Electron scattering experiment off proton at ultra-low Q^2

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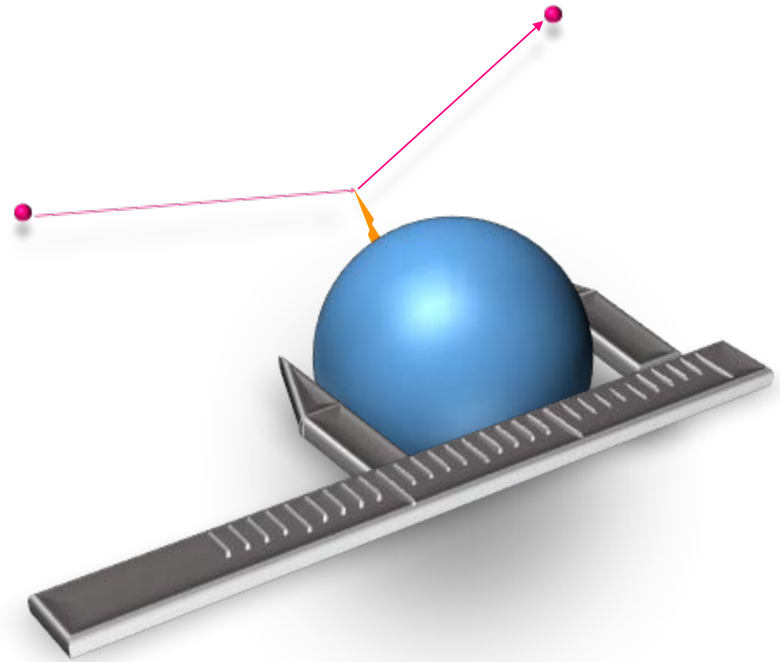
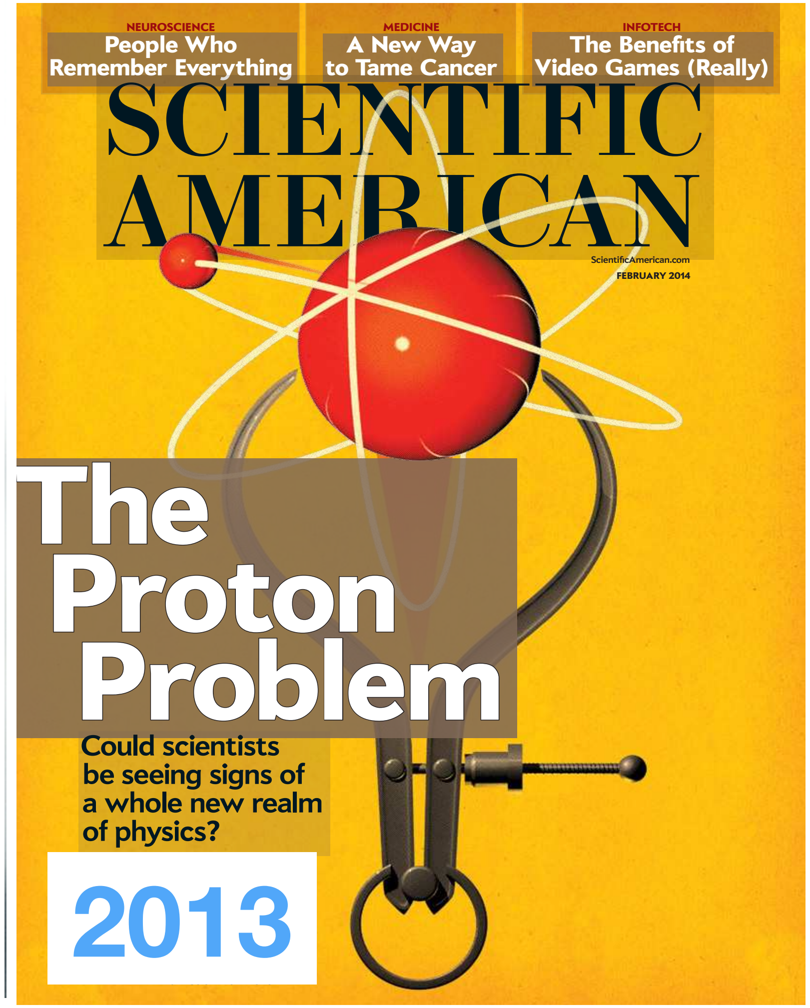
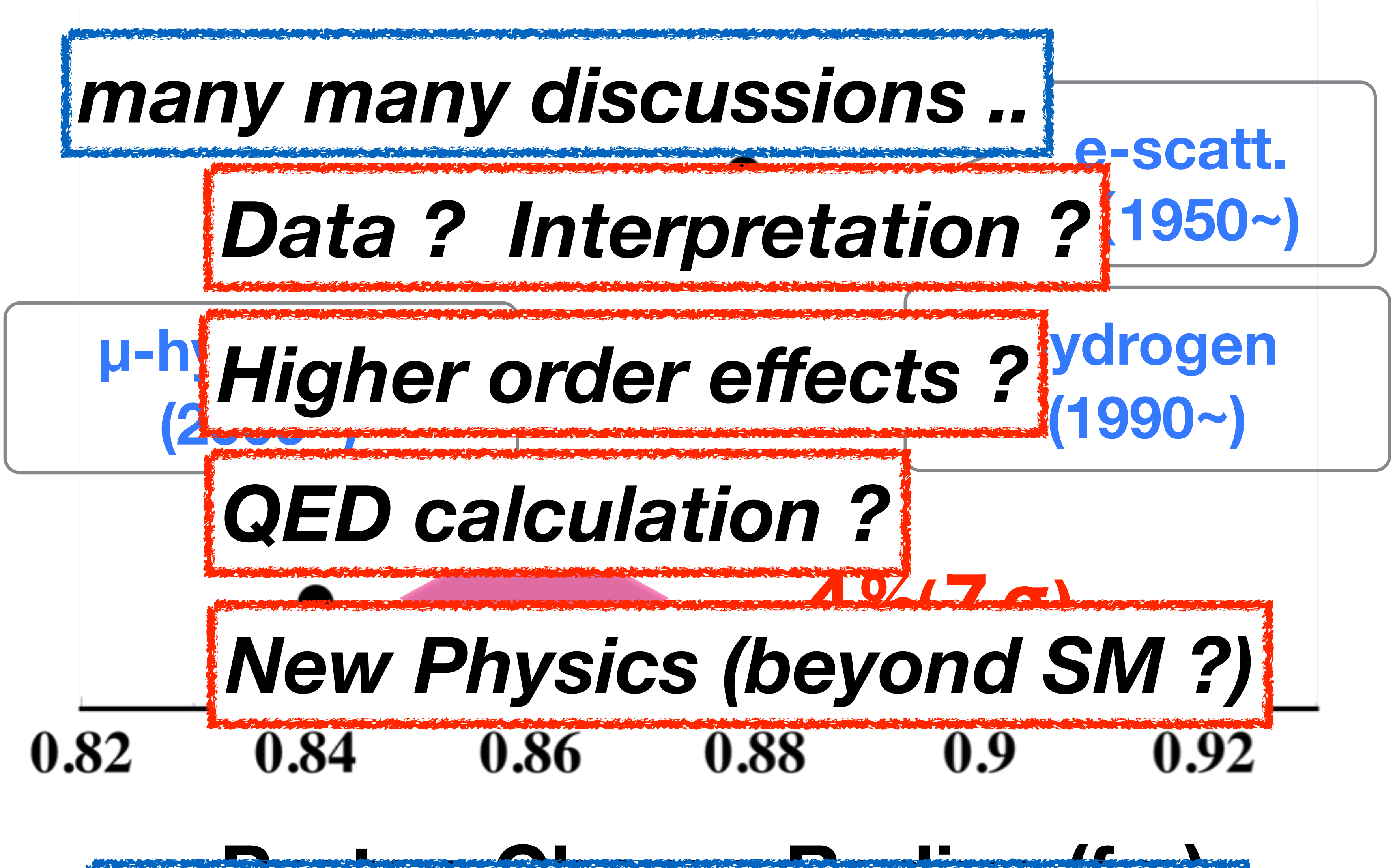


“Proton Radius Puzzle”



" Proton charge radius puzzle"



many many discussions ..

Data ? Interpretation ?

Higher order effects ?

QED calculation ?

New Physics (beyond SM ?)

so far, not yet settled (2016)

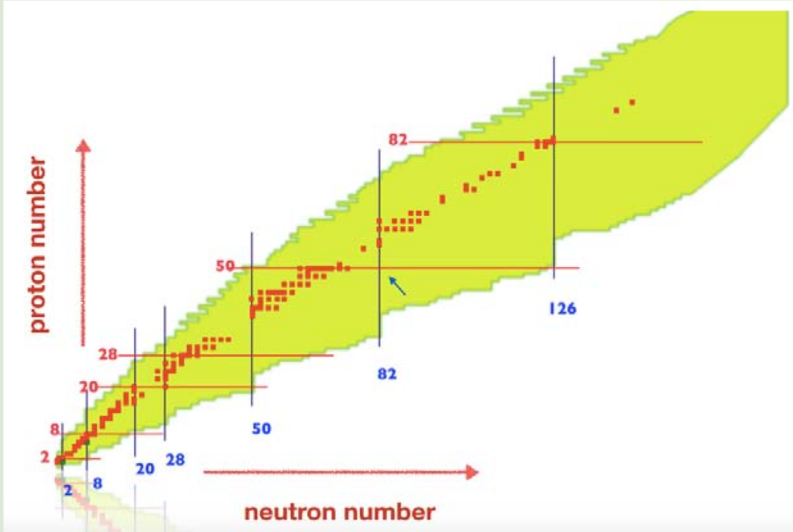
Who are we ?

We are " Electron Scatterers".

"classical" elastic electron scattering
to study the charge density distributions
pioneered by R. Hofstadter in 1950s !

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

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



Not for stable nuclei,,,,,

BUT never-yet-performed Short-Lived Exotic Nuclei !

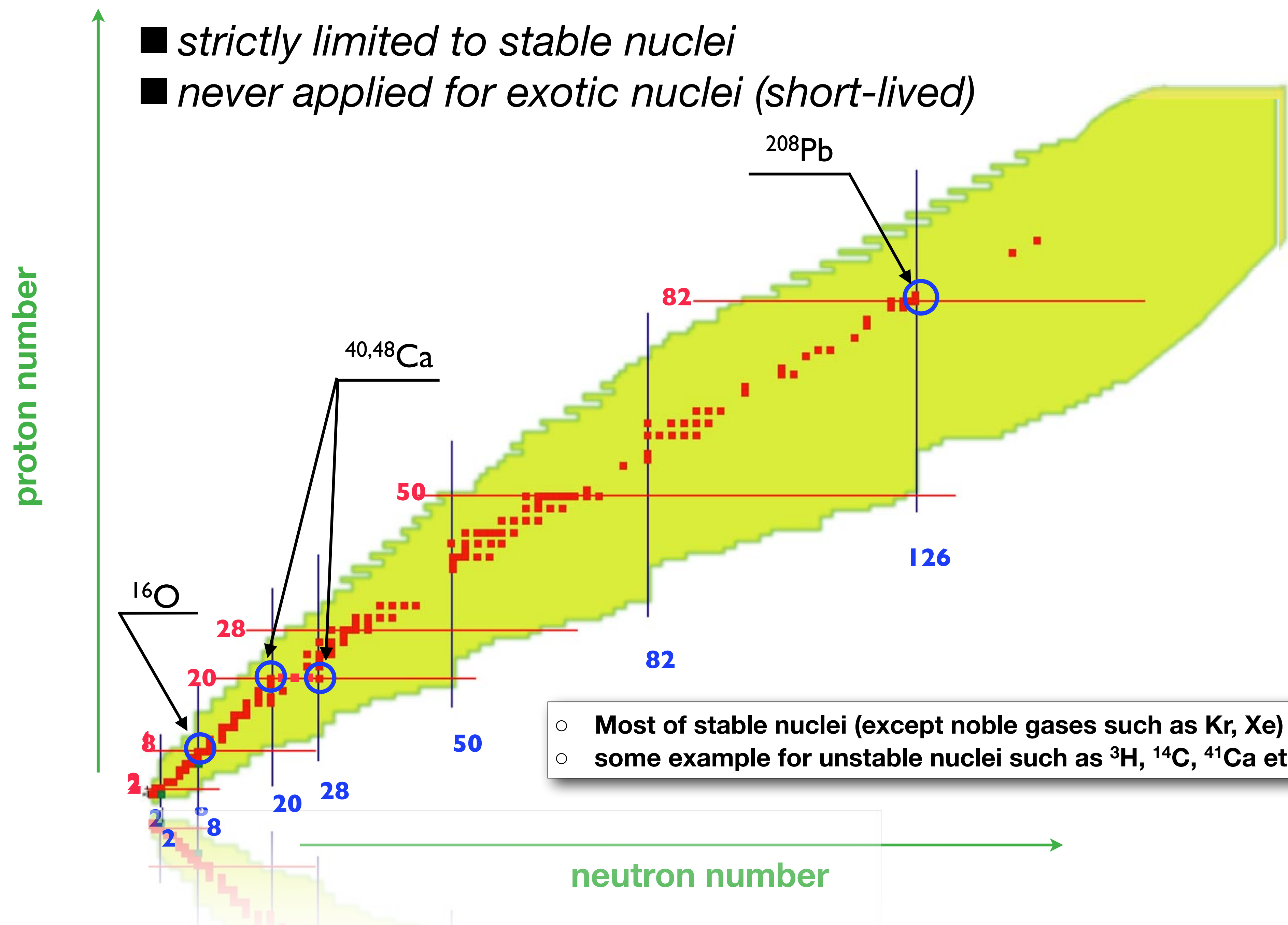
"Hofstadter's experiments" for exotic nuclei

we are currently operating
the World's first electron scattering facility
dedicated for exotic nuclei.

Nuclei studied by electron scattering

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

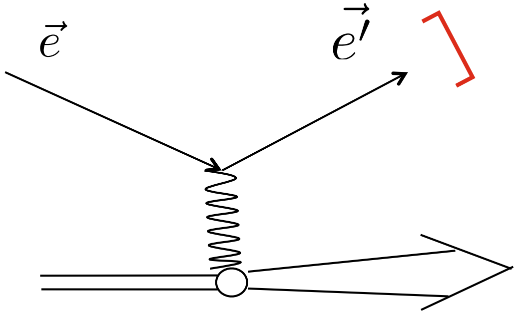
- *strictly limited to stable nuclei*
- *never applied for exotic nuclei (short-lived)*



- Most of stable nuclei (except noble gases such as Kr, Xe)
- some example for unstable nuclei such as ^{3}H, ^{14}C, ^{41}Ca etc...

