Elastic Electron Scattering for Proton Charge Radius Determination

Toshimi Suda

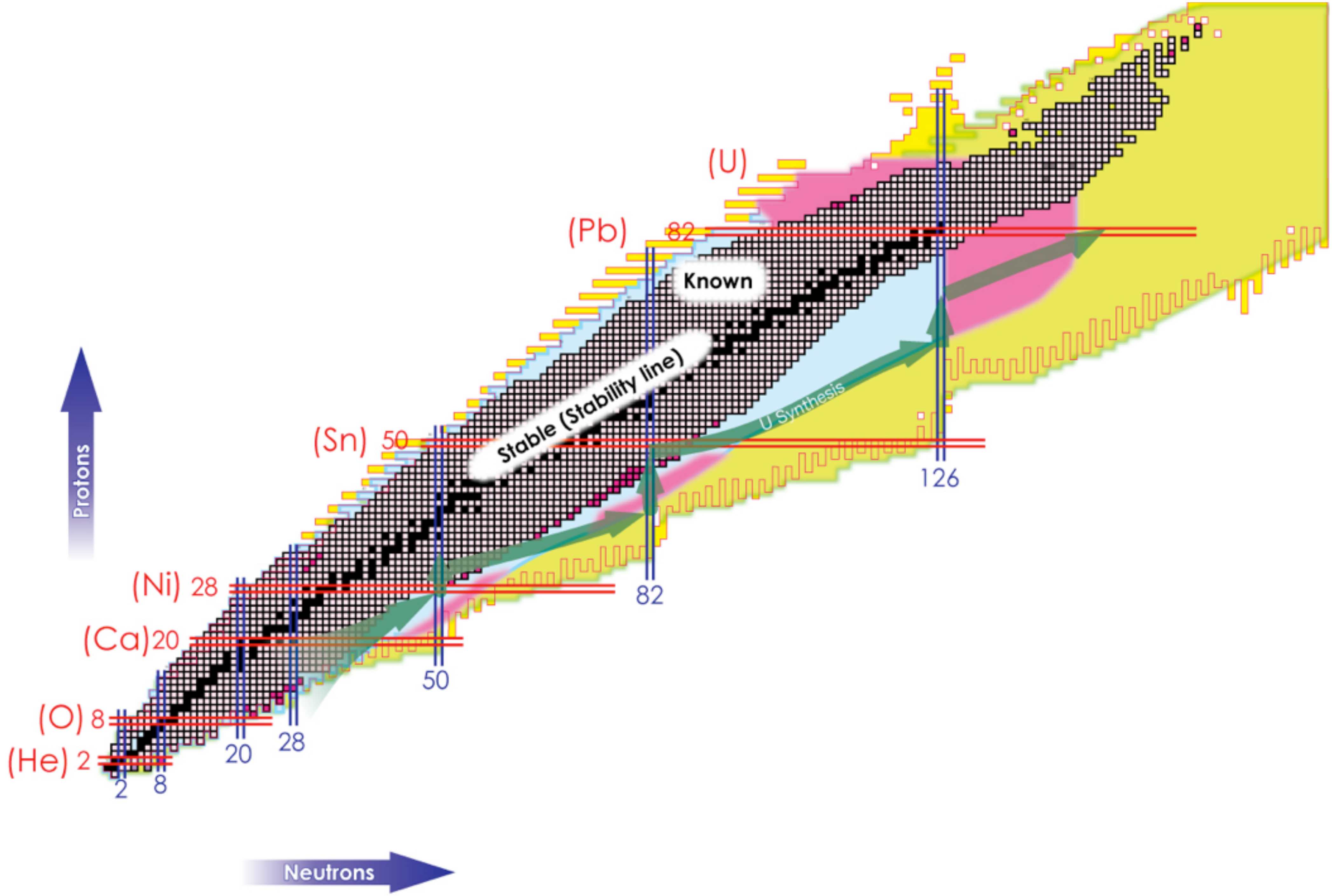
**Tohoku University
Sendai, Japan**

for ULQ² (Ultra-Low Q²) Collaboration

Tohoku Univ. : *K. Tsukada, Y. Honda, T. Tamae. T. Mutoh, K. Takahashi, K. Nambu, M. Miyabe, A. Tokiyasu, K. Nanba, T. Aoyagi*
Miyazaki Univ. : *Y. Maeda*

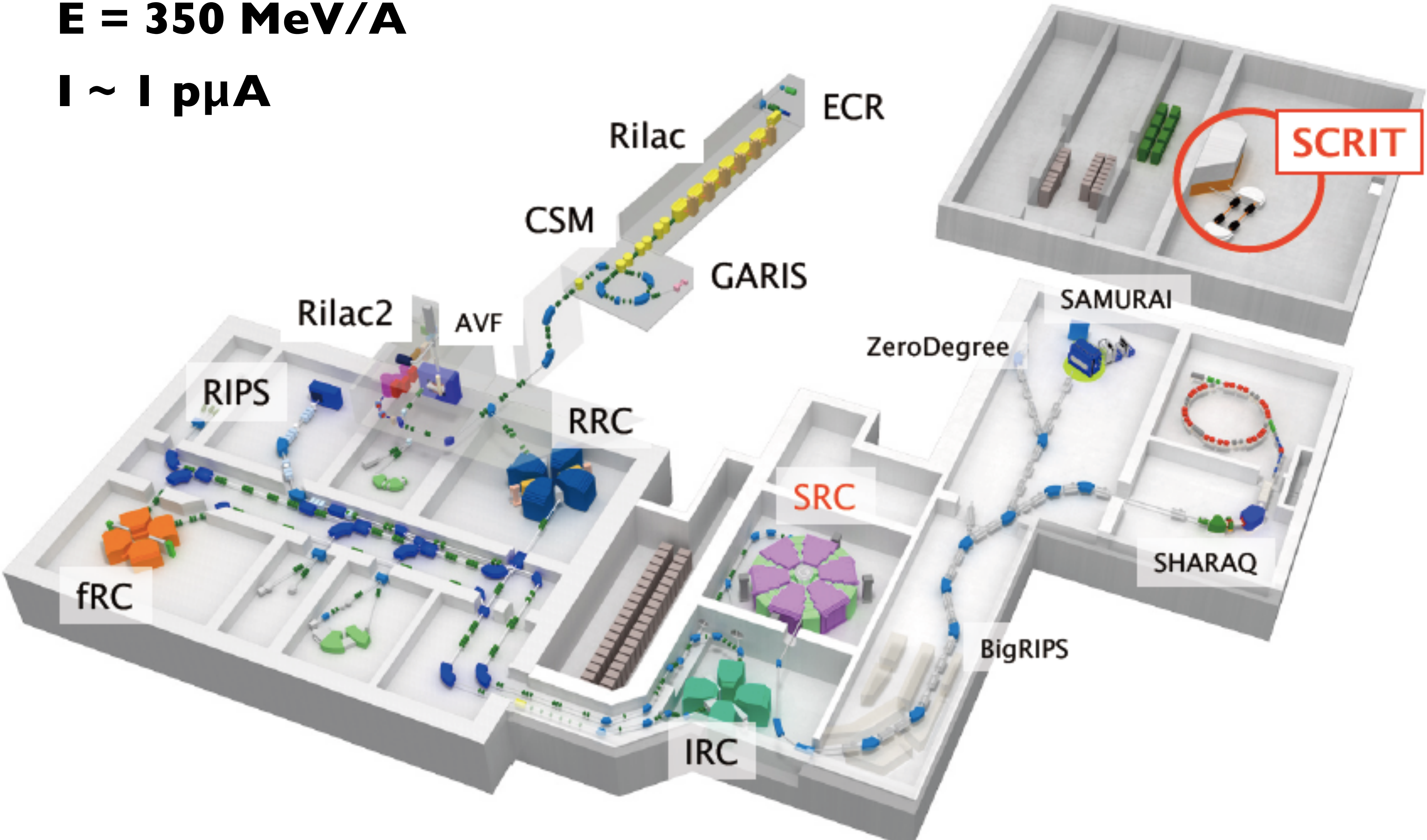
Ee = 20 - 60 MeV !!

