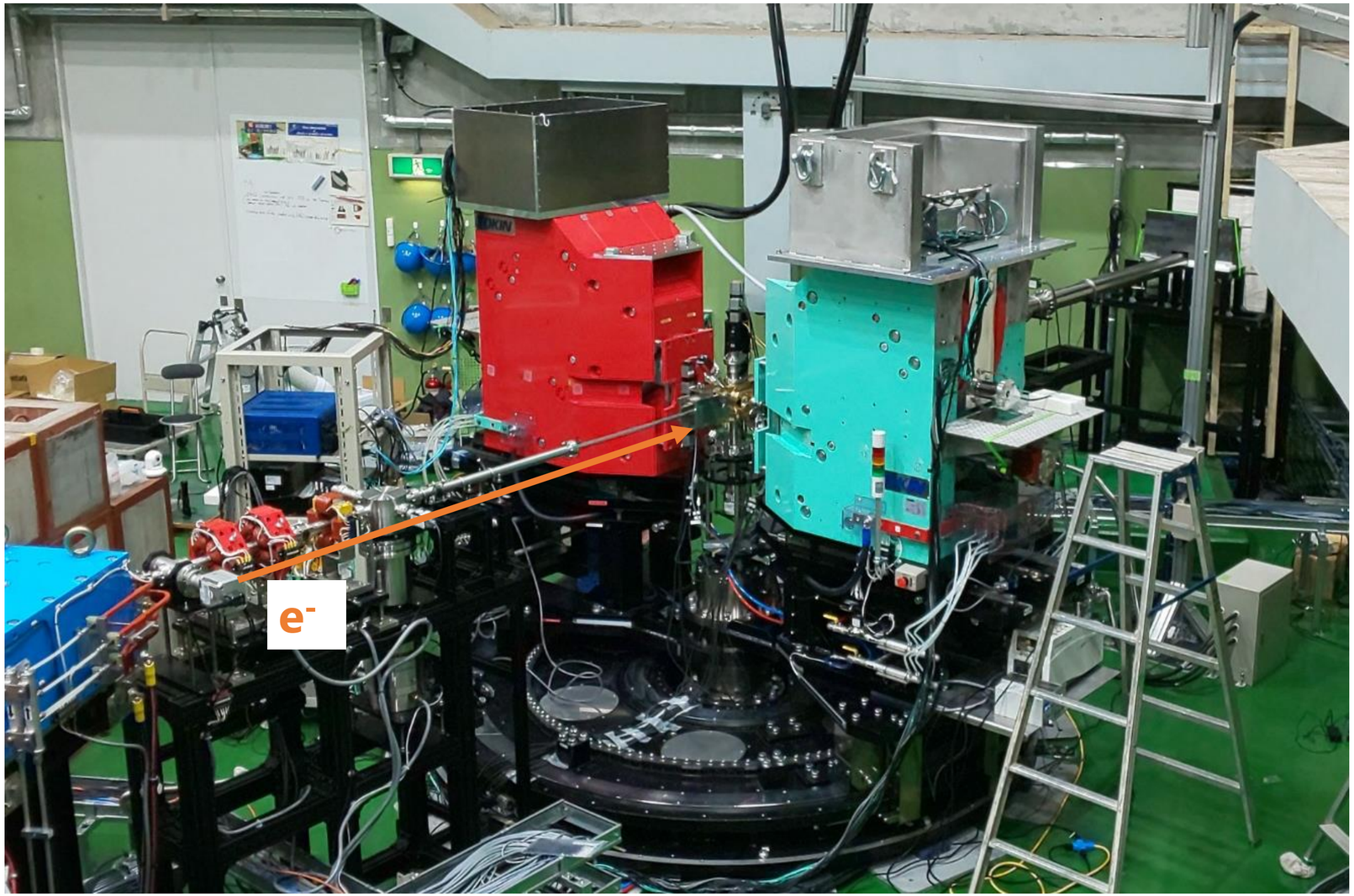
Accelerators in RARIS Mikamine cite (old ELPH)