Electron Scattering

Electron scattering provides direct and unambiguous structure information of atomic nuclei including proton



$$\omega = e - e'$$
$$\vec{q} = \vec{e} - \vec{e'}$$

1. *point particle*
2. *electromagnetic interaction*
   - *i) coupling : charge and current => el.mag. structure*
   - *ii) "weak" -> probing whole volume*
     perturbation theory
   - *iii) exp. data => structure information*
3. *variable q for fixed ω*

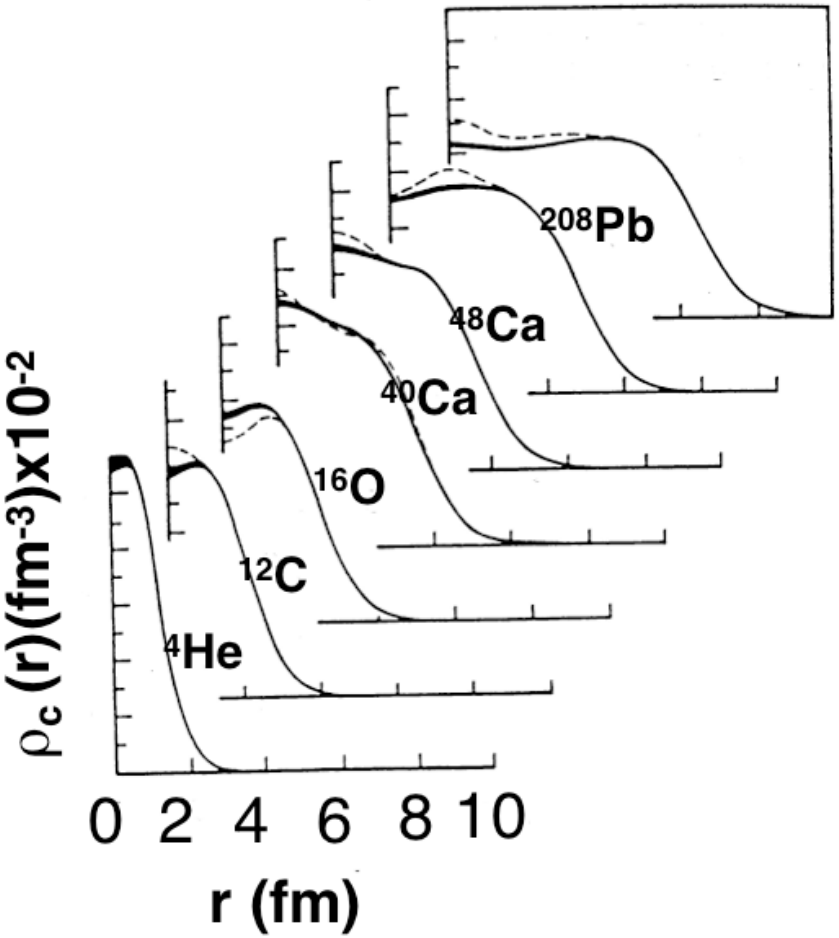
Elastic Electron Scattering

For 0+ nuclei

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

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

$$\rho_c(\vec{r}) = \sum_{i=1}^{Z} |\psi_i(\vec{r})|^2$$

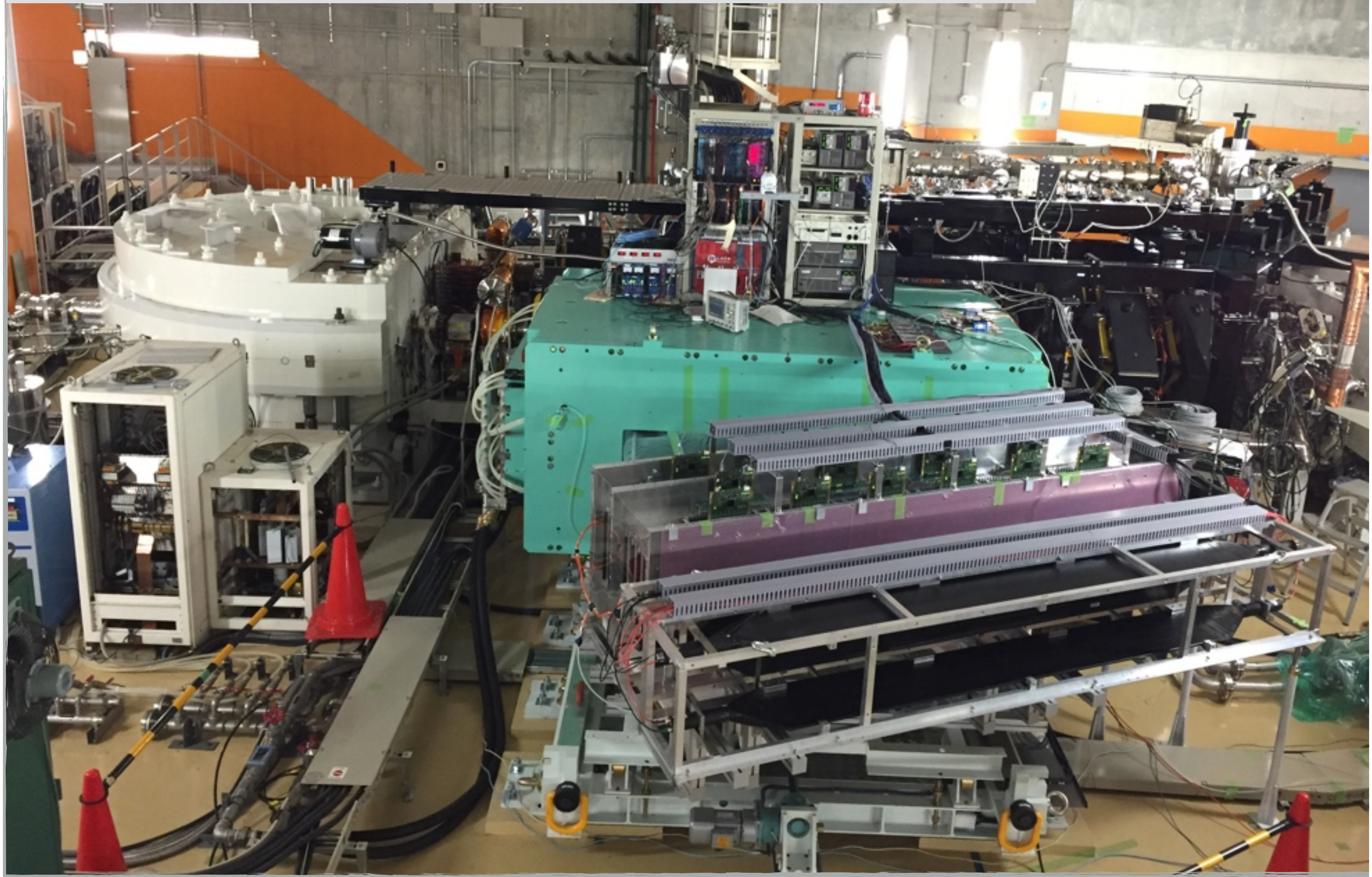


For non-0+ nuclei

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega} \text{ [Charge+Magnetic]}$$

SCRIT electron scattering facility

the world's first facility dedicated for exotic nuclei



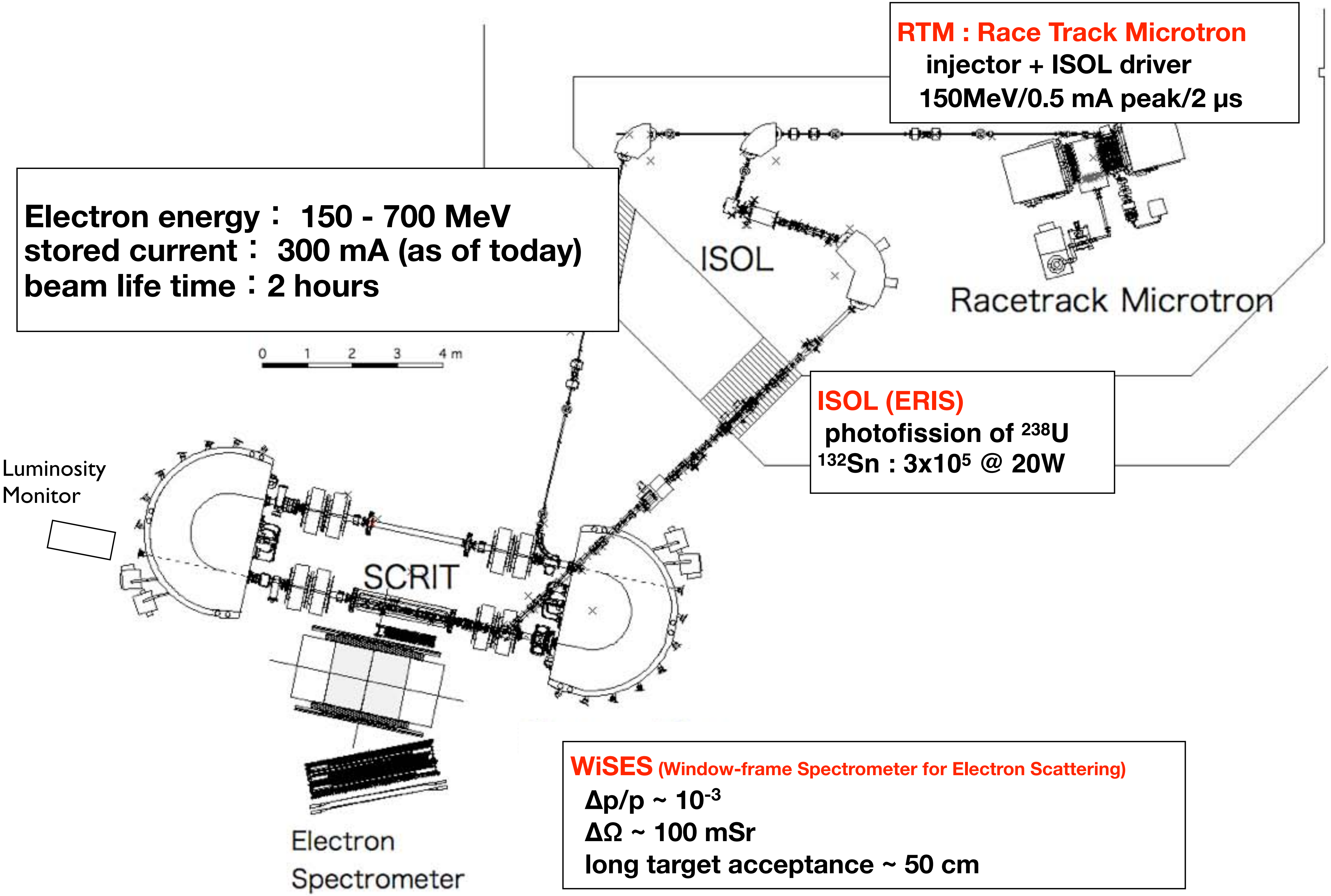
SCRIT facility at RIKEN RIBF

Electron energy : 150 - 700 MeV
stored current : 300 mA (as of today)
beam life time : 2 hours

RTM : Race Track Microtron
injector + ISOL driver
150MeV/0.5 mA peak/2 μs

ISOL (ERIS)
photofission of ^{238}U
^{132}Sn : $3x10^5$ @ 20W

WiSES (Window-frame Spectrometer for Electron Scattering)
$\Delta p/p \sim 10^{-3}$
$\Delta\Omega \sim 100$ mSr
long target acceptance ~ 50 cm



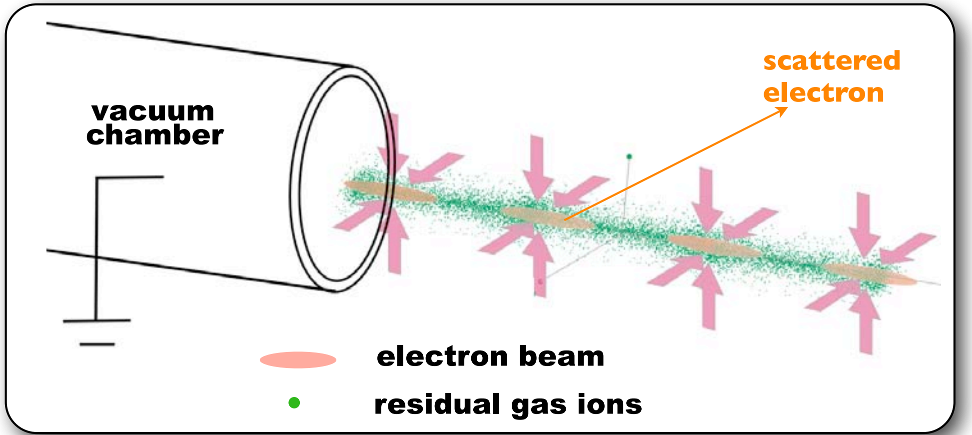
SCRIT (Self-Confining RI Target)

M. Wakasugi, T. Suda and Y. Yano
Nucl. Instrum. and Method A278 (2004) 216.

Idea

Problematic ion trapping phenomena
@
electron storage ring

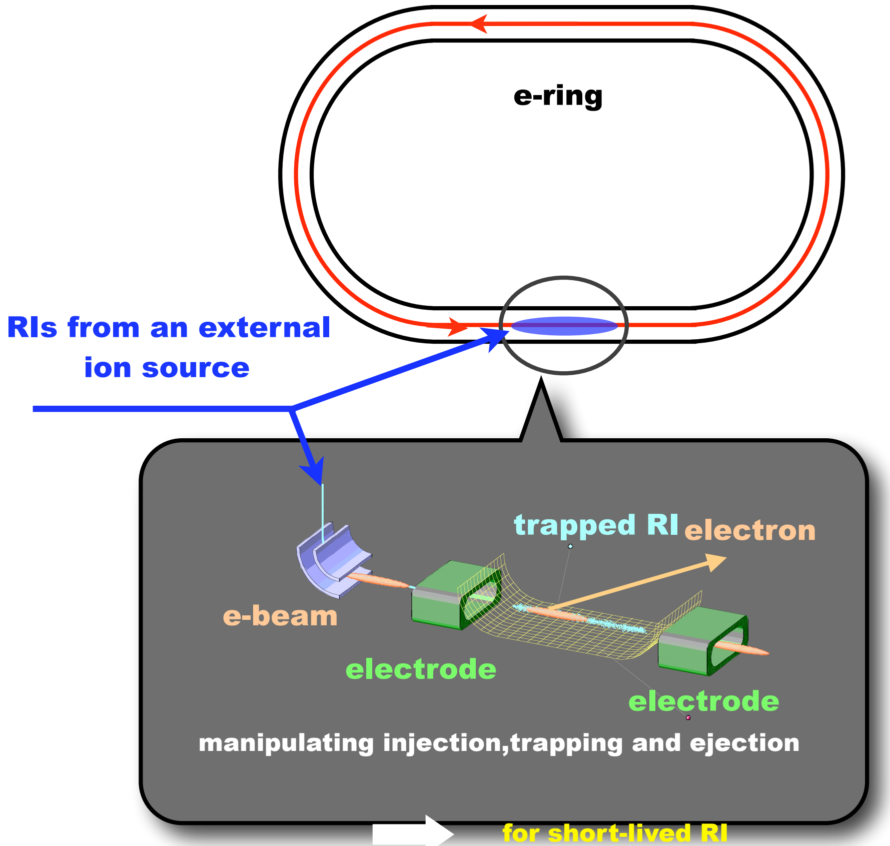
ionized residual gases are trapped by the circulating electron beam



