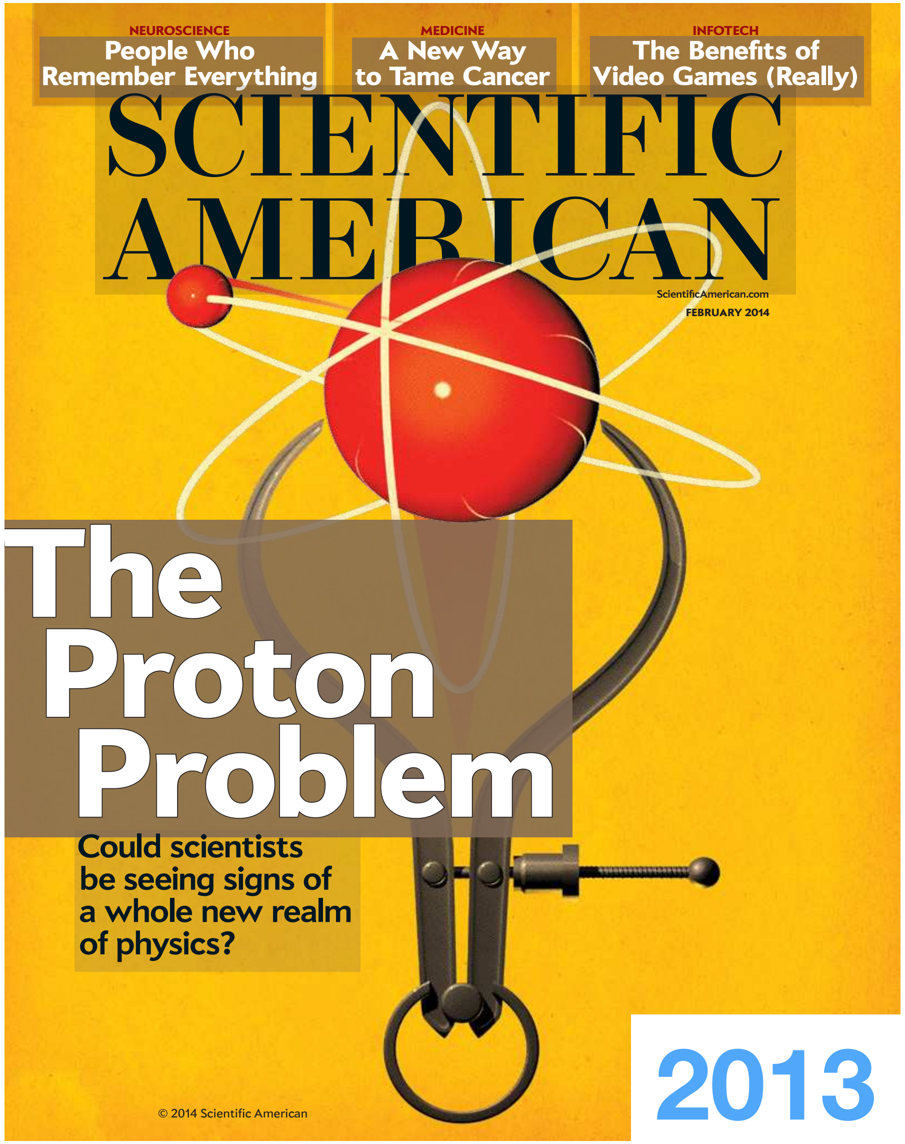
Proton Size

東北大学電子光理学研究センター
須田利美

Proton Radius Puzzle ?

2010



2013

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

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

全国共同研究・共同利用拠点

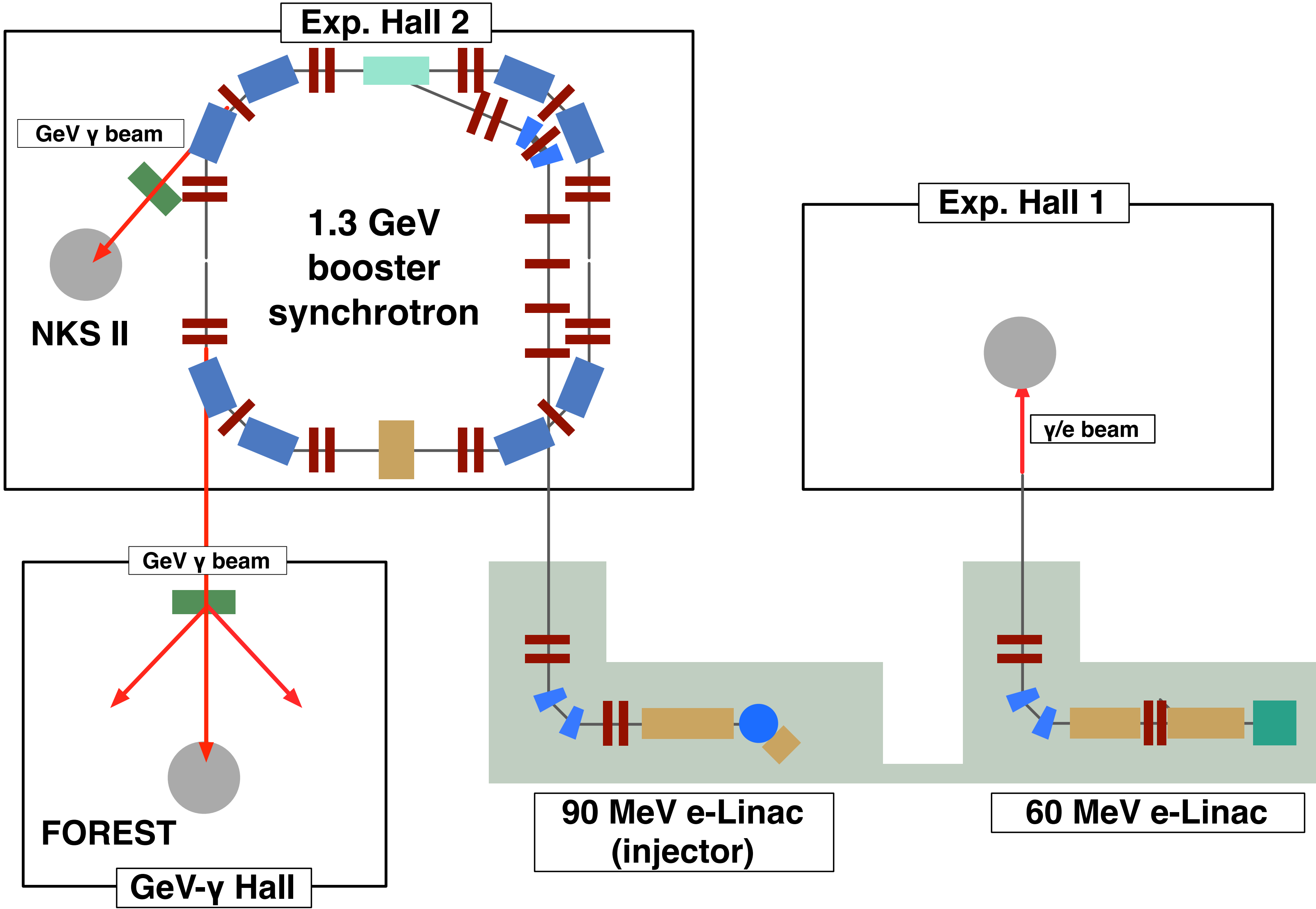

至 盛岡
至 盛岡
至 盛岡
仙山線
雨宮
星陵
48
45
仙台駅
仙台
仙台西道路
青葉山
川内
片平
青葉城跡
仙台宮城ＩＣ
八木山動物公園
野草園
八木山小
文
東北縦貫自動車道
赤十字病院
長町中
文
電子光理学研究センター
三神峯公園
文
西多賀中
東北大キャンパス
286
新仙台郵便局
山田ＩＣ
仙台南部道路
仙台南ＩＣ


三神峯公園
電子光理学研究センター

東北大学電子光理学研究センター（共同利用拠点）

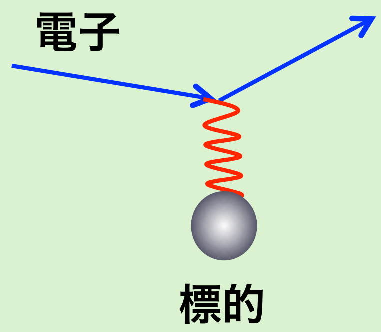
1.3 GeV Booster Ring
tagged photons (~ 1 GeV)
exp. on hadron, hypernucleus