E = 10 – 65 MeV

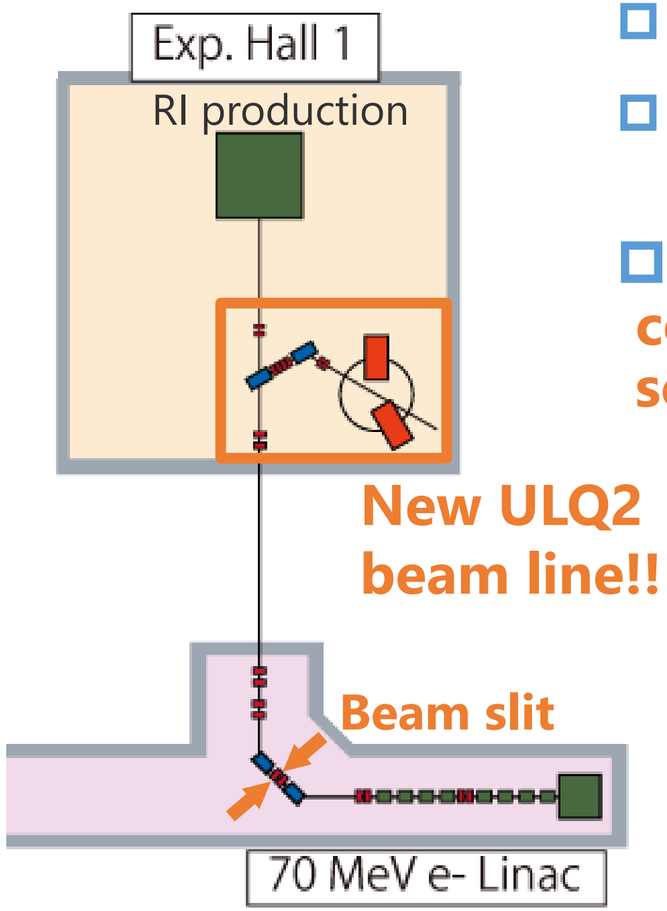
$I_e = 180\ \mu A$

ULQ2 equipment



Developed for low-energy electron scattering
① ULQ2 beam line
② Twin spectrometers

70 MeV electron linac



- Used for radio-isotope production
- Beam duty is ~ 0.1%
  (3 us bunch, 300 pps).
- **ULQ2 beam line was constructed for the electron scattering.**

