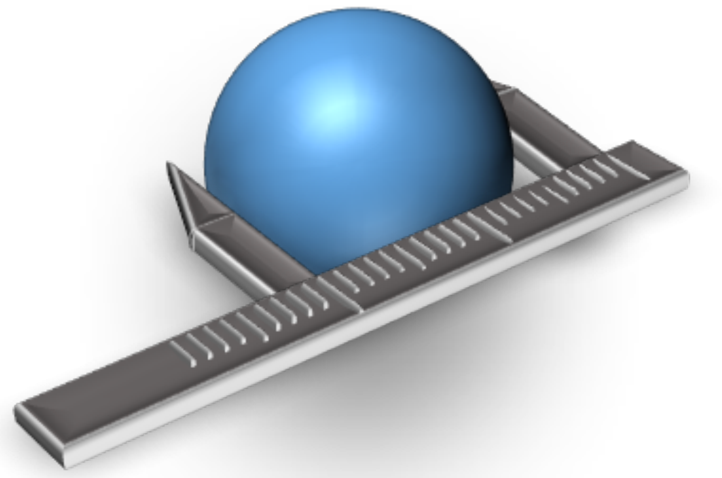
# Proton Charge Radius

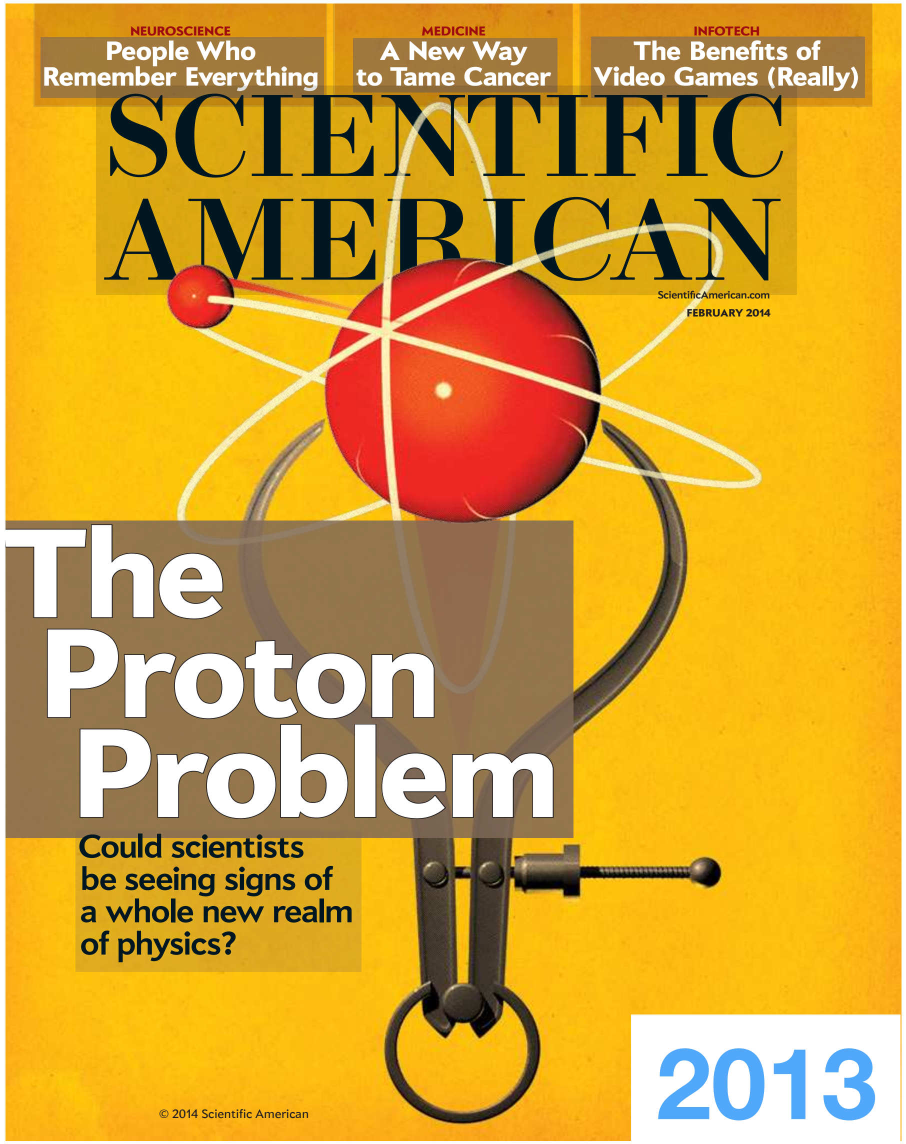
## by electron scattering under the lowest-ever momentum transfer



**Toshimi Suda**
**Research Center for Electron-Photon Science (ELPH), Tohoku University, Sendai, JAPAN**

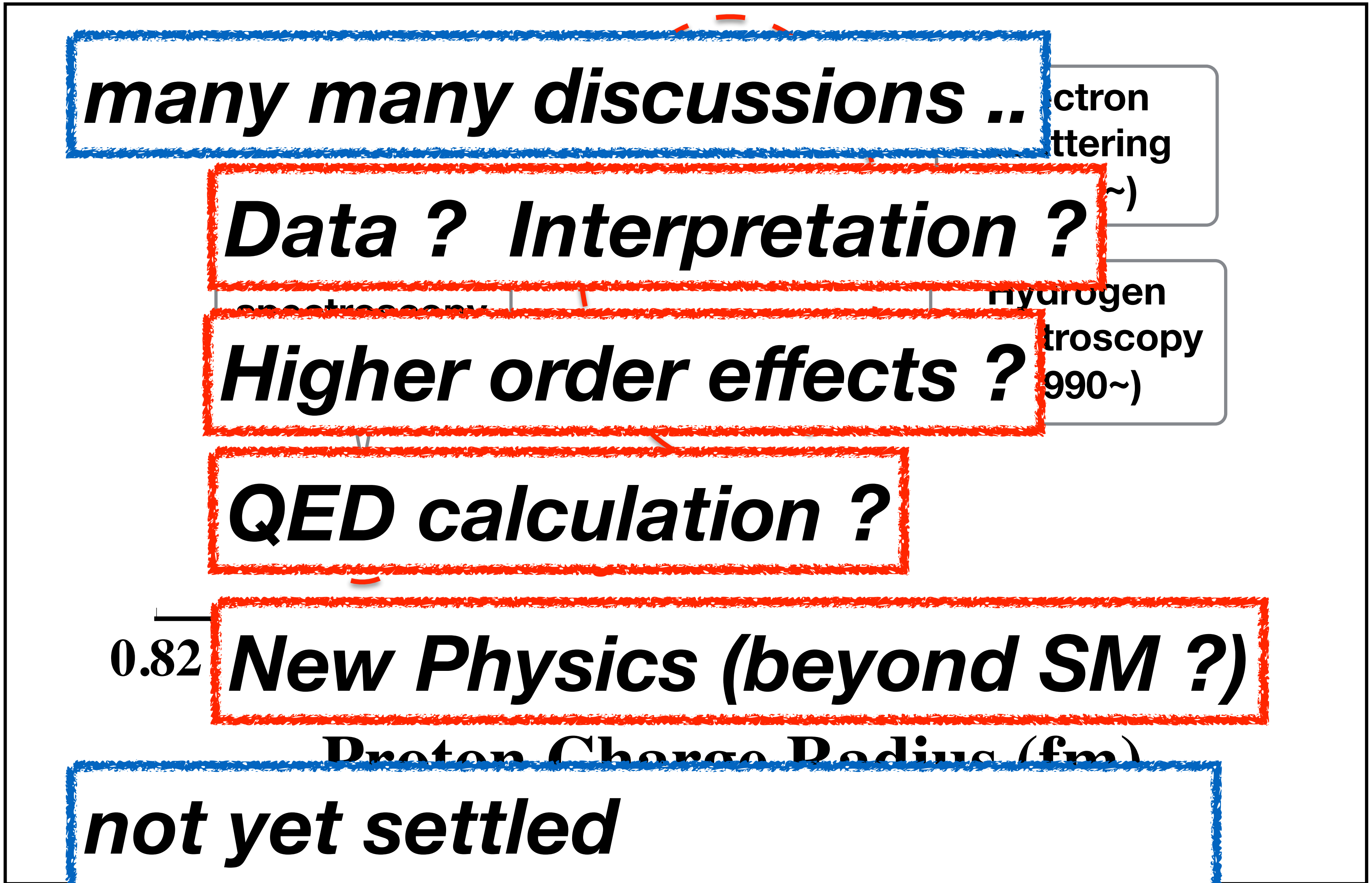
# Proton Charge Radius Puzzle

# Proton Radius Puzzle ?


**R. Pohl *et al.*,**
**Nature 466 (2010) 213.**

**A. Antognini *et al.*,**
**Science 339 (2013) 417.**




***many many discussions ..***

***Data ? Interpretation ?***

***Higher order effects ?***

***QED calculation ?***

***New Physics (beyond SM ?)***

***not yet settled***

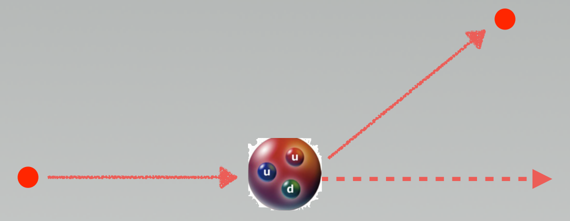
***New experiments …***

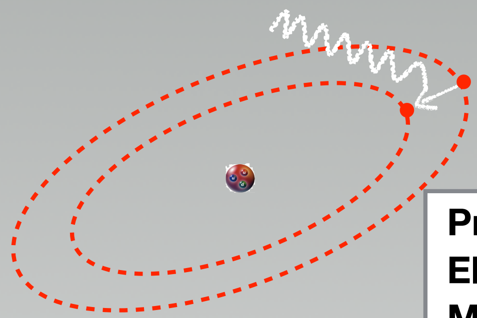
C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

# Proton Charge Radius measurements

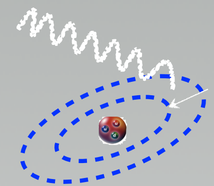
*FPUA @ Nagoya*
*Jan. 8-9, 2018*

| Electron Scattering (1950~) | eH-Spectroscopy (1990 ~) | μH-Spectroscopy (2000~) |
| --- | --- | --- |