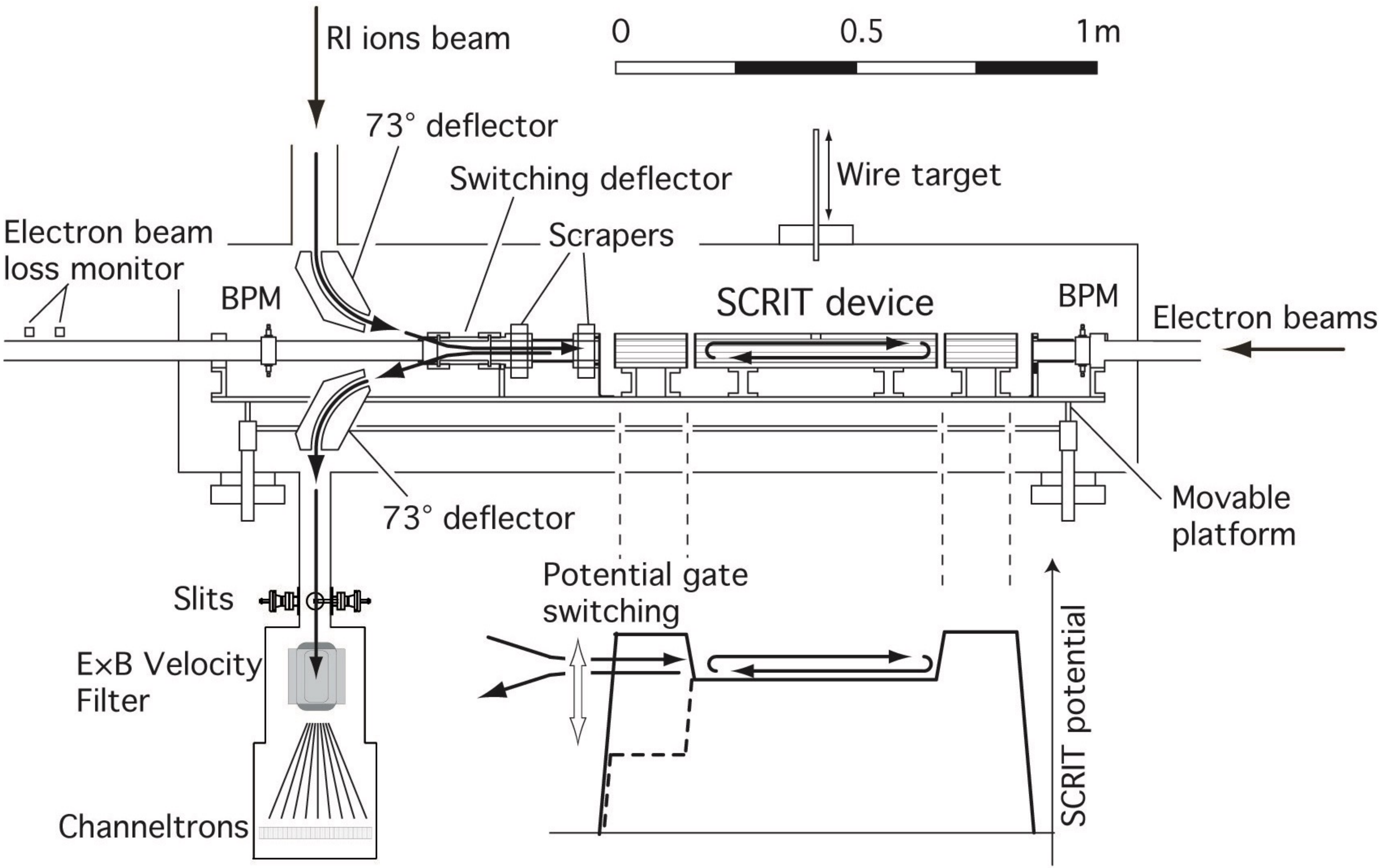
ill problem of e-storage ring

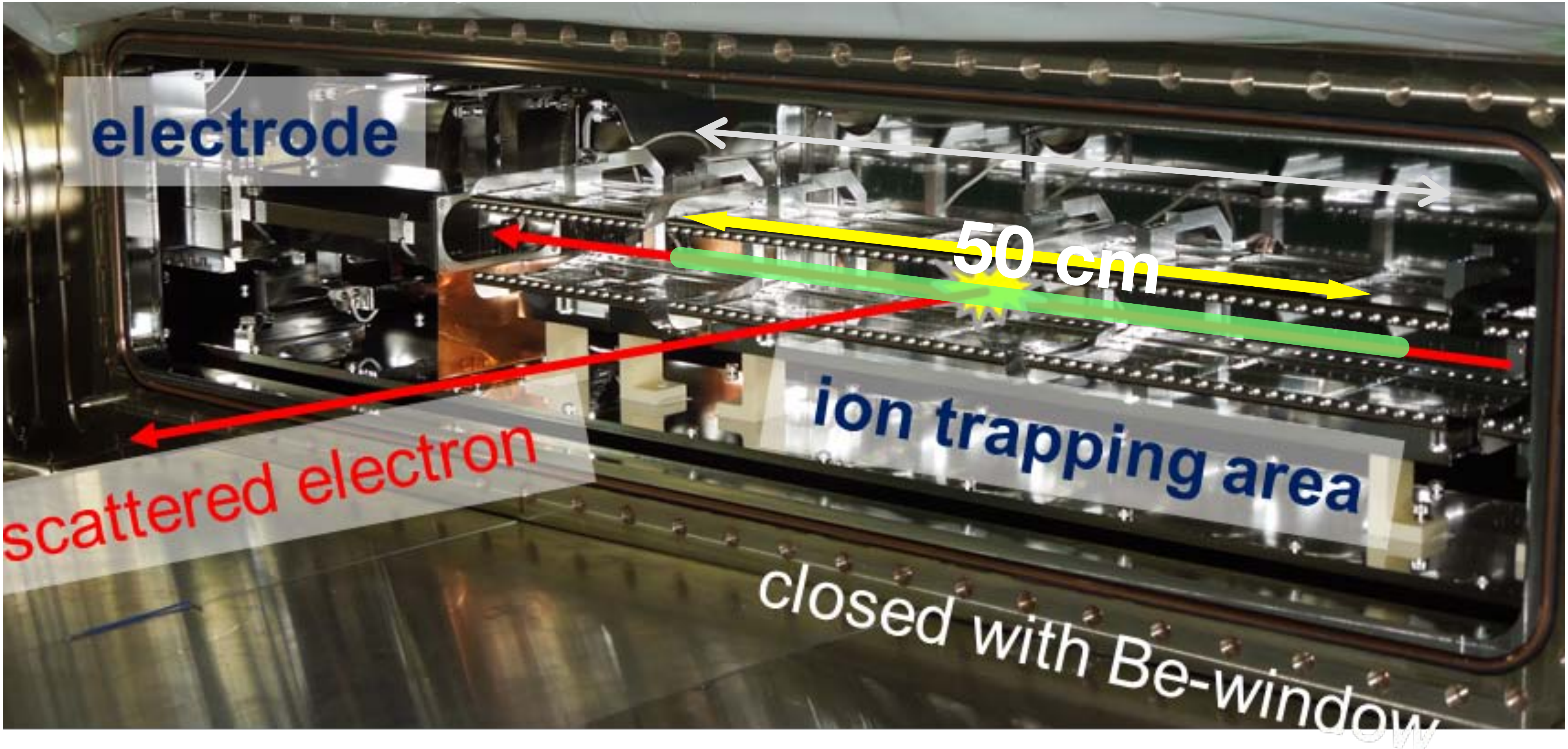
new ion trap for e-RI scattering

trapping RIs on electron beam
(automatic e-scattering off trapped RIs)

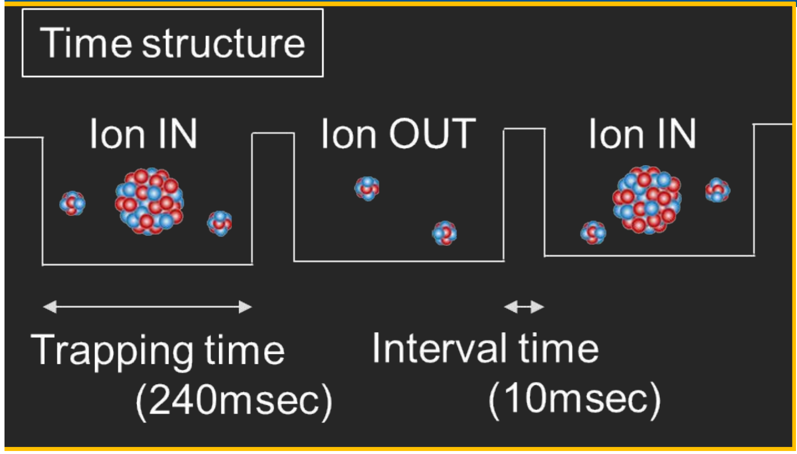


SCRIT system



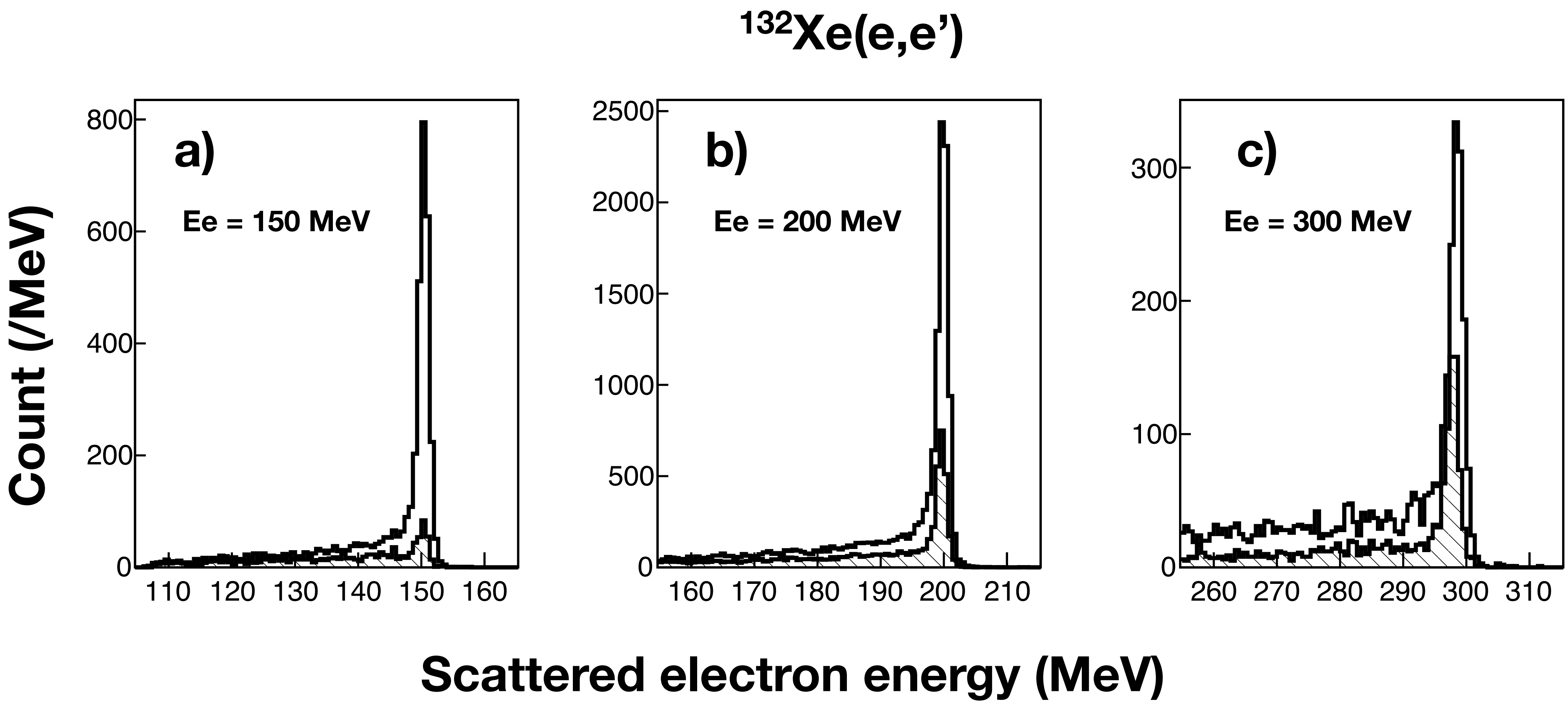

electrode
50 cm
ion trapping area
scattered electron
closed with Be-window

^{132}Xe(e,e')



Ion IN - Ion OUT

for comparative measurements

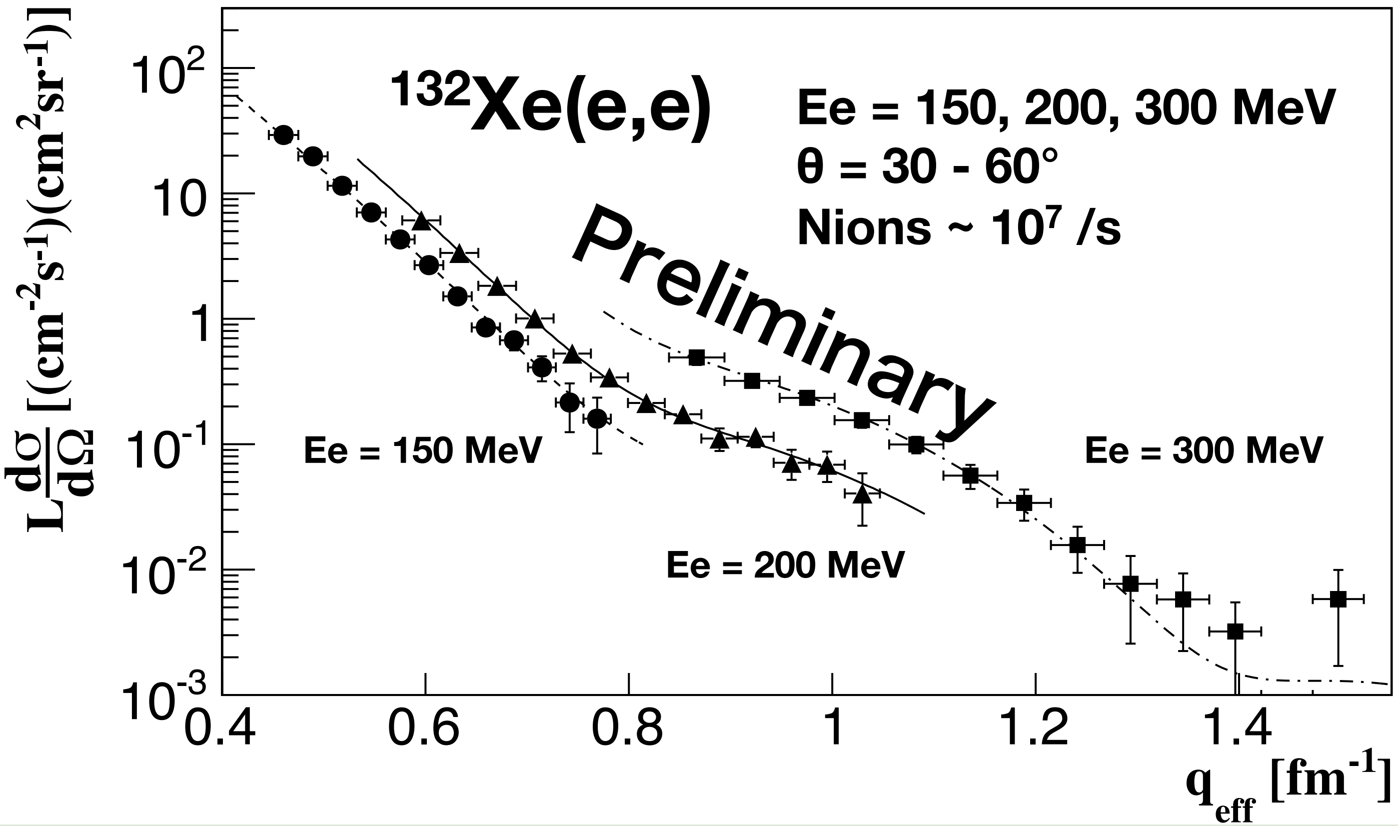


First Data from the SCRIT facility

The facility started its full operation, and the first physic run was carried out since April, 2016.

^{132}Xe is a stable nucleus but has never been targeted.