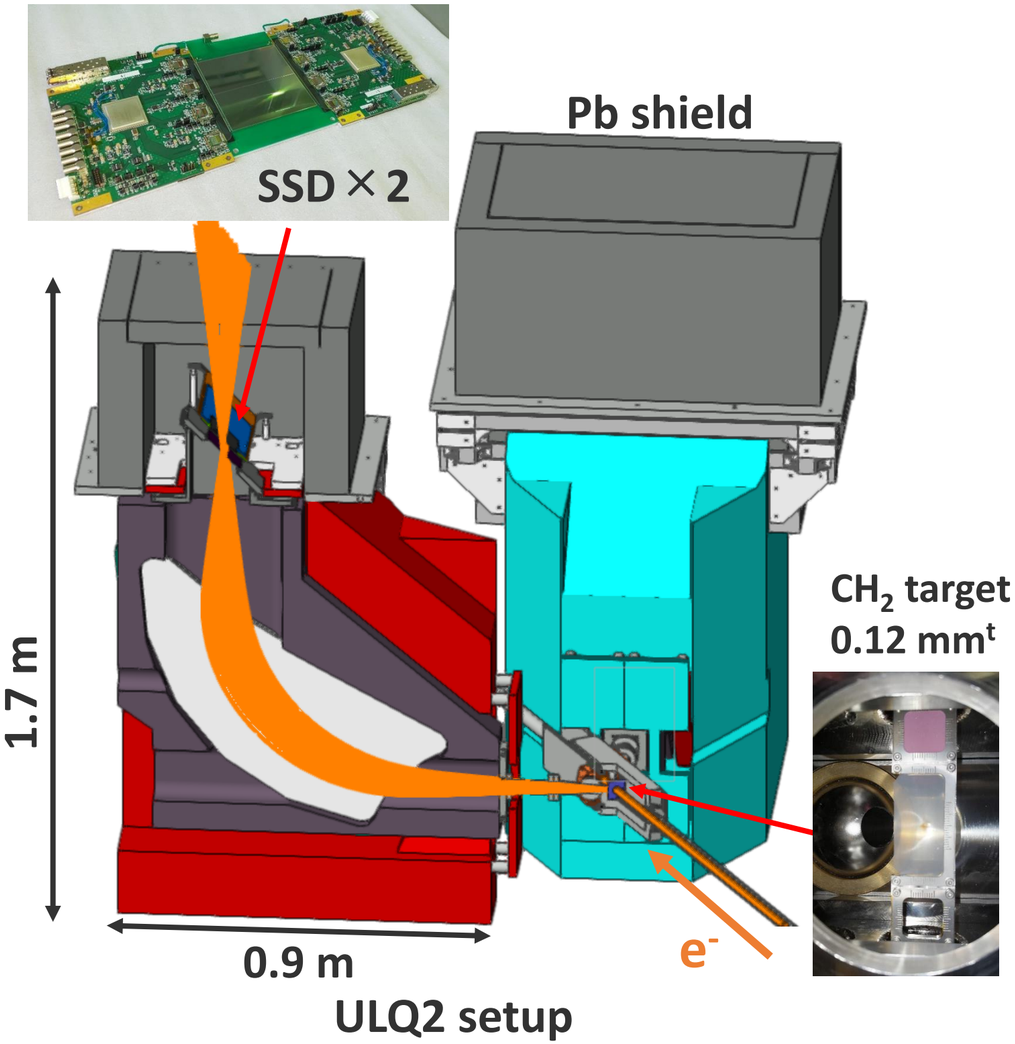
■ Previous status

- $E_e = 20\ -60$ MeV
- $\sigma_E/E_e \sim 0.5$ %
- $\sigma_{x,y} \sim 3$ mm
- $I_{\max} \sim 180$ μA

■ ULQ2 beamline

- $E_e = 10\ -65$ MeV
- $\sigma_E/E_e \leq 0.1$ %
- $\sigma_{x,y} \leq 1$ mm
- $I_{\max} \sim 1$ μA