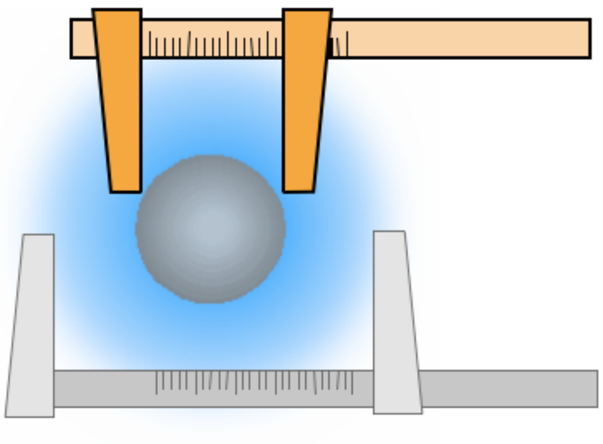
Short-Lived Exotic Nuclei



world's highest intensities of exotic beams (2007 ~)

- **in-flight fragmentation of U**
- **E = 350 MeV/A**
- **I ~ 1 pμA**



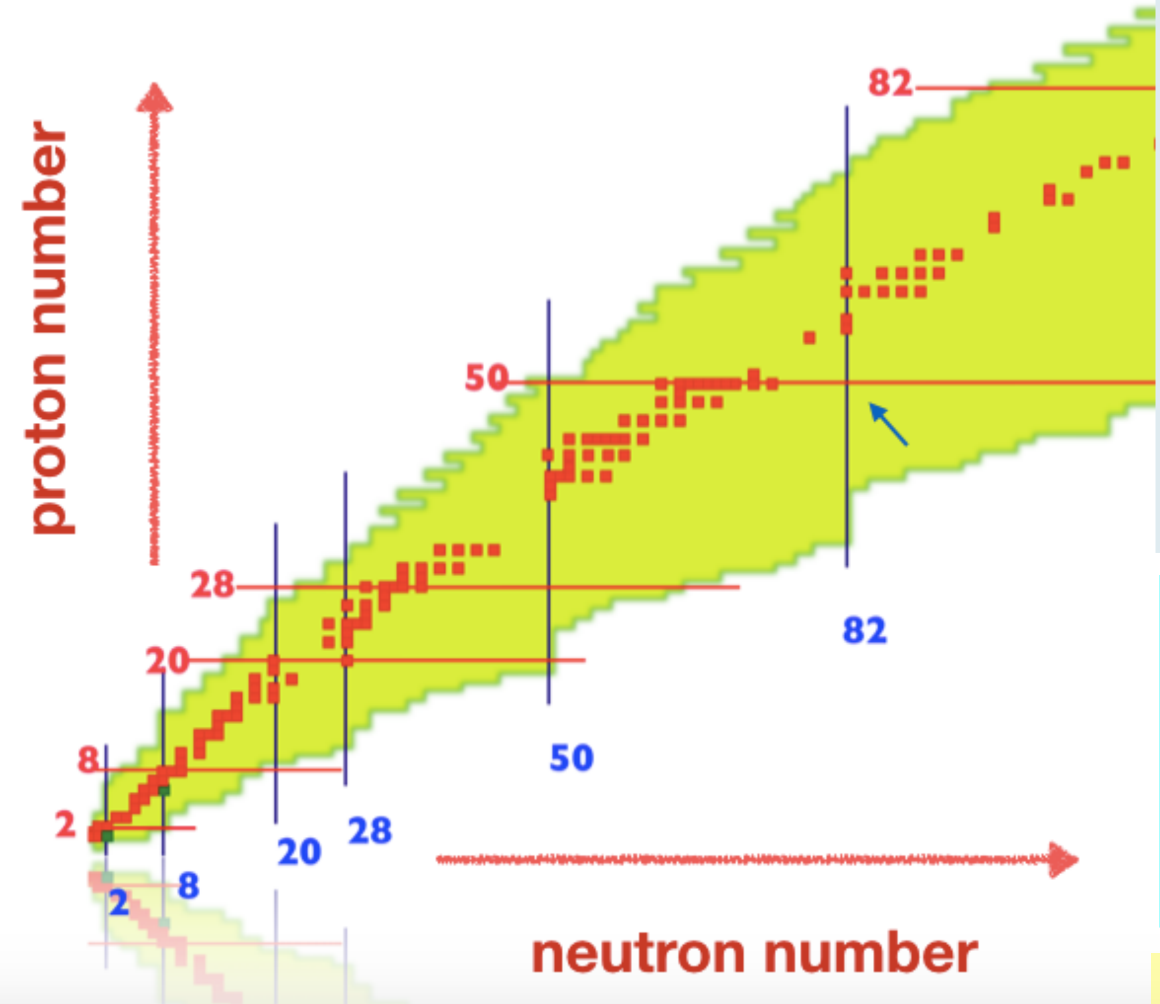


$$< r_c^2 >= \int r^2 \rho_c(r)\ \mathrm{d}\vec{r}$$

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

	size	shape
proton	isotope shift	electron scattering
matter	reaction cross section	proton scattering