Luminosity, 10^{27} cm^{-2}s^{-2}, is achieved with only ~10^{7} target nuclei



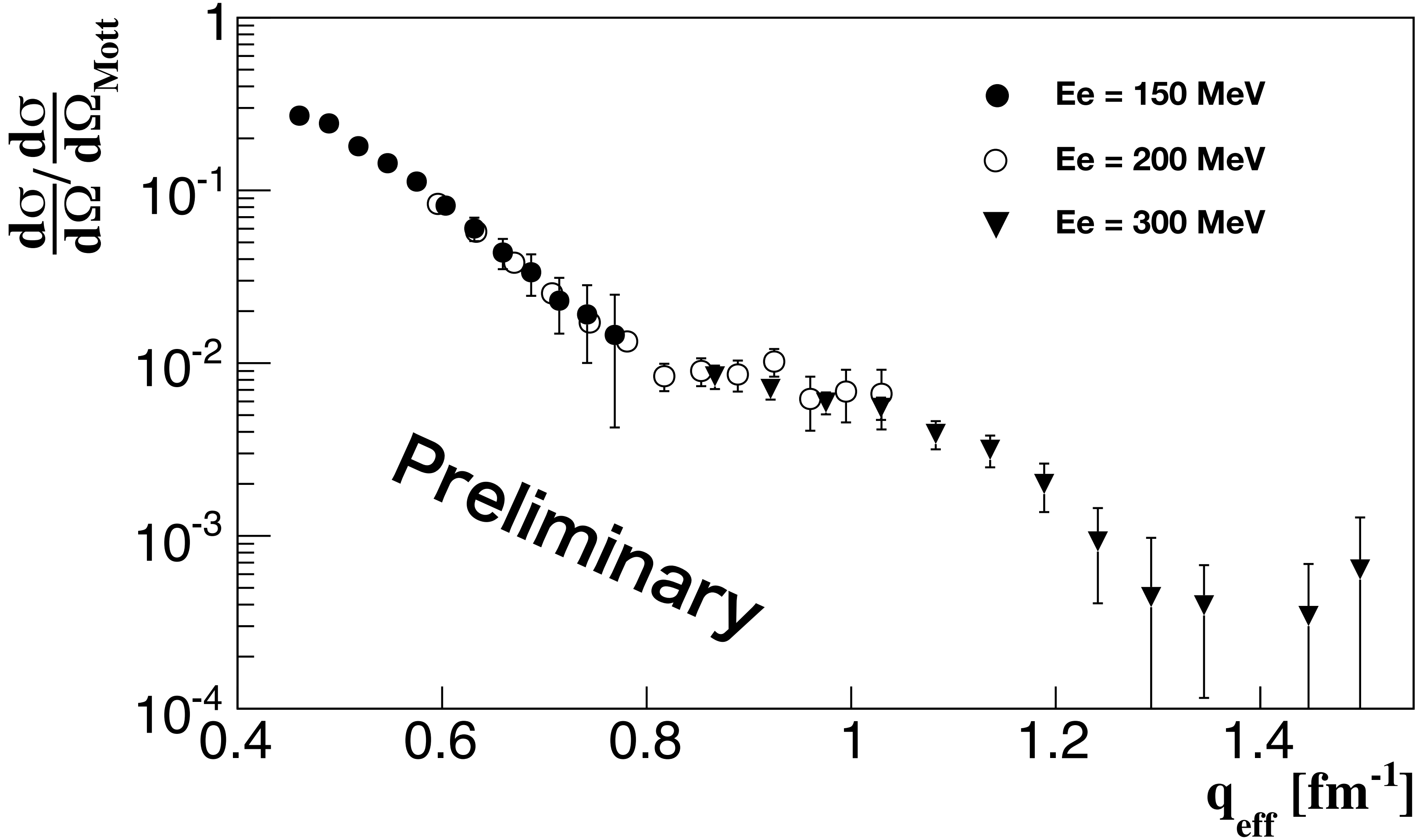
First experiment for exotic nucleus, ^{138}Xe (14 min.), this autumn. and to be followed by doubly magic nucleus, ^{132}Sn (50s).

PWIA

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

DWBA

$$|F_C^{DWBA}|^2 \sim \frac{d\sigma}{d\Omega} / \frac{d\sigma_{Mott}}{d\Omega}$$



Luminosities and Number of target nuclei

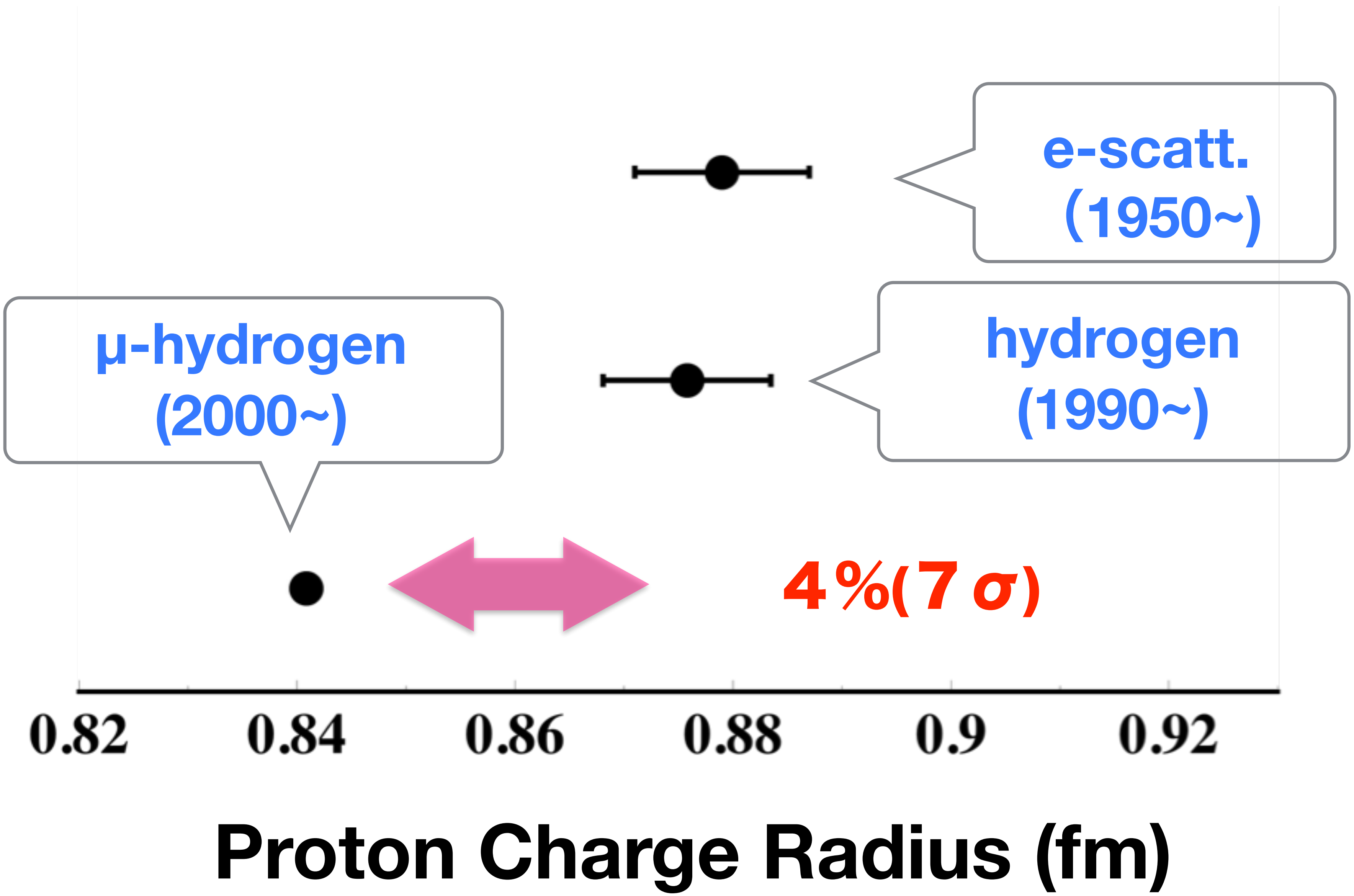
	Ee	N_{beam}	$\rho \cdot t$	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^{9} /s)	~10^{19} /cm^2	~10^{28} /cm^2/s
JLAB	6 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm^2/s
SCRIT	150 - 300 MeV	~200 mA (~10^{18} /s)	~ 10^{9} /cm^2	~10^{27} /cm^2/s

~10^{7} ions are trapped
on the electron beam of ~ 1 mm^2 cross section

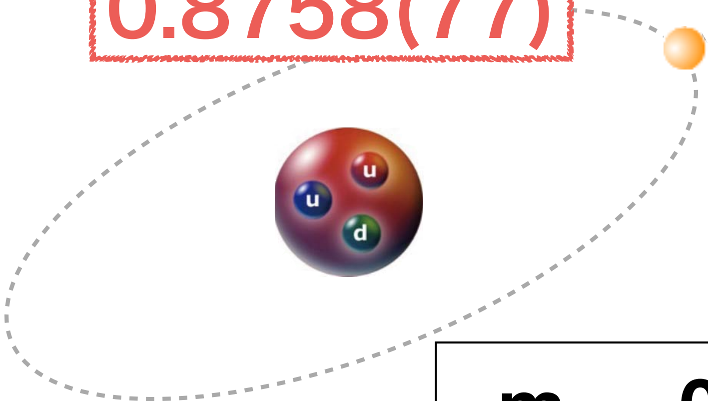
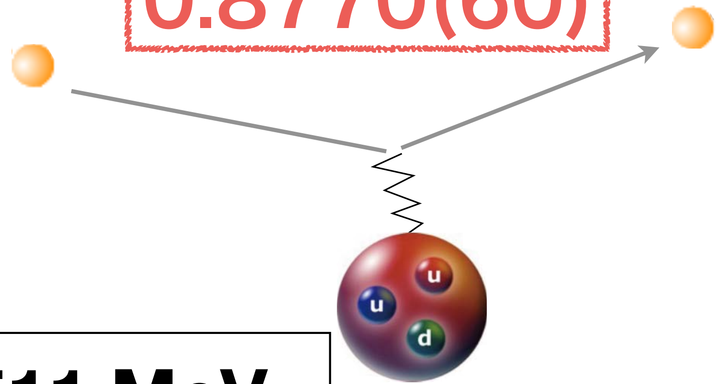
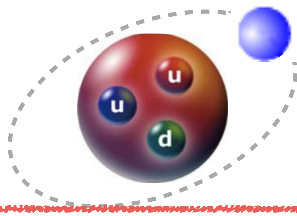
~10^{7} /mm^2 -> 10^{9} /cm^2

Proton Charge Radius

Proton charge radius puzzle



Proton charge radius determination

	Spectroscopy	Scattering
e^-	0.8758(77) 	0.8770(60) 
μ^-	 0.8409(4)	MUSE@PSI

m_e = 0.511 MeV
m_μ = 105.6 MeV

μH spectroscopy

P. Randolf et al., Nature 466 (2010) 213

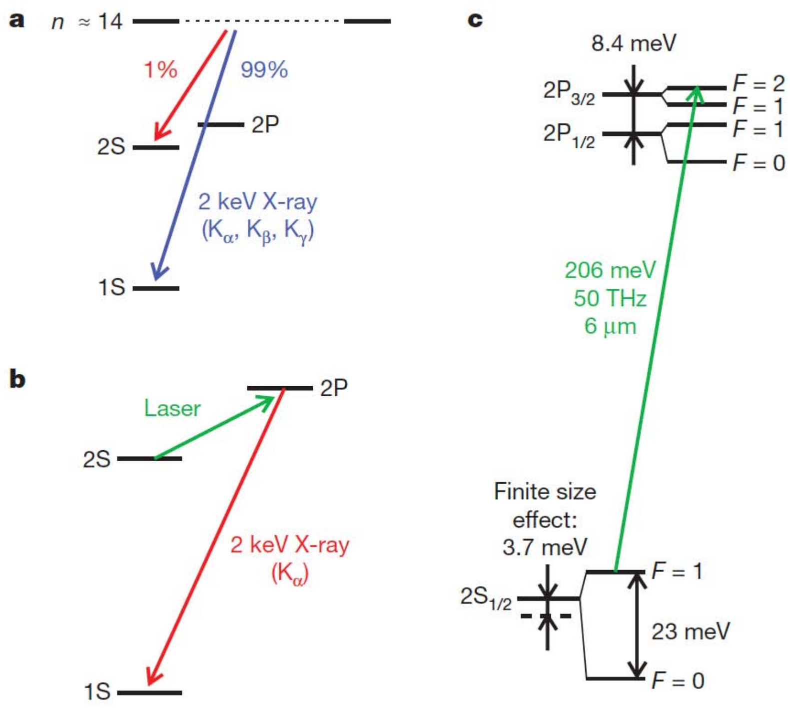
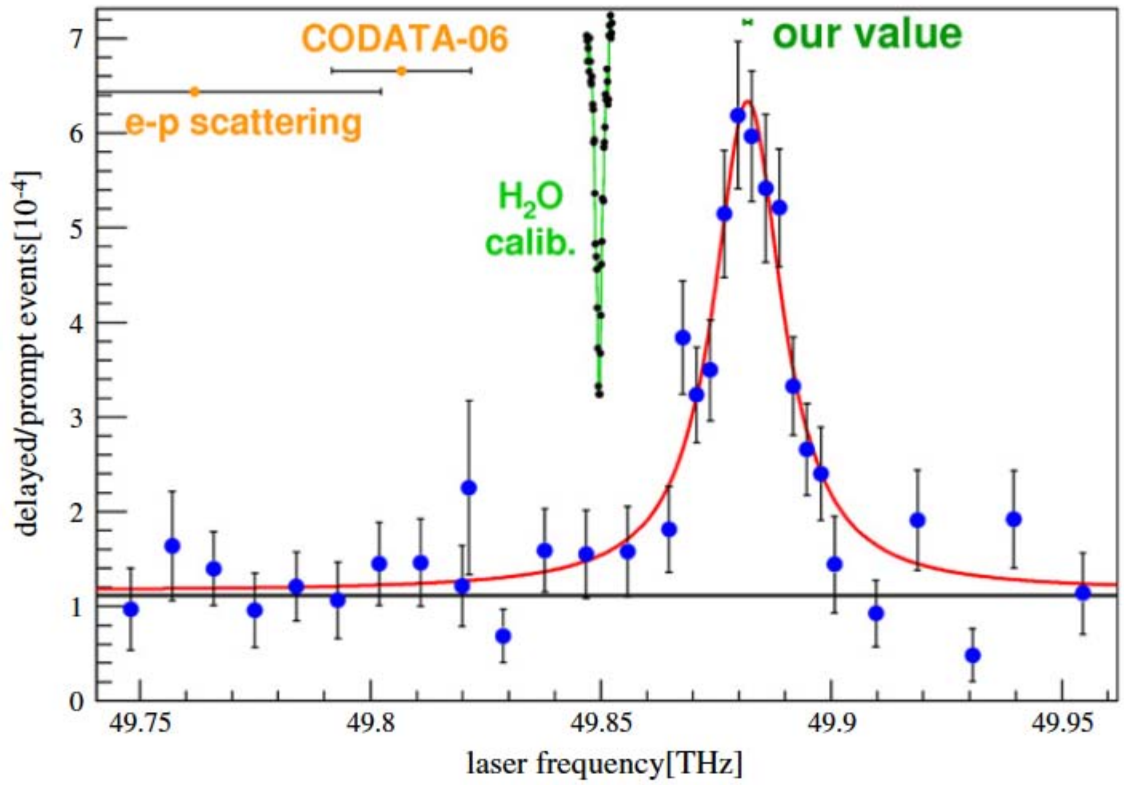


Figure 1 | Energy levels, cascade and experimental principle in muonic hydrogen. a, About 99% of the muons proceed directly to the 1S ground state during the muonic cascade, emitting 'prompt' K-series X-rays (blue). 1% remain in the metastable 2S state (red). **b**, The μp(2S) atoms are illuminated by a laser pulse (green) at 'delayed' times. If the laser is on resonance, delayed K_α X-rays are observed (red). **c**, Vacuum polarization dominates the Lamb shift in μp. The proton's finite size effect on the 2S state is large. The green arrow indicates the observed laser transition at $\lambda = 6$ μm.