Spectrometer for low-energy electron

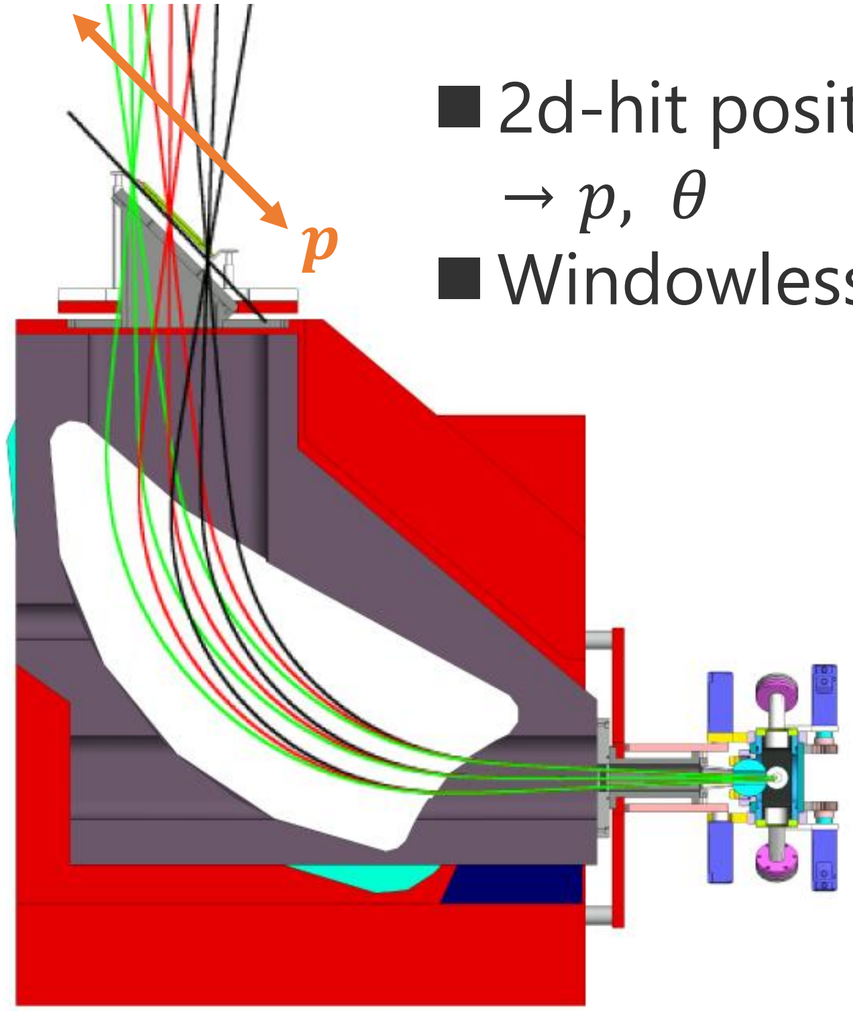


- Twin electro-magnetic spectrometer
  - ① Foreground measurement
  - ② Luminosity monitor, CH/CD ratio monitor
- Specialized for low-energy electron
  - ① Windowless
  - ② Tracking less