60 MeV electron linac
~10 kW electron beam
Radioactive Isotope photo production



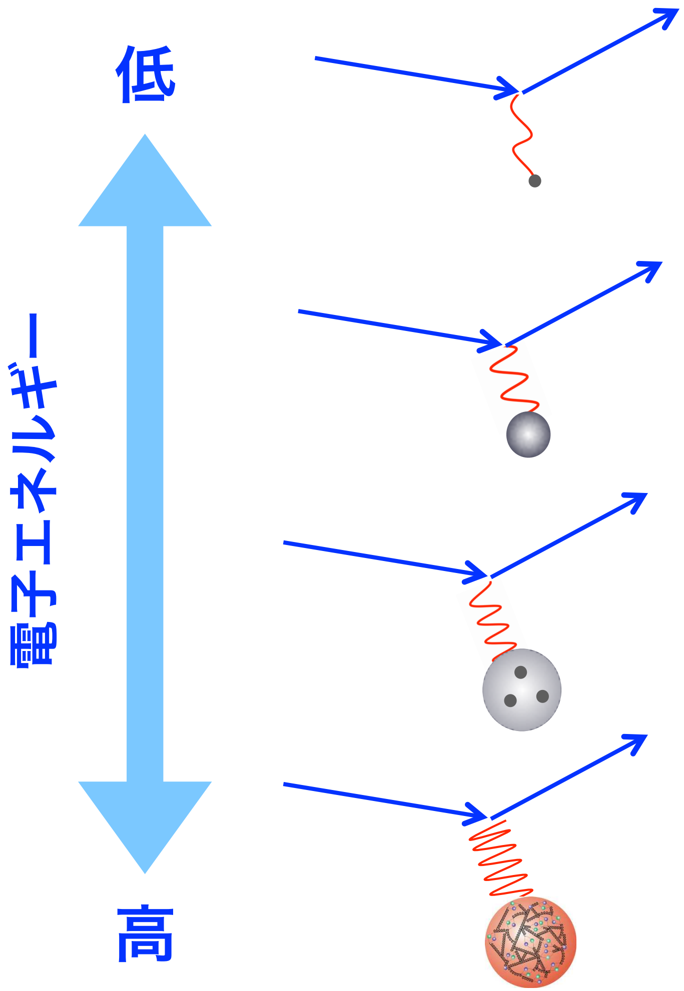
Electron Scattering

電子散乱



特徴

1）素粒子　　　　　内部構造を持たない
2）電磁相互作用　　反応機構の不定さなし
3）相互作用が弱い　内部構造の解明



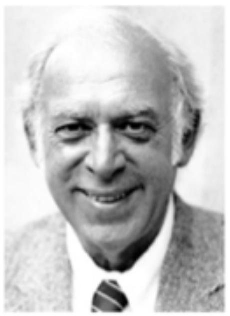
点状粒子

半径
電荷分布

クォーク

より詳細な
内部構造

R. Hofstadter

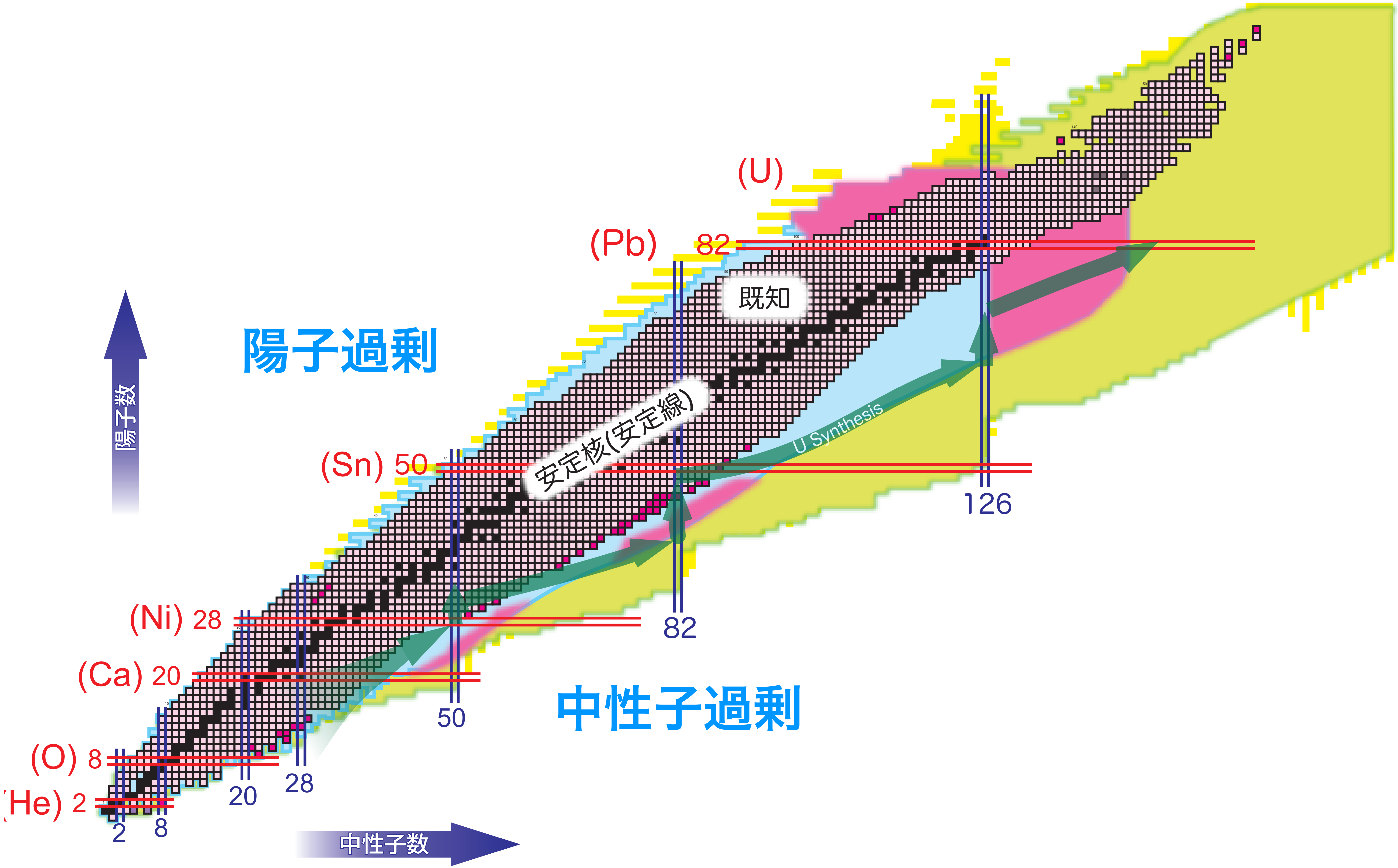


J. Friedman, H. Kendall,R. Taylor

Structure studies of neutron-rich nuclei by electron scattering

電子散乱による短寿命中性子過剰核の構造研究

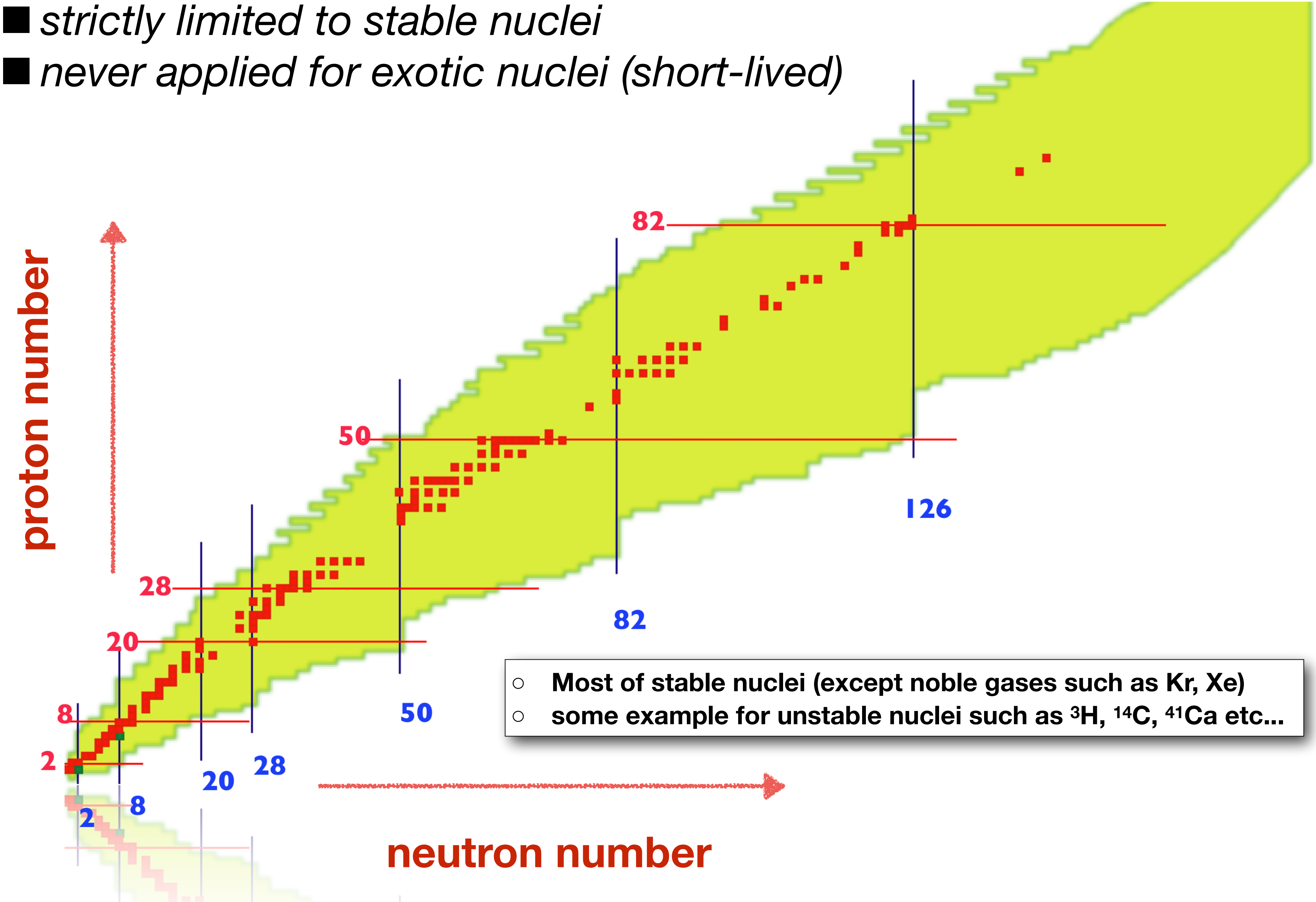
キーワードは短寿命不安定核



電子散乱の対象となった原子核

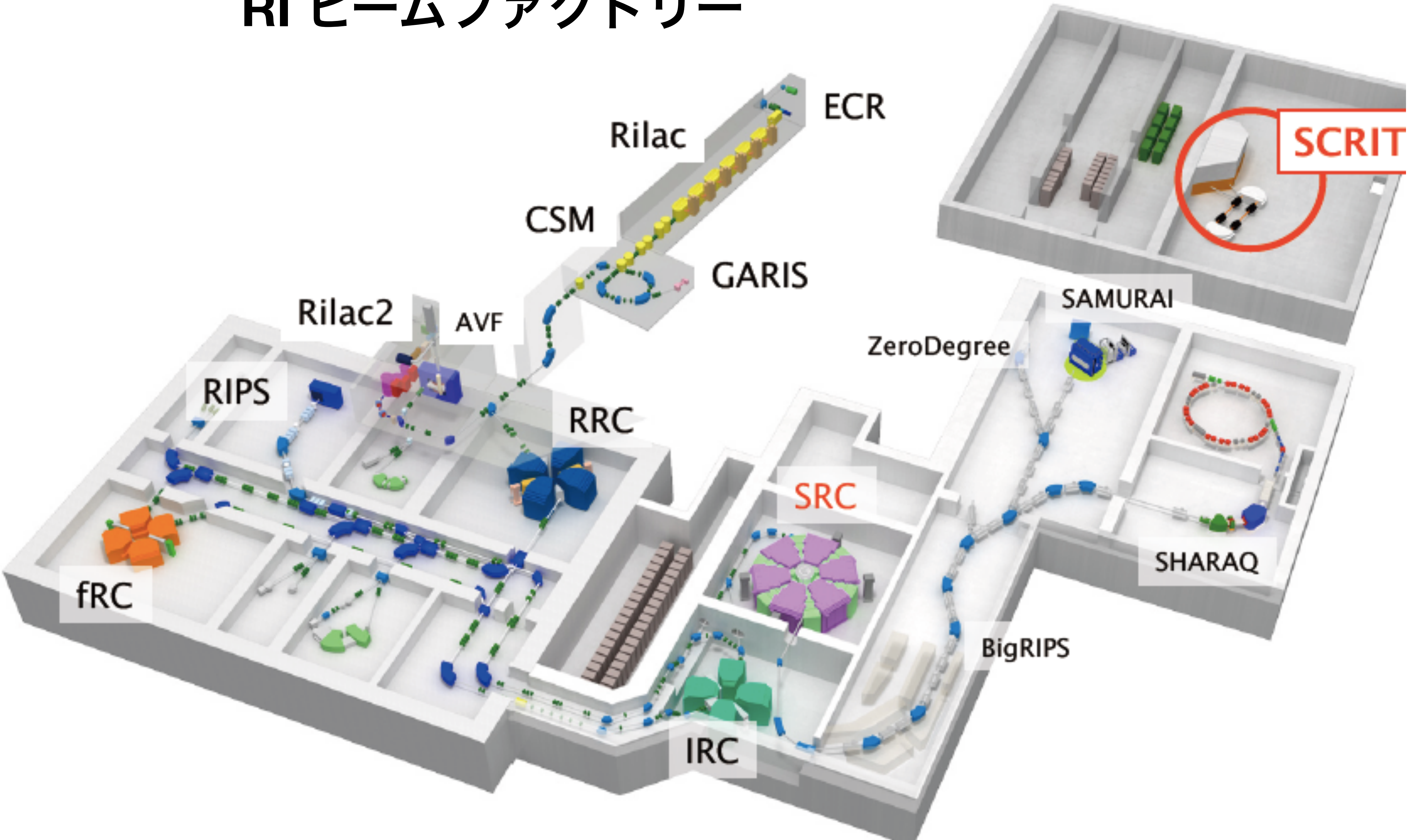
H.deVries, C. deJager and C. deVries
Atomic Data and Nuclear Data Tables 36 (987)495

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



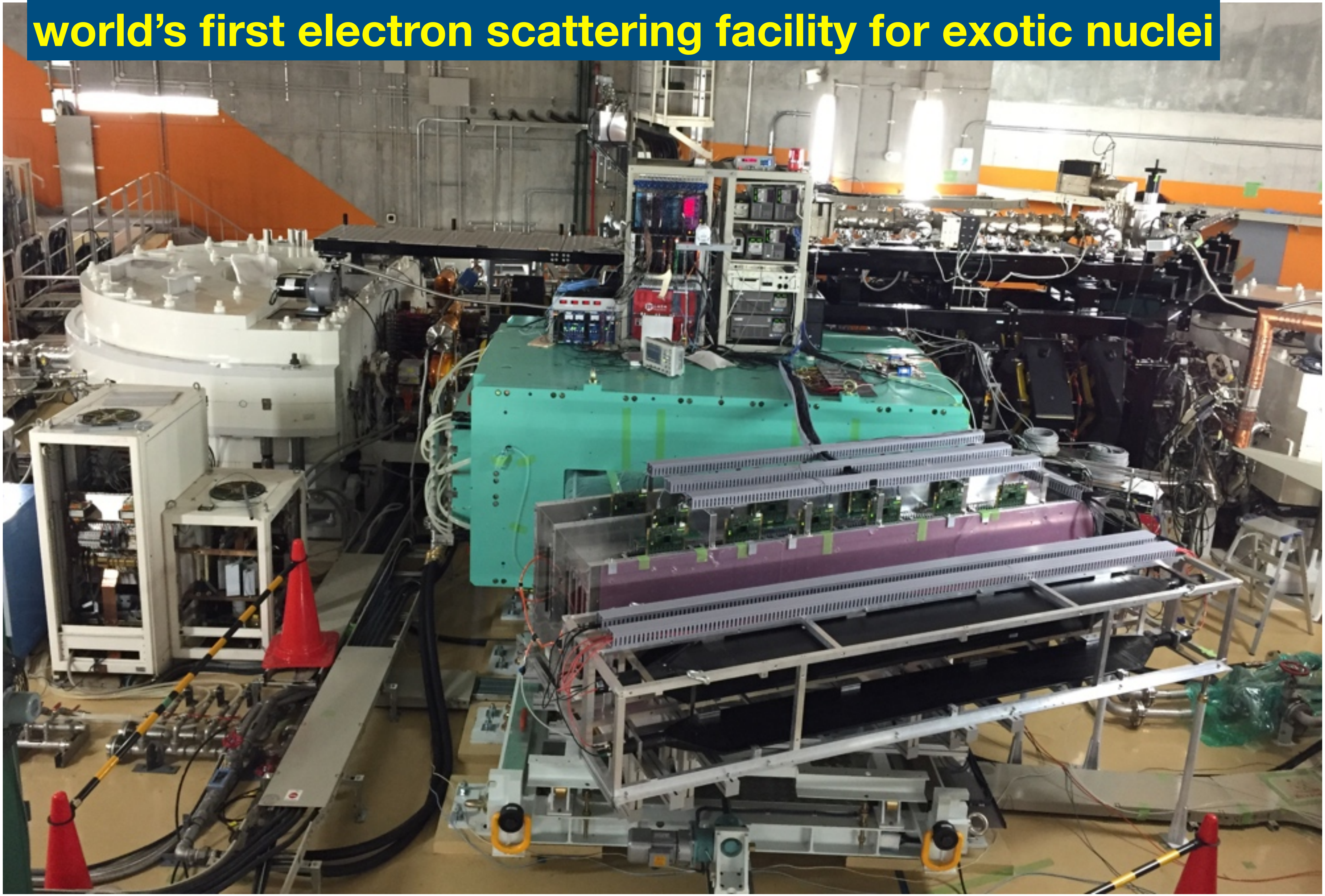
- Most of stable nuclei (except noble gases such as Kr, Xe)
- some example for unstable nuclei such as ^{3}H, ^{14}C, ^{41}Ca etc...

理化学研究所・仁科加速器研究センター
RI ビームファクトリー



SCRIT facility in RIKEN/RI Beam Factory

world’s first electron scattering facility for exotic nuclei



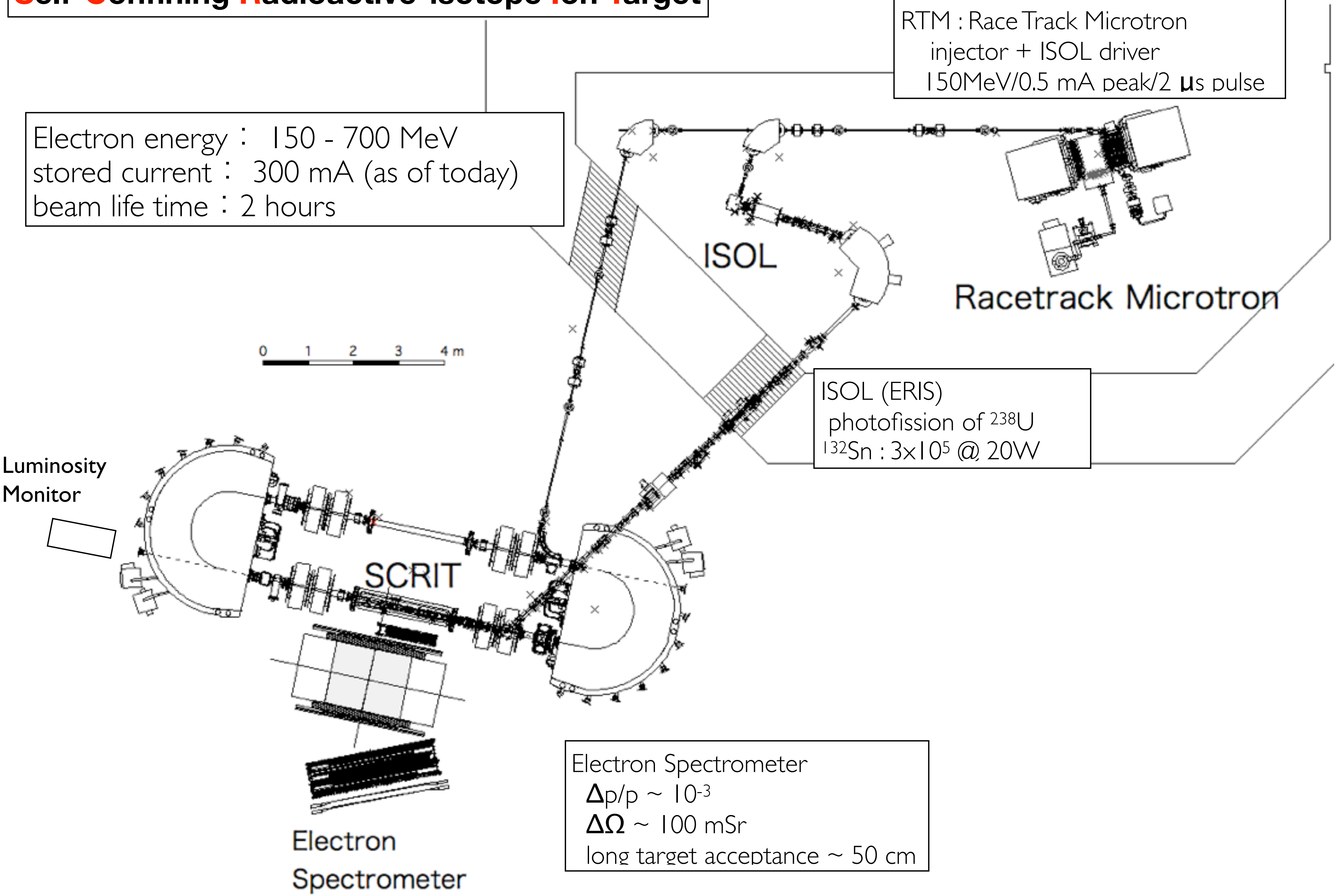
SCRIT electron scattering facility@RIBF

基研研究会　2018/8/6-8/10
素粒子物理学の進展2018

Self-Confining Radioactive-isotope Ion Target

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

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



ISOL (ERIS)
photofission of ^{238}U
^{132}Sn : 3×10^5 @ 20W

Electron Spectrometer
$\Delta p/p \sim 10^{-3}$
$\Delta\Omega \sim 100$ mSr
long target acceptance ~ 50 cm

Luminosities

	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**

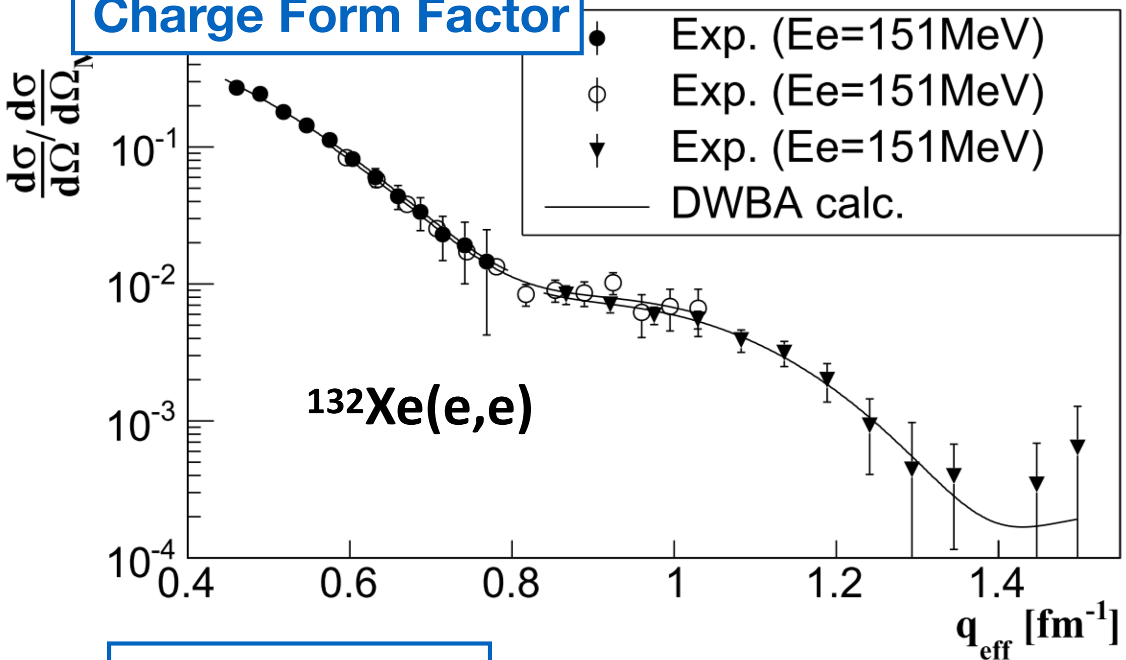
~10^8 ions are trapped on e-beam (~ 1 mm^2)