Nuclei targeted so far 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

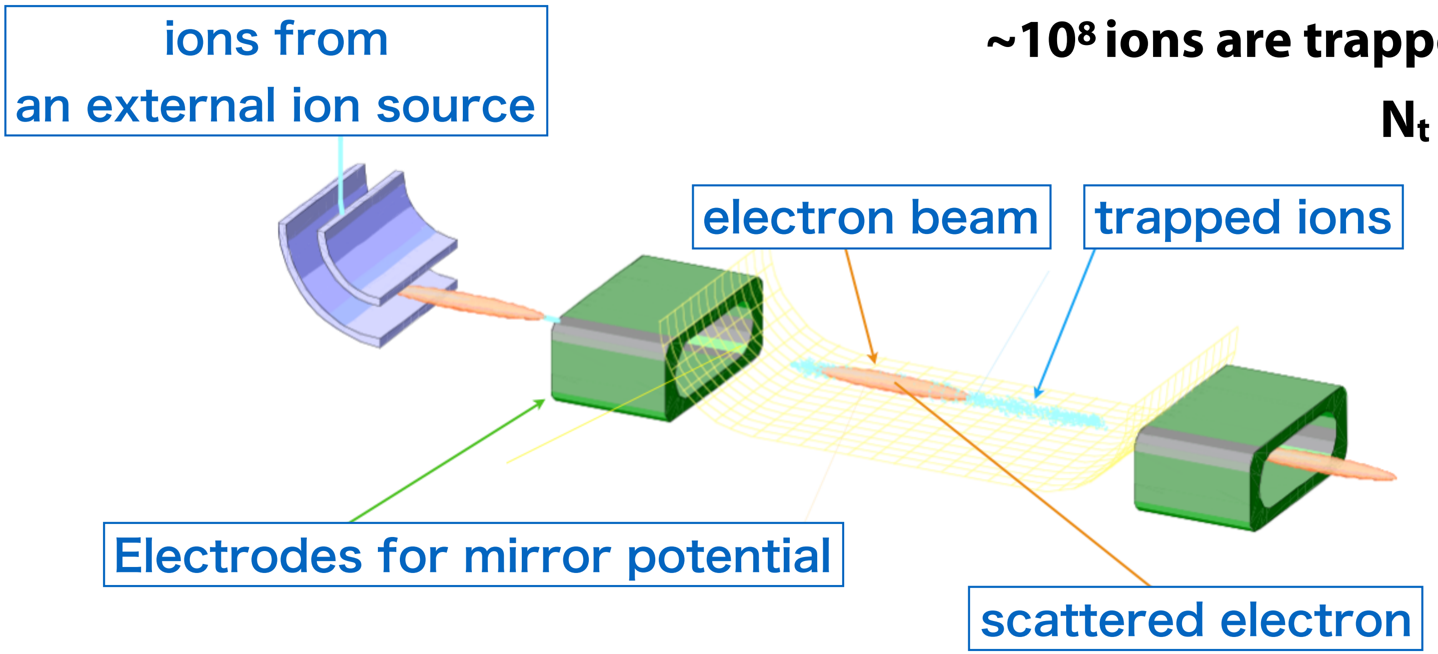
Expected low luminosities

Charge density distribution
Charge radius

SCRIT (Self-Confining RI Ion Target) : ion trapping

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

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



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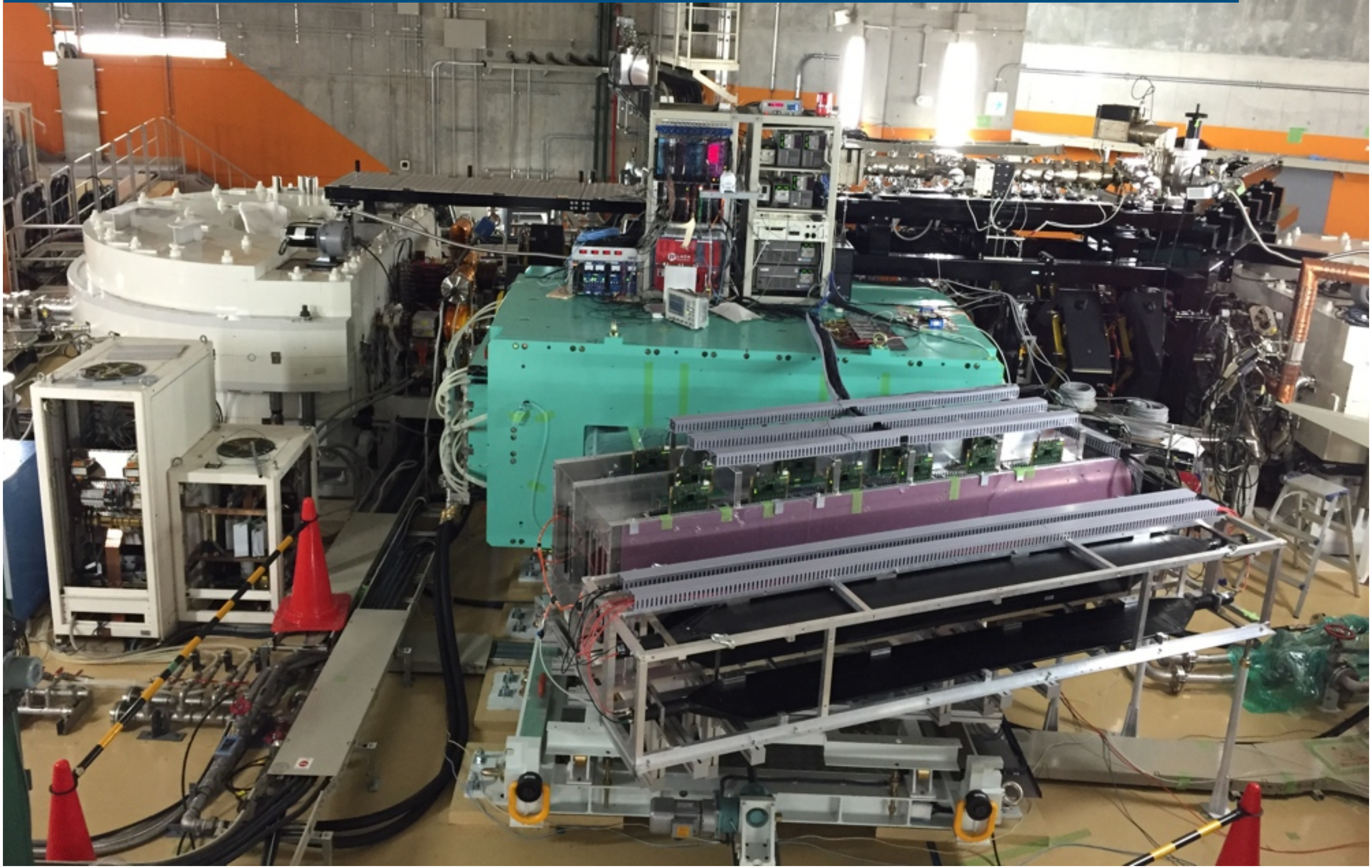
Prog.Part.Nucl.Phys. 96 (2017) 1.
....