$m_\mu \sim 200\ m_e$



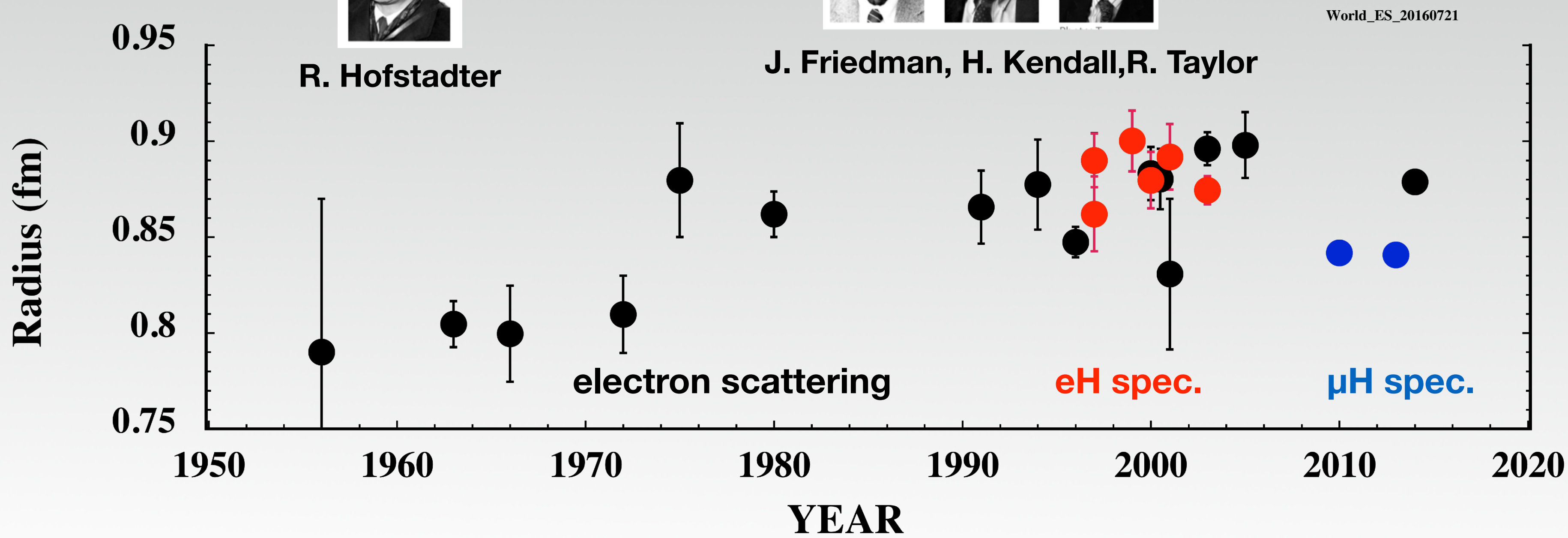
**Proton Radius ~ $10^{-15}$ m**
**Electron Orbit ~ $10^{-10}$ m**
**Muon Orbit ~ $10^{-12}$ m**

ρ(r) or $<r^2>$

$$\Delta E = \alpha \cdot R_{Rydberg} + \beta \cdot < r^2 >$$

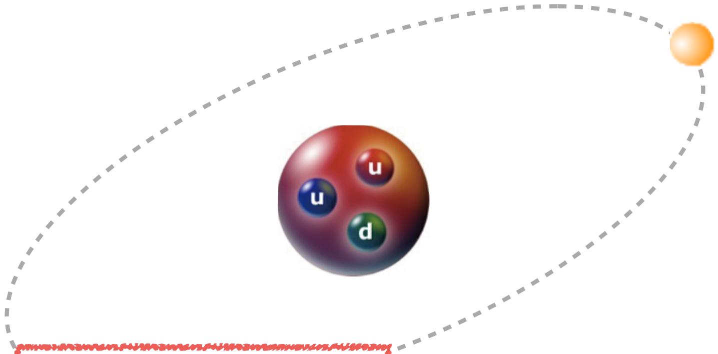
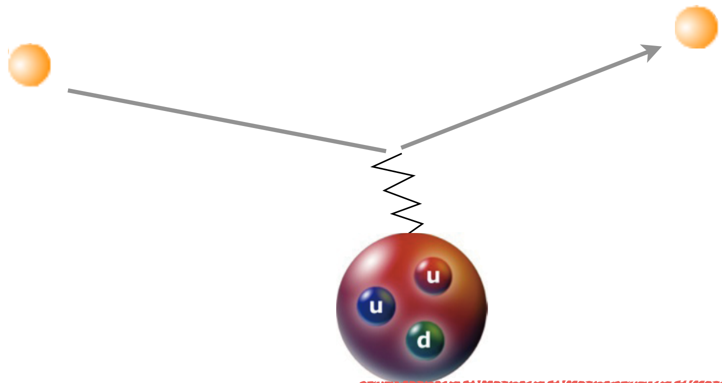
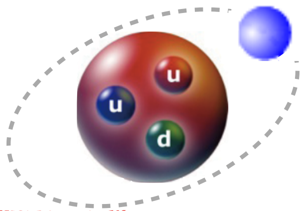
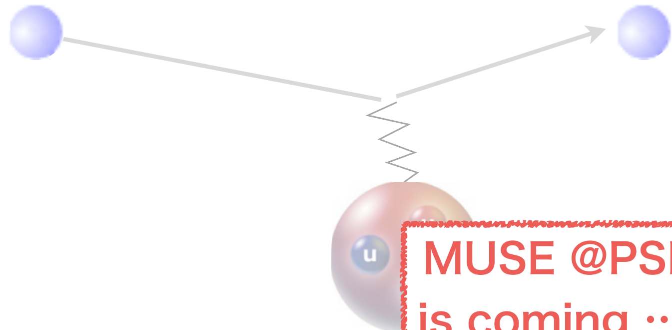
**R. Hofstadter**

**J. Friedman, H. Kendall, R. Taylor**



# Proton Charge Radius



| | Spectroscopy | Scattering |
|---|---|---|
| $e^-$ |  0.8758(77) |  0.8770(60) |
| $\mu^-$ |  0.8409(4) |  MUSE @PSI is coming ··· |

$m_e$ = 0.511 MeV
$m_\mu$ = 105.6 MeV

*C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59-77.*

# To understand the puzzle



**e-scattering ：re-analysis of world data**

*model dependence of radius determination*
*radiative correction, higher order effects …*

**H-spec. ：QED calculations by several groups**

*higher order effects such as two-photon exchange …*

→ **No serious problem yet identified**

**possible non identical nature of e-μ ?** *Lepton universality*

## New experiments

| | |
|---|---|
| **e-scatt.** | **JLAB（US）、Mainz（Germany）、Tohoku（Japan)** |
| **H-spec.** | **Toronto （Canada）、Garching （Germany)**<br>**LKB（France）、 NIST（US）etc.** |
| **μH-spec** | **PSI（Switzerland)、RIKEN（Zemach moment)** |
| **$\mu^{\pm}$scatt.** | **PSI（Switzerland)** |

# Electron scattering group of Tohoku Univ.

**World's first**

## 1) short-lived exotic nuclei @ RIKEN-SCRIT facility

**World's first electron scattering facility**

*charge radii and charge density distributions*

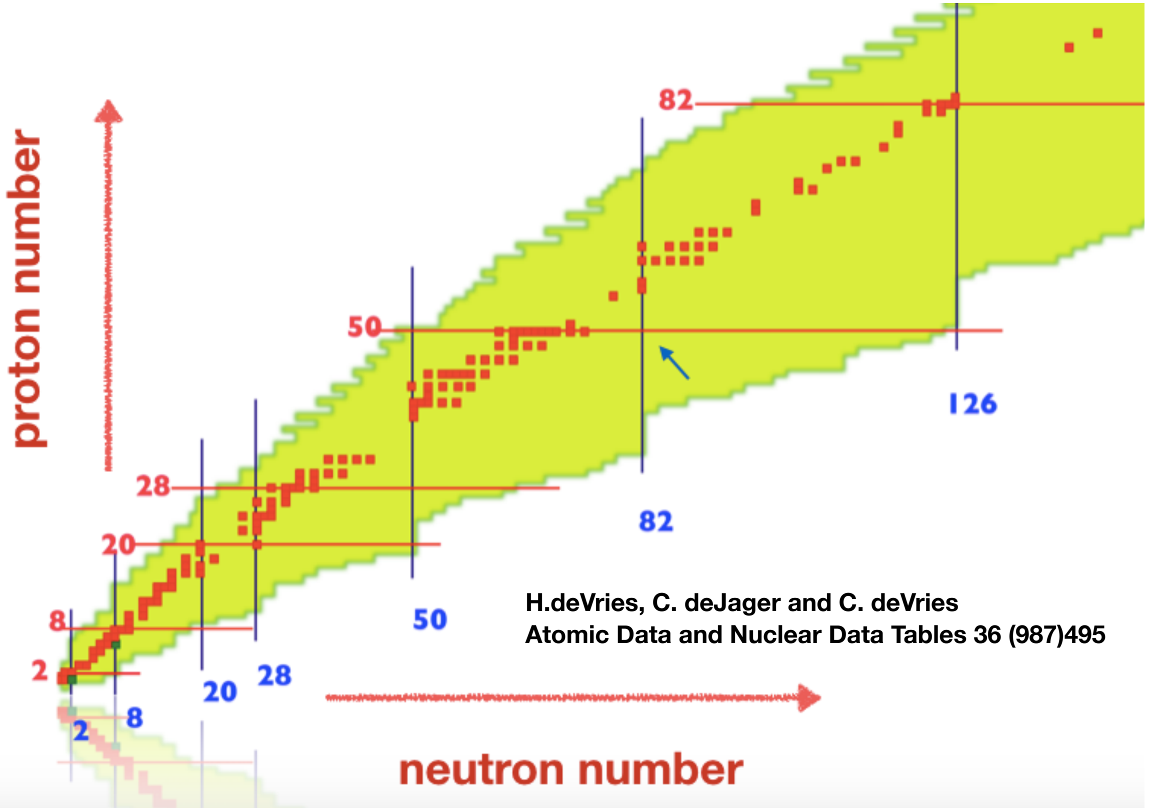
## 2) proton @ Tohoku Univ. (Sendai)

**World's lowest $Q^2$**

# Electron scattering off short-lived exotic nuclei

FPUA @ Nagoya
Jan. 8-9, 2018

## Nuclei targeted for electron scattering




H.deVries, C. deJager and C. deVries
Atomic Data and Nuclear Data Tables 36 (987)495

### Short-lived Exotic Nuclei

**Production-hard + Short-lived**

### Elastic electron scattering

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\mathrm{Mott}}}{d\Omega} |F_c(q)|^2$$