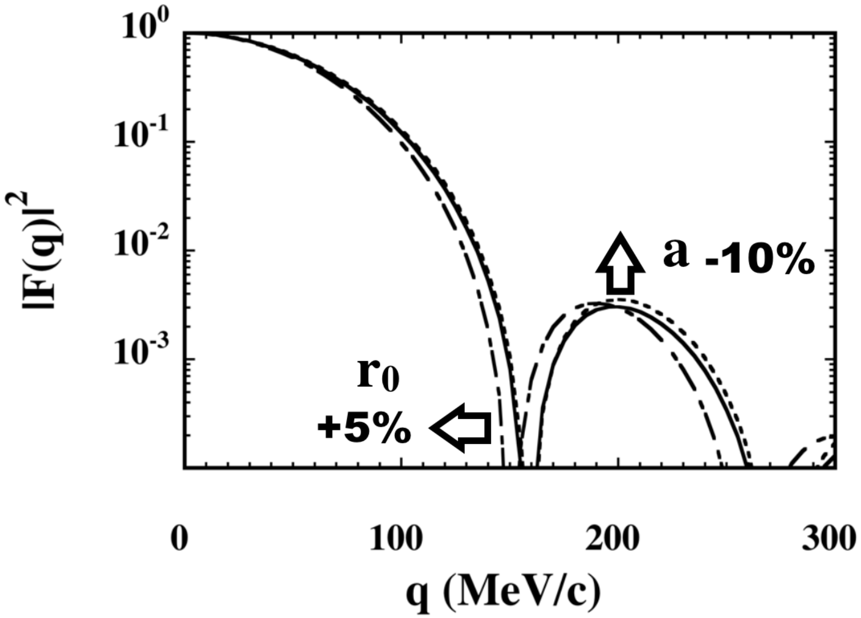
N_t ~10^8 /mm^2 => 10^{10} /cm^2

First experiment at SCRIT facility

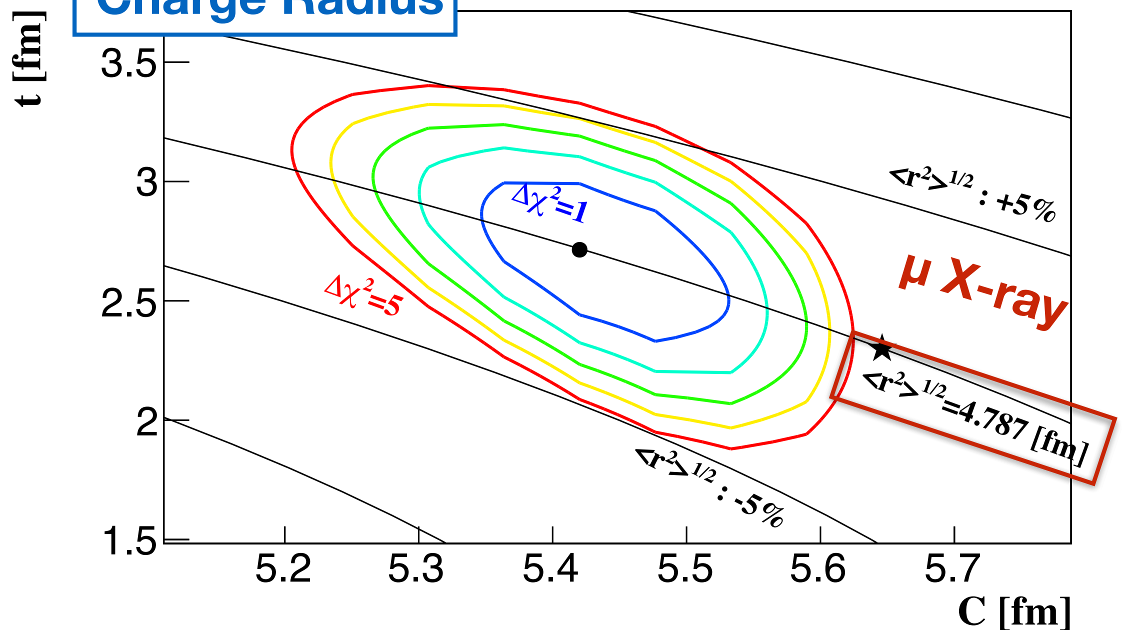
^{132}Xe(e,e') with only ~10^8 target ions

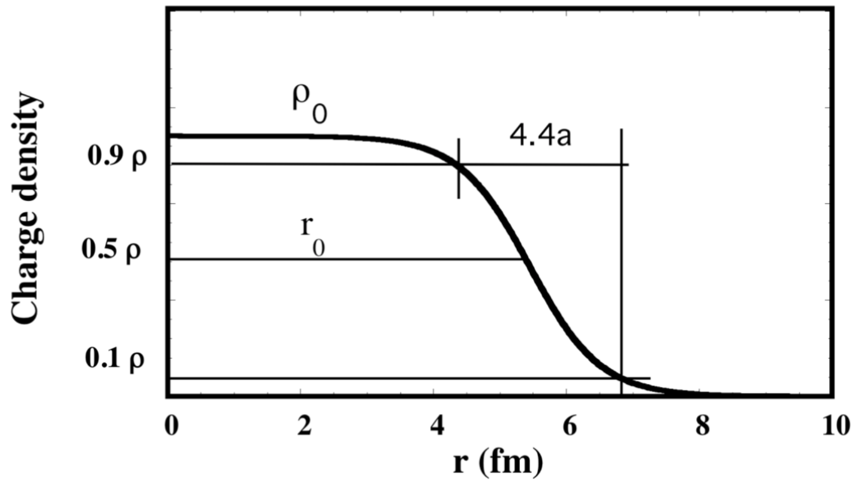
Charge Form Factor





Charge Radius





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

９月１５日

60 years of Physical Review Letters

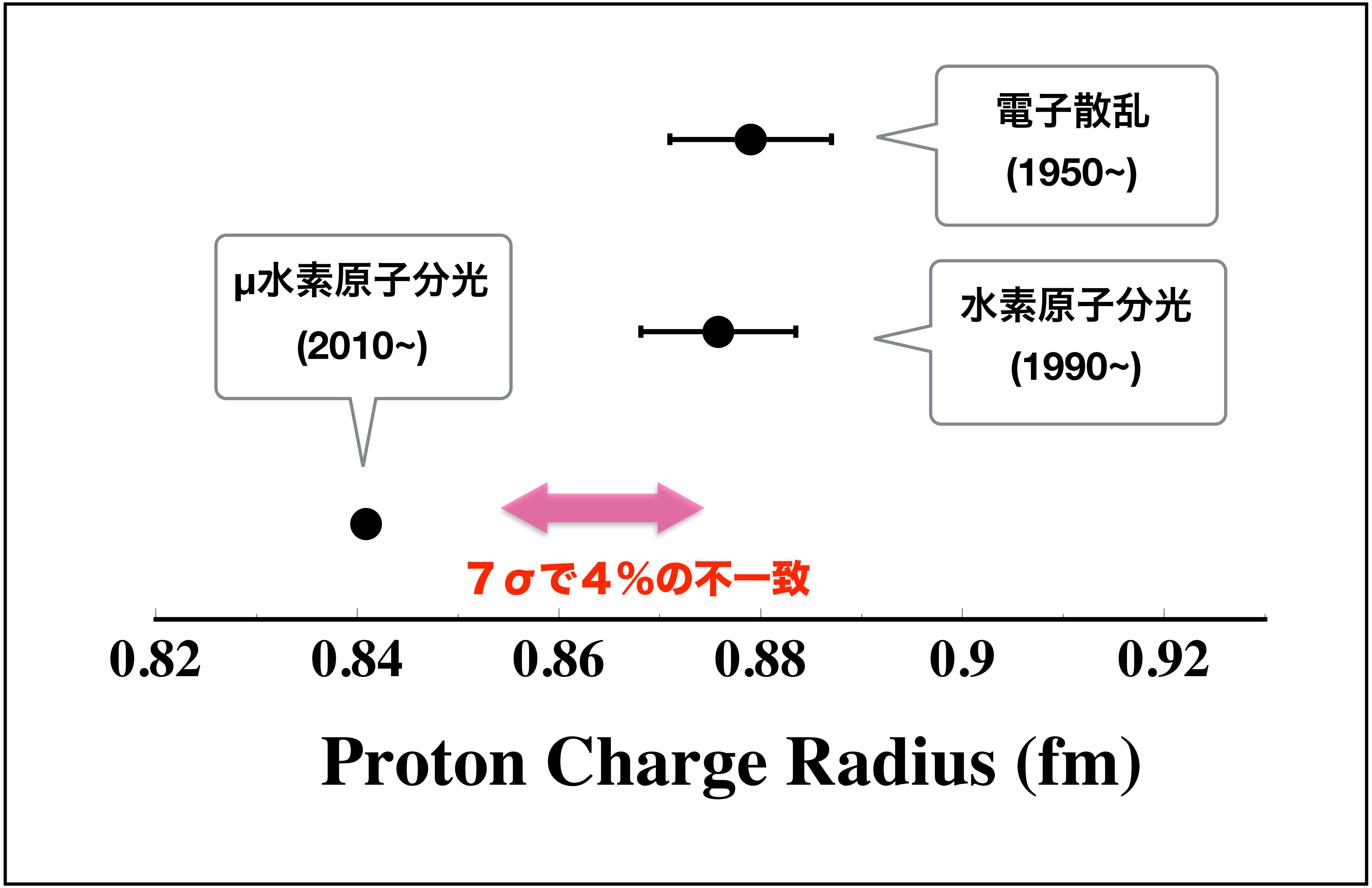
15日 S20会場 13:30~17:10
領域横断
(共催：American Physical Society　)

1. 60 years of PRL: looking back and forward	PRL, APS Garisto Robert
2. The Calorimetric Electron Telescope (CALET) Experiment on the International Space Station	Sci. Eng. Waseda Univ. Shoji Torii
3. Lovely phase space	Kavli-IPMU, Univ. Tokyo Melia Thomas Edward
4. Nuclear experimental approach toward the nucleosynthesis in the universe	Sci. Osaka Univ. Takahiro Kawabata
Break	
5. The SCRIT electron Scattering facility: Toward the world's first study of unstable nuclei by electron	ELPH, Tohoku Univ. Kyo Tsukada
6. Observation of high-energy cosmic rays with the Tibet air shower array	ICRR, Univ. Tokyo Masato Takita
7. From CP violation to XYZ particles	Sci., Nara Women's Univ. Kenkichi Miyabayashi
8. Quest for CP violation in neutrino oscillation	Sci., Kyoto Univ. Atsuko K. Ichikawa

Proton Radius Puzzle

2010~

Proton Radius Puzzle ?



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

Particle Data (2017)

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

N BARYONS
$(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

p

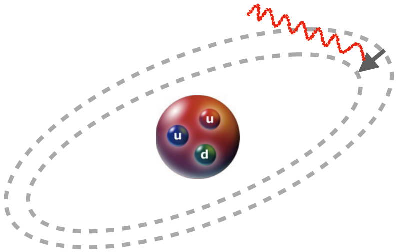
$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.792847351 \pm 0.000000009 \; \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0.3 \pm 0.8) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ e cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift = 0.84087 ± 0.00039 fm [d]
Charge radius, $e p$ CODATA value = 0.8751 ± 0.0061 fm [d]
Magnetic radius = 0.78 ± 0.04 fm [e]
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

Why is the proton (charge) 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



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

3) possible new physics beyond SM (??)

Lepton Universality ??

possible MeV-order force carrier ⟷ (g-2) μ 3.5 σ discrepancy

(dark photon …?)

4) (bound) QED high precision calculations

e-p scattering and form factor

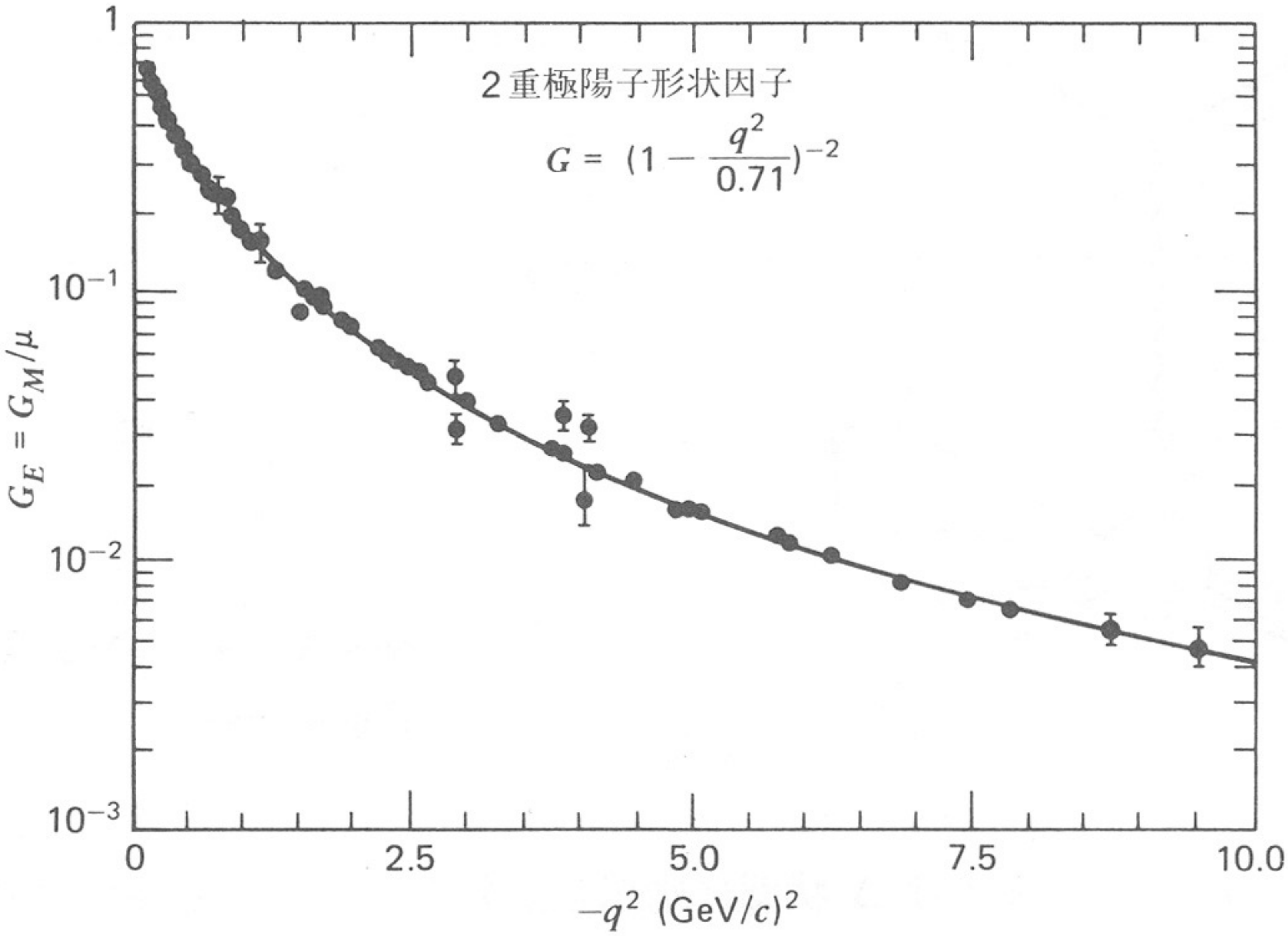


図8·4　q^2の関数としての陽子形状因子

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)