	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^{24} /cm2	~10^{38} /cm^2/s
SCRIT	**150 - 300 MeV**	**~200 mA (~10^{18} /s)**	**~ 10^{10} /cm^2**	**~10^{27} /cm^2/s**

SCRIT facility in RIKEN/RI Beam Factory

world's first electron scattering facility for exotic nuclei



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The SCRIT Electron Scattering Facility at RIKEN: The World's First Electron Femtoscope for Short-Lived Unstable Nuclei

A. Enokizono, T. Ohnishi & K. Tsukada

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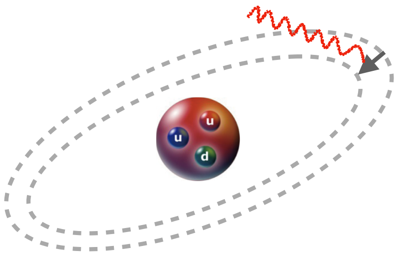
Proton Charge Radius
by
Elastic Electron Scattering

Why is the proton radius a hot topics ?

1) the radius is one of the basic properties of the nucleon

2) the radius is strongly correlated to the Rydberg constant



$$\Delta E = R_{Rydberg}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

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

$$R_\infty = 10973\ 731.568\ \underline{539} \pm 0.000\ 055 \quad \mathrm{m}^{-1}$$

r_p uncertainty

3) possible new physics beyond Standard Model (??)

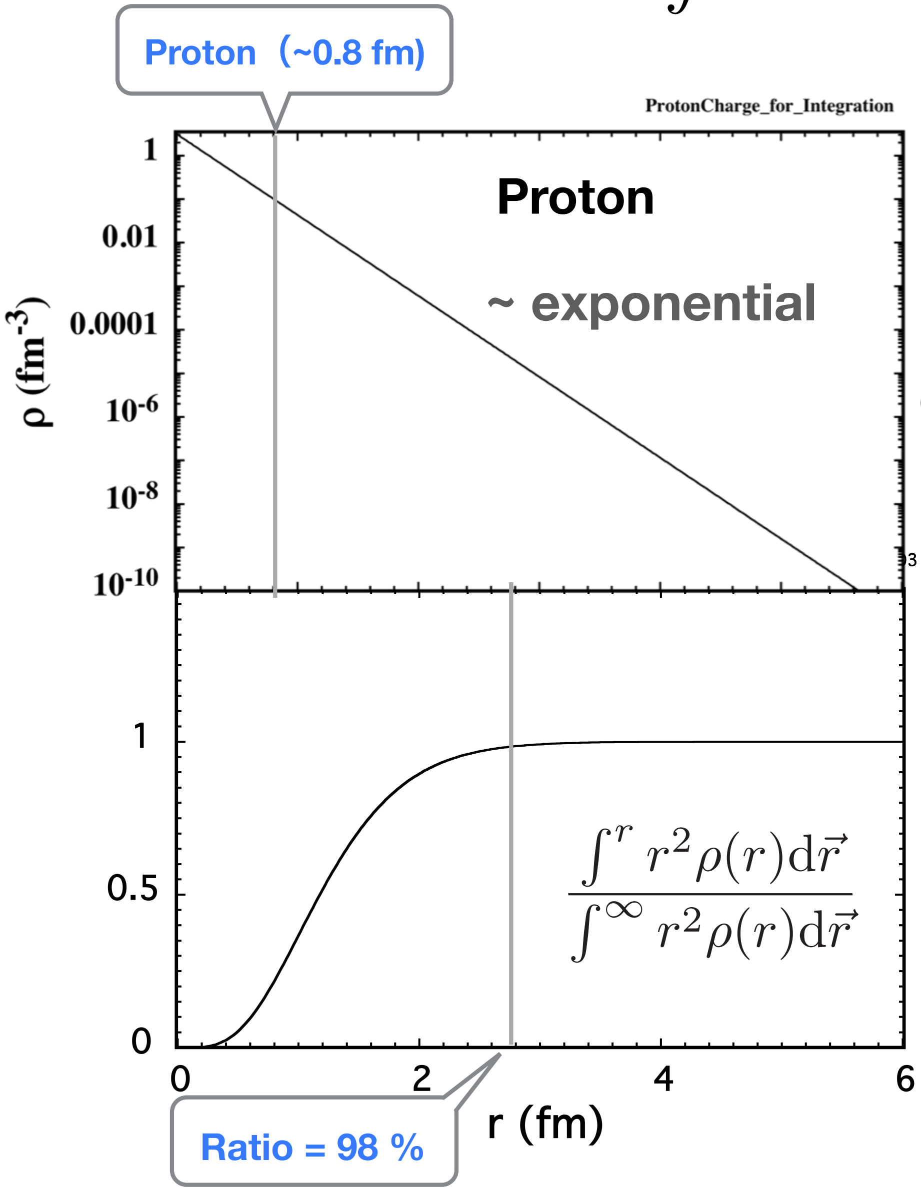
Lepton Universality (e <-> μ) ??

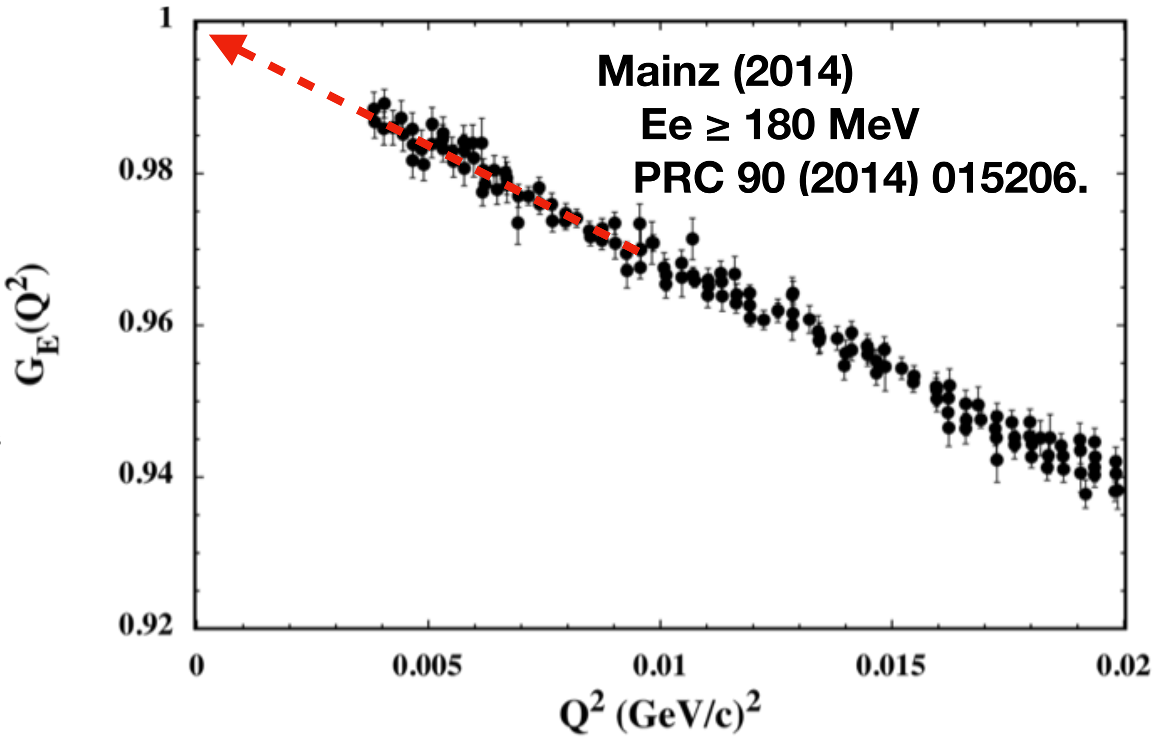
4) the neutron-skin thickness of neutron-rich nuclei