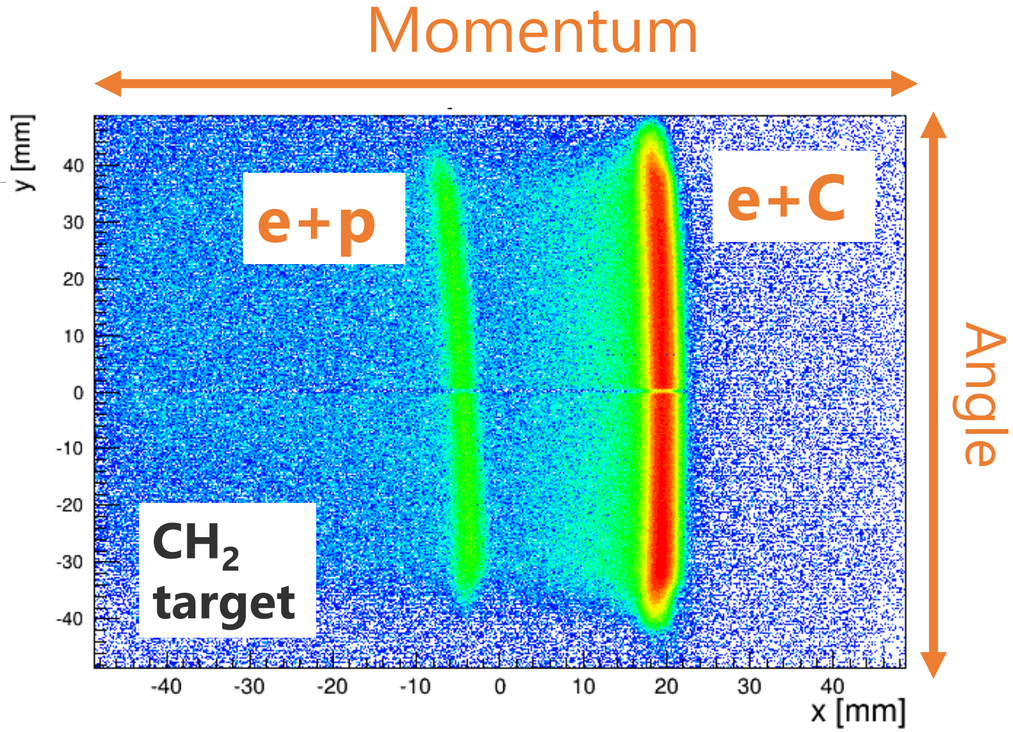
$E_e = 10 - 65$ MeV

- Consist of
  - ① Dipole magnet
  - ② Focal plane detector
  - ③ Target chamber

Spectrometer

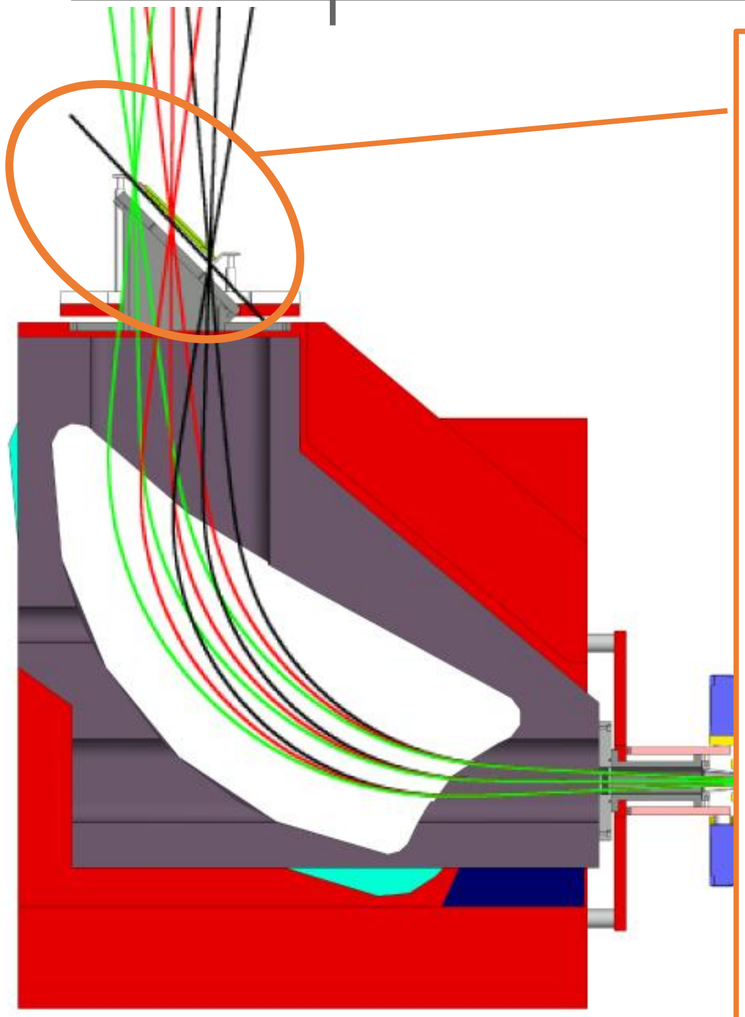


- 2d-hit position
  $\rightarrow p,\ \theta$
- Windowless

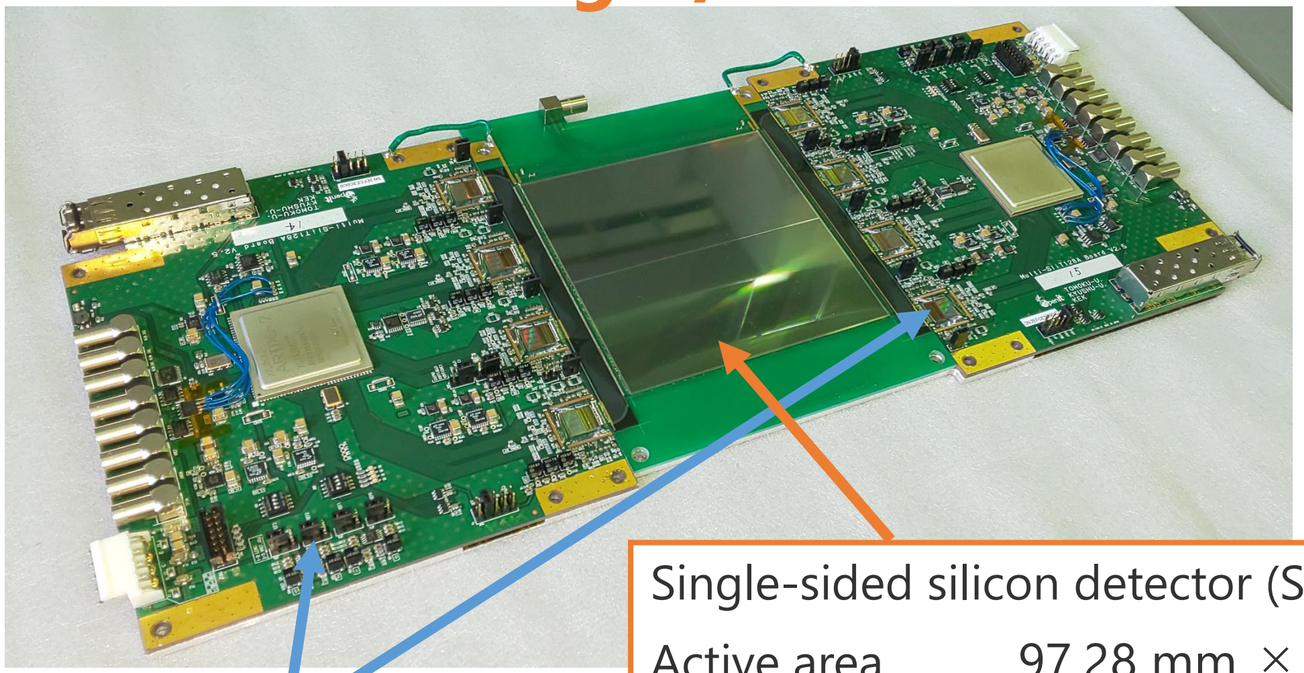


σ_p/p	0.05%
$\Delta p/p$	11%
σ_θ	5 mrad
$\Delta\Omega$	7 mSr (10 mSr)