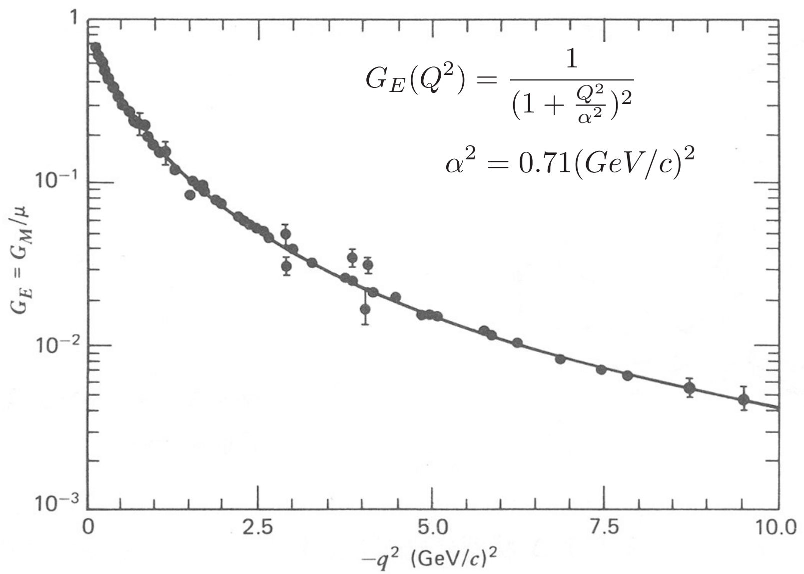
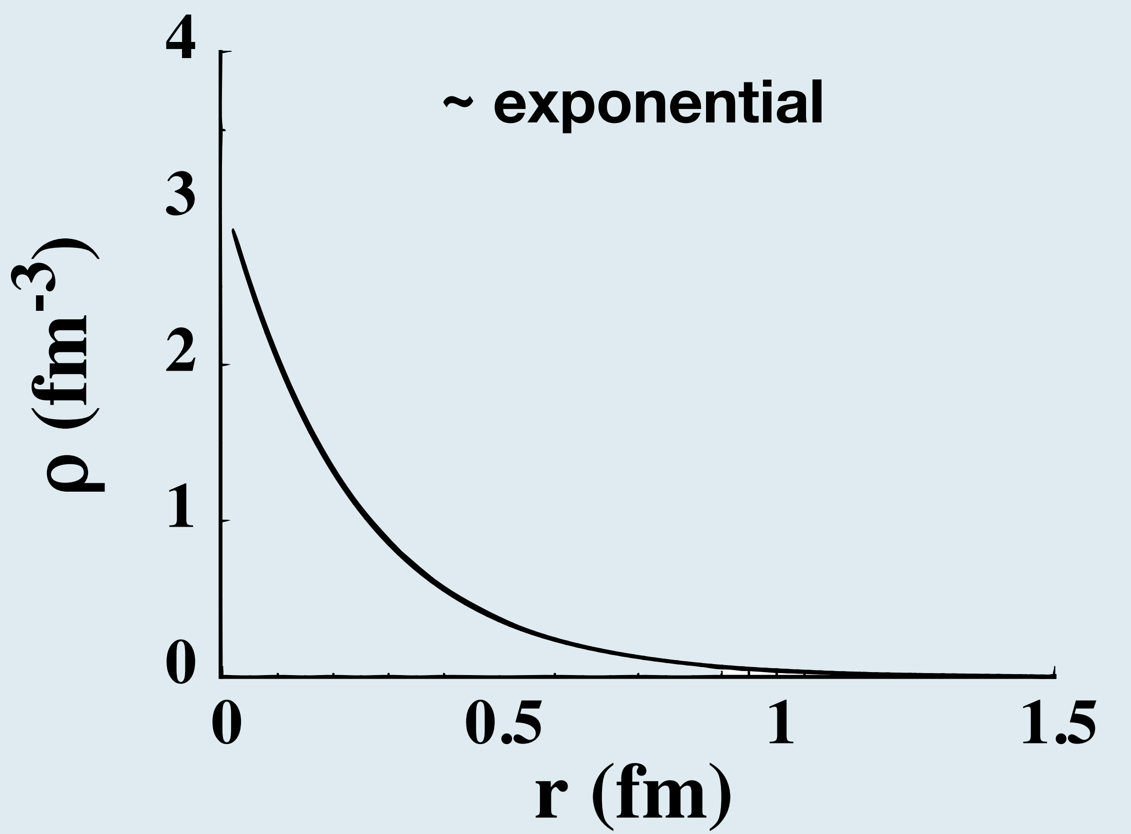


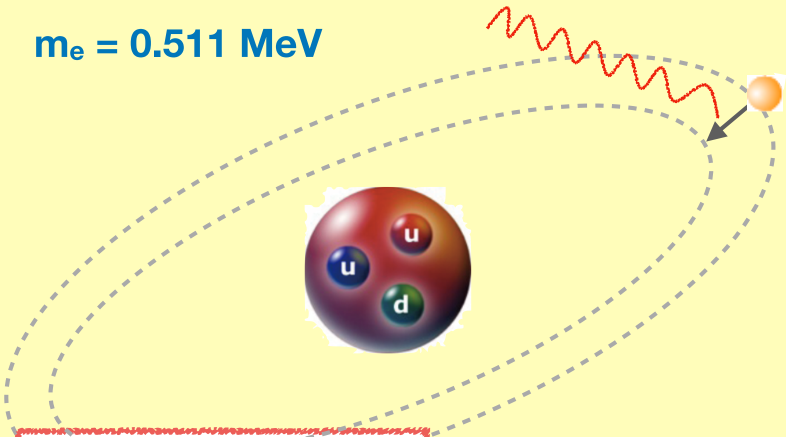
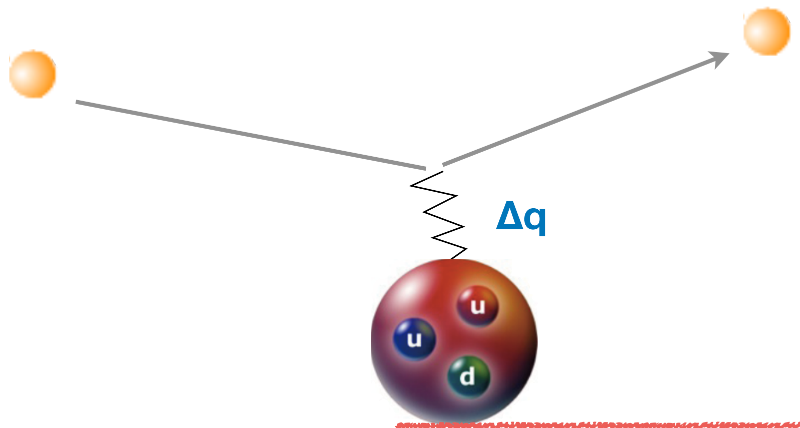
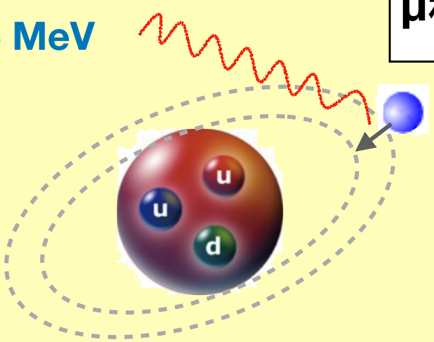
図 8·4　q^2 の関数としての陽子形状因子

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



Proton Charge Radius
by
Hydrogen spectroscopy

陽子電荷半径測定方法

	Spectroscopy	Scattering
e^-	m_e = 0.511 MeV  0.8758(77)	 0.8770(60)
μ^-	m_μ = 105.6 MeV  0.8409(4)	

陽子半径 ~ 10^{-15} m
電子軌道 ~ 10^{-10} m
μ粒子軌道 ~ 10^{-12} m

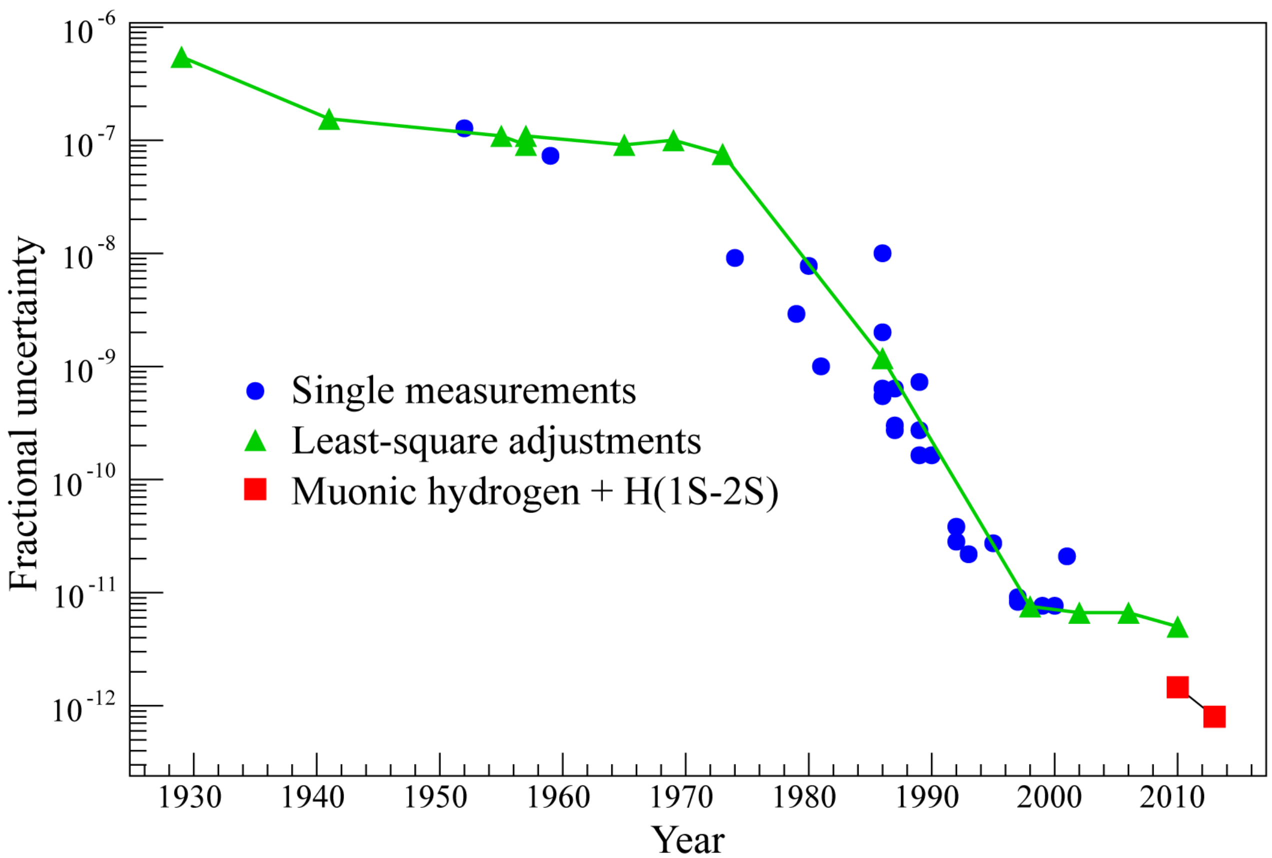
Rydberg constant

the most accurately determined fundamental constant

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

r_p uncertainty

Uncertainty of Rydberg constant determination over time



Hydrogen Spectroscopy

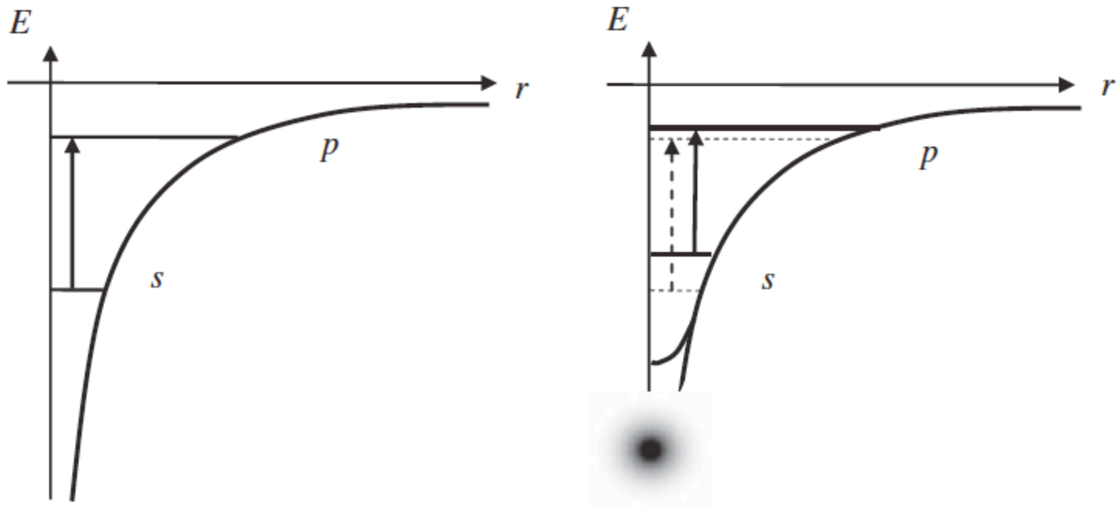
$$E(n,l,j) = -\frac{R_\infty}{n^2}\frac{m_{red.}}{m} + \frac{E_{NS}}{n^3}\delta_{l0} + \Delta(n,l,j)$$

Main　　**Proton size**　　**Higher order**

R_∞ : Rydberg constant

$$E_{NS} = \frac{2m}{3h}\alpha^2\left(\frac{m_{red.}}{m}\right)^3\left(\frac{<r>^2}{\lambda_C}\right)^2$$

Δ : radiative correction, polarizability etc.



$$\Delta E = -e^2 \int\int \frac{\rho_n(\boldsymbol{r}_n)\,\rho_e(\boldsymbol{r}_e)}{|\boldsymbol{r}_n - \boldsymbol{r}_e|}d\boldsymbol{r}_n d\boldsymbol{r}_e - \left[-Ze^2\int\frac{\rho_e(\boldsymbol{r}_e)}{r_e}d\boldsymbol{r}_e\right]$$

$$= -4\pi e^2 \int_0^\infty \rho_n(r_n)r_n^2dr_n \cdot 4\pi\left[\int_0^{r_n}\frac{\rho_e(r_e)}{r_n}r_e^2dr_e + \int_{r_n}^\infty\frac{\rho_e(r_e)}{r_e}r_e^2dr_e - \int_0^\infty\frac{\rho_e(r_e)}{r_e}r_e^2dr_e\right]$$

proton charge radius

μ-hydrogen Spectroscopy

PSI **(Paul Scherrer Institute)**

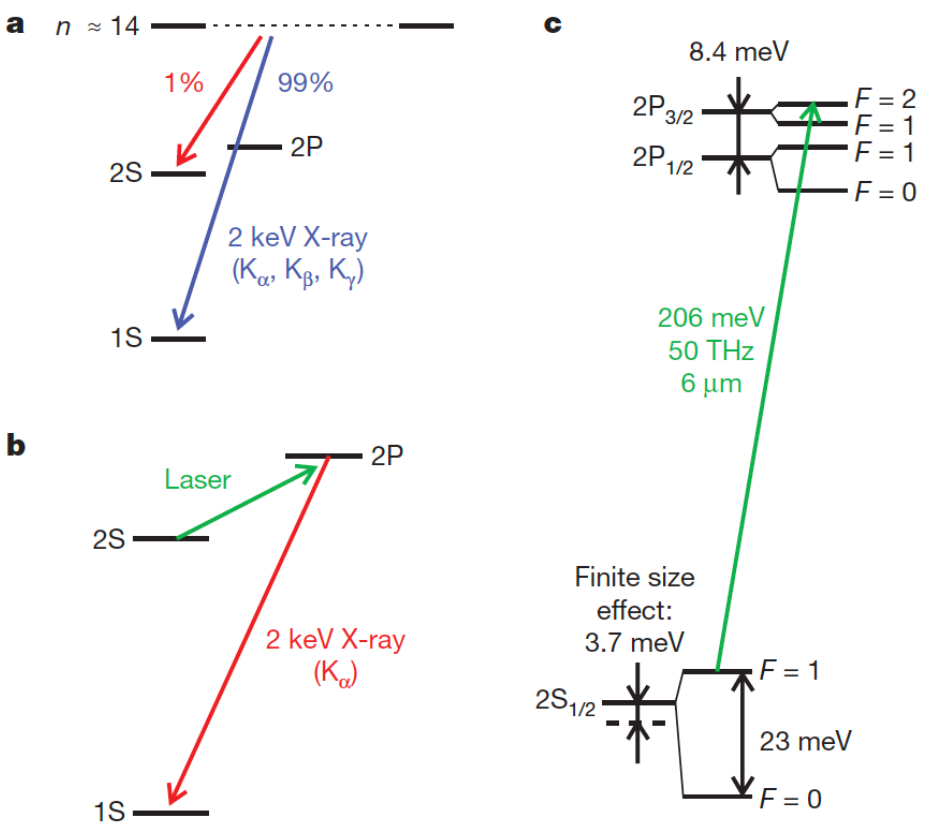
N_μ ~ 600 /s
E_μ = 3 - 6 keV
beam cross section : 0.5 x 1.5 cm^2