$$F_c(q) = \int \rho_c(\vec{r}) e^{i\vec{q}\vec{r}} d\vec{r}$$

$$\rho_c(\vec{r}) = \sum_p \psi_p^*(\vec{r})\psi_p(\vec{r})$$

### SCRIT ( Self-Confining RI ion Target )

**L ~ $10^{27}$ /cm²/s with only ~$10^8$ target nuclei**

**target thickness used to be ~$10^{20}$ /cm²/s**

### Low Luminosity

**Charge density distribution**
**Charte radius**

### SCRIT collaboration

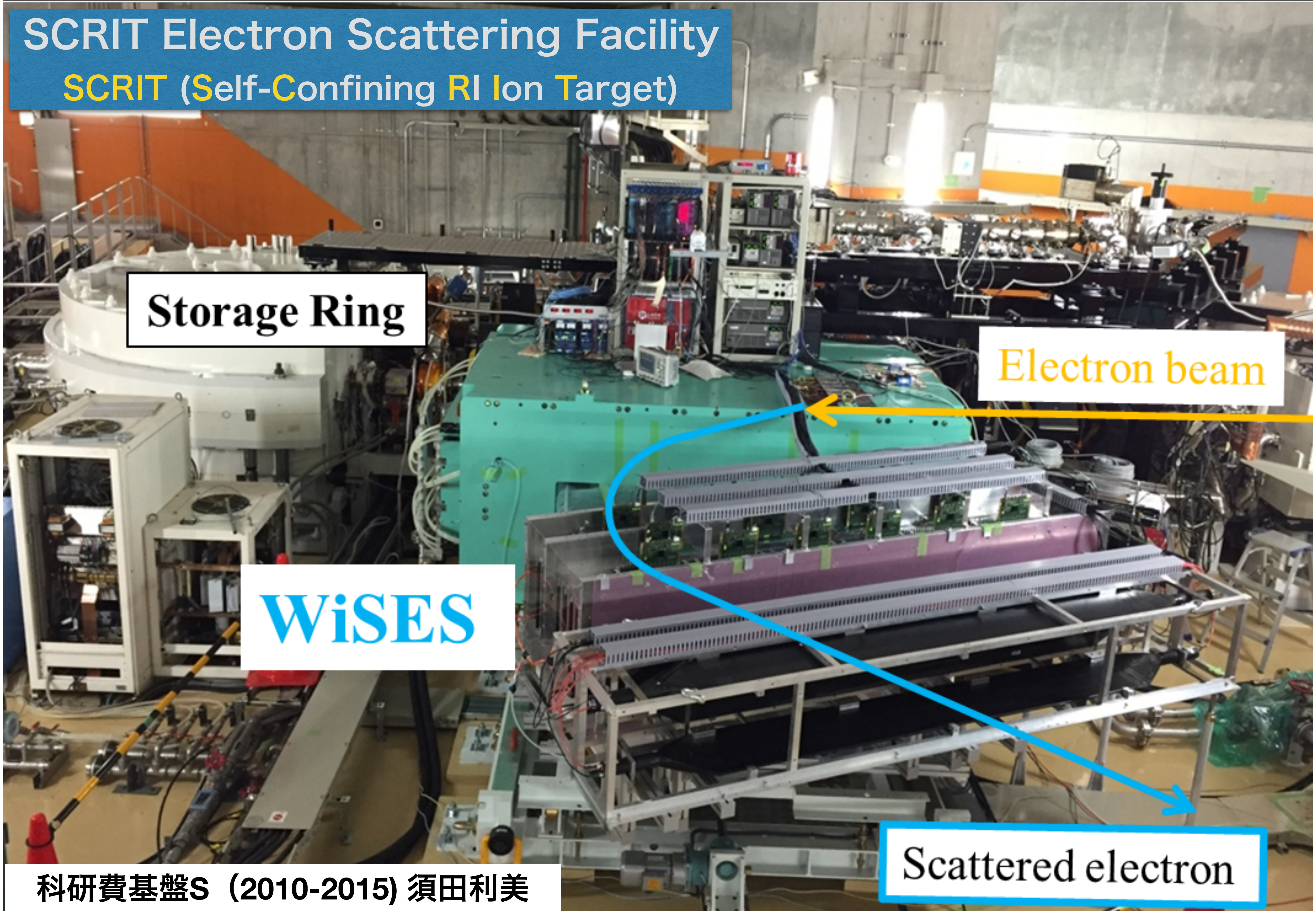
**RIKEN + Rikkyo U. + Tohoku U.**

*(Review) T. Suda and H. Simon, Prog. Part. Nucl. Phys. 96 (2017) 1-31.*

*(First Physics Data) K. Tsukada et al., Phys. Rev. Lett. 118(2017) 262501.*

# World's first facility for exotic nuclei@RIBF



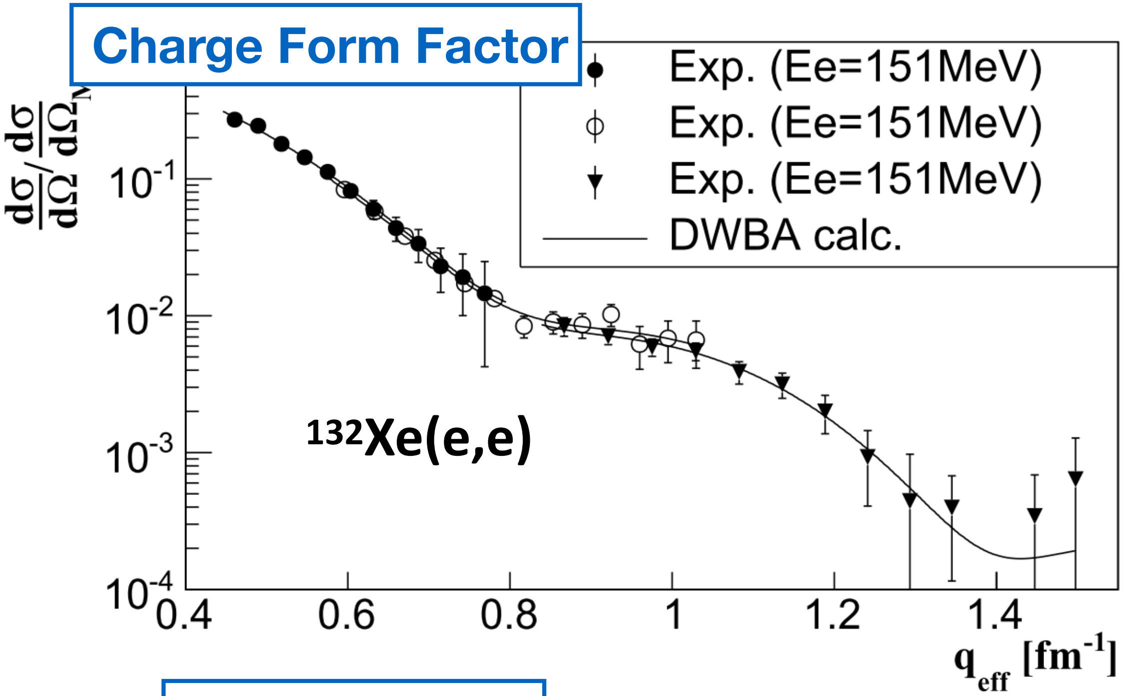


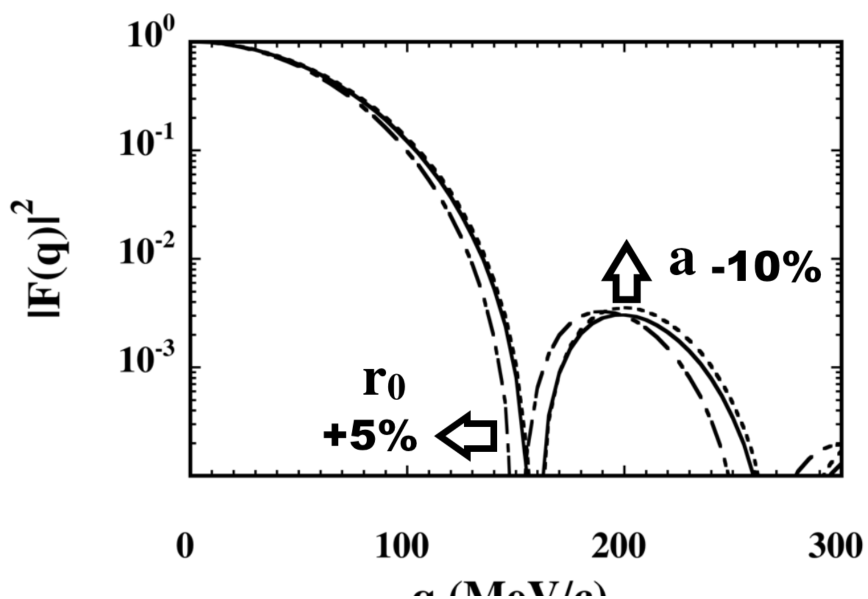

科研費基盤S（2010-2015) 須田利美

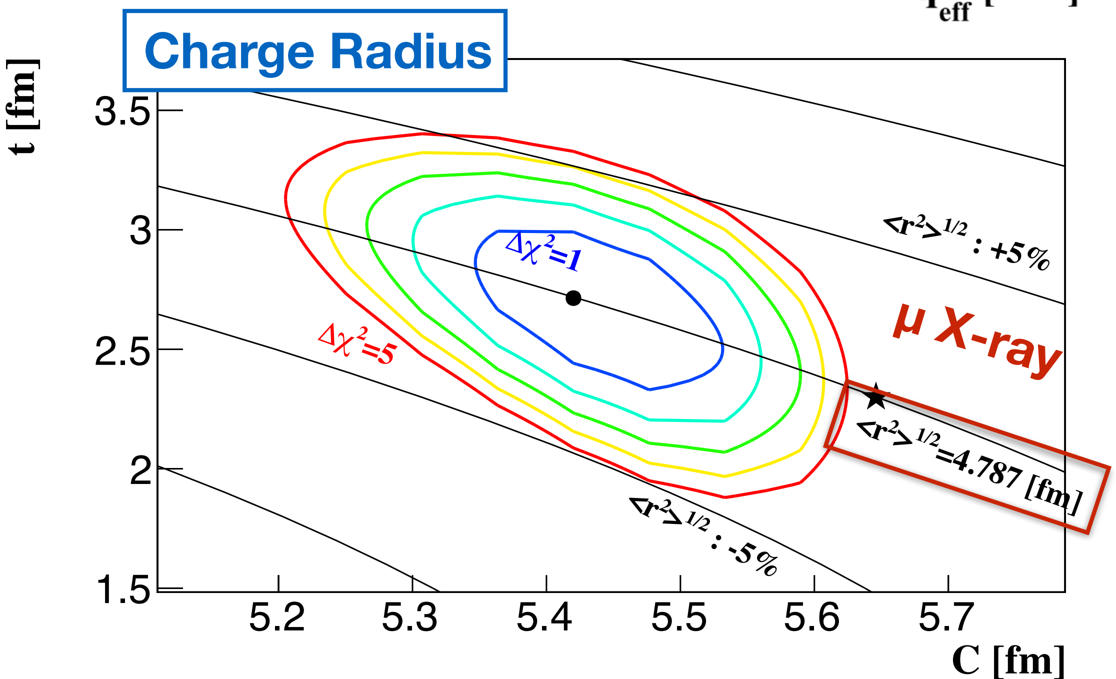
# First experiment (¹³²Xe(e,e’))