=> EOS of neutron matter

Charge radius and charge density

$$< r^2 >= \int r^2 \rho(\vec{r}) d\vec{r} = 4\pi \int r^4 \rho(r)\, \mathrm{d}r$$



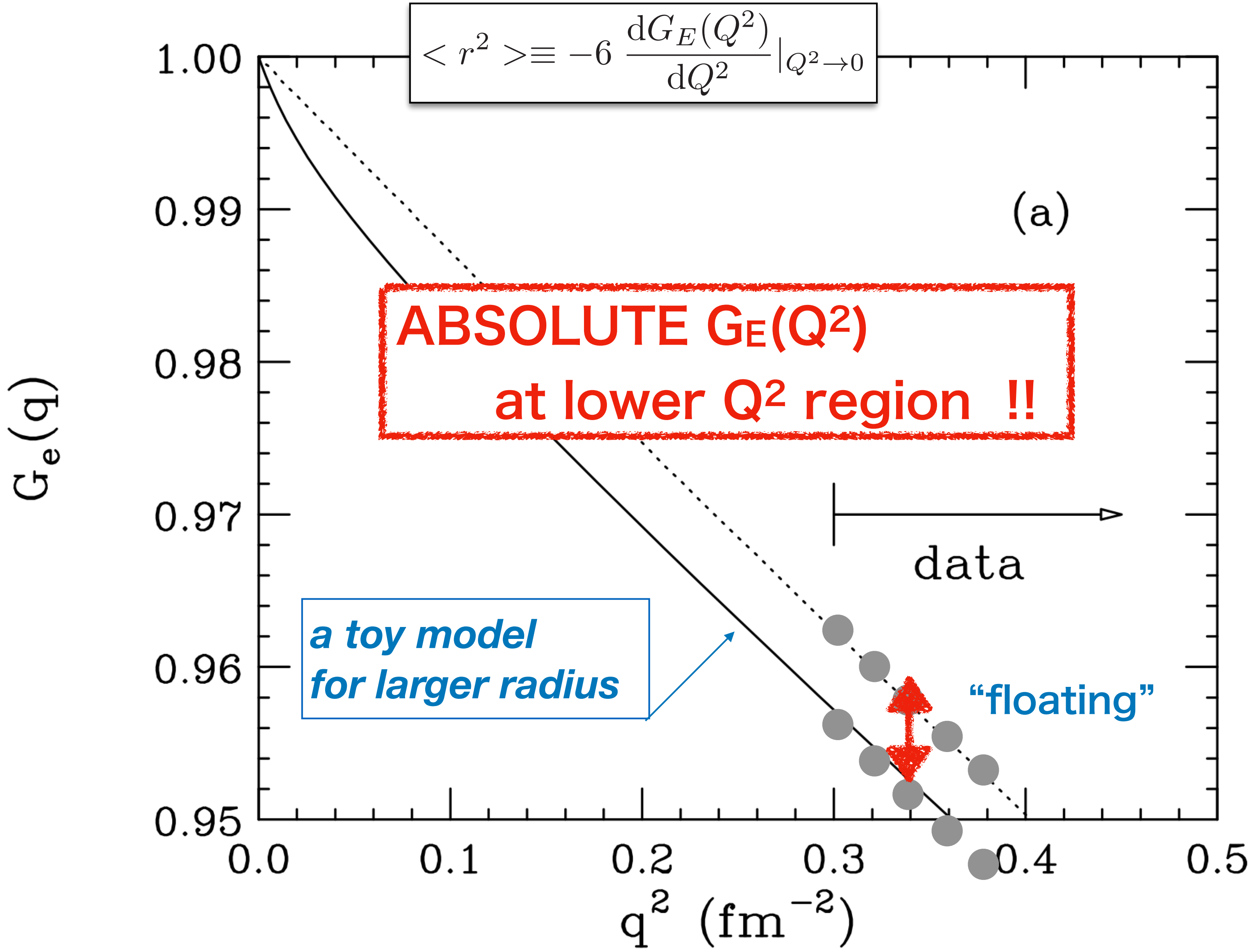


$$G_E(Q^2) \sim 1 - \frac{< r^2 >^{1/2}}{6} Q^2 + \frac{< r^4 >^{1/2}}{120} Q^4 - ..$$