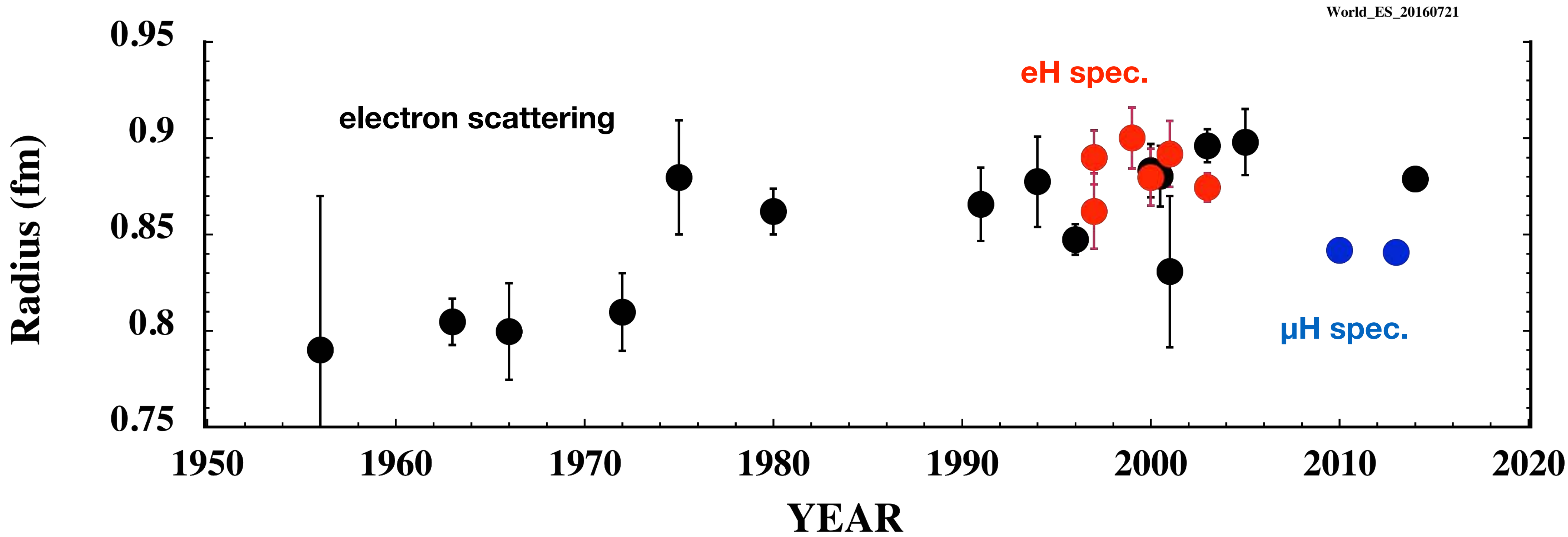
$$\Delta E(2S - 2P) = 209.978(5) - 5.226 r_p^2 + \ldots \text{ meV}$$

Electron scattering off proton

1960 1970 1980 1990 2000 2010

e+p, e+A elastic scattering
R. Hofstadter
(1961)

e+p deep inelastic scattering
J. Friedman, H. Kendall and R. Taylor
(1990)



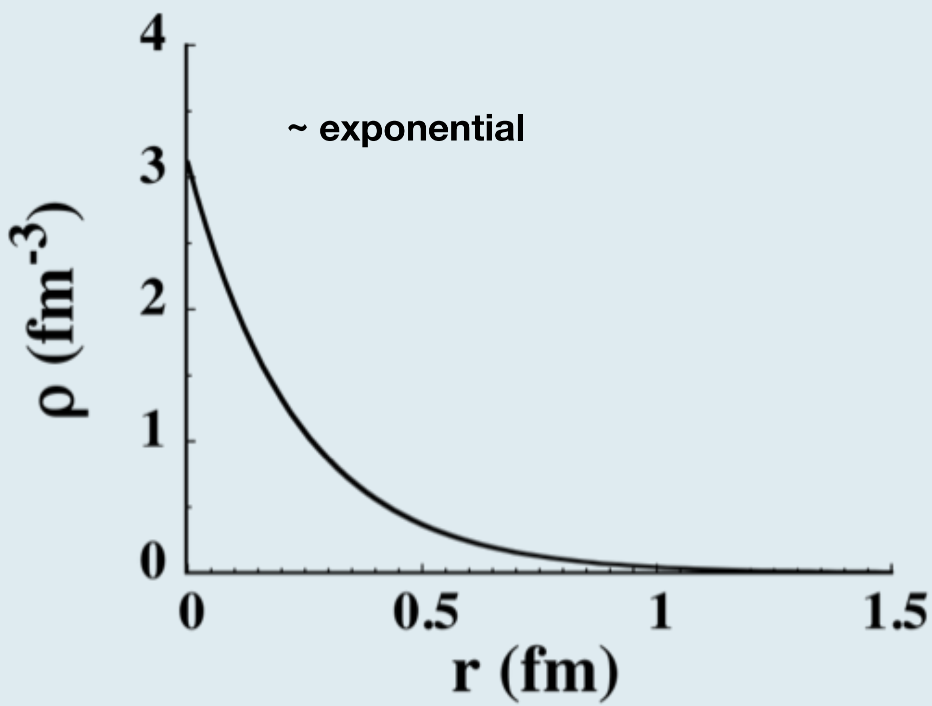
Proton charge radius

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)



Charge Form Factor at high Q^2

$$G_E(Q^2) = \frac{1}{(1+\frac{Q^2}{\alpha^2})^2}$$

$$\alpha^2 = 0.71(GeV/c)^2$$

$$G_E(Q^2) \rightarrow \rho(r) \qquad Q^2 << M_p^2$$

Fourier transformation

$$\rho(r) = \frac{\alpha^3}{8\pi} e^{-\alpha r} \qquad (r > 0)$$

$$< r^2 >^{1/2} = \frac{2\sqrt{3}}{\alpha}$$

$$< r^2 >^{1/2} = 0.81 fm$$

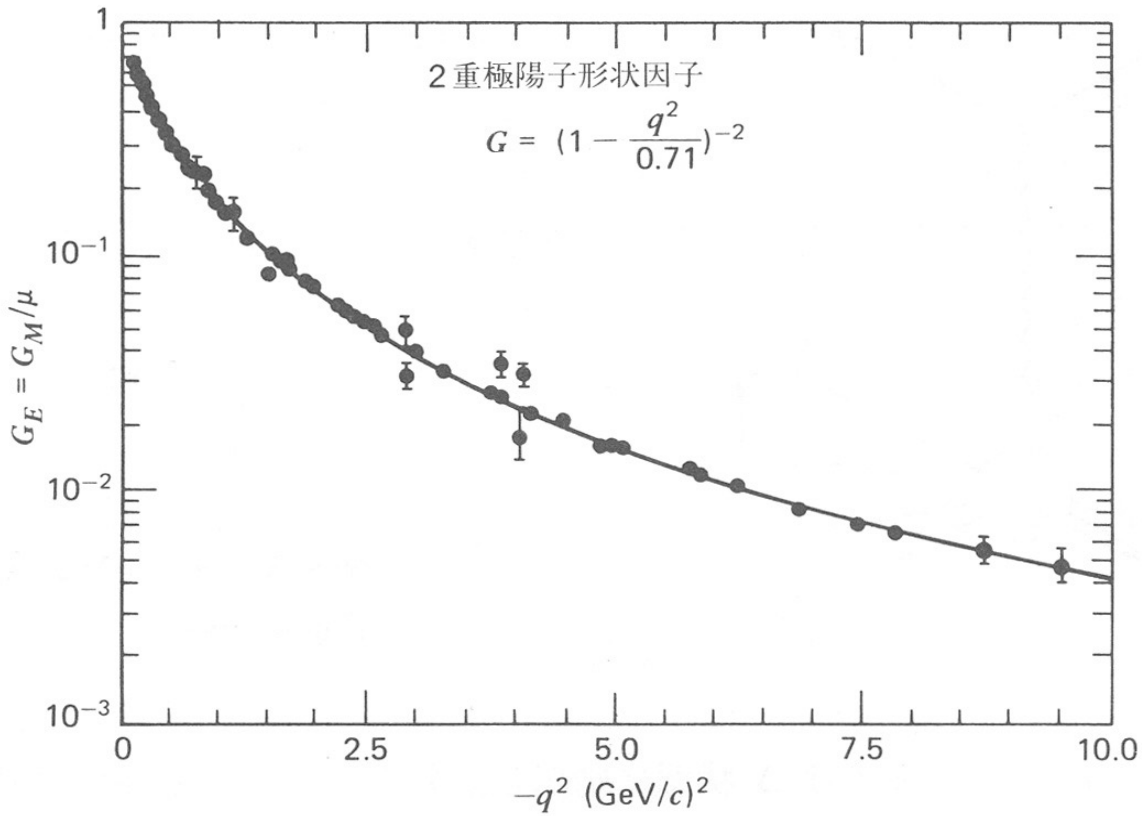
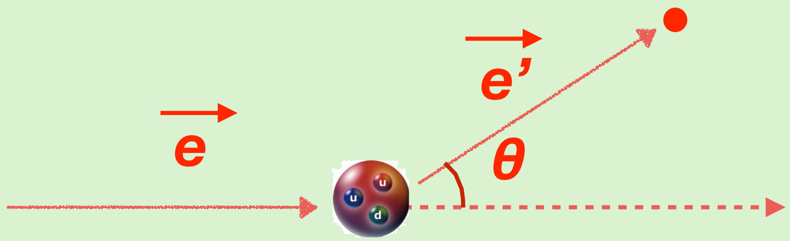


図8·4 q^2 の関数としての陽子形状因子

Proton charge radius by e-scattering



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

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

energy transfer $\omega = e - e'$

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

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

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

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

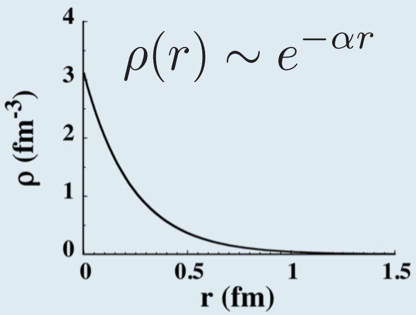
1） high Q^2: charge density ρ(r)