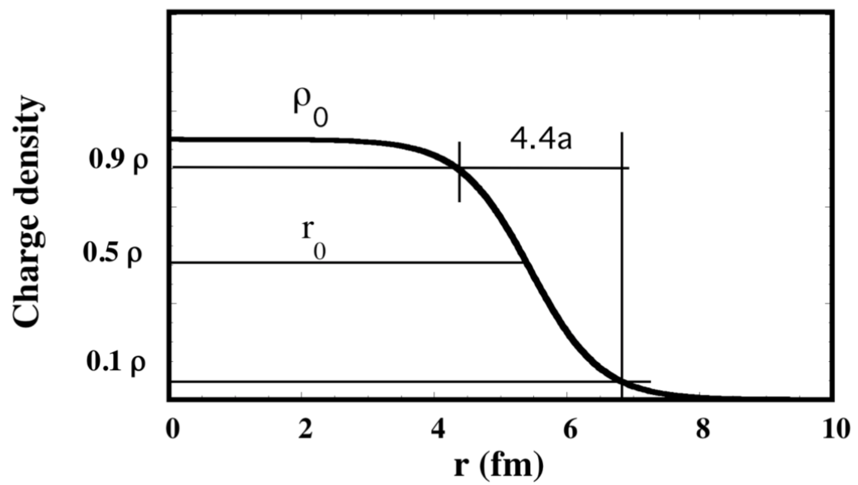


## using only ~$10^8$ target nuclei



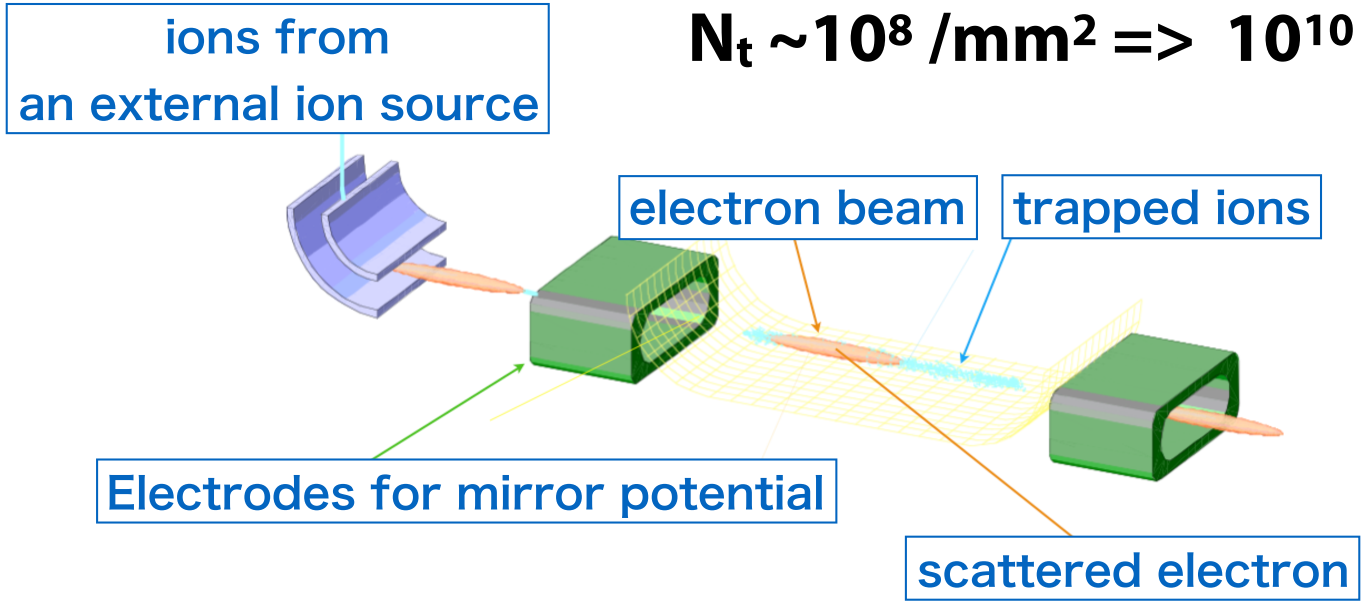




K. Tsukada *et al.* Phys. Rev. Lett. 118 (2017) 262501

# Luminosities

## ~$10^8$ ions are trapped on e-beam (~ 1 $mm^2$)

$N_t$ ~$10^8$ /$mm^2$ => $10^{10}$ /$cm^2$




| | Ee | $N_{beam}$ | ρ • t | L |
|---|---|---|---|---|
| **Hofstadter's era (1950s)** | 150 MeV | ~ 1nA (~$10^9$ /s) | ~$10^{19}$ /$cm^2$ | ~$10^{28}$ /$cm^2$/s |
| **JLAB** | 6 GeV | ~100μA (~$10^{14}$ /s) | ~$10^{22}$ /cm2 | ~$10^{36}$ /$cm^2$/s |
| **SCRIT** | **150 - 300 MeV** | **~200 mA (~$10^{18}$ /s)** | **~ $10^{10}$ /$cm^2$** | **~$10^{27}$ /$cm^2$/s** |

**The SCRIT technique reduces the required target thickness by ~$10^{-10}$ !!**

# Proton Charge Radius

# Charge Radius and Density Distribution

## RMS radius

$$< r^2 > = \int r^2 \rho(\vec{r}) d\vec{r}$$

$$= 4\pi \int r^4 \rho(r) \, \mathrm{d}r$$

## ρ(r)

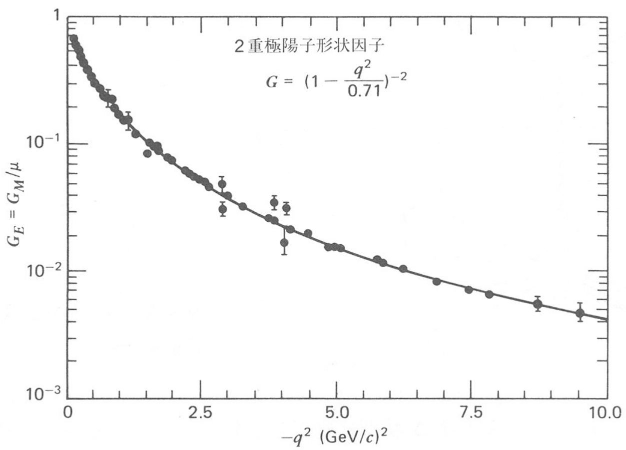
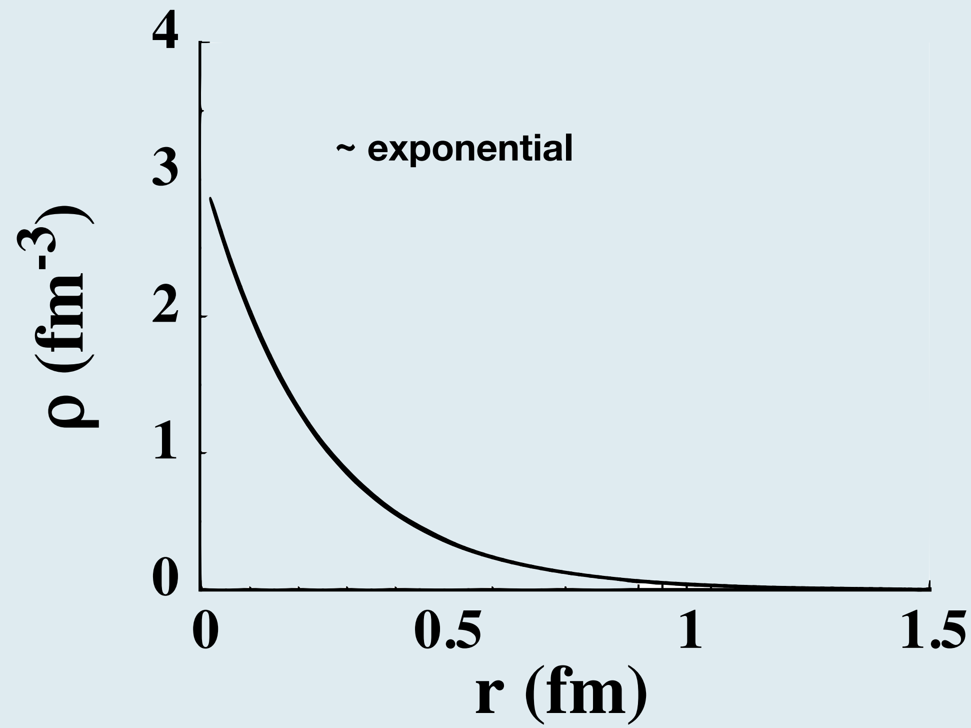