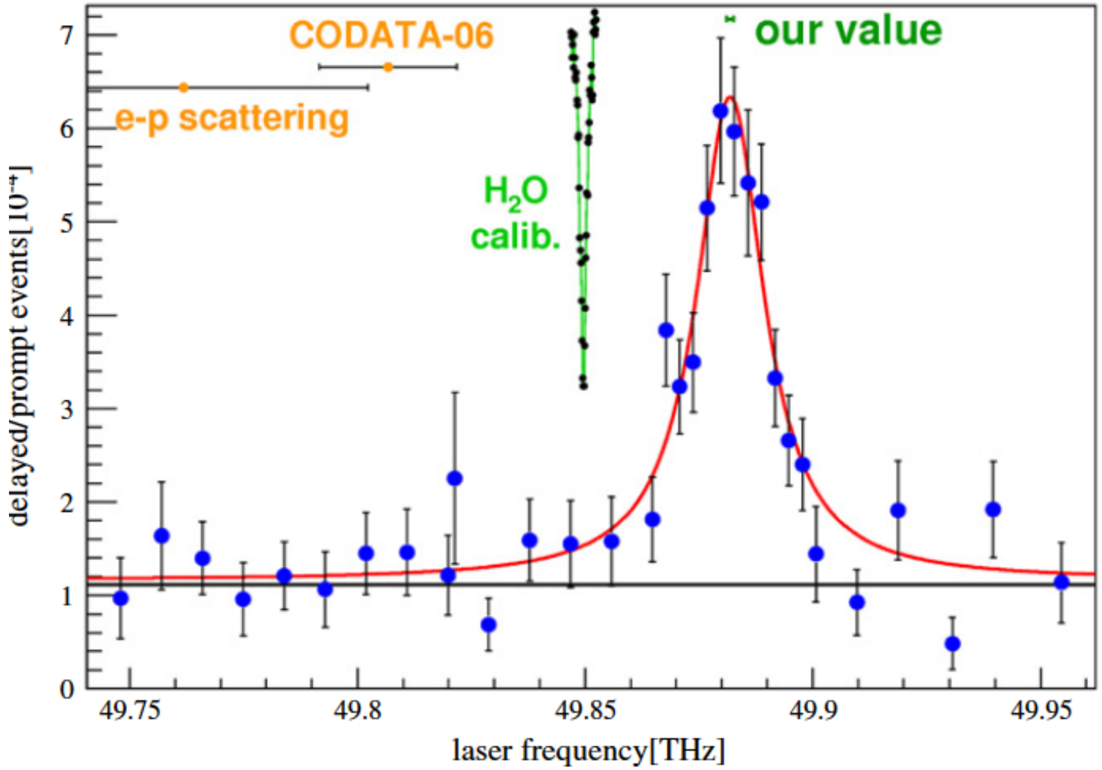
H_2 gas target　:　~1mbar, 20cm

μ^- beam

trapped to the hydrogen orbital（n ~ 14)
〜1% of μ trapped in metastable 2S（~1μS)

Laser excitation for 2S -> 2P
measuring the decay 2keV X-rays

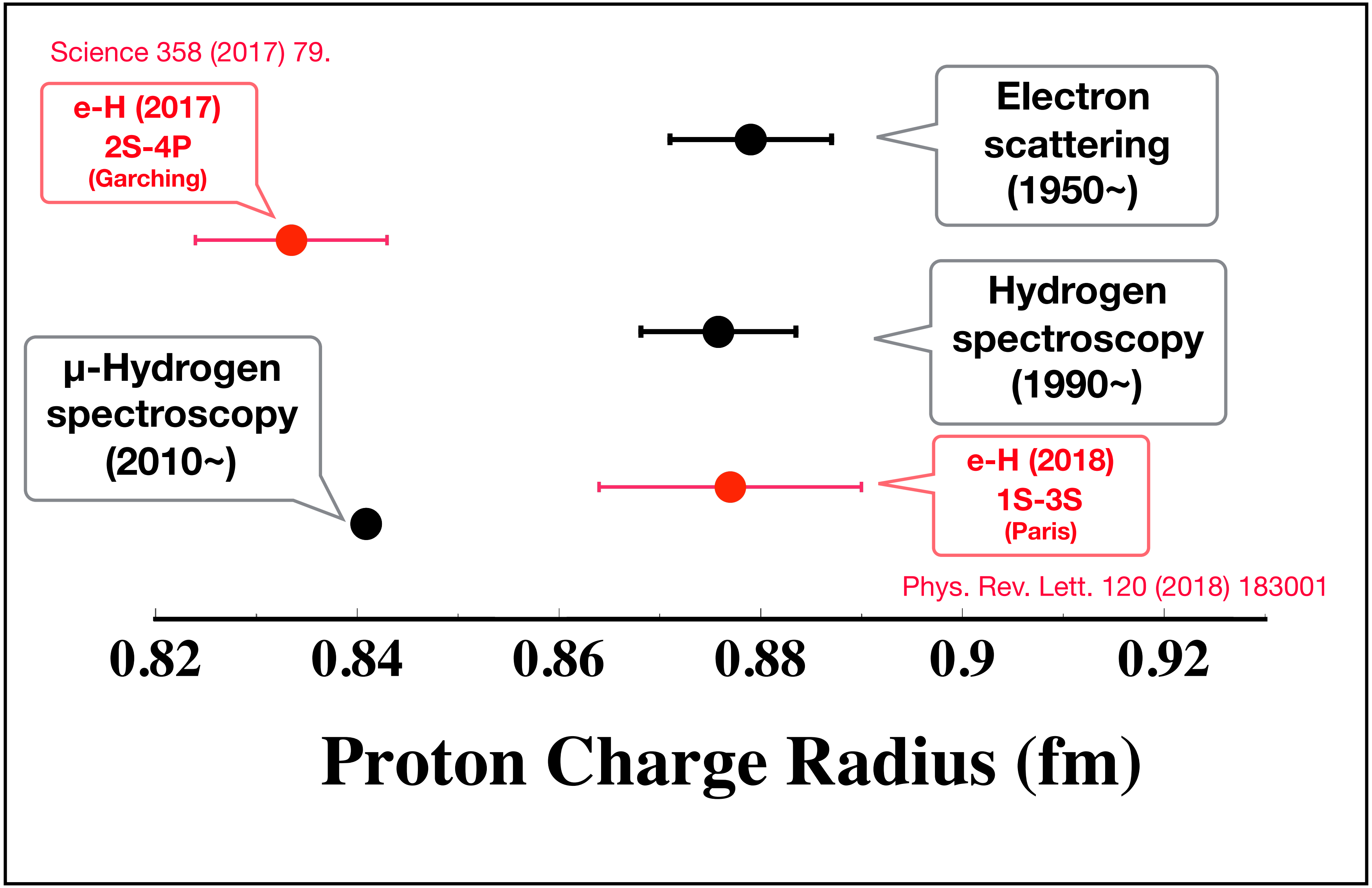




$$\Delta E_{2S->2P} = 209.9779(49) - 5.2262 \ < r_p >^2 + \Delta(2S, 2P)$$

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

Recent results from hydrogen spectroscopy



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

Hydrogen spectroscopy

	transition	f (kHz)	R_∞ (m^{-1})	r_p (fm)
Garching	2S-4P	616 520 931 626.8(2.3)	10 973 731.568 076(96)	0.8335(95)
LKB-Paris	1S-3S	2 922 743 278 671.5(2.6)	10 973 731.568 53(14)	0.877(13)

Uncertainty Budget (Garching)

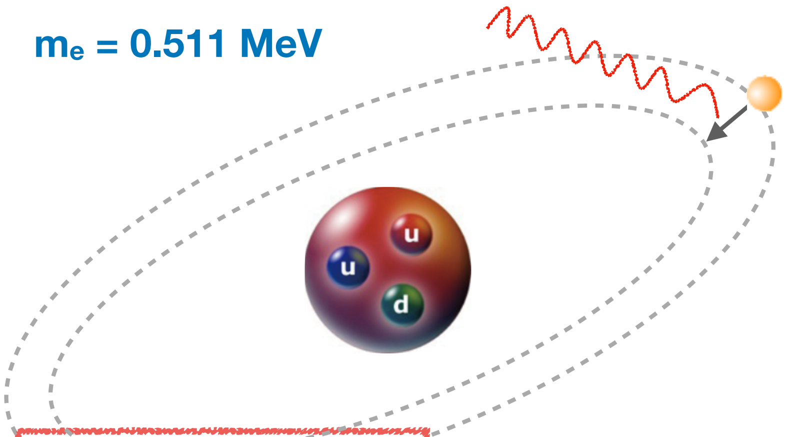
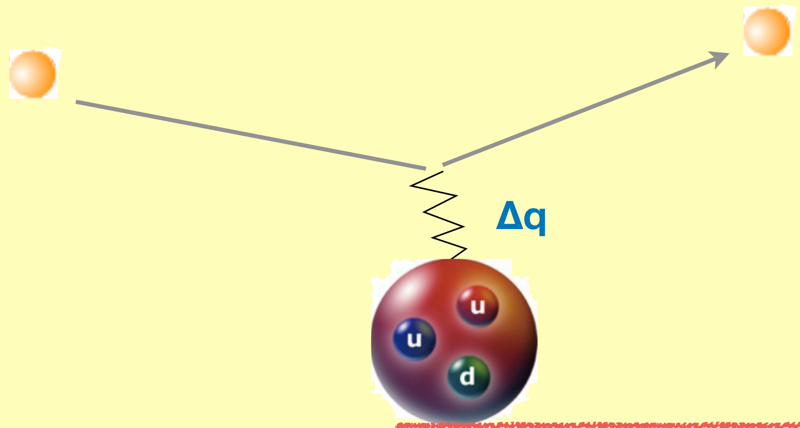
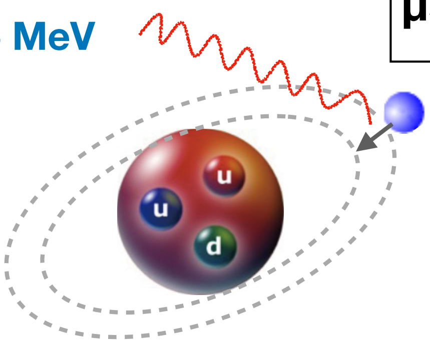
	$\Delta\nu$ (kHz)	σ (kHz)
Statistics	0.00	0.41
First-order Doppler shift	0.00	2.13
Quantum interference shift	0.00	0.21
Light force shift	-0.32	0.30
Model corrections	0.11	0.06
Sampling bias	0.44	0.49
Second-order Doppler shift	0.22	0.05
DC Stark shift	0.00	0.20
Zeeman shift	0.00	0.22
Pressure shift	0.00	0.02
Laser spectrum	0.00	0.10
Frequency standard (H maser)	0.00	0.06
Recoil shift	-837.23	0.00
Hyperfine structure (HFS) corrections	-132552.092	0.075
Total	-133388.9	2.3

proton size effect ~ 9kHz (Garching)

Science 358 (2017) 79-85.
PRL 120 (2018) 183001.

Proton Charge Radius
by
Electron Scattering

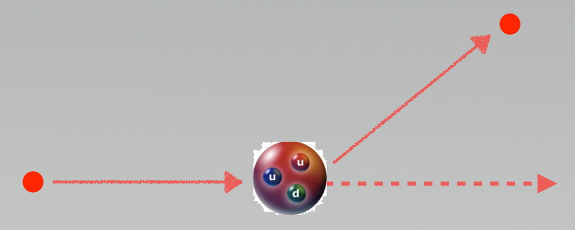
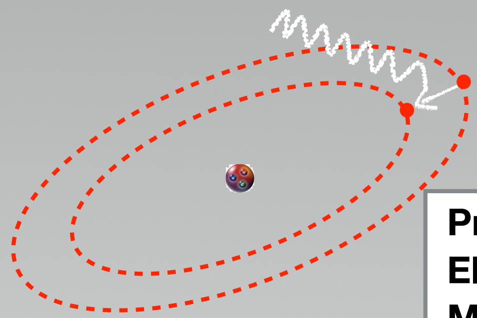
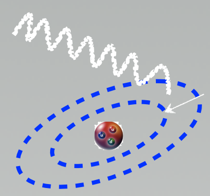
陽子電荷半径測定方法

	Spectroscopy	Scattering
e⁻	m_e = 0.511 MeV  0.8758(77)	 0.8770(60)
μ⁻	m_μ = 105.6 MeV  0.8409(4)	

陽子半径　~ 10^{-15} m
電子軌道　~ 10^{-10} m
μ粒子軌道 ~ 10^{-12} m

Proton Charge Radius measurements

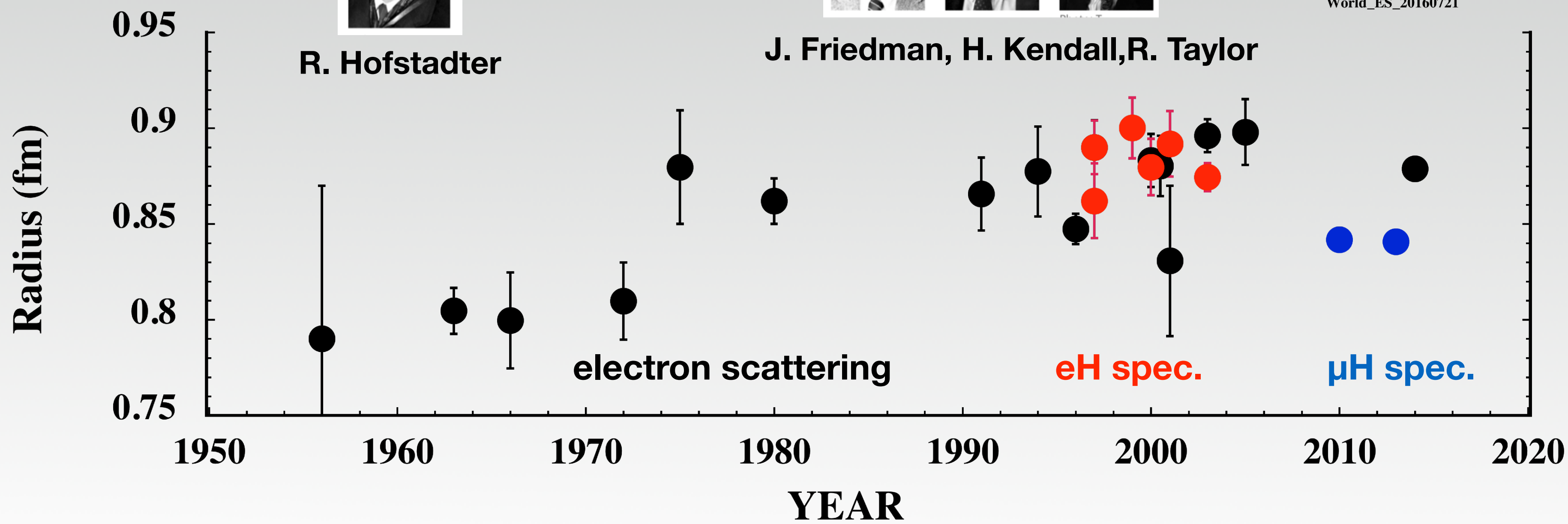
基研研究会　2018/8/6-8/10
素粒子物理学の進展2018

Electron Scattering (1950~)	eH-Spectroscopy (1990 ~)	μH-Spectroscopy (2000~)
		