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

Absolute $G_E(Q^2)$ at lower Q^2 region

1) no absolute $G_E(Q^2)$ ("floating")
2) χ^2 is quite similar



I. Sick, Atoms 2018, 6, 2

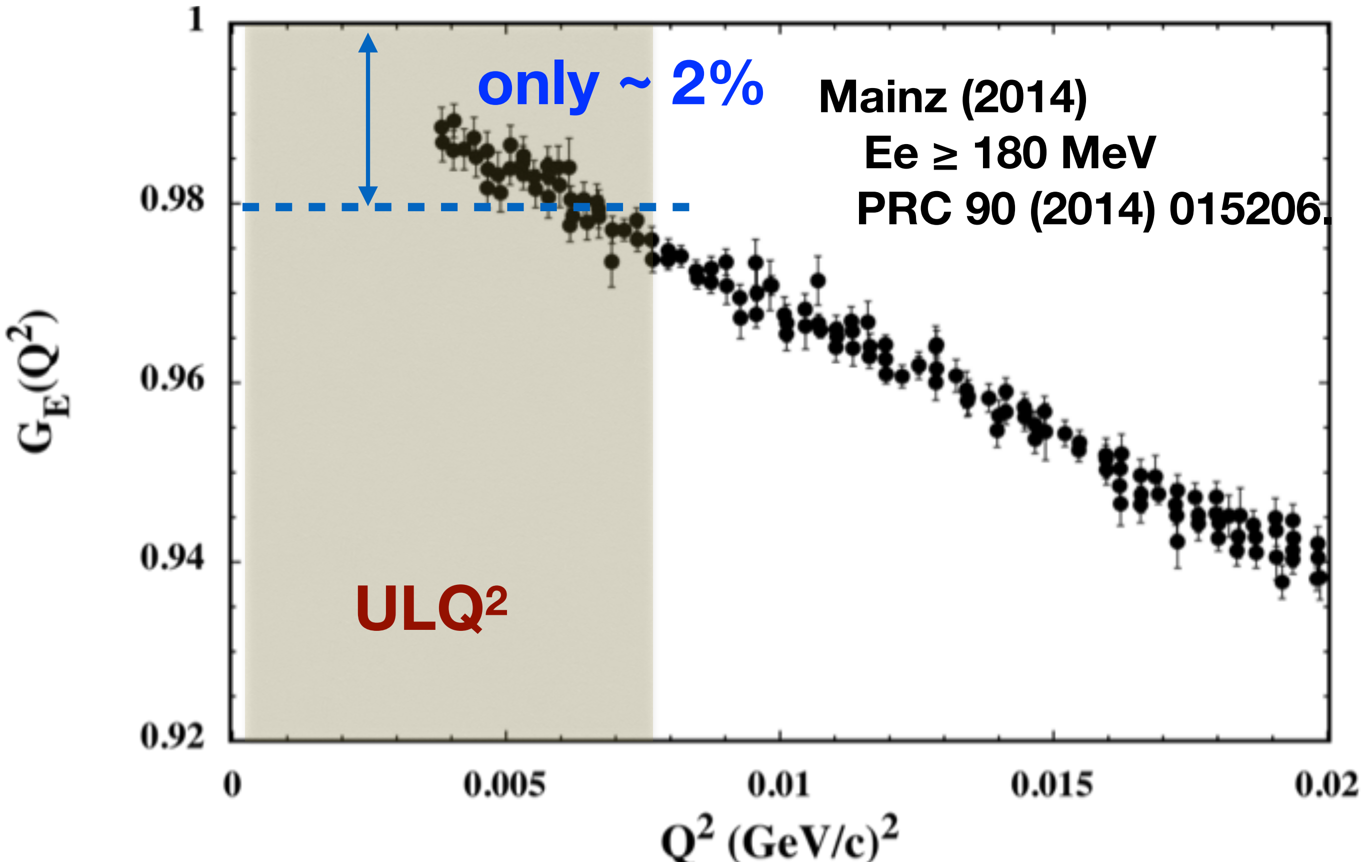
The goal of this project

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

Absolute cross section measurement with 10^{-3} precision

Rosenbluth separated $G_E(Q^2)$, $G_M(Q^2)$

Exp. @ Tohoku Low-Energy Electron Linac (Ee = 20 - 60 MeV)

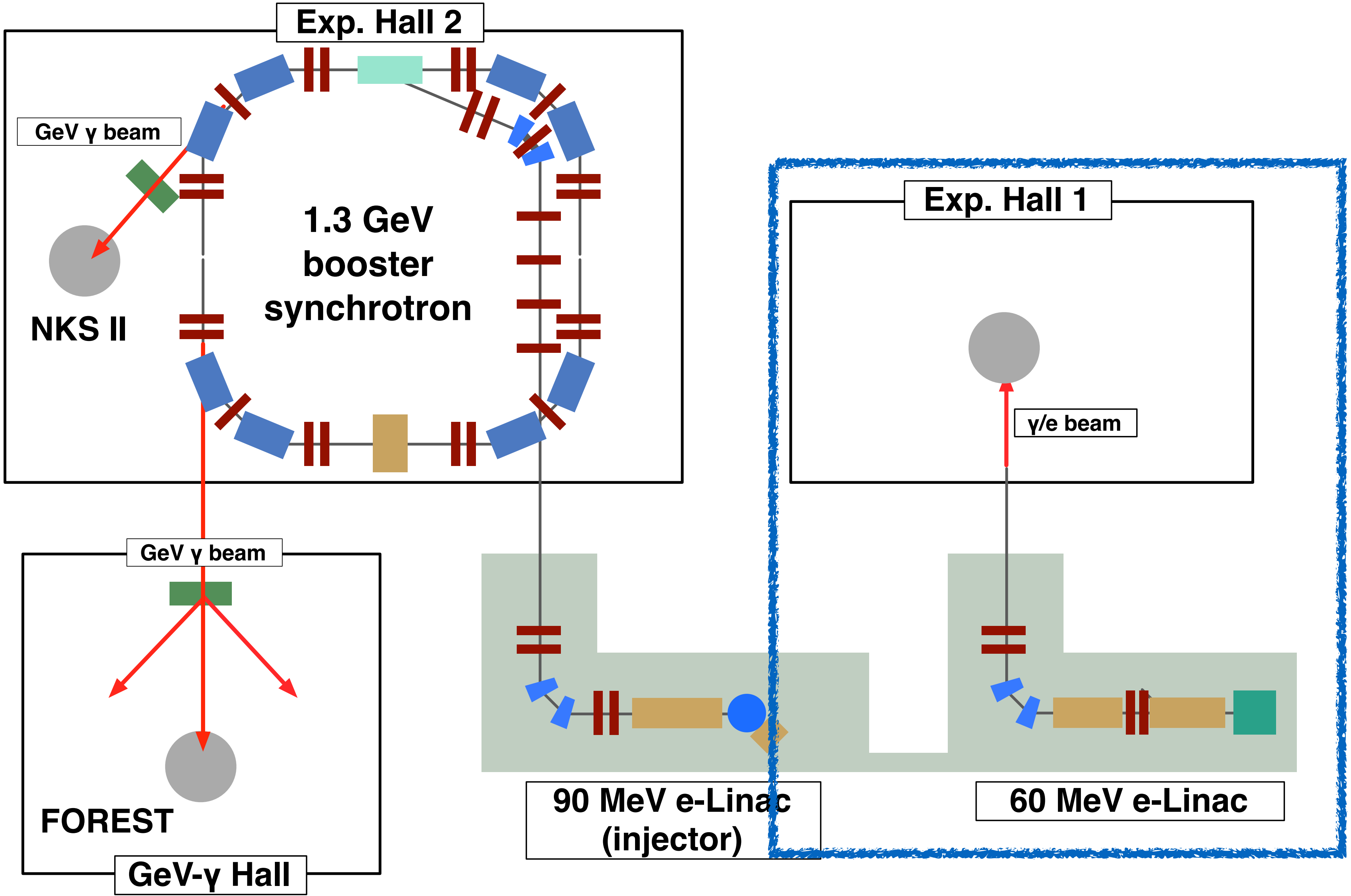


ULQ^2 @ Sendai

ULQ^2 collaboration
(Ultra-Low Q^2)

1.3 GeV Booster Ring
tagged photons (~ 1 GeV)
meson photoproduction, hypernucleus

60 MeV electron linac
~10 kW electron beam (150 uA)
Radioactive Isotope photo-production



e-scattering off proton at ultra-low Q^2 region

Goal of our experiment

$G_E(Q^2)$ measurements in $0.0003 \lesssim Q^2 \lesssim 0.008$ $(GeV/c)^2$

Our experiments

Low-energy electron scattering
Absolute cross section measurement
Rosenbluth separation ($G_E(Q^2)$, $G_M(Q^2)$)

accelerator, instruments

Tohoku low-energy electron linac + experimental hall

$20 \lesssim E_e \lesssim 60$ MeV
$30 \lesssim \theta \lesssim 150°$
$\Delta p/p \sim 10^{-3}$

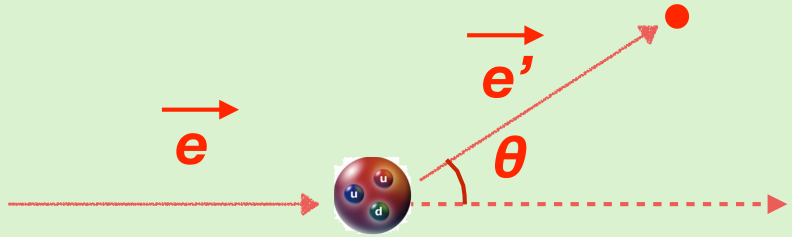
new beam line + double-arm spectrometer

Challenges

Absolute cross section ($G_E(Q^2)$) with **10^{-3} accuracy**

experimental challenges for measurement
theoretical challenges for interpretation

Proton charge radius by e-scattering



One Photon Exchange Approx.