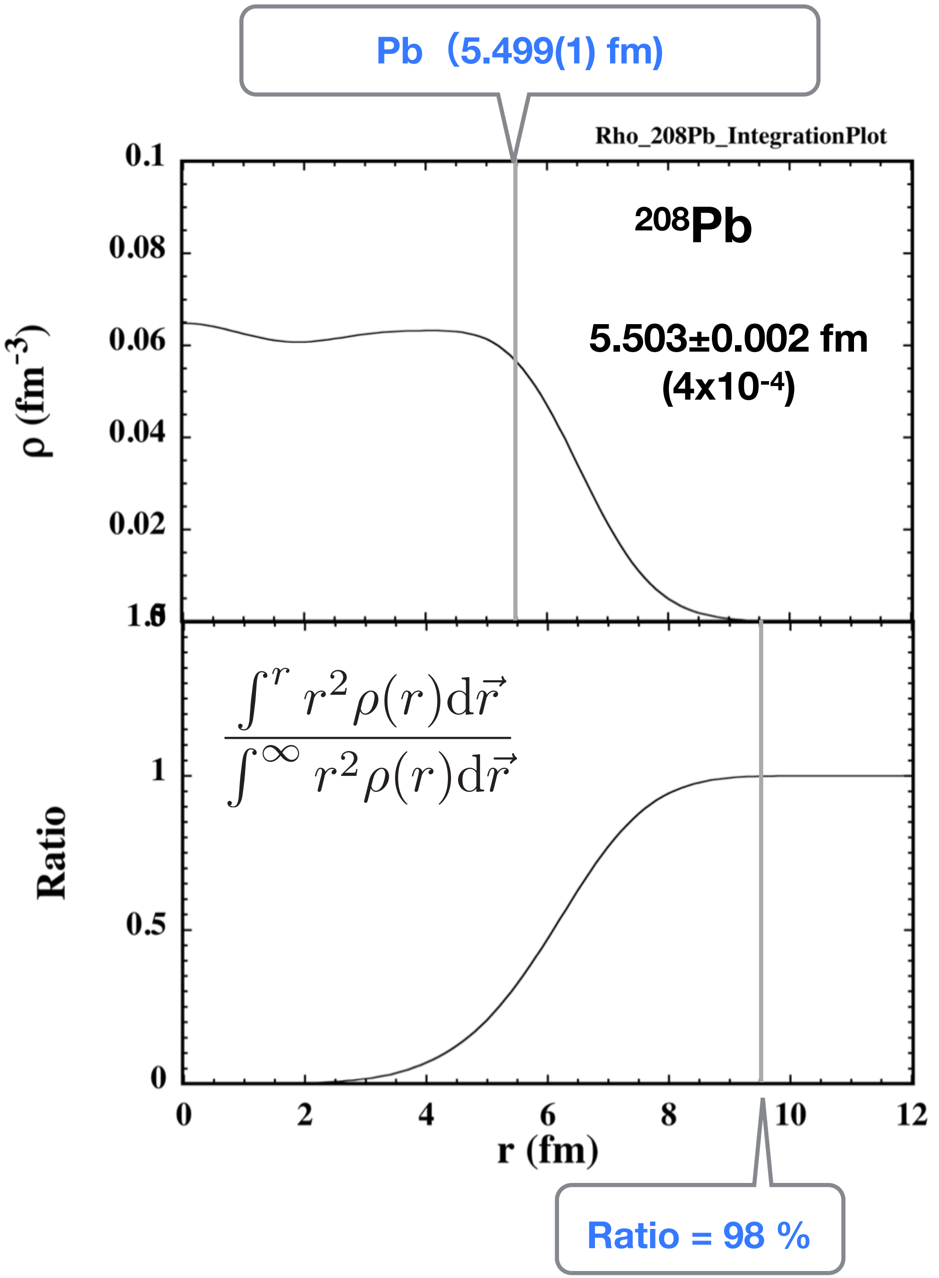

図8·4 $q^2$の関数としての陽子形状因子

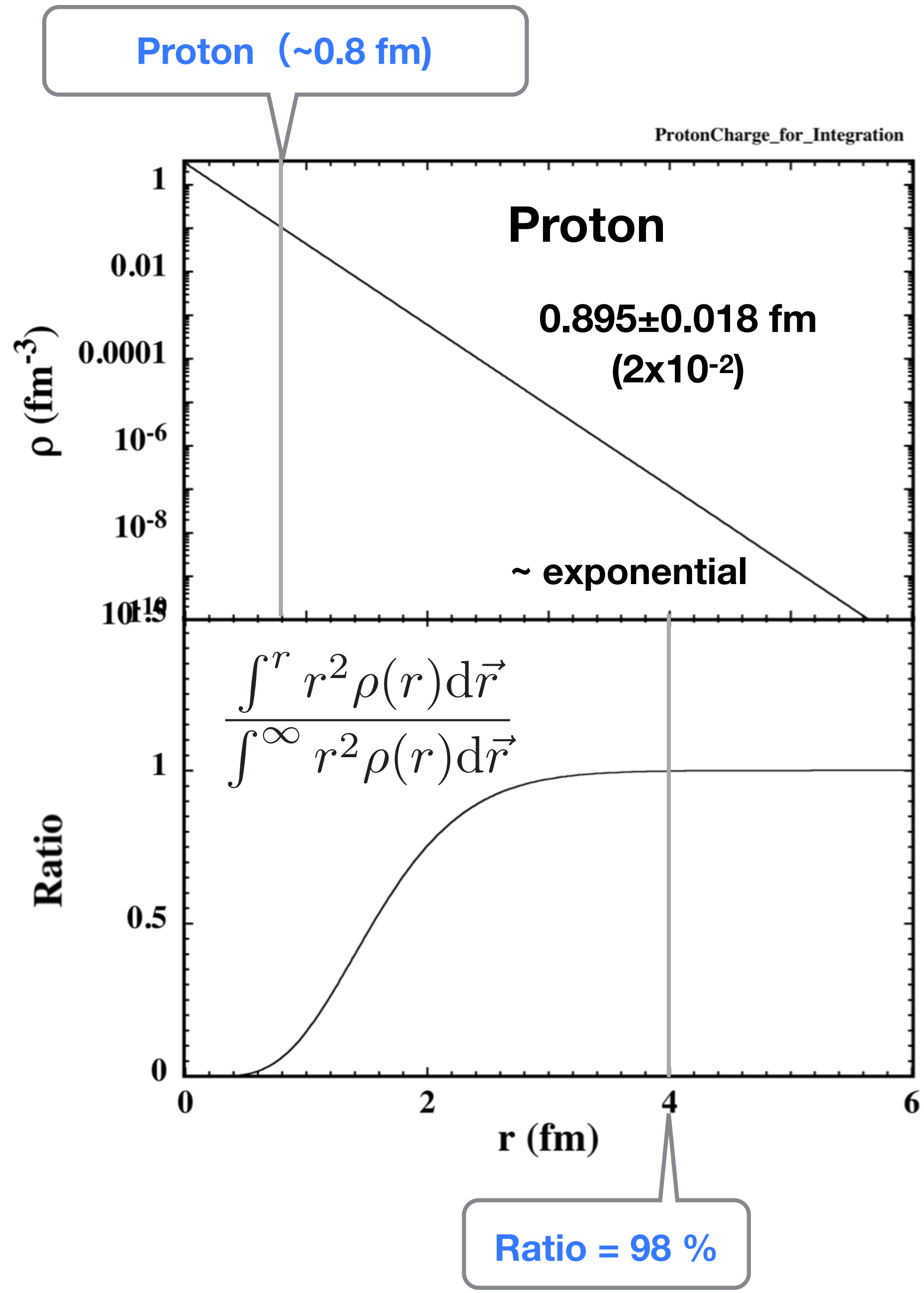


# Charge Radius and Density Distribution



*Charge Radius* $< r^2 >= \int r^2 \rho(\vec{r}) d\vec{r}$



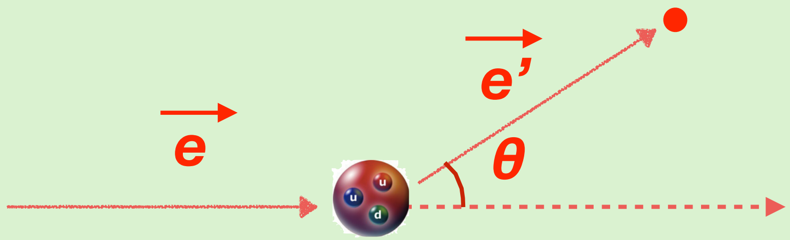
# Charge Radius

# by

# Electron Scattering

# Proton charge radius by e-scattering






$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)}{1+\tau}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{z^2\alpha^2}{4e^2}\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)} \propto \frac{e^2}{q^4}$$

$$\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}$$

$$\tau = \frac{Q^2}{4m_p^2}$$

**momentum transfer** $\vec{q} = \vec{e} - \vec{e'}$

**energy transfer** $\omega = e - e'$

**4 momentum transfer** $Q^2 = q^2 - \omega^2$
$= 4\, e\, e'\sin^2(\theta/2)$

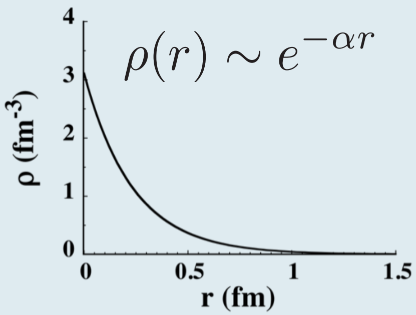
Under One-Photon Exchange approximation

## 1）high Q²: charge density ρ(r)

**Electric Form FactorGE**

**ρ(r)**

$$<r^2>= \int r^2\rho(\vec{r})d\vec{r}$$




**radius is sensitive to ρ(r) at large distance ( even at r ~ 4 fm )**

## 2）low Q²

$$G_E(Q^2) \sim 1 - \frac{<r^2>^{1/2}}{6}Q^2 + \frac{<r^4>^{1/2}}{120}Q^4 - \ldots$$

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

**ill problem : higher order contribution**

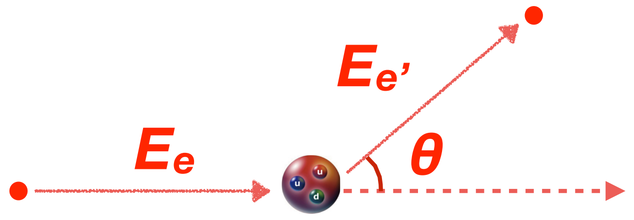
**lower Q² as possible**

# Charge Radius by Electron Scattering

## Elastic scattering off proton

$$\frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + \alpha(\theta)\, G_M^2(Q^2)$$

Charge F.F. — Magnetic F.F.



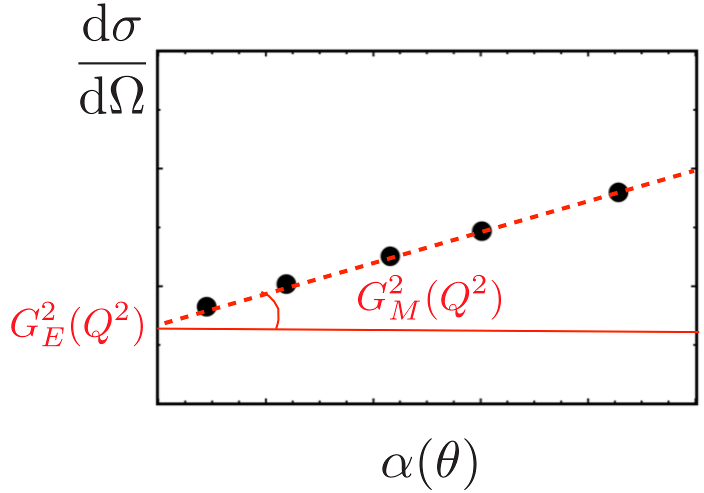

**4 momentum transfer**

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

### 1 Rosenbluth separation for $G_E(Q^2)$

***measurements at various θ under fixed $Q^2$***

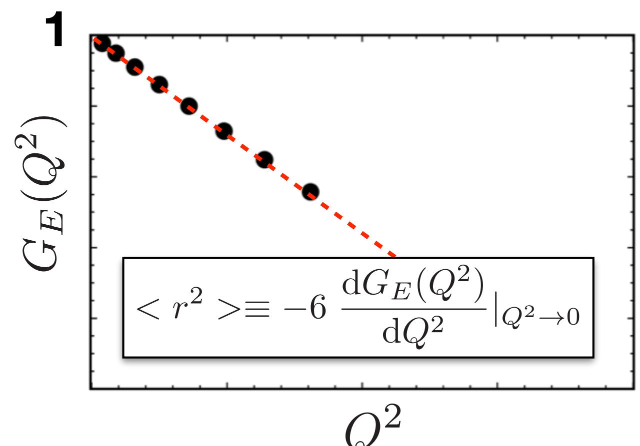
- **frequent change of Ee required**
- **$G_E(Q^2)$ determination for various $Q^2$**




### 2 $G_E(Q^2)$ and Charge Radius

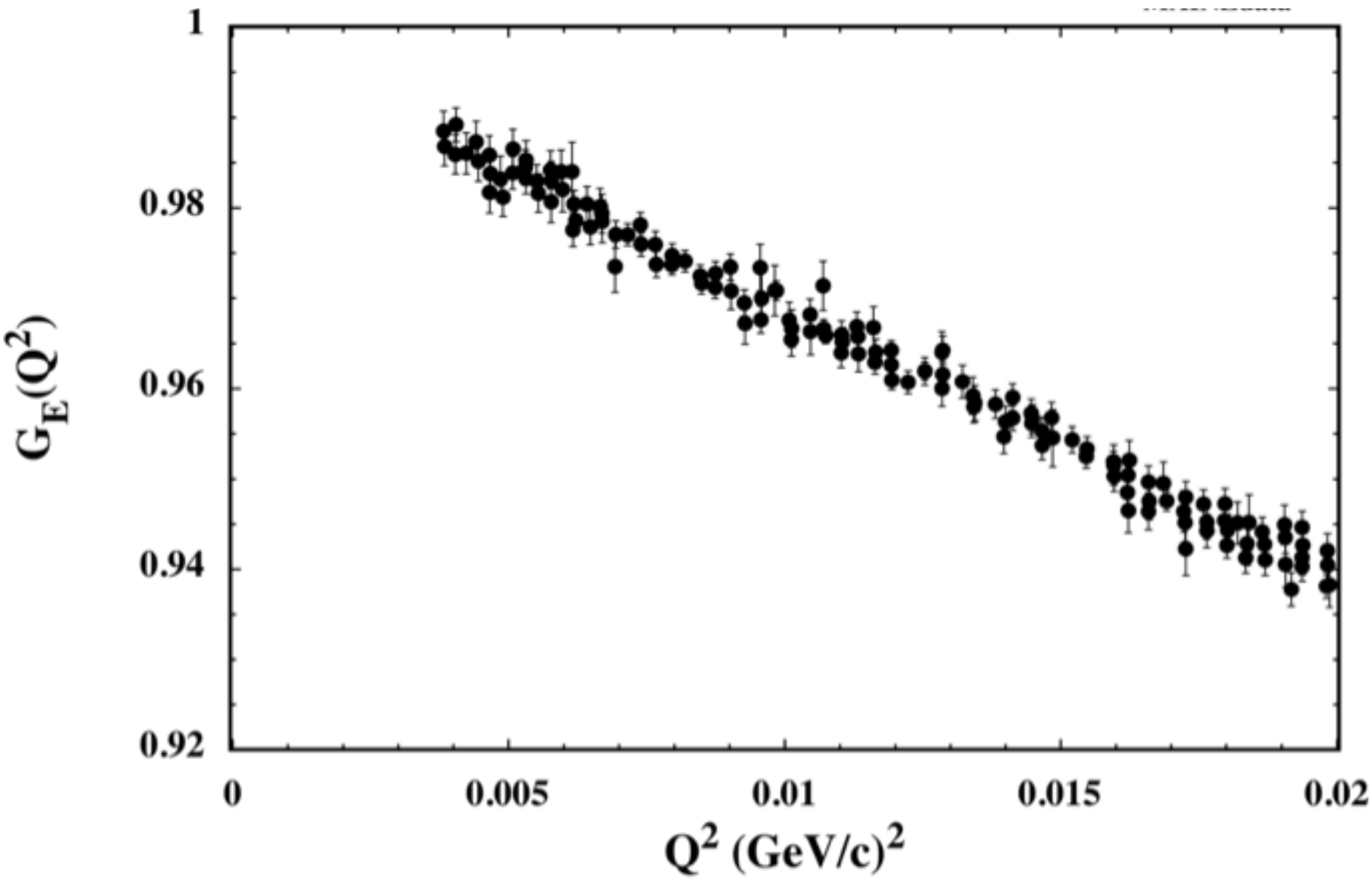
$$G_E(Q^2) \sim 1 - \frac{<r^2>}{6}Q^2 + \frac{<r^4>}{120}Q^4 - \frac{<r^6>}{5040}Q^6 + \ldots$$