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 Q^2

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

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

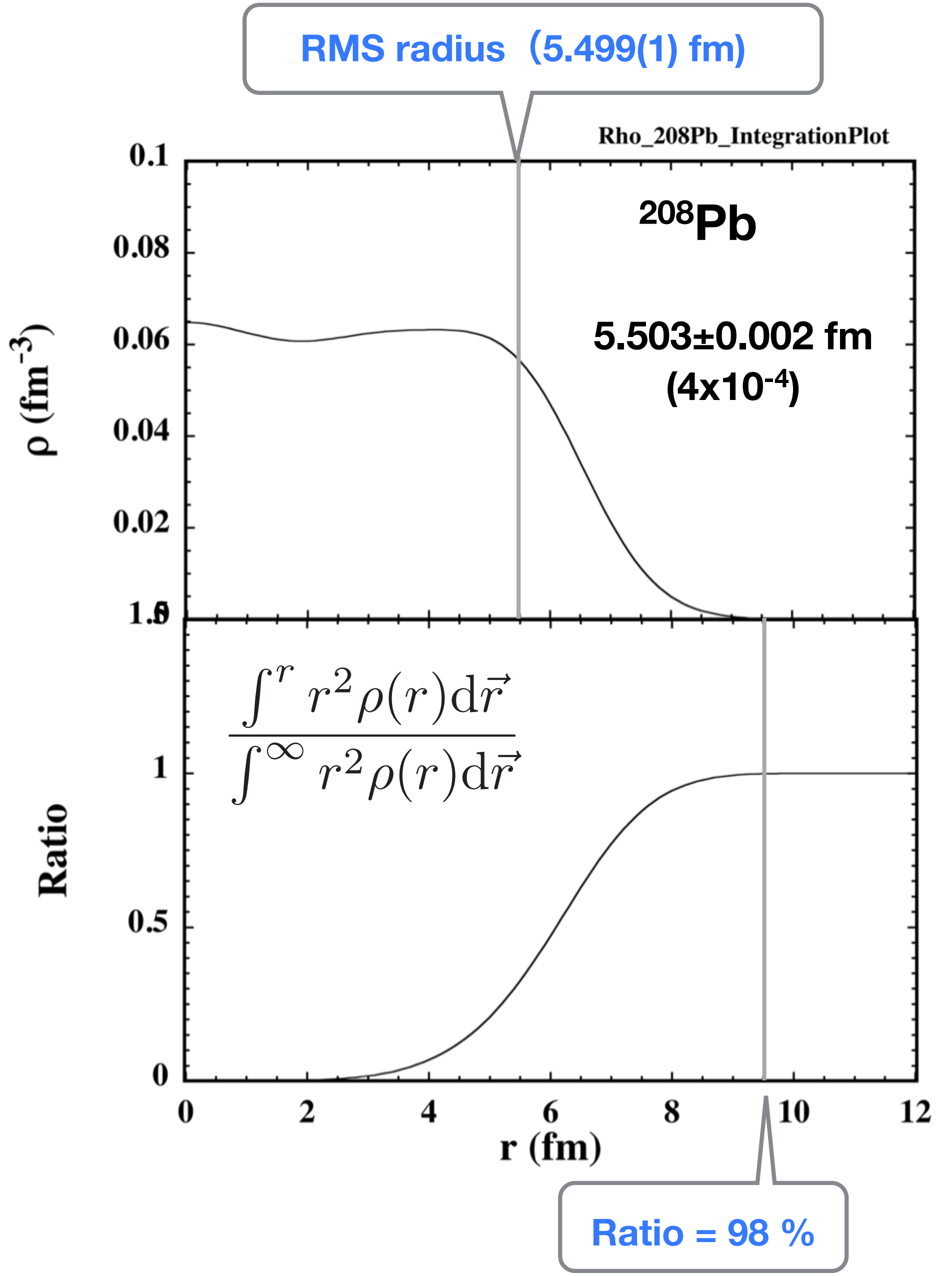
ill problem : higher order contribution

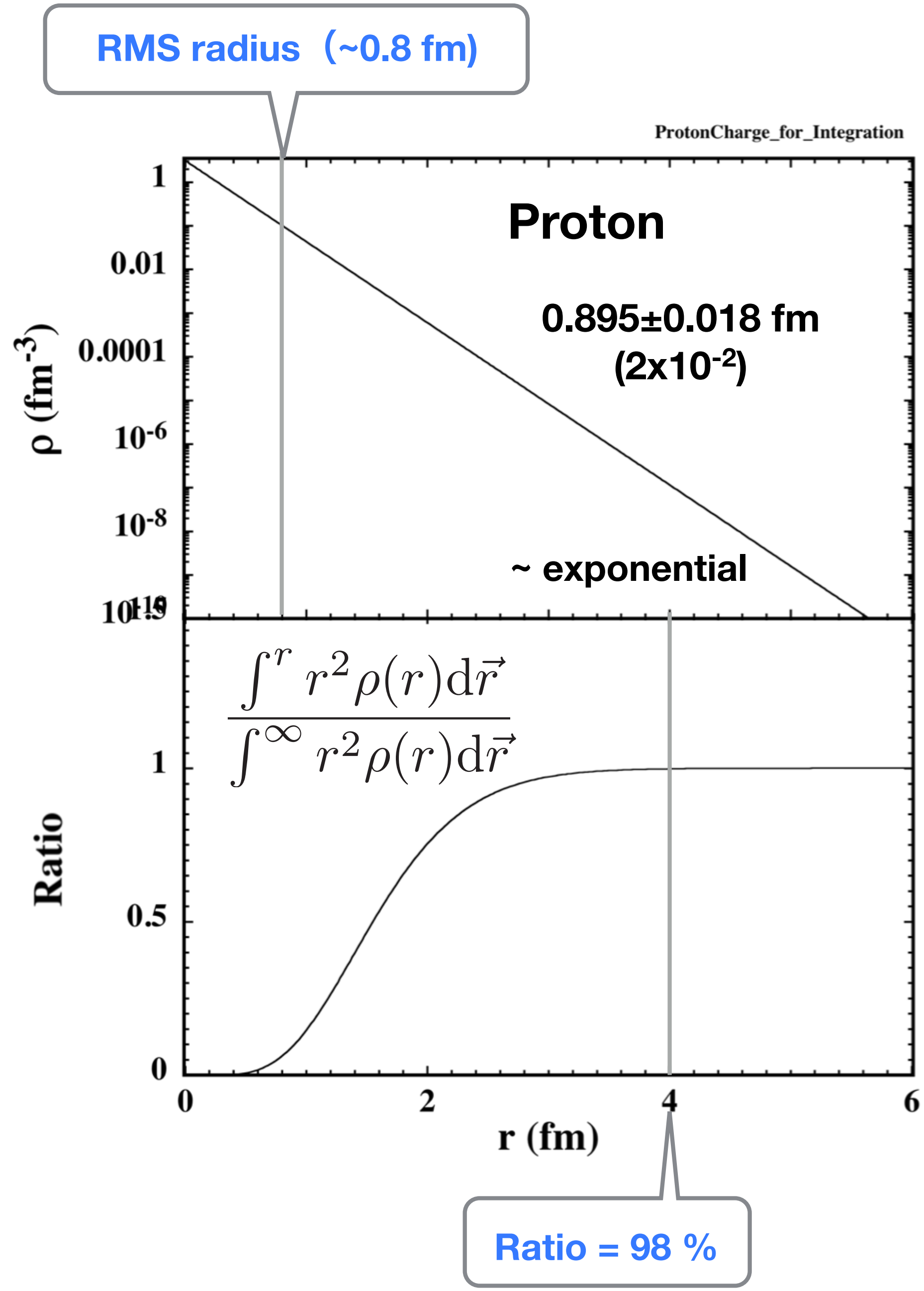
⇕

lower Q^2 as possible

Density distribution and RMS radius

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



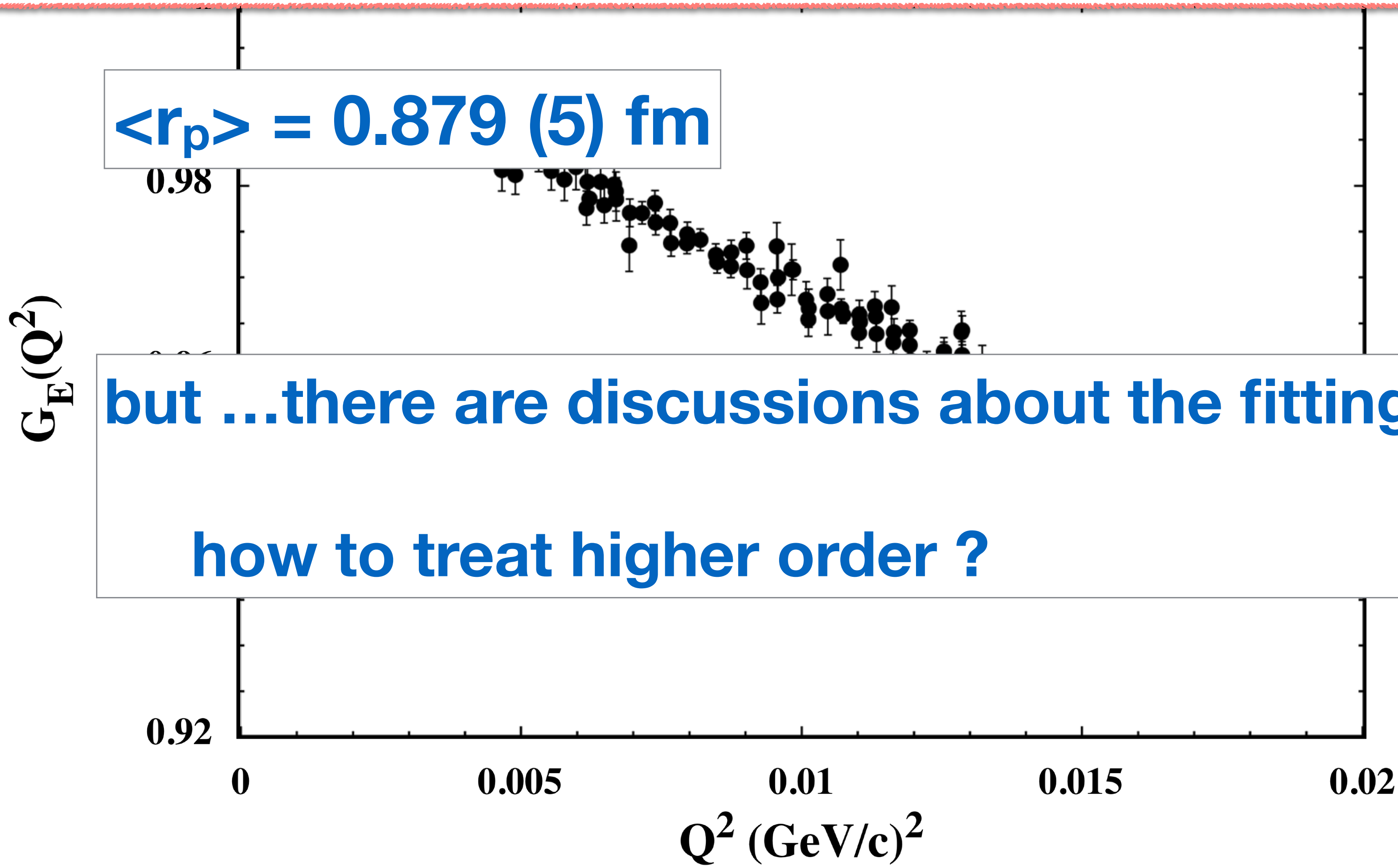


Electron scattering at Low Q^2

ULQ2@JPARC
Nov. 1, 2016

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

$<r_p> = 0.879$ (5) fm



but …there are discussions about the fitting

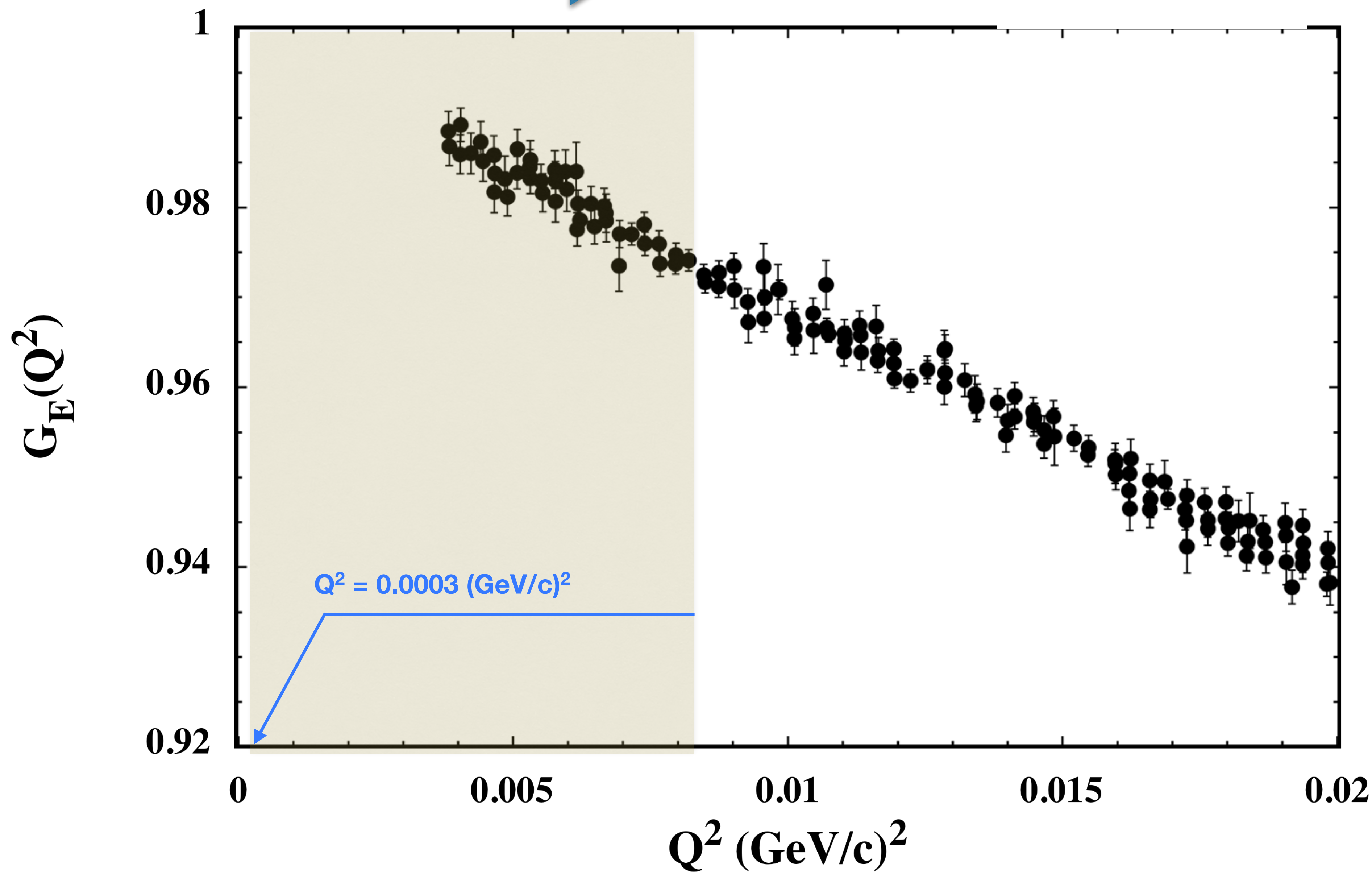
how to treat higher order ?

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

What are we going to do ???

Reduction of the higher order contribution

➡ $G_E(Q^2)$ at lower Q^2 region



What are we going to do ?

	Mainz 2014	Tohoku
Q^2_{min} $(GeV/c)^2$	0.004	0.0003
Ee (MeV)	180 ~ 850	20 ~ 60
absolute $d\sigma/d\Omega$	x	○
G_E/G_M separation	x	○

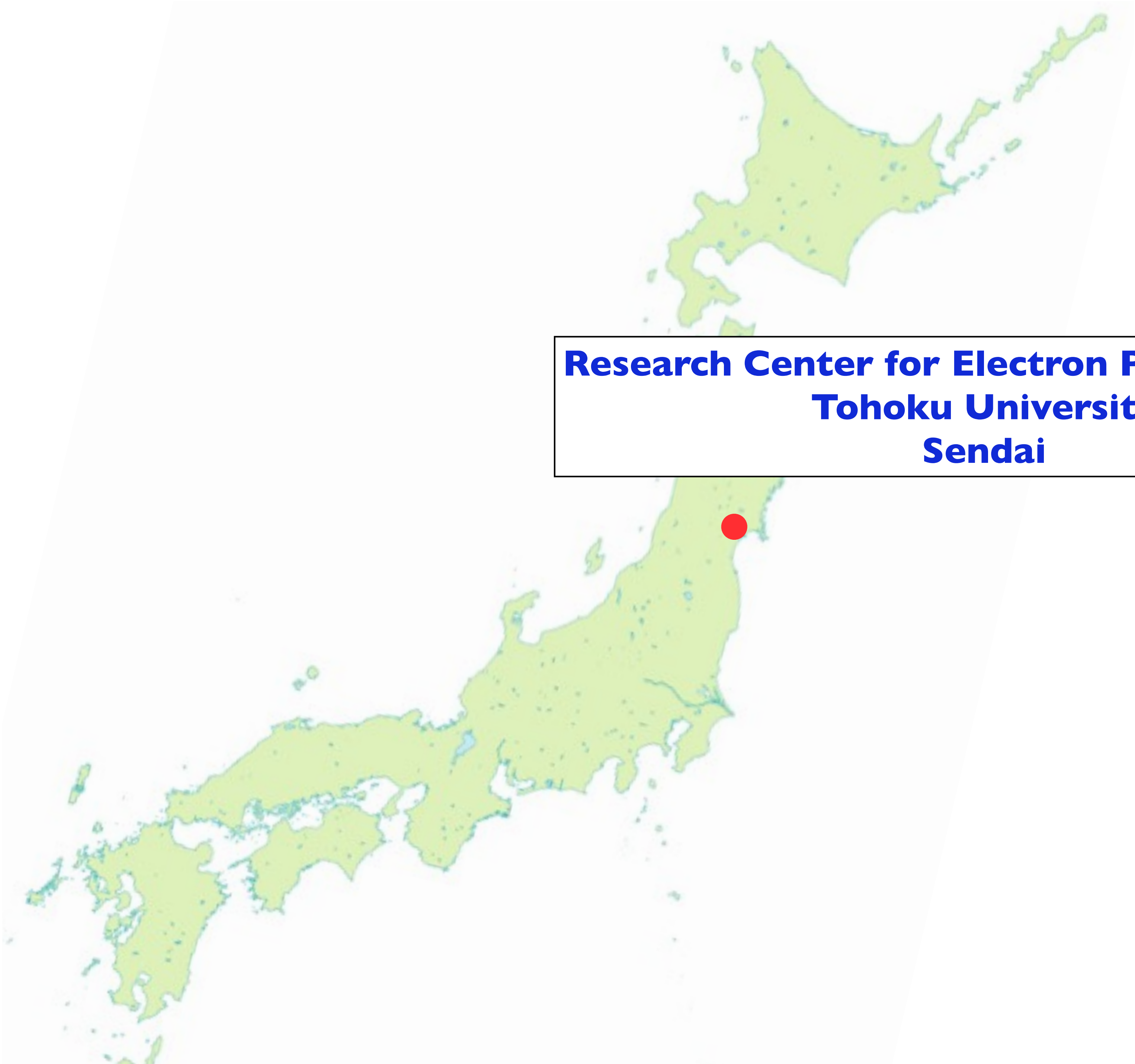
Electron scattering at Lower Q^2

experimental GE separation at ultra-low Q2

ELPH, Tohoku Univ. : only a electron scattering facility.

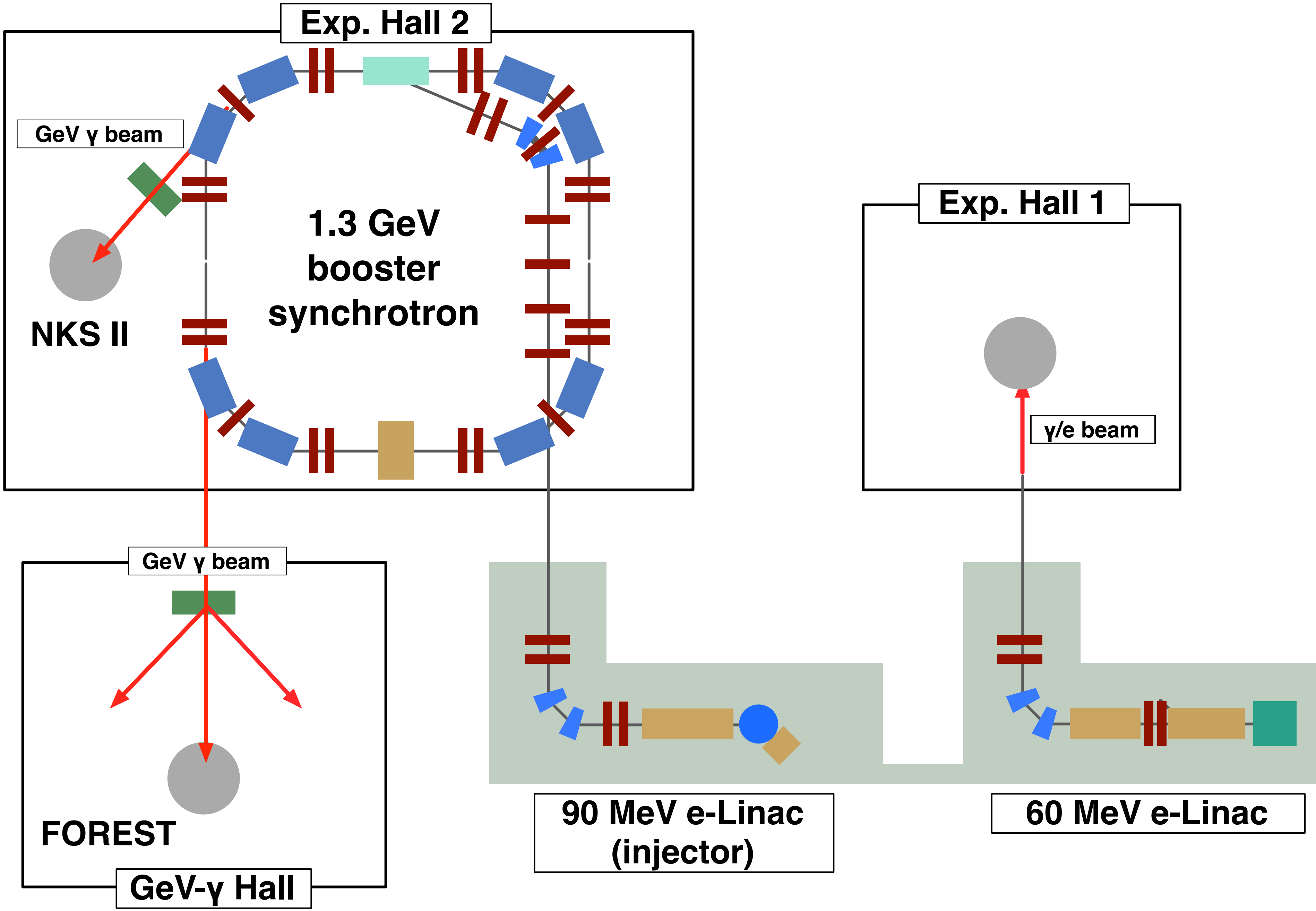
Lab.		Ee	θ	absolute dσ/dΩ	G_E, G_M separation
JLAB (USA)	Ultra-forward	1.1 - 2.2 GeV	1 - 4 deg.	○	X
Mainz (Germany)	lower Ee by Bremsstrahlung	195, 330, 490 MeV		X	X
TOHOKU	low Ee	20 - 60 MeV	30 - 150 deg.	○	○

Where are we ?