ρ(r) or $<r^2>$	$\Delta E = \alpha \cdot R_{Rydberg} + \beta \cdot < r^2 >$	

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

R. Hofstadter

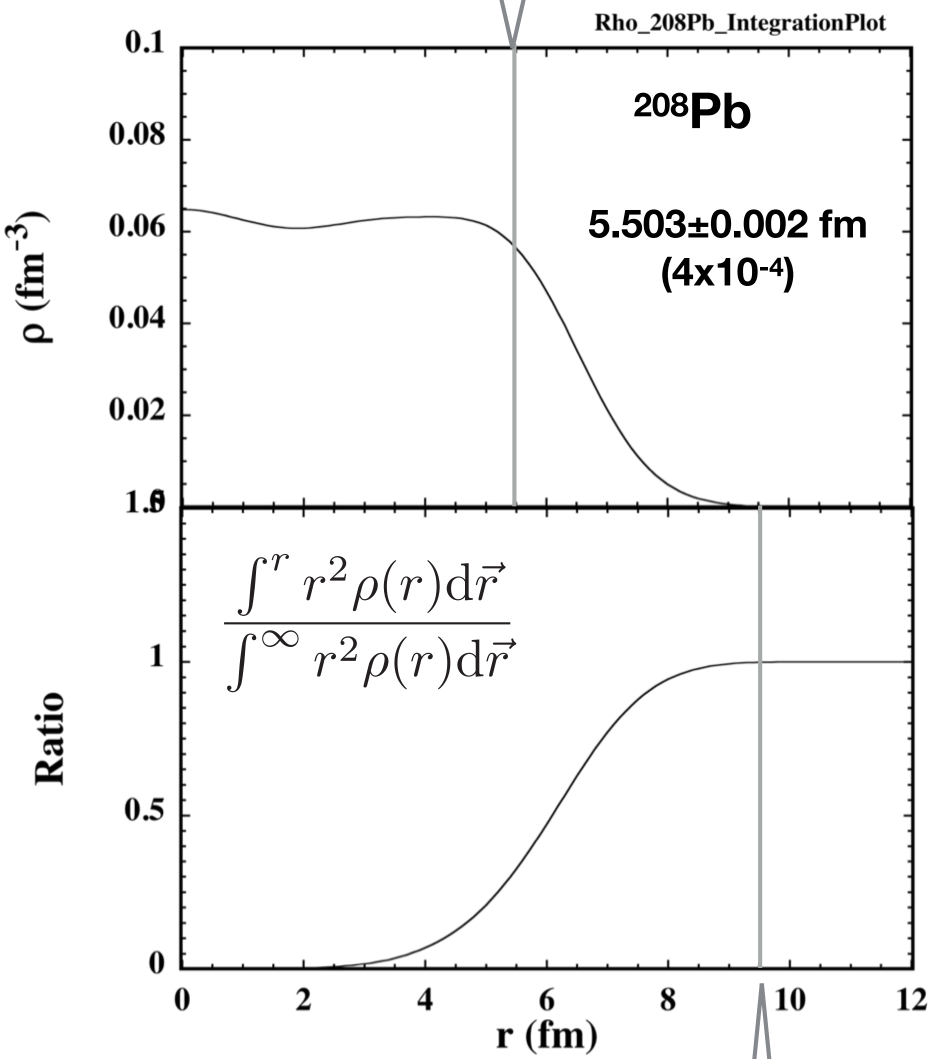
J. Friedman, H. Kendall, R. Taylor



Charge Radius and Density Distribution

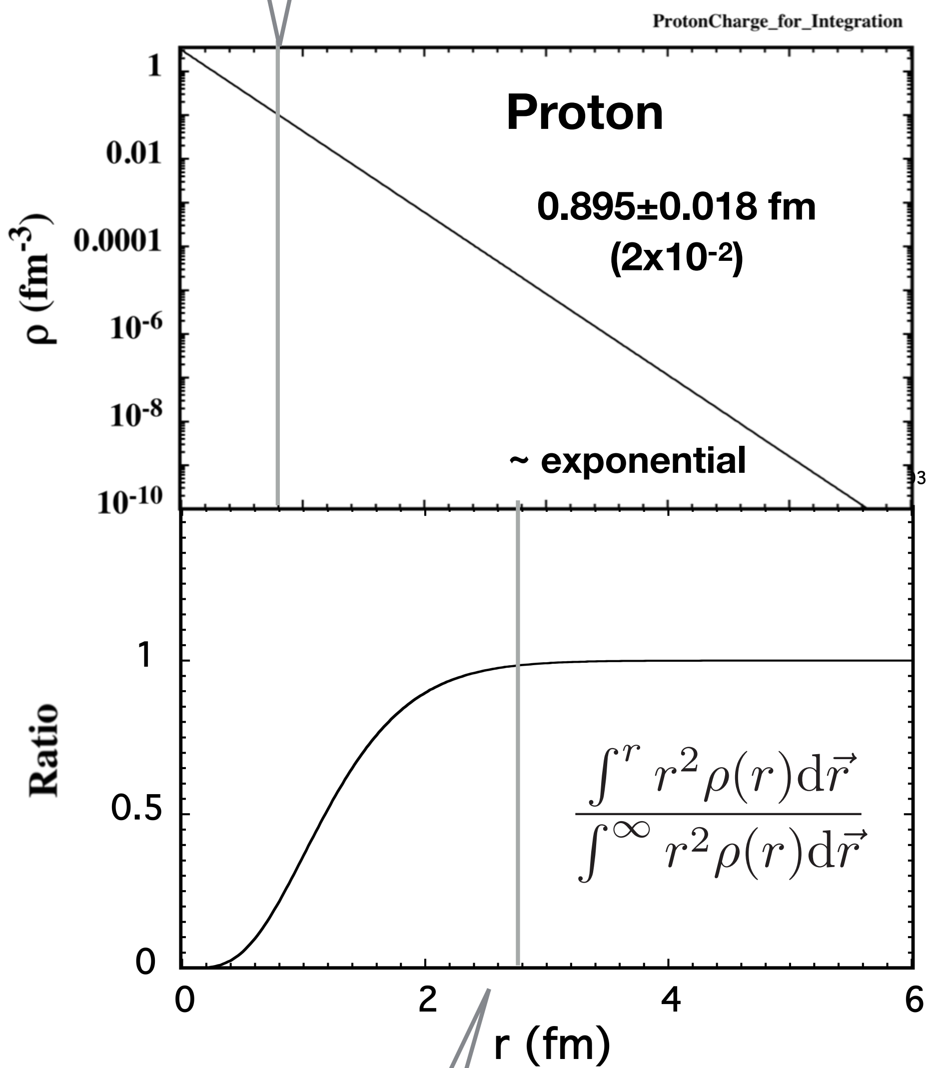
Charge Radius $<r^2>=\int r^2\rho(\vec{r})d\vec{r}$

Pb（5.499(1) fm)



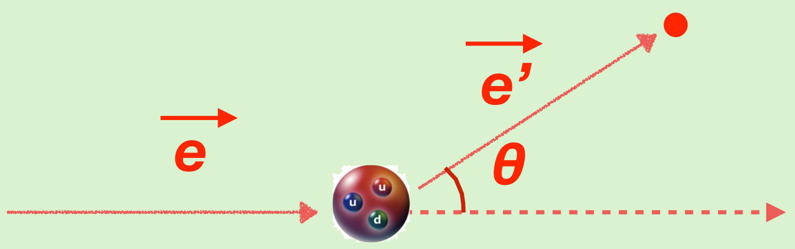
Ratio = 98 %

Proton（~0.8 fm)



Ratio = 98 %

電子散乱と陽子電荷半径



電荷形状因子　　磁気形状因子

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

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

energy transfer $\omega = e - e'$

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

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

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

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

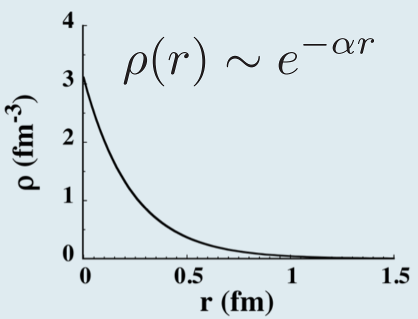
1） high Q²: charge density ρ(r)

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

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

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

ill problem : higher order contribution

⇕

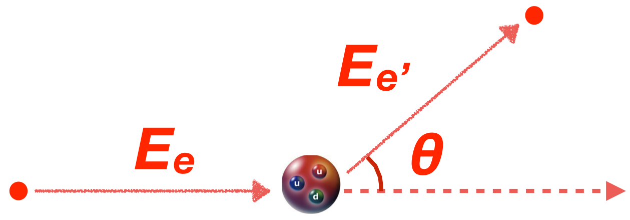
lower Q² as possible

電子散乱による電荷半径決定法

電子と陽子の弾性散乱断面積

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

電荷形状因子　θのみの関数　磁気形状因子



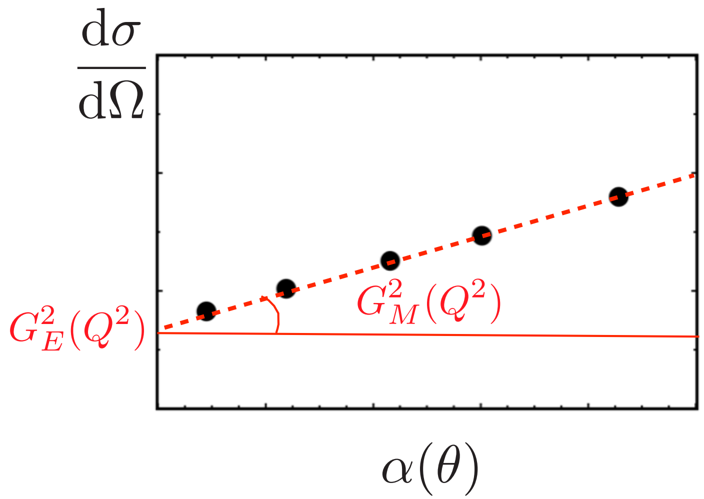
４元運動量移行

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

1　$G_E(Q^2)$ の分離・決定 (Rosenbluth分離)

Q^2一定で θ を変えた測定

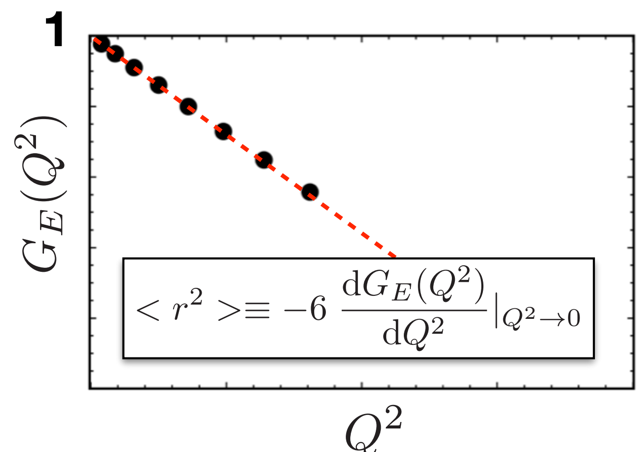
- 測定毎に**ビームエネルギー変更**が必要
- 異なるQ^2で$G_E(Q^2)$ 測定



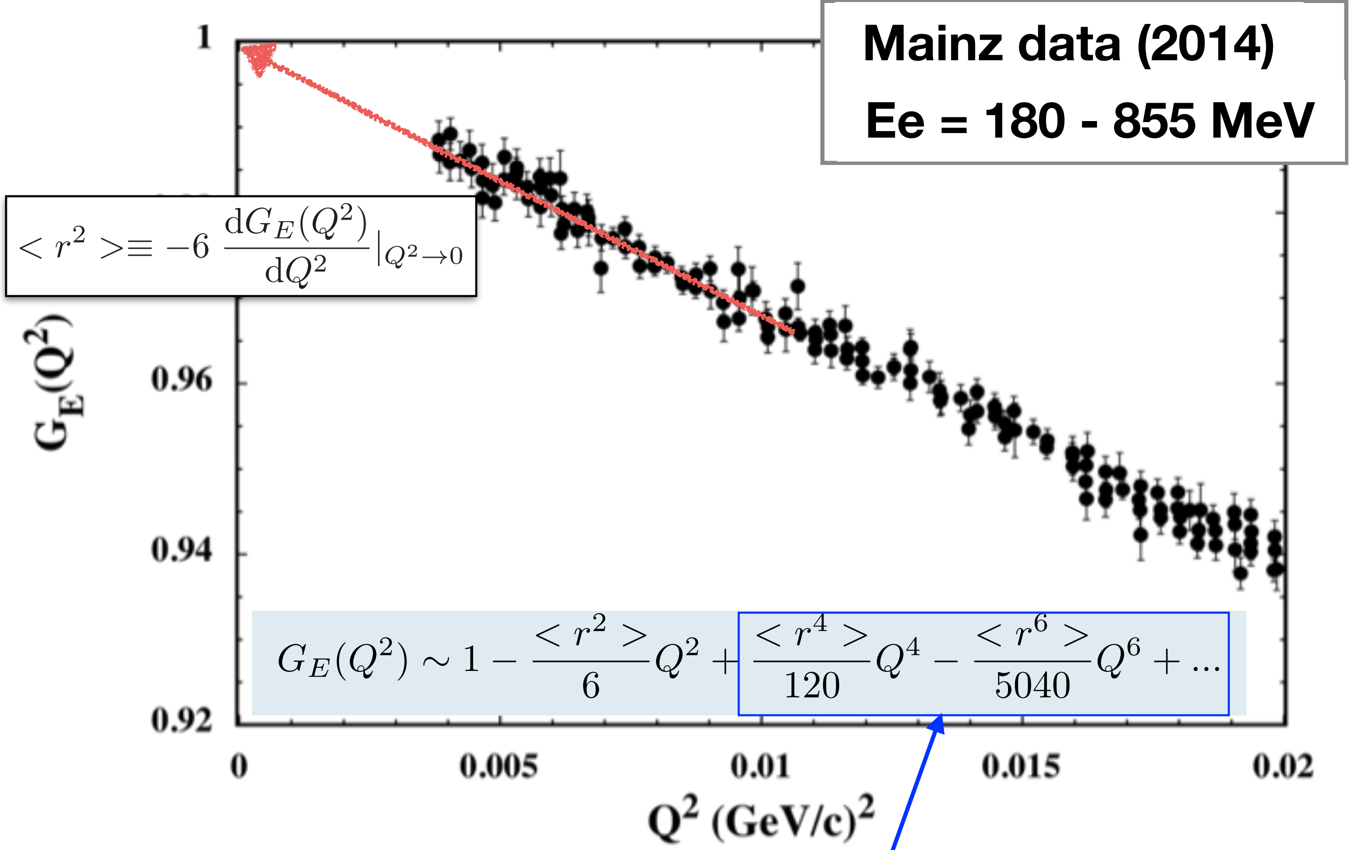
2　$G_E(Q^2)$ と荷電半径の関係（Q^2-> 0）

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

低Q^2領域での $G_E(Q^2)$ 測定から電荷半径決定



低運動量領域の測定データの問題点？

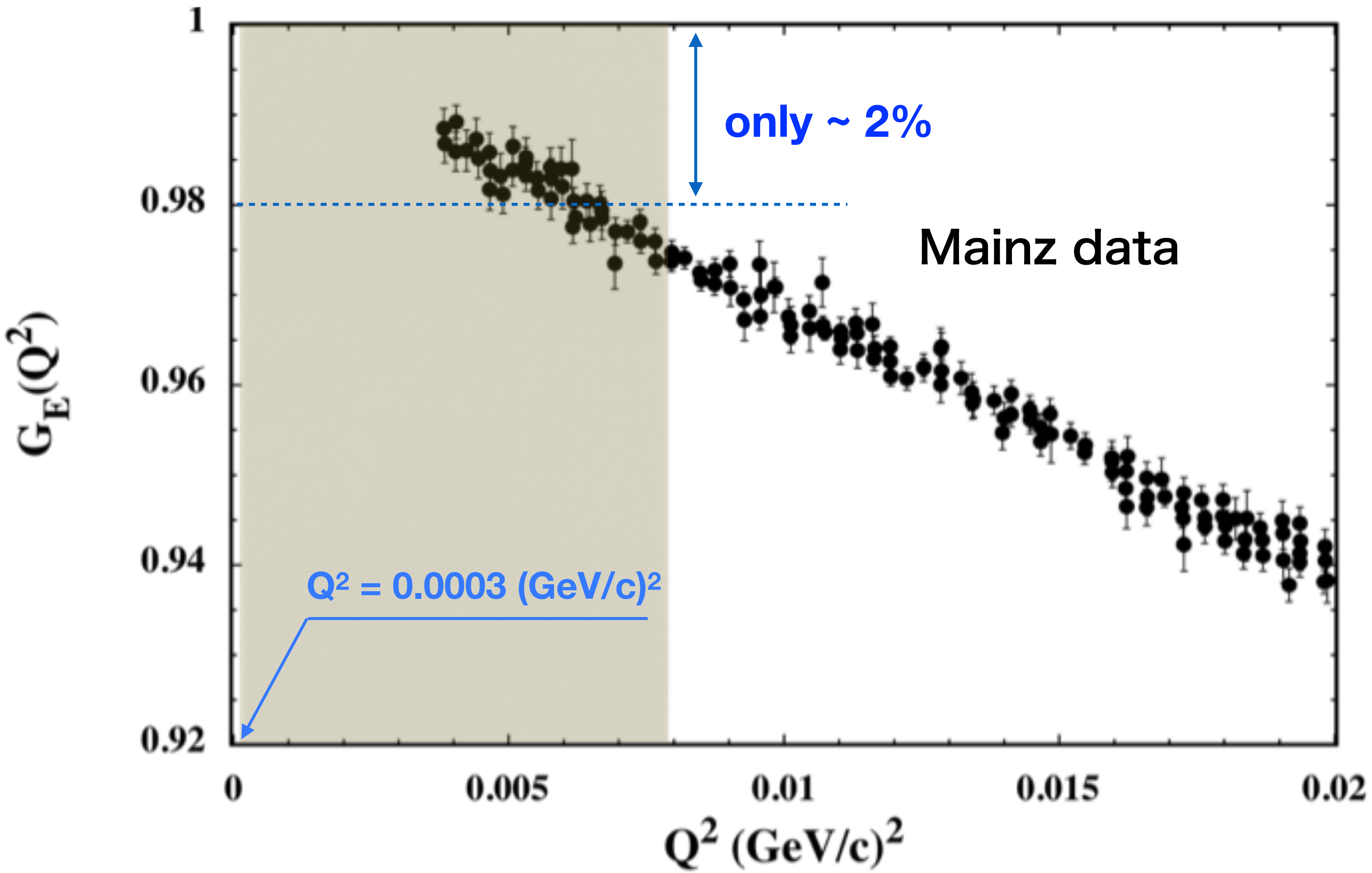


問題点	理由
極低Q² 領域 のデータなし	高エネルギー加速器で困難
Rosenbluth 分離測定なし	頻繁なビームエネルギー変更が不可
断面積は**相対値測定**	大きな液体水素標的＋スペクトロメータ