θ	$30° - 150°$

Focal plane detector



J-PARC muon g-2/EDM Test module2



Readout boards
“Multi-Slit128A board”
Four ASICs “Slit128A”
(128 ch/chip)

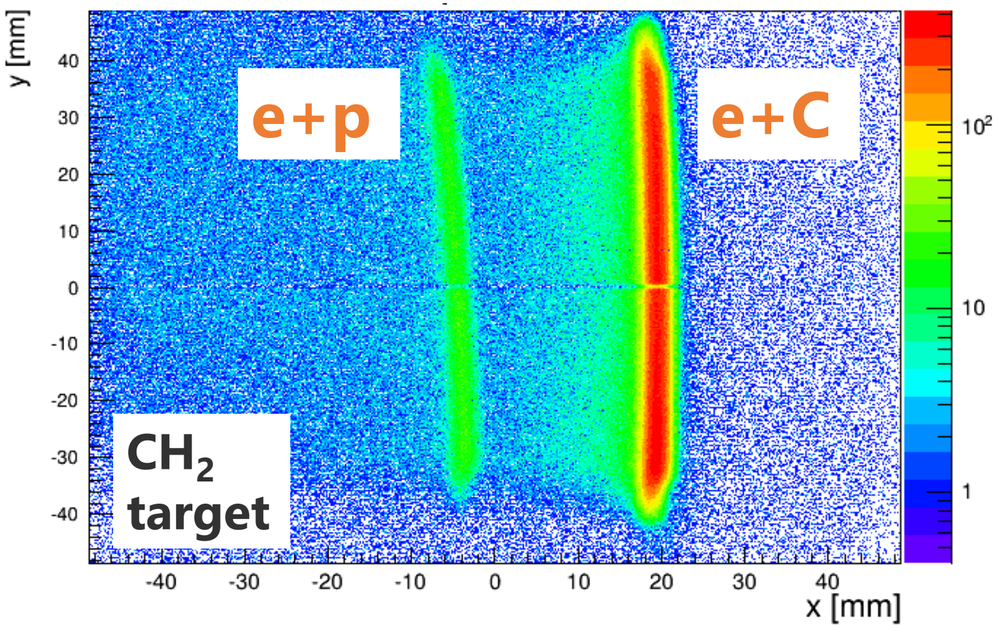
Single-sided silicon detector (SSSD)

Active area	97.28 mm × 97.28 mm
Thickness	0.32 mm
Strip pitch	0.19 mm
Strip length	48.575 mm
No. of strips	512 ch × 2