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

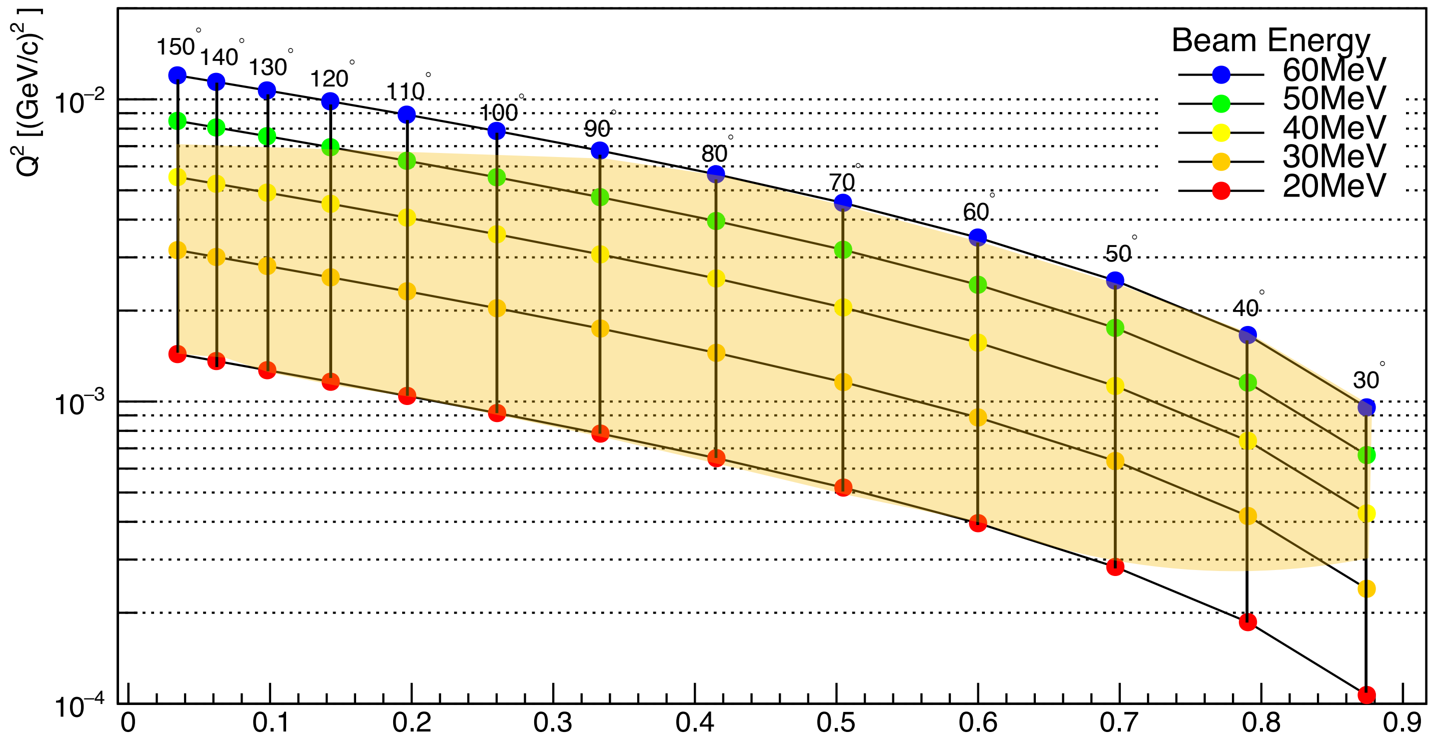
momentum transfer $\vec{q} = \vec{e} - \vec{e'}$

energy transfer $\omega = e - e'$

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

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

$$\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}} \qquad \tau = \frac{Q^2}{4m_p^2}$$



Challenges ….