**Taylor expansion of $G_E(Q^2)$ at low $Q^2$**



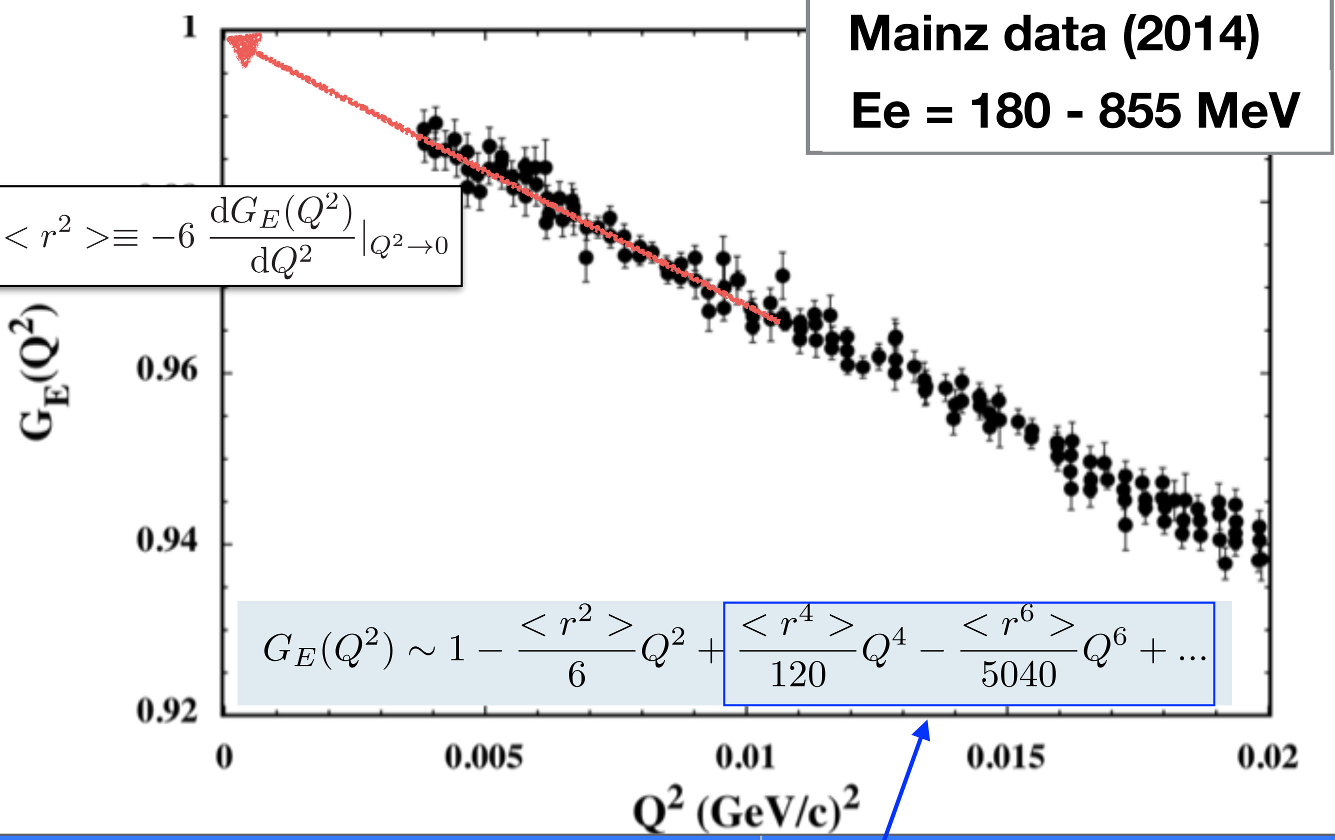
# $G_E(Q^2)$ data

**Mainz data**
**Ee = 180- 855 MeV**




J. Bernauer et al. Phys. Rev. C90 (2014) 015206.

# Deduced Radius from Mainz data




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

$$G_E(Q^2) \sim 1 - \frac{< r^2 >}{6} Q^2 + \frac{< r^4 >}{120} Q^4 - \frac{< r^6 >}{5040} Q^6 + \ldots$$

| potential problems | backgrounds |
|---|---|
| No very low-$Q^2$ data | high-energy electron accelerator |
| No Rosenbluth separation | frequent Ee change : impractical |
| No absolute cross section | spatially extended Liq-H2 target + spectrometer |

**treatments of higher-order effects**

→ **introduce large uncertainty in the radius**

(Phys. Rev. C90 (2014) 045206)

# Electron Scattering at Lowest-ever Momentum Transfer

**ULQ² (Ultra-Low Q²) Collaboration**

Tohoku Univ.：H. Kikunaga, K. Tsukada, Y. Honda, T. Tamae. T. Mutoh, K. Takahashi,
K. Nanbu, M. Miyabe, A. Tokiyasu, K. Nanba, T. Aoyagi
S. Sasaki, N. Tsukamoto
Miyazaki Univ.： Y. Maeda
Hampton Univ. : Michael Kohl

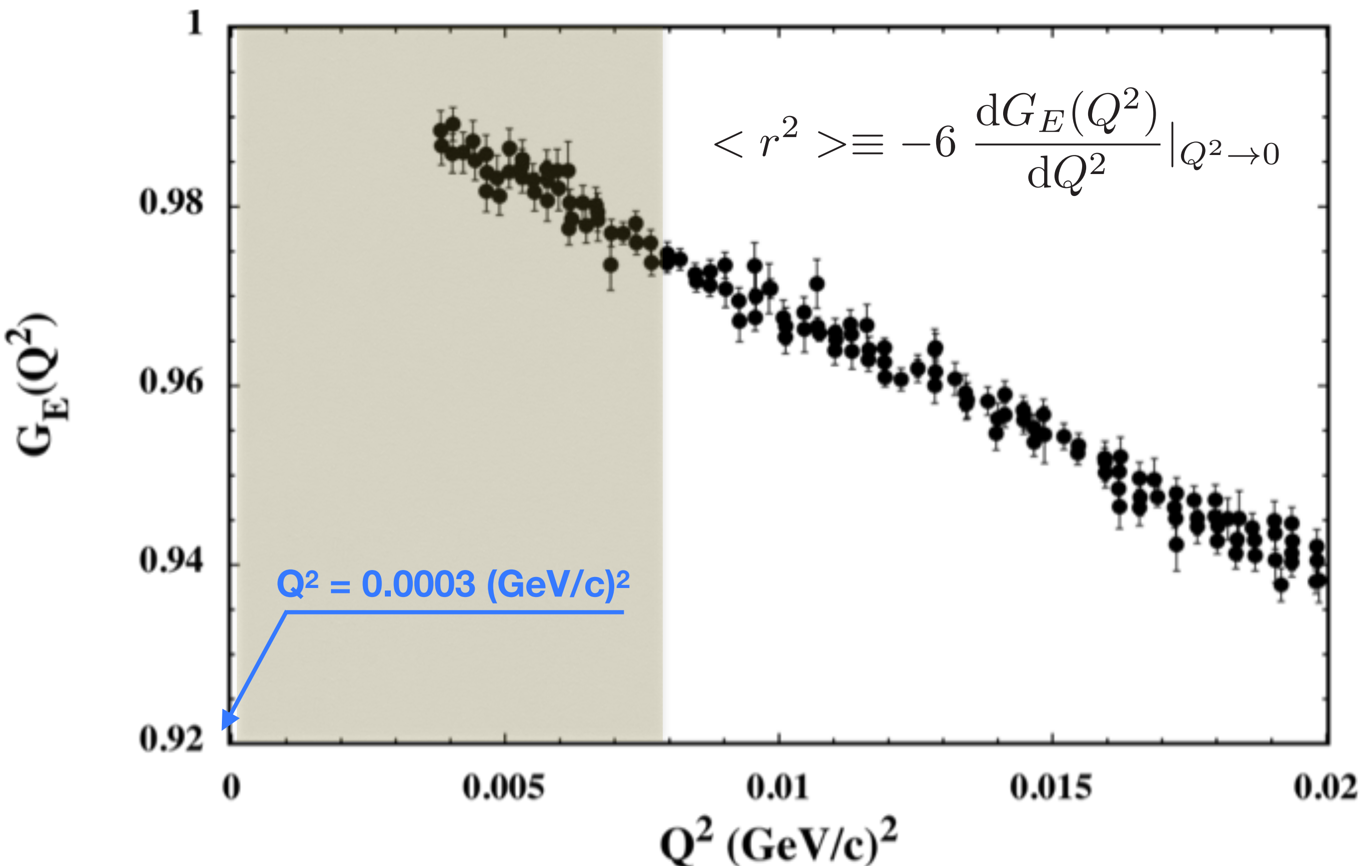
# e-scattering off proton at ultra-low $Q^2$



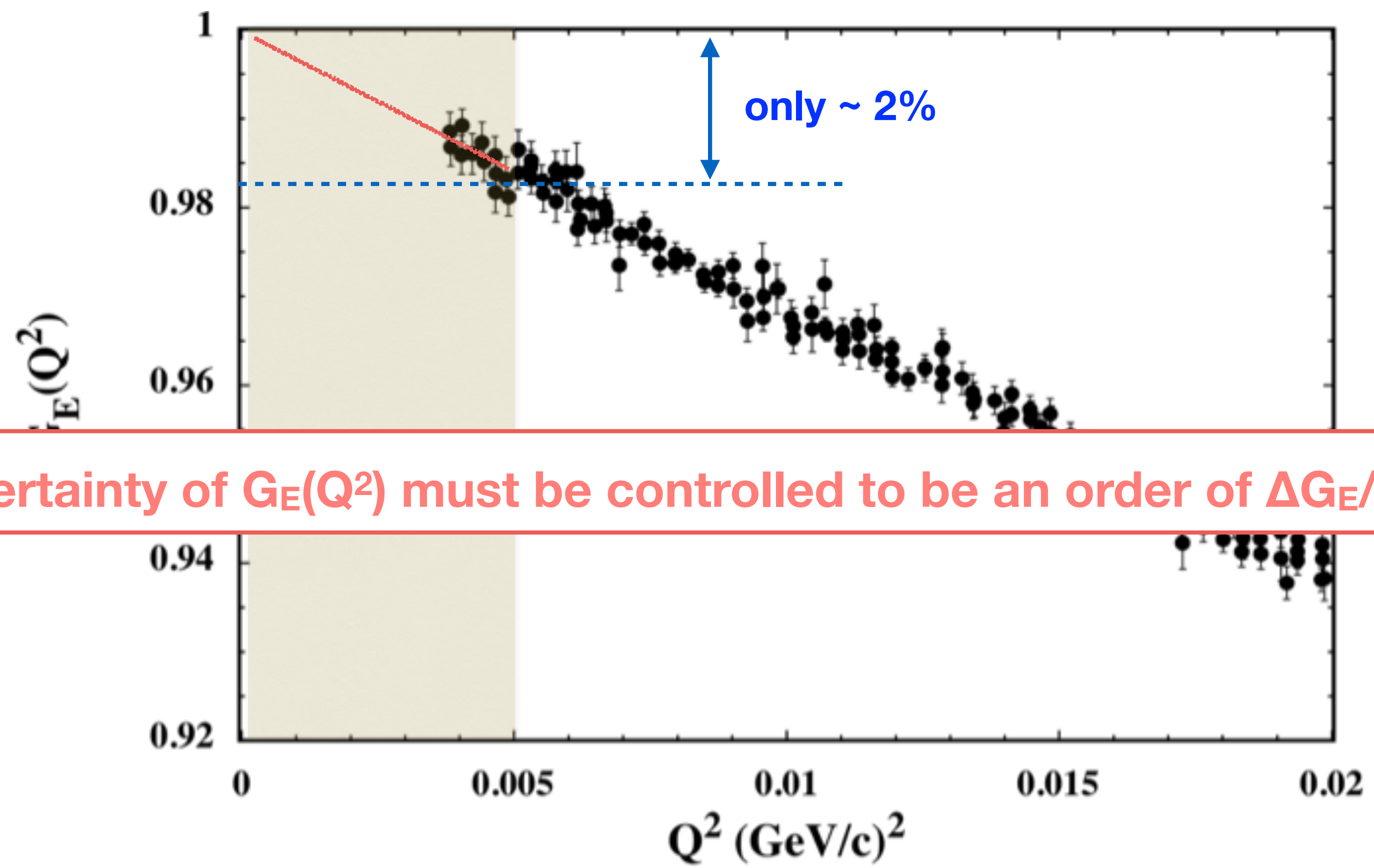
## Our Goal !