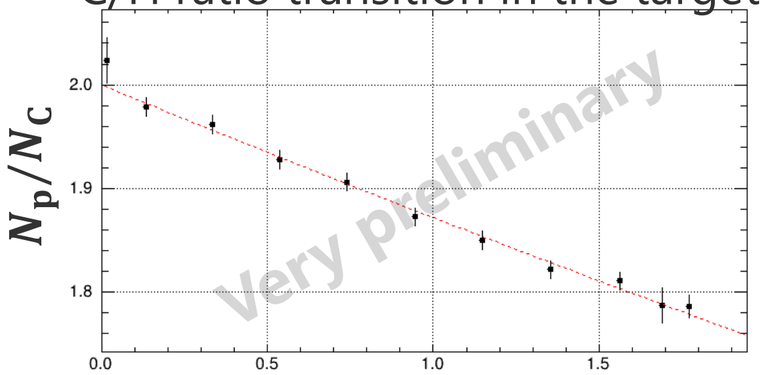
Physics run

$$\left(\frac{d\sigma}{d\Omega}\right)_{e+p} = \frac{N_{e+p}(\Delta\Omega)/N_{e+C}(\Delta\Omega)}{N_p/N_C}\left(\frac{d\sigma}{d\Omega}\right)_{e+C}$$

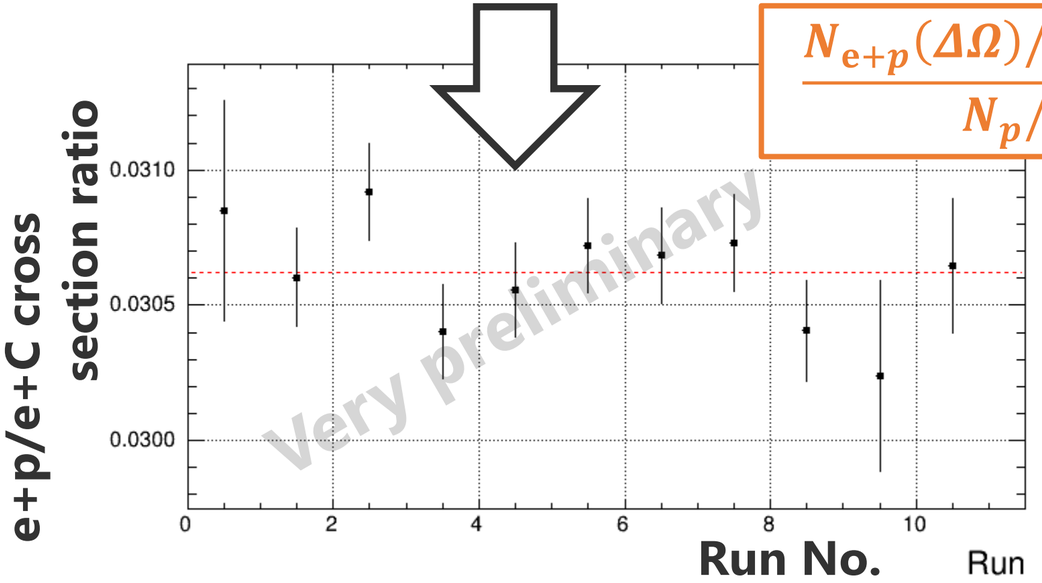
Precisely calculatable



C/H ratio transition in the target from 2nd spectrometer



N_p/N_C



$$\frac{N_{e+p}(\Delta\Omega)/N_{e+C}(\Delta\Omega)}{N_p/N_C}$$

- Data taking is almost finished, and will be completed this Oct.
- Radiative collection study is ongoing.
- The result will be published in this year.

Summary

- Proton and deuteron have puzzle on their charge radius.
- New low-energy electron scattering facility has been constructed at RARiS Tohoku University, Japan.
- ULQ2 experiment aims to determine the proton and deuteron charge radii with accuracies of 1% and 0.5 %.
- Data taking will finish next month.
- The results will be published in this year.