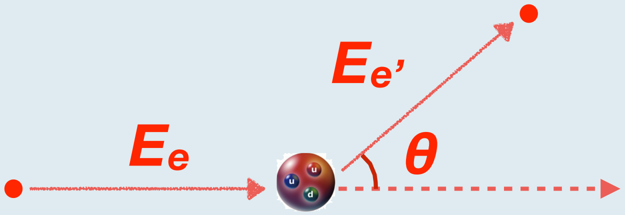
高次モーメント取り扱い次第では

➡ 陽子荷電半径の問題解消　？？

(Phys. Rev. C90 (2014) 045206)


only ~ 2%
Mainz data
Q² = 0.0003 (GeV/c)²
1
0.98
0.96
0.94
0.92
0
0.005
0.01
0.015
0.02
GE(Q²)
Q² (GeV/c)²

低運動量移行量領域での $G_E(Q^2)$ 測定



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

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

低い運動量移行　低いビームエネルギー
小さな散乱角度

$G_E(Q^2)$ 決定用Rosenbluth 分離のためには散乱角の変更が必須

低エネルギー且つ様々なビームエネルギーの電子ビームが不可欠

世界最先端の高エネルギー大型加速器では不可能！

頻繁な加速エネルギー変更は不可能

1) 低エネルギー電子加速器
2) 広い実験室（散乱角可変の電子スペクトロメータ）
3) 電子散乱を専門とする原子核研究者

電子光センターのみ

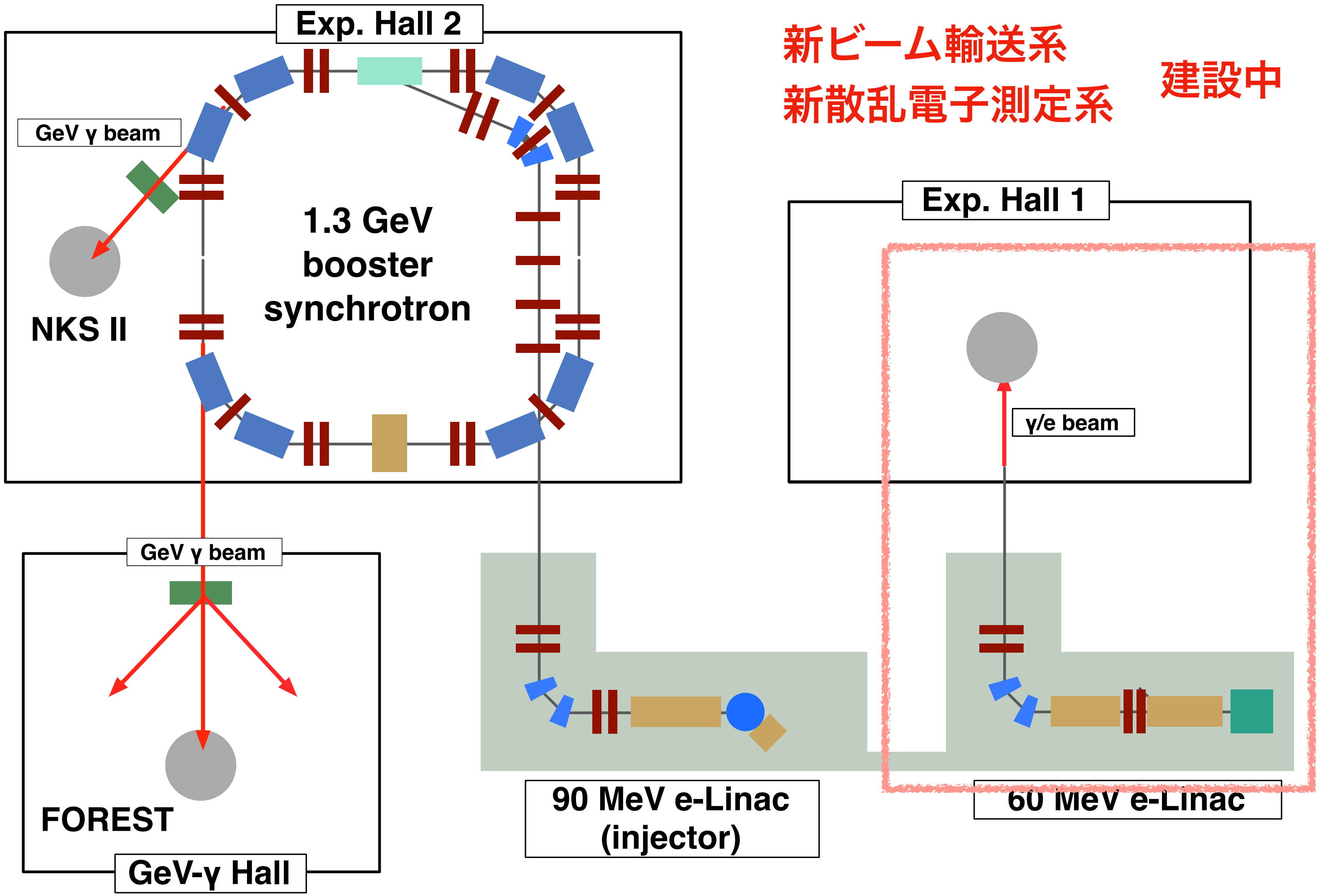
ELPH 低エネルギー電子加速器の特徴を最大限に活かせる実験

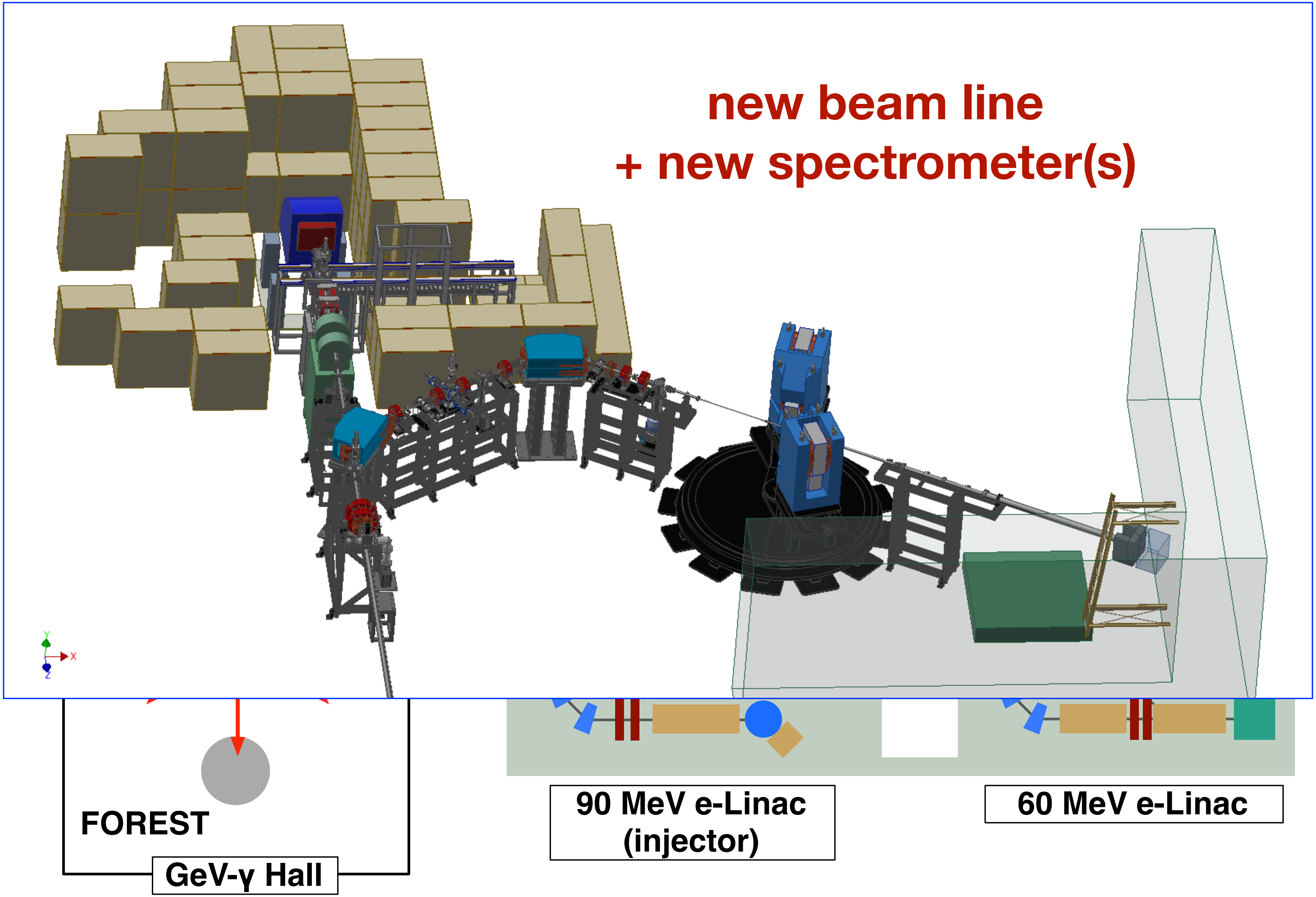
電子光理学研究センターでの電子散乱実験

低エネルギー電子加速器：　Ee = 20 - 60 MeV

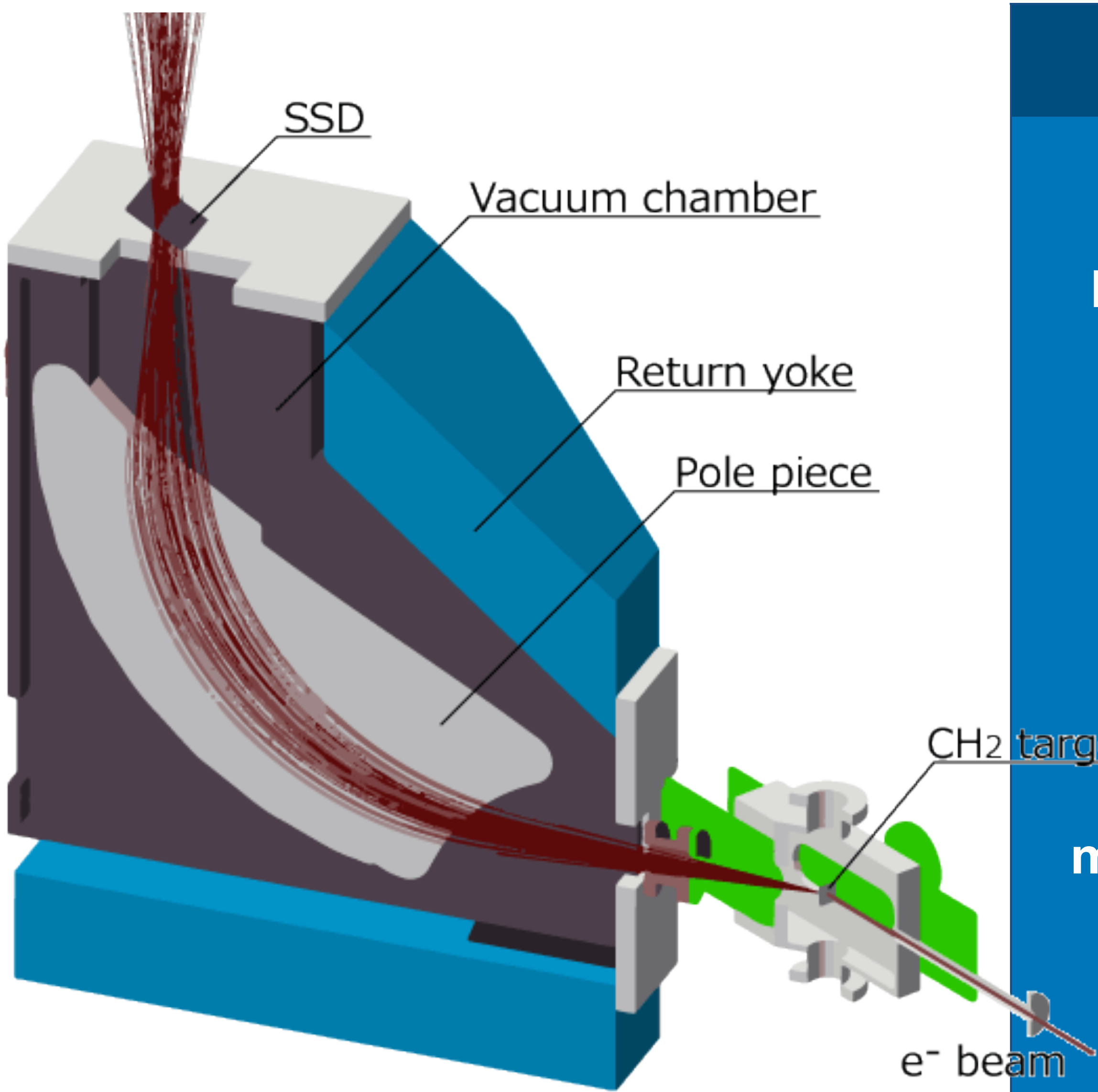
史上最低電子エネルギーによる電子・陽子弾性散乱

➡ 電子散乱では最も信頼度の高い陽子半径測定が可能



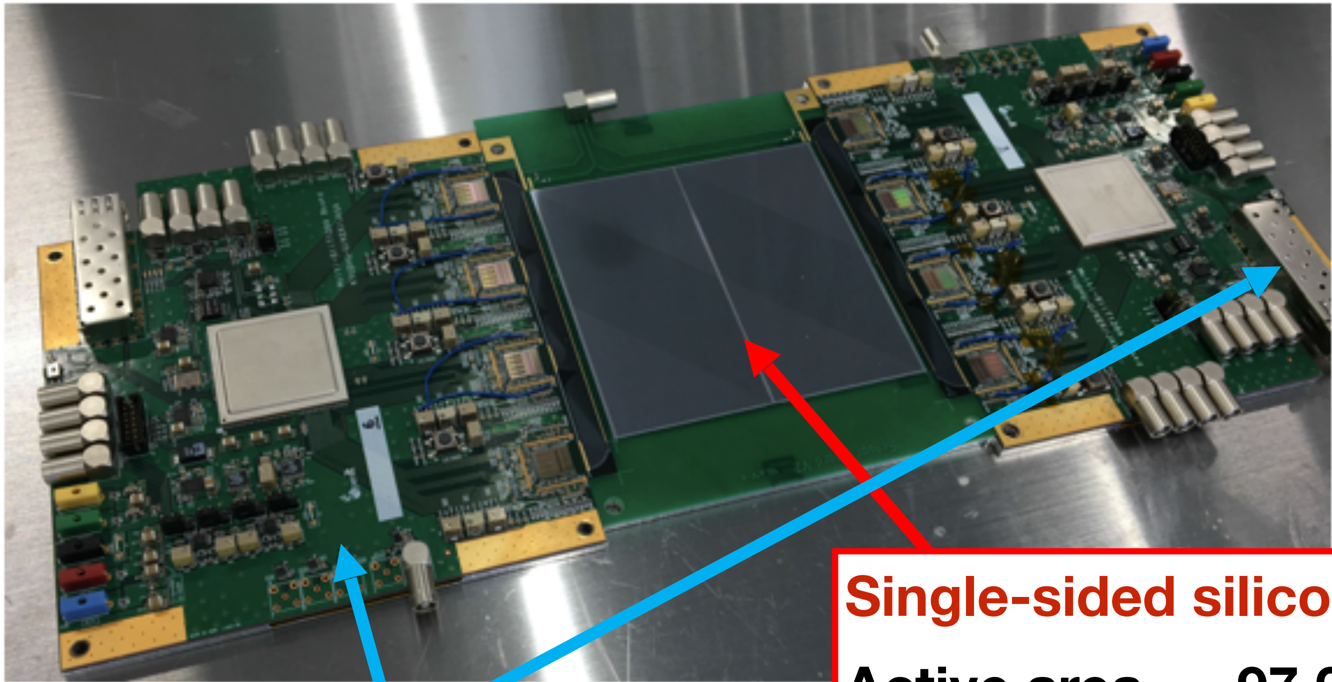

new beam line
+ new spectrometer(s)
FOREST
GeV-γ Hall
90 MeV e-Linac
(injector)
60 MeV e-Linac