Research Center for Electron Photon Science
Tohoku University
Sendai

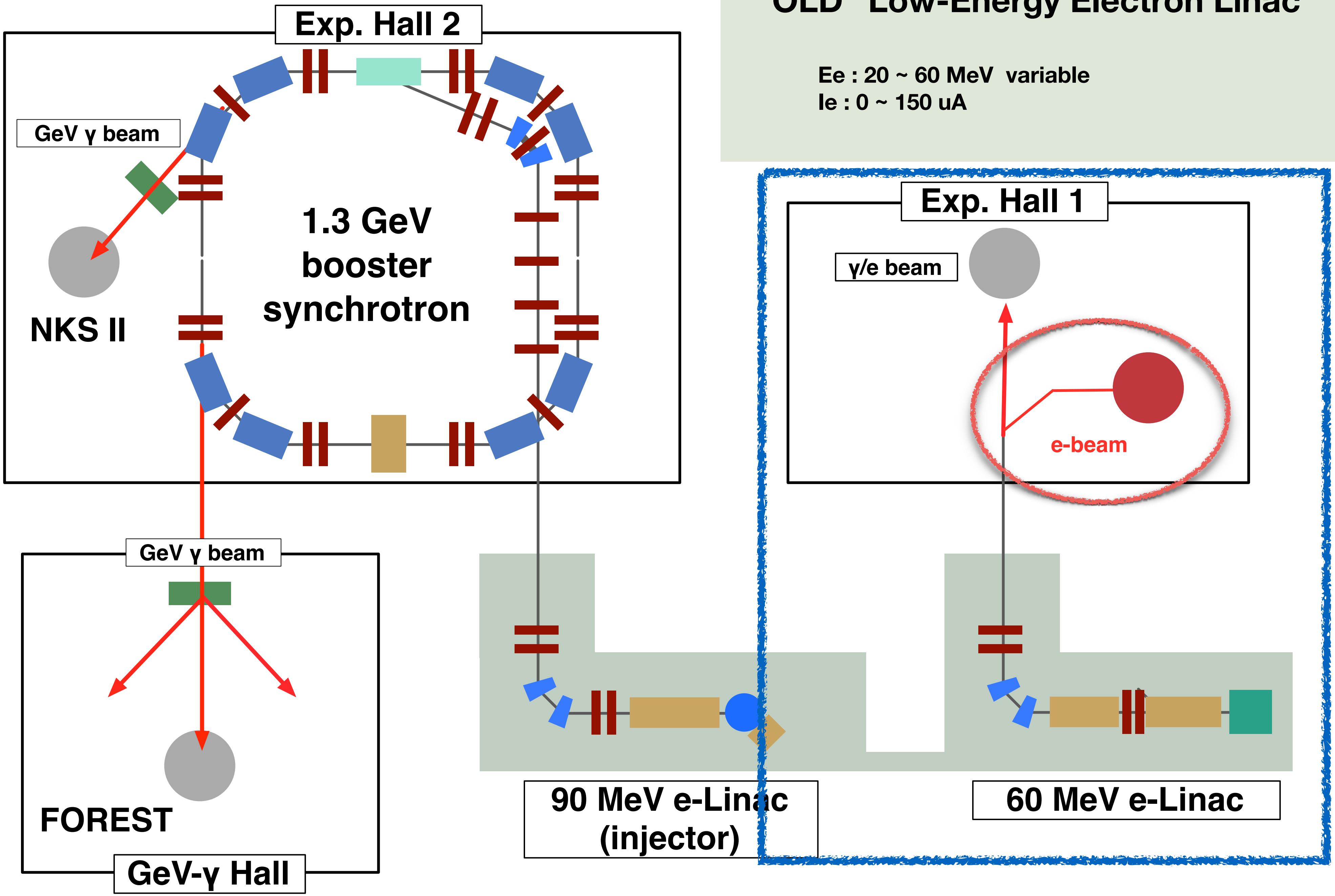
Research Center for Electron-Photon Science



Low-energy branch

“OLD” Low-Energy Electron Linac

Ee : 20 ~ 60 MeV variable
Ie : 0 ~ 150 uA



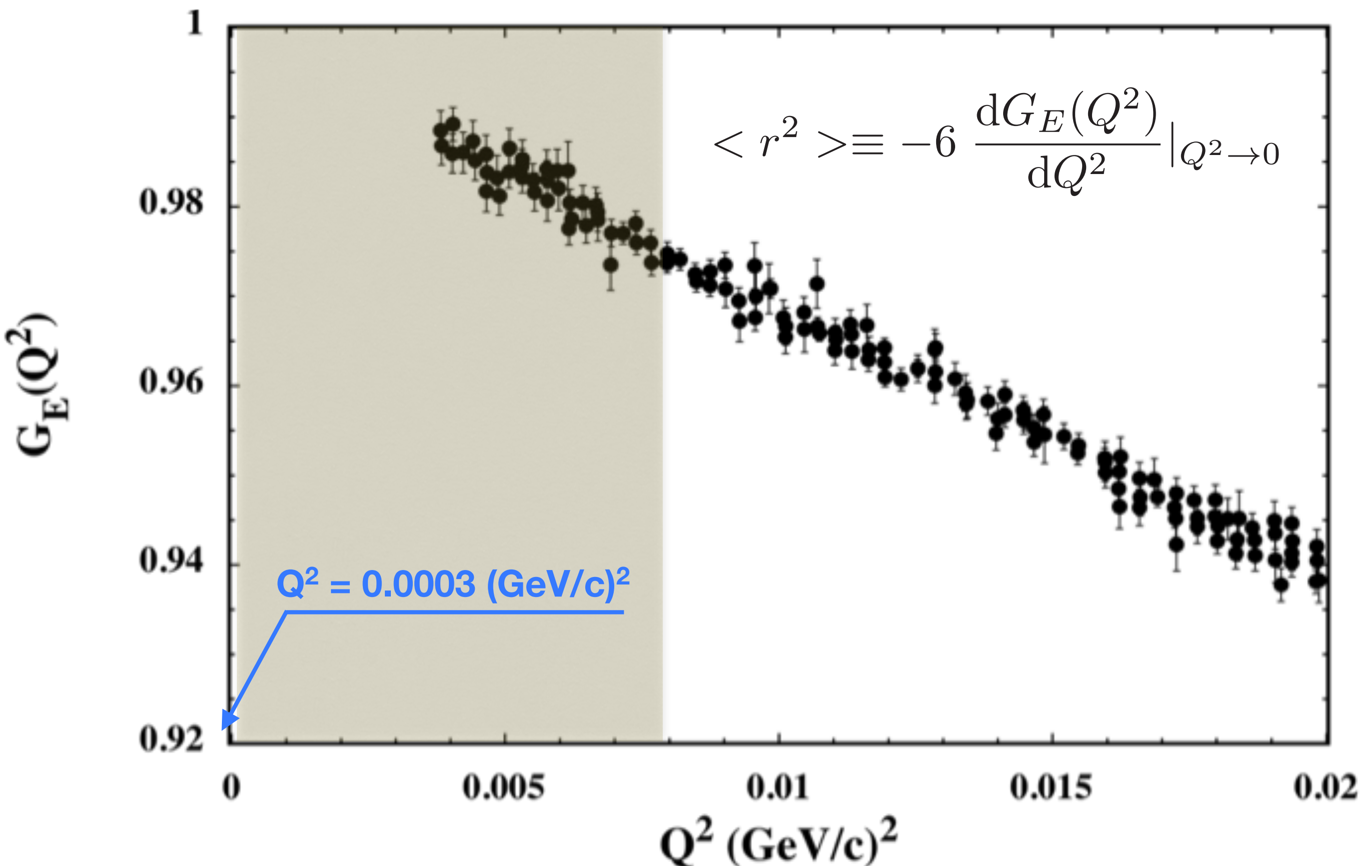
e-scattering off proton at ultra-low Q^2

Goal of our experiment

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

Our experiments

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



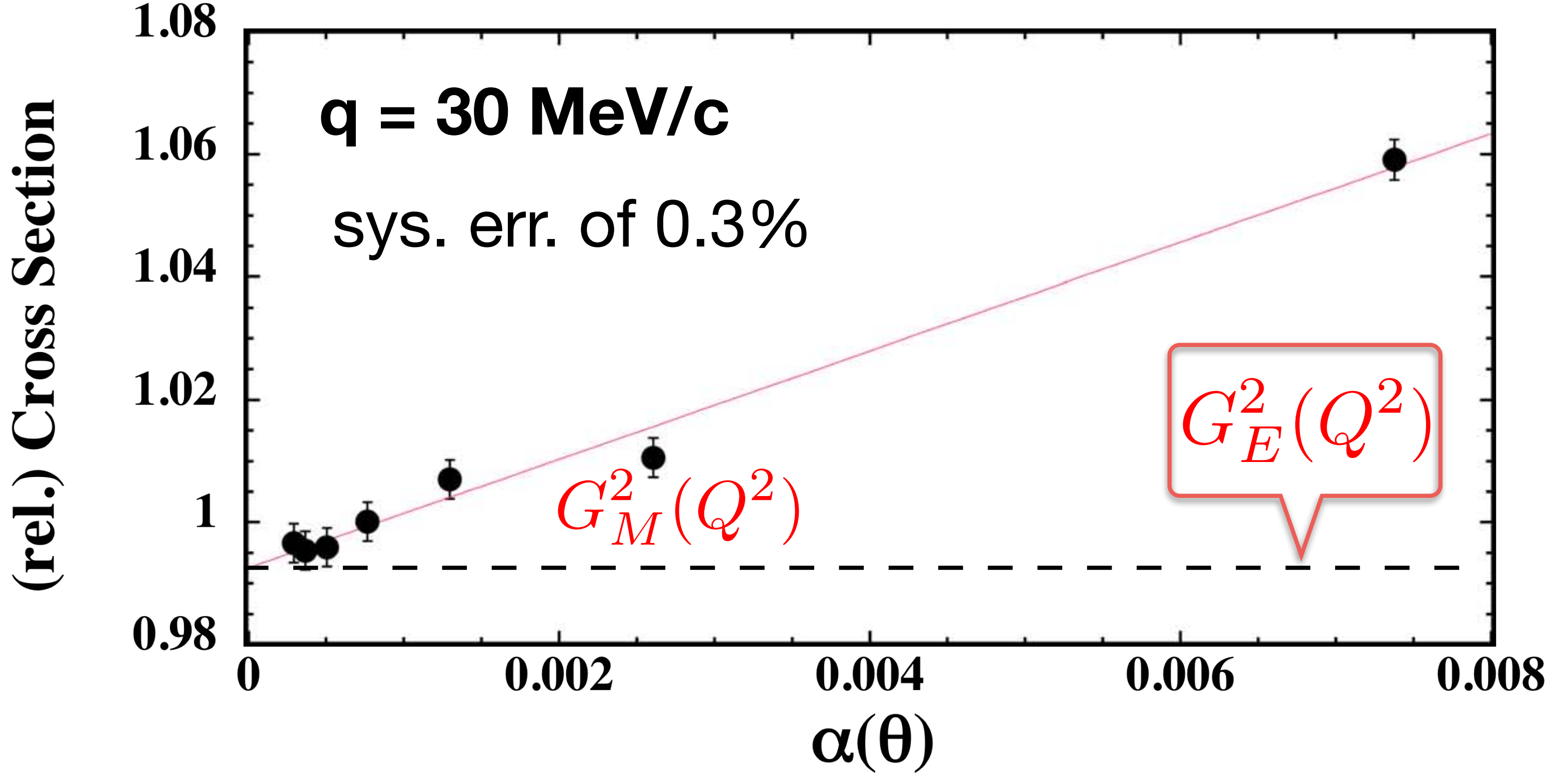
Rosenbluth separation (G_E/G_M)

Elastic cross section

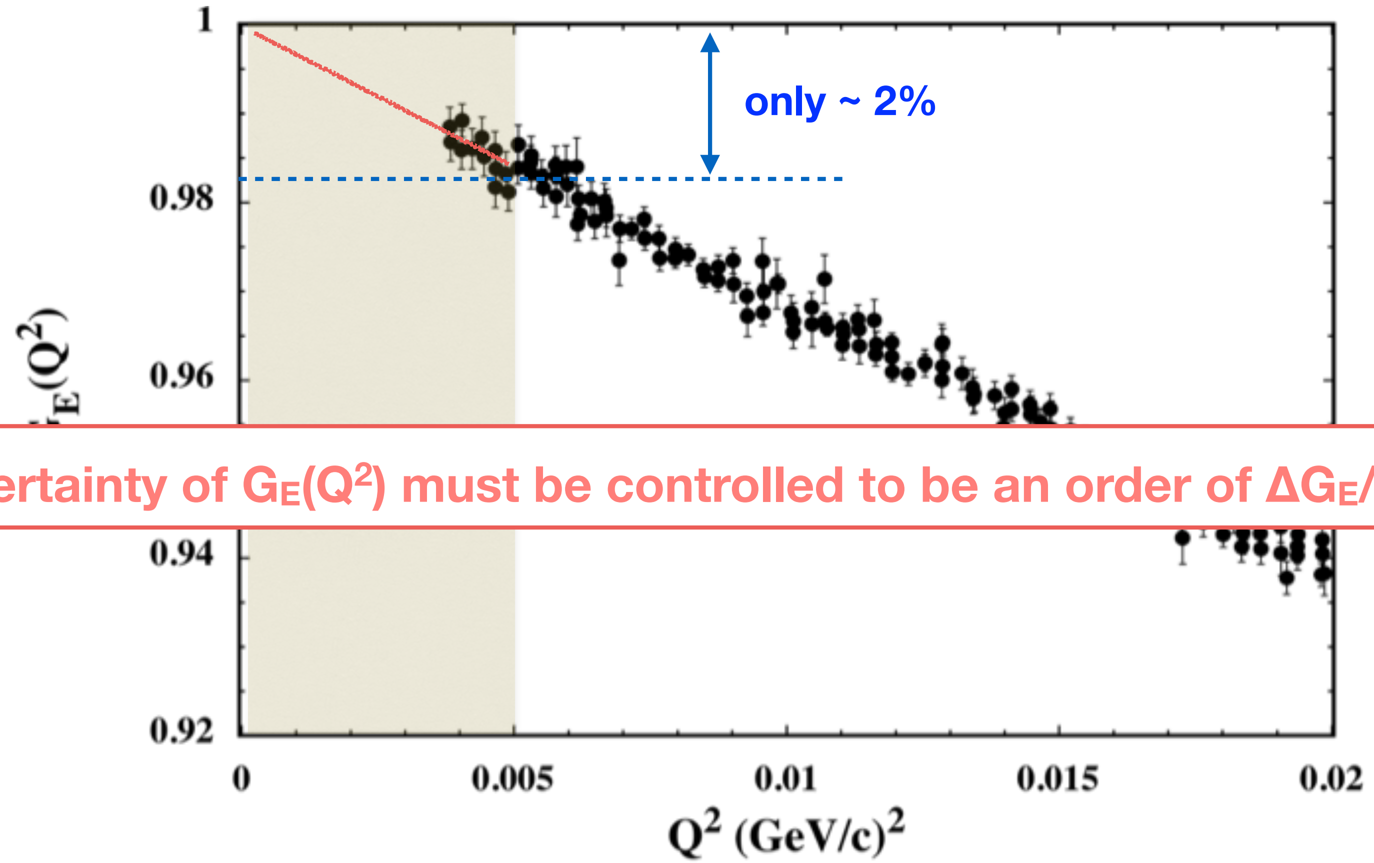
$$\frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + \alpha(\theta) G_M^2(Q^2) \qquad Q^2 = 4ee'\sin^2(\theta/2)$$

change $\alpha(\theta)$ under fixed Q^2 → different electron beam energies

Rosenbluth separation



A key of the e+p experiments at ULQ²



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

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

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

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

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

Canceled out in relative measurements

1) RMS charge radius (or ρ(r)) of ^{12}C ??