$G_E(Q^2)$ measurements at $0.0003 \leq Q^2 \leq 0.008$ $(GeV/c)^2$

Low energy electron beam ( $20 \leq Ee \leq 60$ MeV)
Absolute cross section measurement
Rosenbluth separation ($G_E(Q^2)$, $G_M(Q^2)$ separation)



# A key of the e+p experiments at ULQ²




**Uncertainty of $G_E(Q^2)$ must be controlled to be an order of $\Delta G_E/G_E \sim 10^{-3}$**

$$\frac{\mathrm{d}N_{evt}}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \boxed{N_{target}} \boxed{N_{beam}} \boxed{\Delta\Omega}$$

beam dose

target thickens

spectrometer acceptance

**Statistics : at least > $10^6$ for each (*Ee,θ*) measurements**

**Target thickness**

**Beam dose at various intensities**

**Acceptance at various scattering angle**

⇨ **accuracy of ~ $10^{-3}$ not obvious !**

# $CH_2$ target for absolute cross section measurement



**Relative measurement for $^{12}C(e,e)^{12}C$ and $p(e,e)p$**

$$\frac{\mathrm{d}N^{e^{12}C}/\mathrm{d}\Omega}{\mathrm{d}N^{ep}/\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma^{e^{12}C}/\mathrm{d}\Omega}{\mathrm{d}\sigma^{ep}/\mathrm{d}\Omega} \cdot \frac{N^{^{12}C}_{target}}{N^{H}_{target}}$$

$$\frac{\mathrm{d}N_{evt}}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} N_{target} \boxed{N_{beam}\ \Delta\Omega}$$

Canceled out in relative measurements

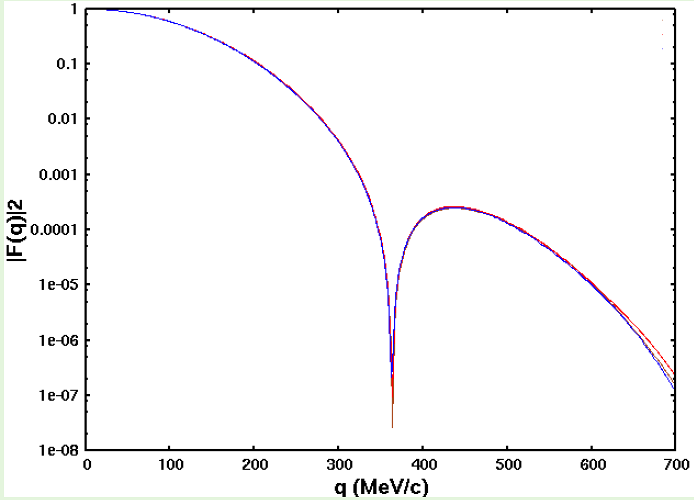
# $CH_2$ (e,e') experiment



## 1) $^{12}C$ : "standard" nucleus for (e,e')

**μ-Xray**
**electron scattering**

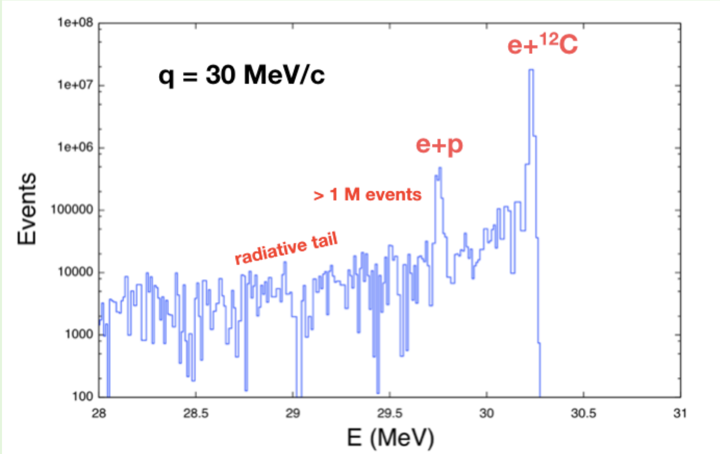
$$\frac{\Delta < r^2_{^{12}C} >^{1/2}}{< r^2_{^{12}C} >^{1/2}} \sim 3 \times 10^{-3}$$