Electron spectrometer (P = 20 - 60 MeV/c)



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

Single-Sided Silicon Detector (SSSD) developed for g-2/EDM experiments at JPARC



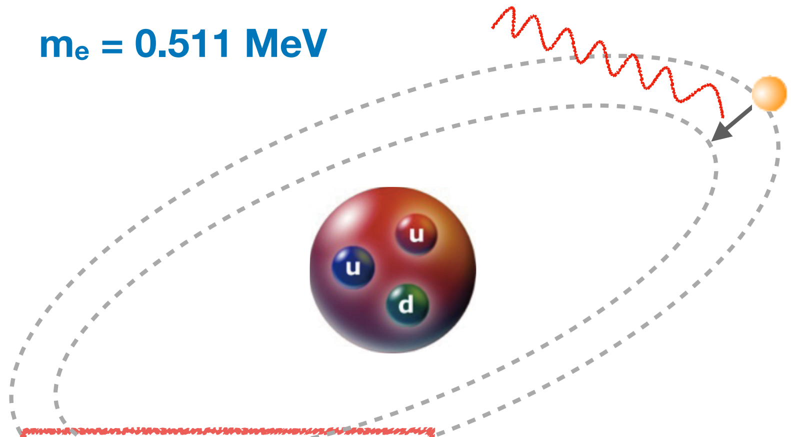
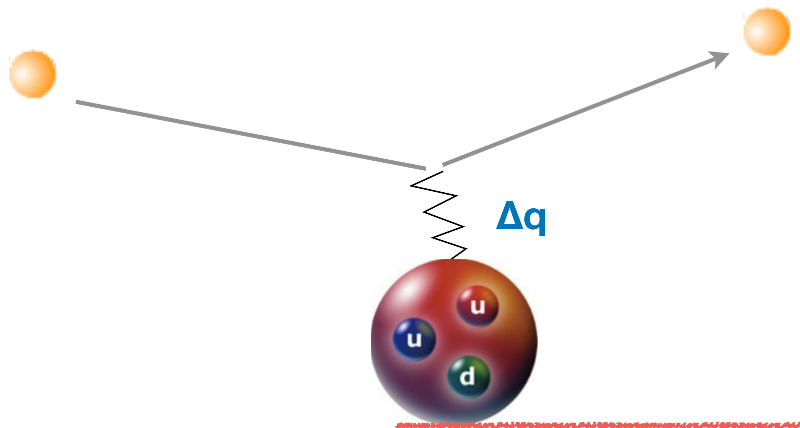
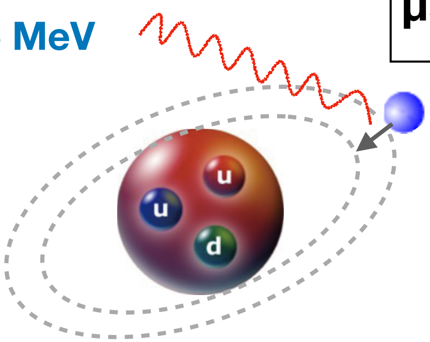
Readout boards
“Multi-Slit128A board”
Four ASICs “Slit128A”
(128 ch/chip)

Single-sided silicon detector (SSSD)

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

other on-going projects
and
future projects

陽子電荷半径測定方法

	Spectroscopy	Scattering
e^-	m_e = 0.511 MeV  0.8758(77)	 0.8770(60)
μ^-	m_μ = 105.6 MeV  0.8409(4)	

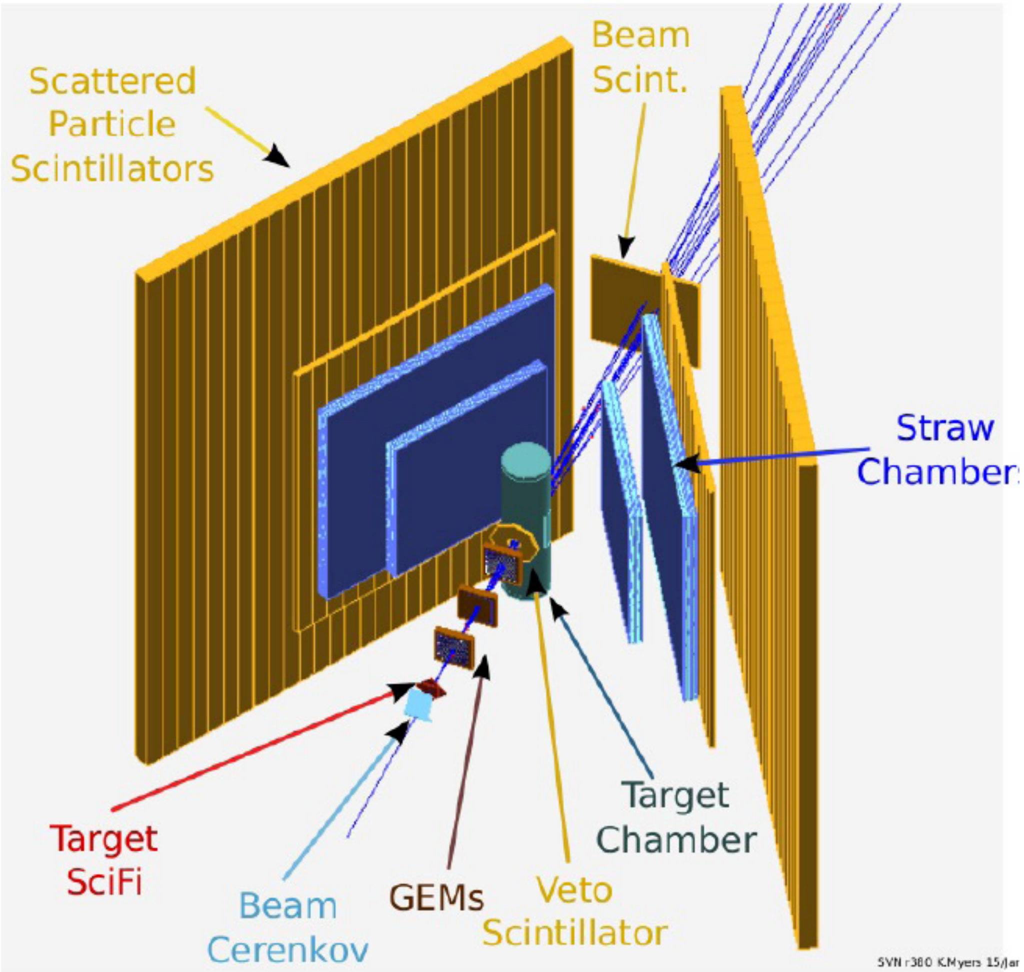
陽子半径　~ 10^{-15} m
電子軌道　~ 10^{-10} m
μ粒子軌道 ~ 10^{-12} m

他の極低運動量移行領域での測定計画

MUSE@PSI

μ± scattering off proton

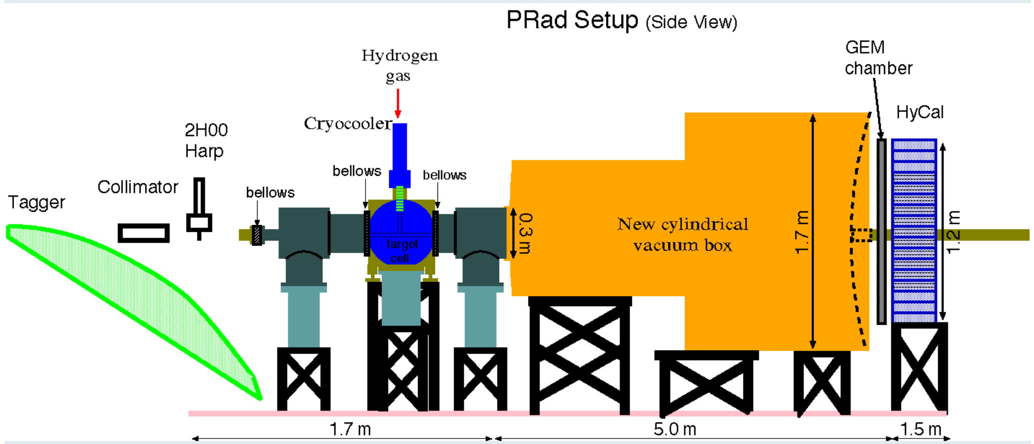
p = 115, 158 and 210 MeV/c
θ = 20 - 100°
Q^2 = 0.002 - 0.07 $(GeV/c)^2$



PRAD@JLAB

E_e^{min} = 1.1 GeV
θ ~ a few deg.
Q^2 = 0.0002 - 0.02 $(GeV/c)^2$

No Rosenbluth separation
(quite small factor for GM(Q2))
Absolute cross section
(relative to Moeller)



p : window-less gas targegt
e : $PbWO_4$ telescope

Courtesy of A. Gasparian

その他の計画

Orsay, CNRS（フランス）

ProRad

An electron-proton scattering experiment

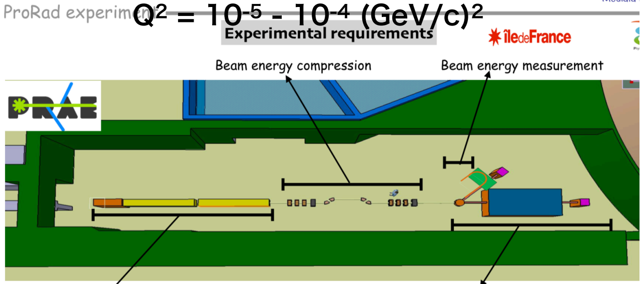
@ PRAE

Mostafa HOBALLAH on behalf of the ProRad collaboration
hoballah@ipno.in2p3.fr
Institut de Physique Nucléaire d'Orsay, CNRS/IN2P3, Universités Paris-Sud & Paris-Saclay

Ee = 30-70 MeV

θ =6-16°

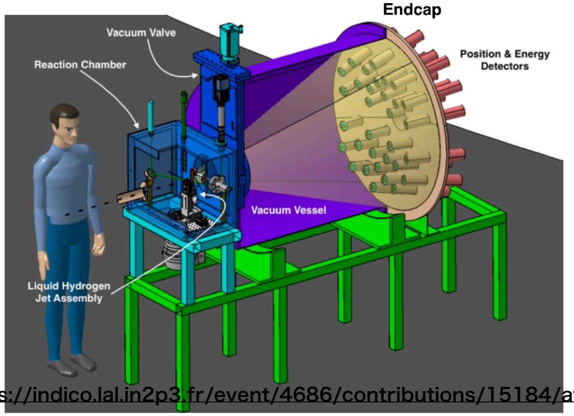
$Q^2 = 10^{-5} - 10^{-4}$ (GeV/c)^2



A high precision measurement of the proton electric form factor

ProRad experiment requirements:

- High precision beam
- Precise knowledge of the beam energy
- A stable target
- Optimised measurement of the scattered electron energy and position



https://indico.lal.in2p3.fr/event/4686/contributions/15184/attachments/12579/14875/FU_workshop_2017_ProRad_at_PRAE.pdf

COMPASS, CERN

d-Quark Transversity

and

Proton Radius

Addendum to the COMPASS-II Proposal

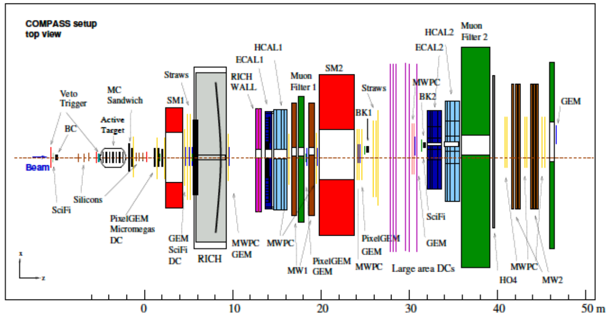


Figure 20: Schematics of the COMPASS MUP set-up. The target region including the gaseous hydrogen TPC is not to scale.

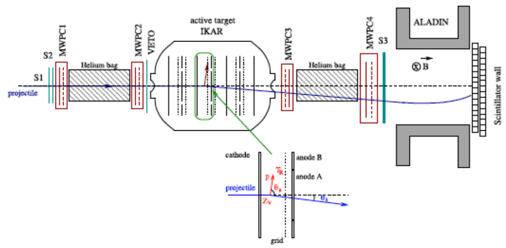


Figure 21: Example for the use of a high pressure active target TPC [57]

E = 100 GeV

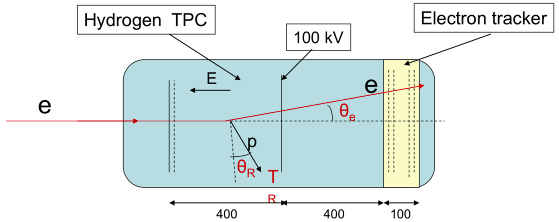
$Q^2 = 10^{-4} - 10^{-1}$ (GeV/c)^2

Mainz, Germany（ドイツ）

Proposal
for high precision measuremens of
the ep - differential cross sections at small
t- values with the recoiled proton detector

Suggested by PNPI to perform
at MAMI (Mainz Microtron)
in 2018

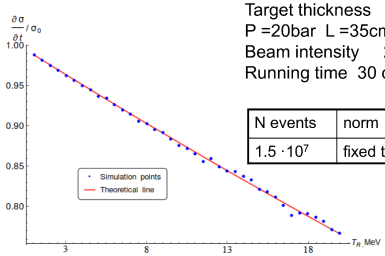
Combined recoiled proton@forward tracker detector



Measured quantities:
Recoil energy T_R
Recoil angle θ_R
Vertex Z coordnate
E scattering angle θ_e

$$-t = \frac{4\varepsilon_e^2 \sin^2\frac{\vartheta}{2}}{1 + \frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}}$$

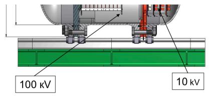
Statistics and beam time



Target thickness = $3.6\cdot10^{22}$ p/cm^2
P =20bar L =35cm
Beam intensity $2\cdot10^6$ sec^{-1}
Running time 30 days

N events	norm	t-scale	σ(Rp)
$1.5\cdot10^7$	fixed to 1	fixed	± 0.002 fm

100 resolved points in th interval
$0.002 < Q^2 < 0.02$ GeV^2



まとめ

電子散乱による陽子電荷半径値決定時のモデル依存性を抑制し、
電子散乱としては最も信頼度の高い陽子半径値を決定するために

東北大学電子光理学研究センターでの低エネルギー電子・陽子弾性散乱

特徴

電子ビームエネルギー： Ee = 20 - 60 MeV

運動量移行 ： Q^2 = 0.0003 - 0.0008 $(GeV/c)^2$

Rosenbluth分離による $G_E(Q^2)$, $G_M(Q^2)$ の分離

断面積絶対値測定 ： $G_E(Q^2)$絶対値

2017 - 2018 : 2連スペクトロメータ、新ビームラインの建設、調整

2019 ~ : 実験開始