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

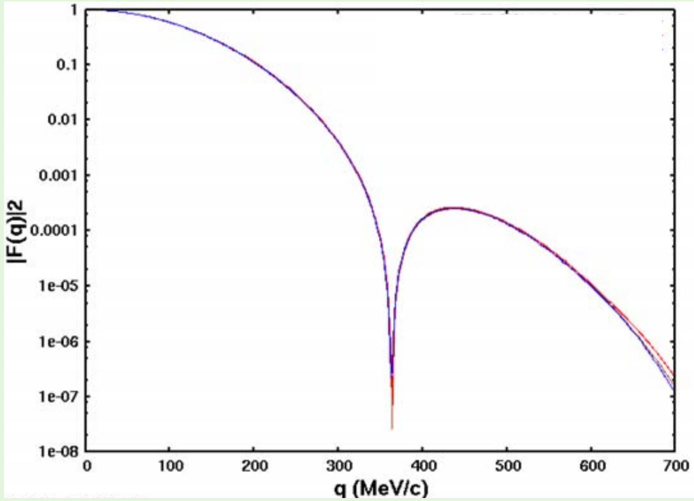
3) change of C/H ratio by beam irradiation ??

CH_2 (e,e') experiment

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

μ-Xray
electron scattering

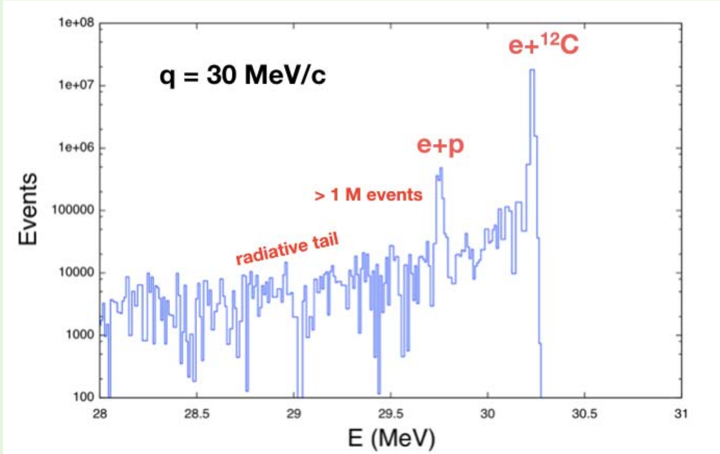
$$\frac{\Delta < r^2_{^{12}C} >^{1/2}}{< r^2_{^{12}C} >^{1/2}} \sim 3 \times 10^{-3}$$



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

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

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

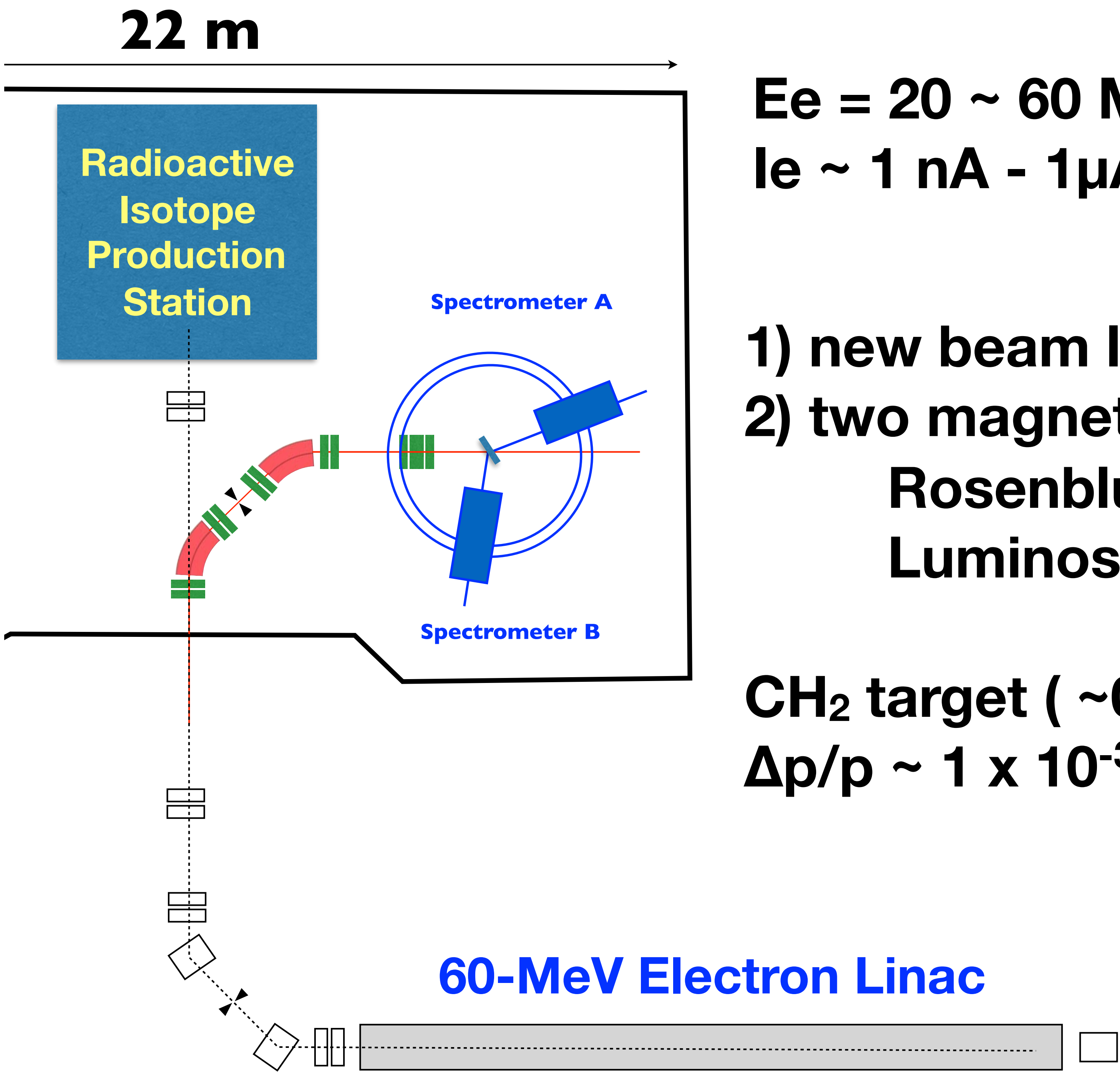


3) no severe damage of target is expected

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

Ie ~ 1 nA - 1 μA

Experimental setup at ULQ² exp.



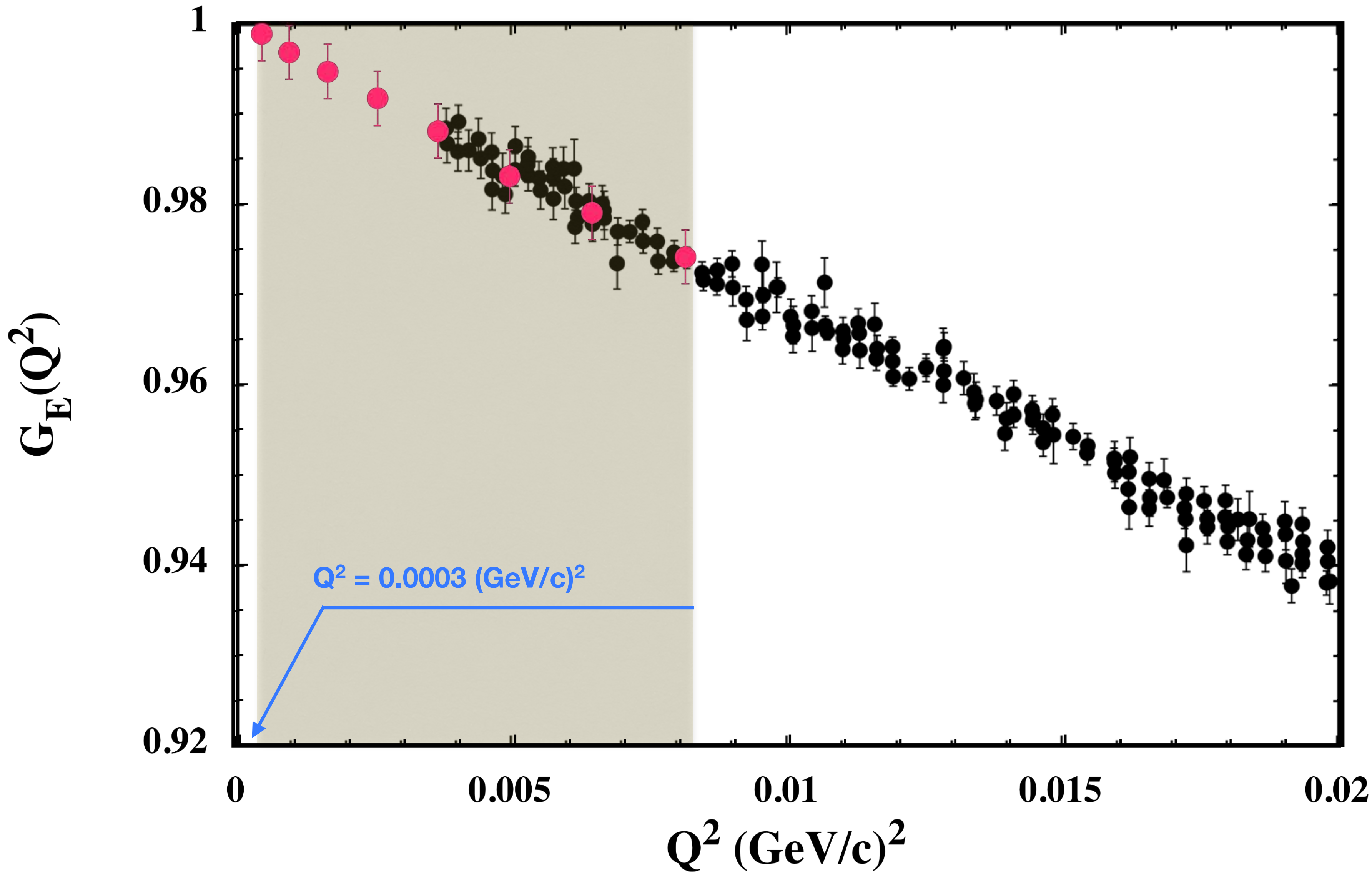
Ee = 20 ~ 60 MeV
Ie ~ 1 nA - 1μA

1) new beam line
2) two magnetic spectrometers
Rosenbluth measurements
Luminosity monitoring

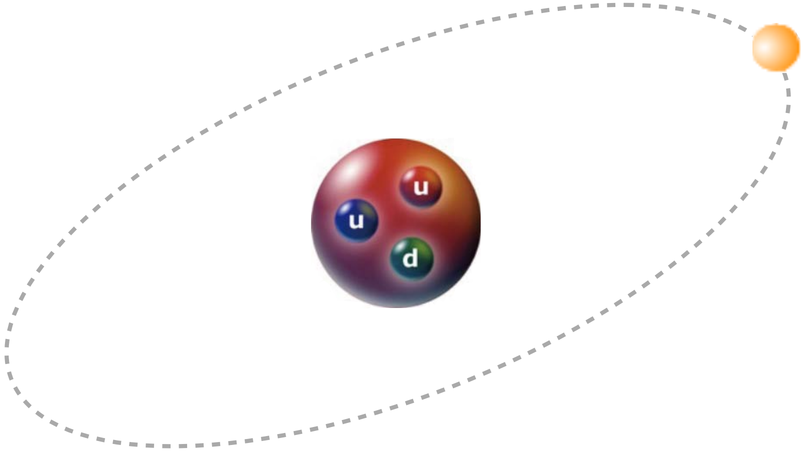
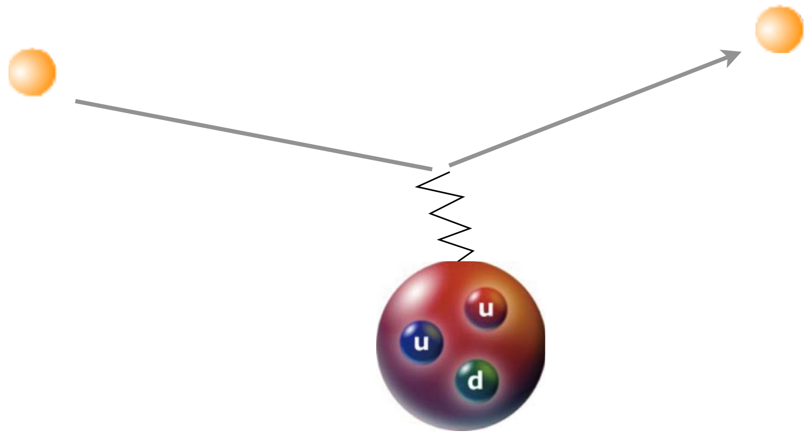
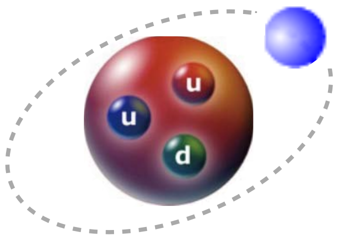
CH_2 target (~0.1 mm t)
$\Delta p/p \sim 1 \times 10^{-3}$

Rosenbluth-Separated $G_E(Q^2)$ at ULQ^2

Absolute cross section
Rosenbluth separation ⇨ $G_E(Q^2)$



How r_p has been determined ??

	Spectroscopy	Scattering
e^-		
μ^-		MUSE exp. @PSI is coming …

Summary

1) elastic e+p scattering at ultra-low Q^2 region

2) $G_E(Q^2)$ at $0.0003 \leq Q^2 \leq 0.008\ (\mathrm{GeV}/c)^2$

3) G_E is extracted by the Rosenbluth separation

4) absolute cross section measurement

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

5) Ee = 20 - 60 MeV, θ = 30 - 150°

6) constructing of new beam line, and spectrometers

7) the experiments will start in 2019

科研費・基盤（S）　2016 ~ 2020