## 2) $^{12}C(e,e)^{12}C$, p(e,e)p by kinematics

**ΔE = 0.2 - 4 MeV**
**for q = 20 - 90 MeV/c**

**$\Delta p/p \sim 10^{-3}$**

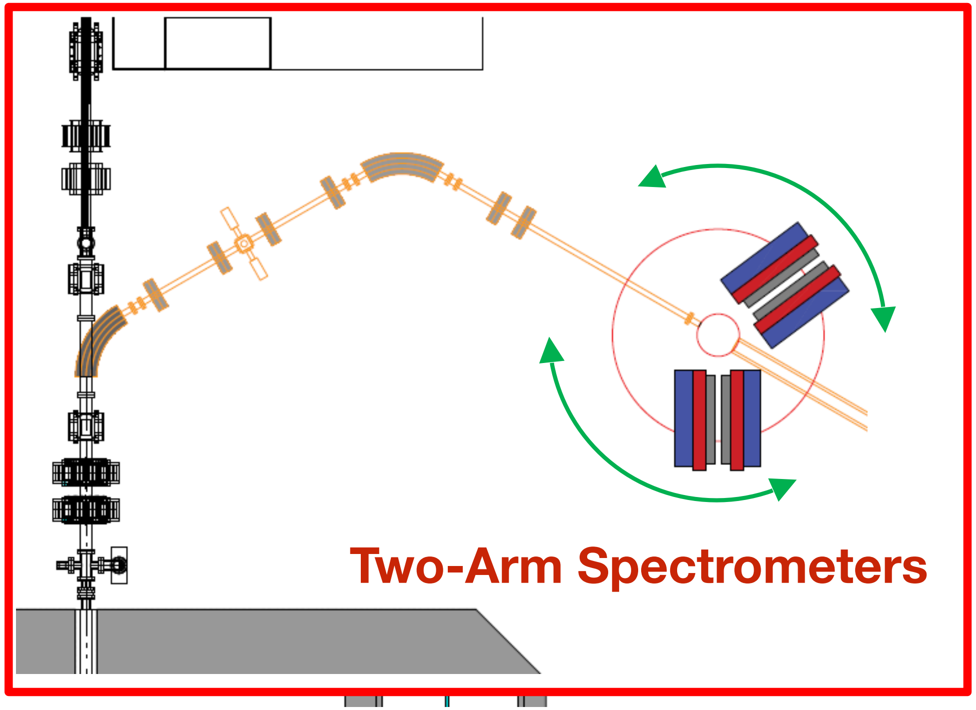


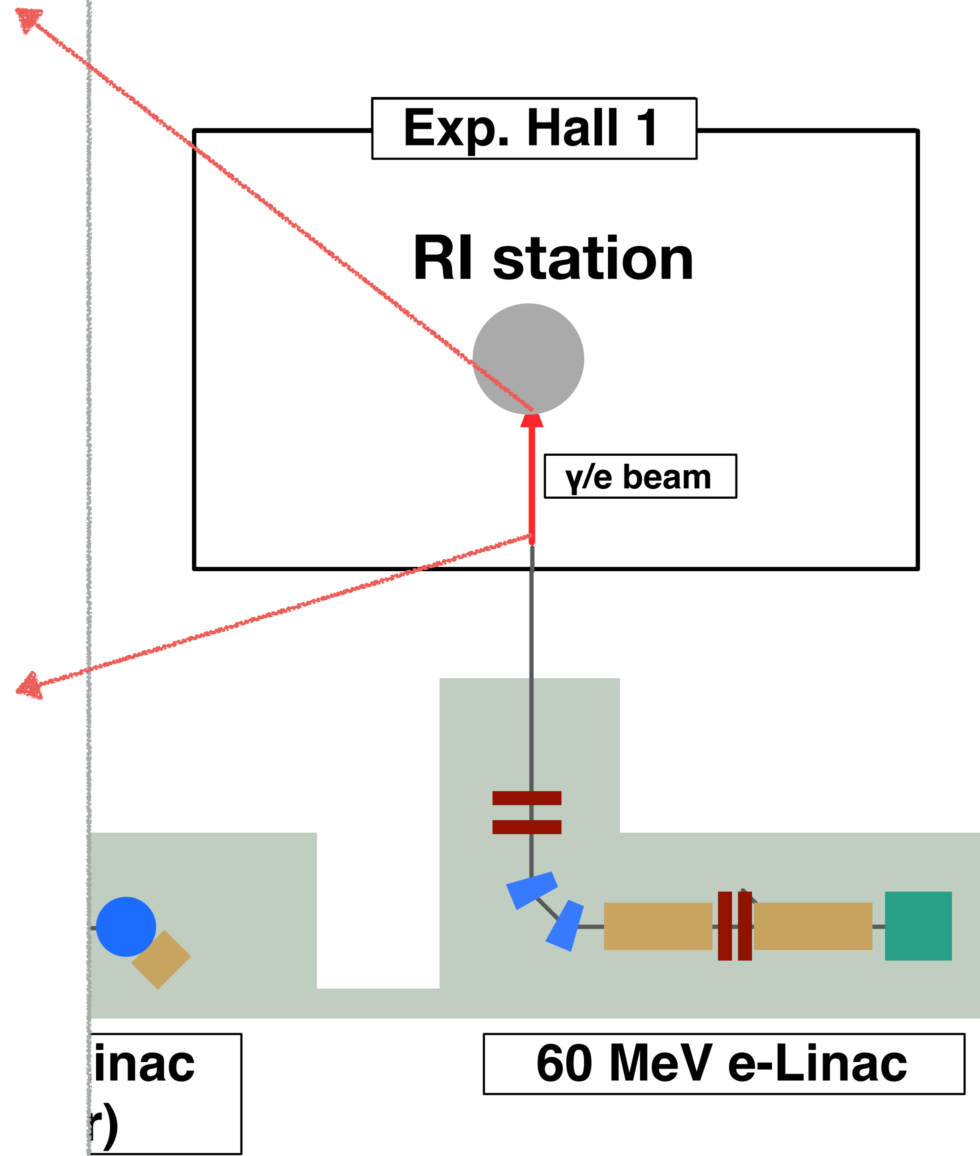

## 3) no severe damage of target is expected

**large cross section :** $\frac{d\sigma}{d\Omega} \propto 1/q^4$

**Ie ~ 1 nA - 1 μA**

## New beam line + Spectrometers




**Ee = 20 - 60 MeV**
**Ie = 1 nA - 0.1 μA**
**beam size on target ≤ 1 mm**
**$\Delta p/p \leq 10^{-3}$**

KAKENHI : Scientific Research (S) : T. Suda

# Electron spectrometer under construction



## Two-Arm Electron Spectrometers

1) Ion-optical pro

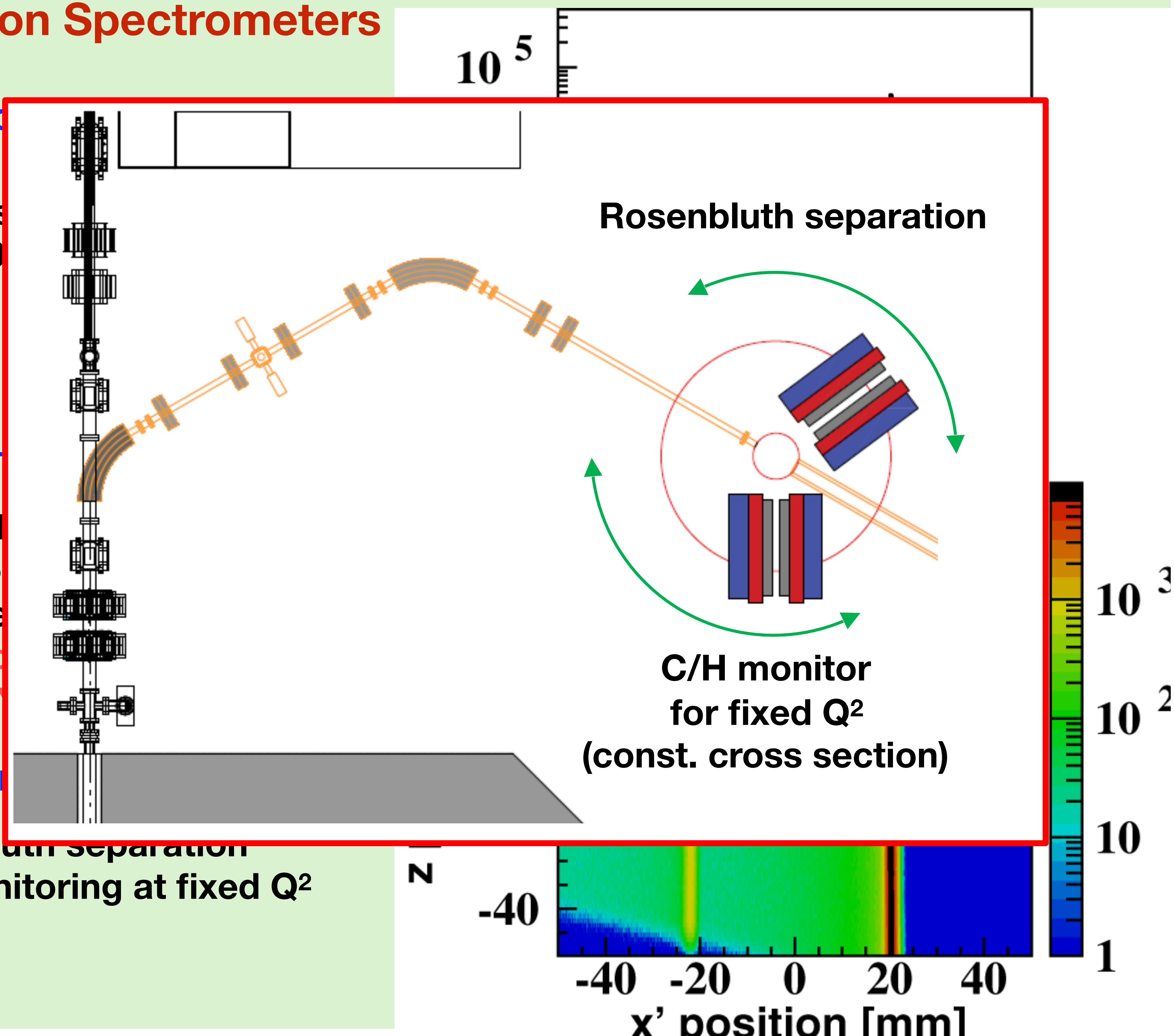
No tracking is
( Pe' = 20 - 60

2) Kinematical e+

mom. res. ≤ 1
mom. bite ~ 6
focal plane de
: "muc
(T. Y

3) Two-arm spect

Spec1 : Rosenbluth separation
Spec2 : C/H monitoring at fixed $Q^2$



# Science Oct. 6, 2017

*Science* 06 Oct 2017:
Vol. 358, Issue 6359, pp. 79-85
DOI: 10.1126/science.aah6677

***RESEARCH***

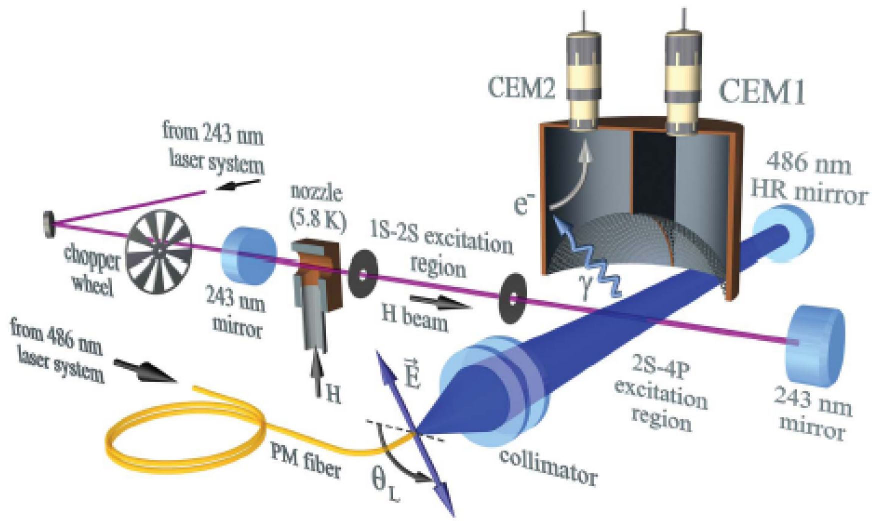
**RESEARCH ARTICLE**

**ATOMIC PHYSICS**

## The Rydberg constant and proton size from atomic hydrogen

Axel Beyer,[1] Lothar Maisenbacher,[1*] Arthur Matveev,[1] Randolf Pohl,[1†] Ksenia Khabarova,[2,3] Alexey Grinin,[1] Tobias Lamour,[1] Dylan C. Yost,[1‡] Theodor W. Hänsch,[1,4] Nikolai Kolachevsky,[2,3] Thomas Udem[1,4]

At the core of the "proton radius puzzle" is a four–standard deviation discrepancy between the proton root-mean-square charge radii ($r_p$) determined from the regular hydrogen (H) and the muonic hydrogen (µp) atoms. Using a cryogenic beam of H atoms, we measured the 2S-4P transition frequency in H, yielding the values of the Rydberg constant $R_\infty$ = 10973731.568076(96) per meter and $r_p$ = 0.8335(95) femtometer. Our $r_p$ value is 3.3 combined standard deviations smaller than the previous H world data, but in good agreement with the µp value. We motivate an asymmetric fit function, which eliminates line shifts from quantum interference of neighboring atomic resonances.



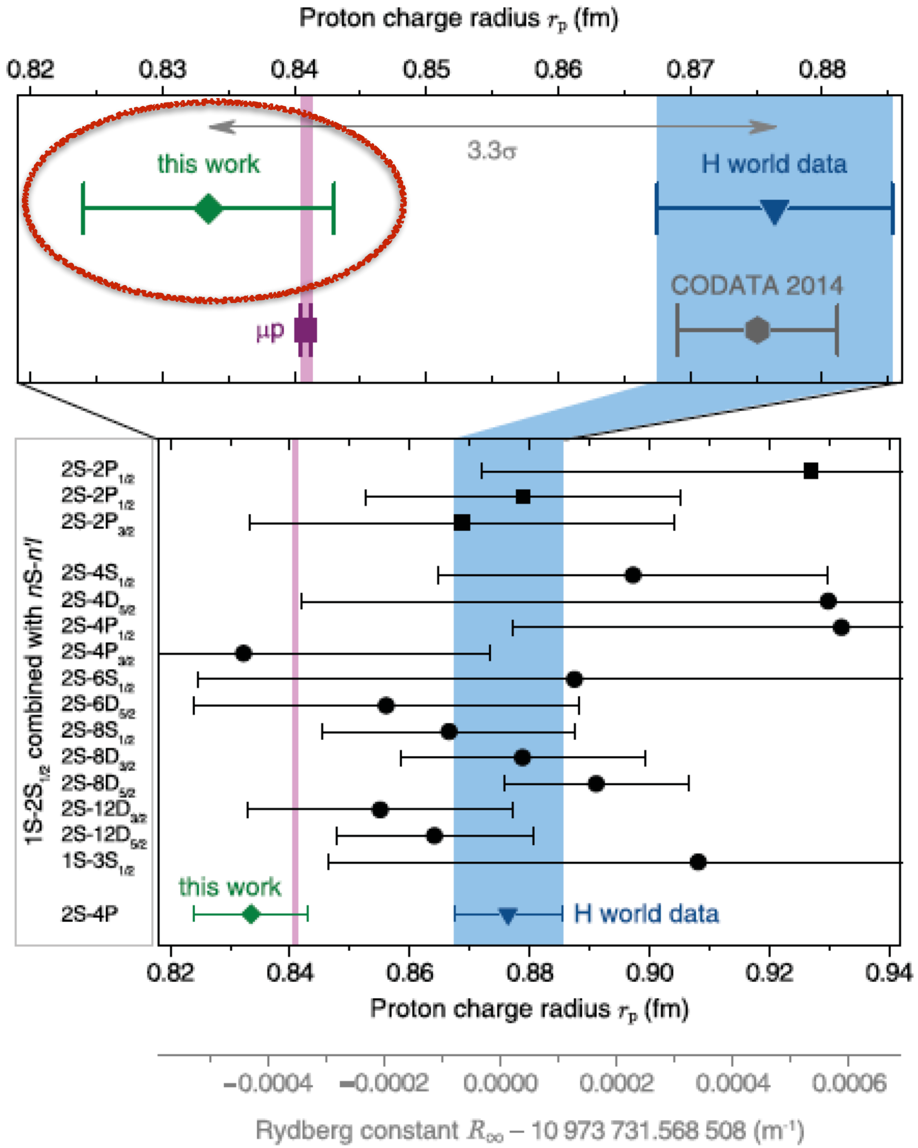




**Fig. 1 Rydberg constant $R_\infty$ and proton RMS charge radius $r_p$.** Values of $r_p$ derived from this work (green diamond) and spectroscopy of µp (µp; pink bar and violet square) agree. We find a discrepancy of 3.3 and 3.7 combined standard deviations with respect to the H spectroscopy world data (*12*) (blue bar and blue triangle) and the CODATA 2014 global adjustment of fundamental constants (*3*) (gray hexagon), respectively. The H world data consist of 15 individual measurements (black circles, optical measurements; black squares, microwave measurements). In addition to H data, the CODATA adjustment includes deuterium data (nine measurements) and elastic electron scattering data. An almost identical plot arises when showing $R_\infty$ instead of $r_p$ because of the strong correlation of these two parameters. This is indicated by the $R_\infty$ axis shown at the bottom.

# Summary



## Electron Scattering off Proton @ ELPH, Tohoku Univ.

1) elastic e+p scattering at lowest-ever $Q^2$ region
2) $G_E(Q^2)$ at $0.0003 \leq Q^2 \leq 0.008$ $(GeV/c)^2$
3) $G_E$ is extracted by the Rosenbluth separation
4) absolute cross section measurement

   relative to $^{12}C(e,e)^{12}C$ : sys. err. ~$3 \times 10^{-3}$

5) Ee = 20 - 60 MeV, θ = 30 - 150°
6) constructing of new beam line, and spectrometers
7) the experiments will start in 2019