Absolute cross section ($G_F(Q^2)$) with 10^{-3} accuracy

➡ relative measurement
to well-known (established) cross section

Moeller cross section : PRAD@JLAB

➡ large scattering angle coverage for GE/GM separation

$^{12}CH_2$(e,e') cross section ULQ^2@Tohoku

Low energy electron detection with high resolution

no tracking, frequent spectrometer setting changes ,,,

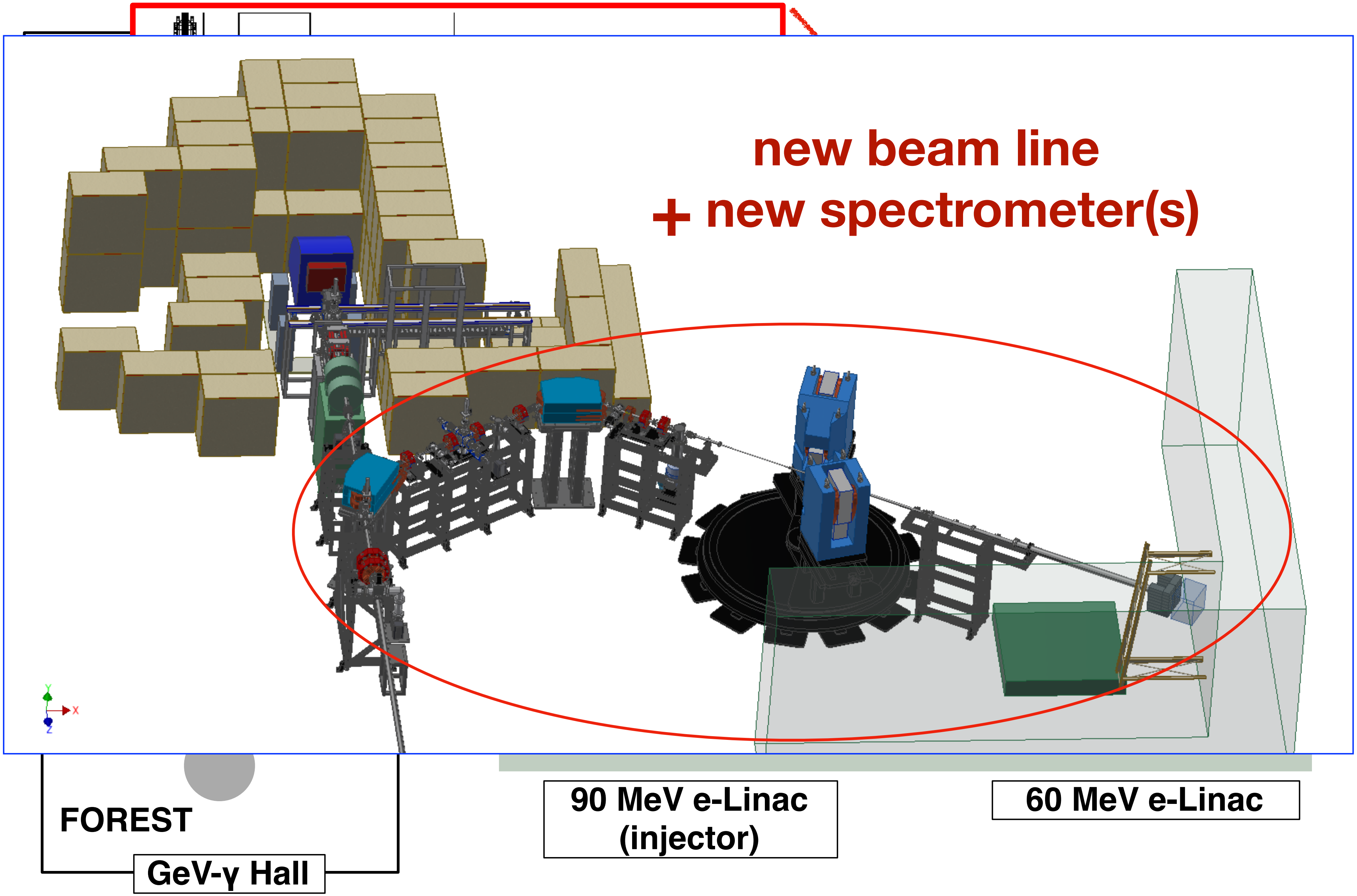
Ultra Relativistic Limit : m_e -> 0 ??

finite effects : up to a few % depending on kinematics

Coulomb distortion effects

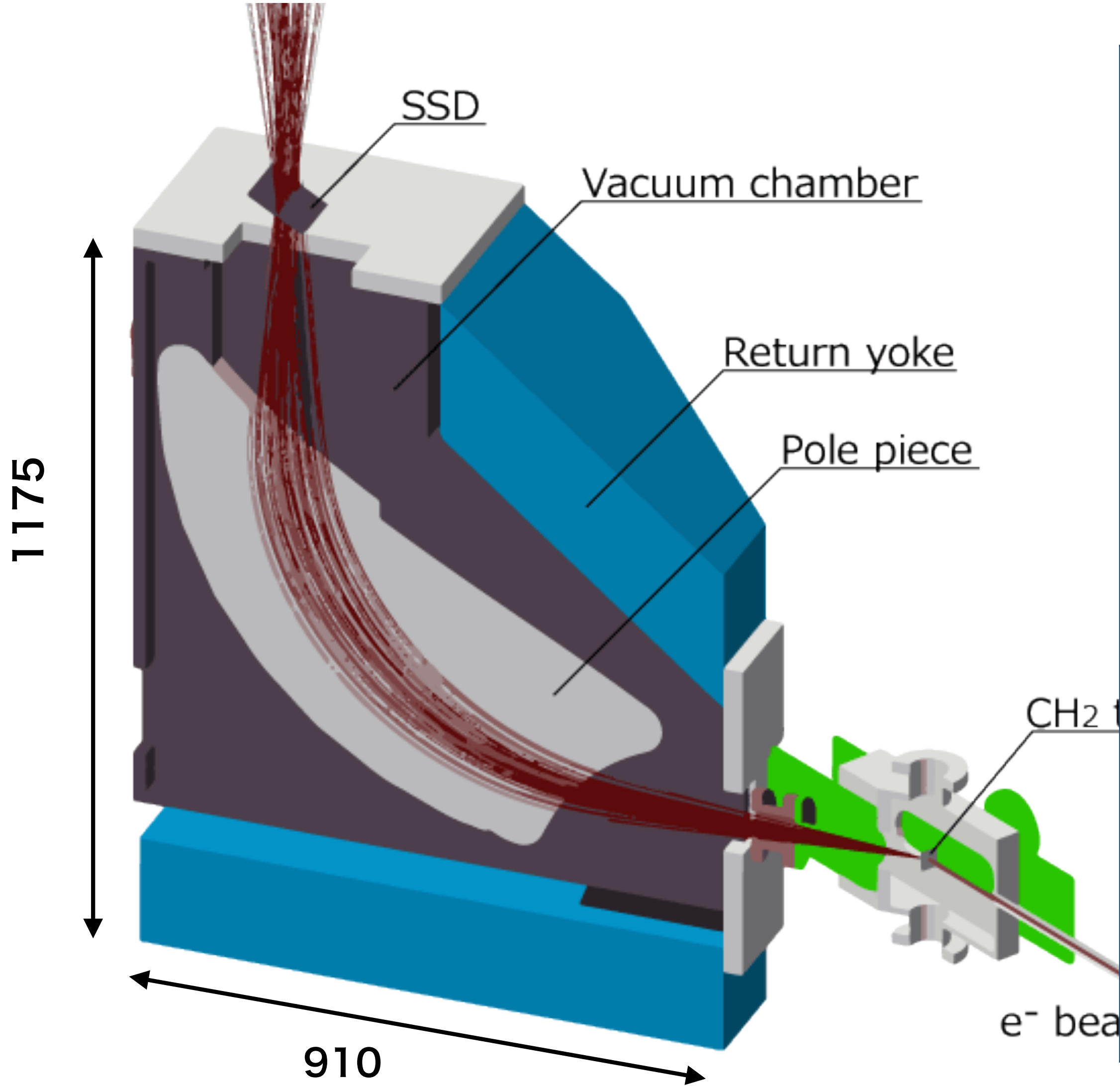
not negligible (~ 0.2 % level)

New beam line and spectrometers



Low energy : Ee = 20 - 60 MeV
high-resolution without tracking

➡ **“old-fashioned” spectrometer**



Electron spectrometer	
radius	500 mm
bending angle	90°
max. B	0.4T@60MeV
gap	70 mm
dispersion	850 mm
$\Delta p/p$	8×10^{-4}
momentum bite	10%
$\Delta\theta$	5 mrad
solid angle	10 mSr

Summary

1) elastic e+p scattering at ultra-low 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 Rosenbluth separation
4) Absolute cross section measurement

   relative to $^{12}C(e,e)^{12}C$: sys. err. $\sim 3 \times 10^{-3}$
5) Ee = 20 - 60 MeV, θ = 30 - 150°
6) the new beam line, and spectrometer are under construction
7) the experiments will start in 2019