Proton Radius

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Research Center for Electron-Photon Science,
Tohoku University
Sendai, Japan

1) Proton radius puzzle ??

2) Proton radius by electron scattering

3) ULQ2 project

low-energy electron scattering off proton

4) Conclusions

1) Proton radius puzzle ??

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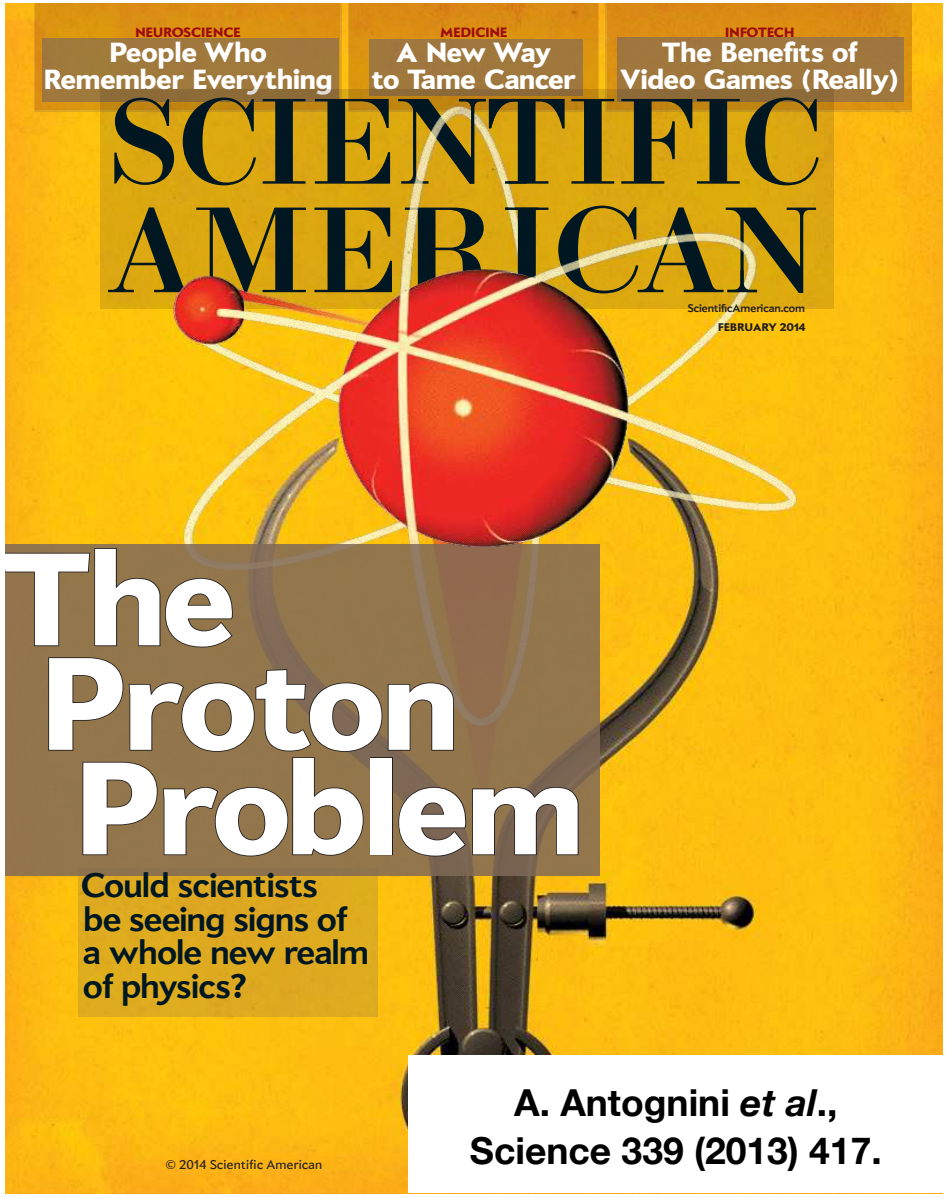
4) Conclusions

the puzzle started in 2010

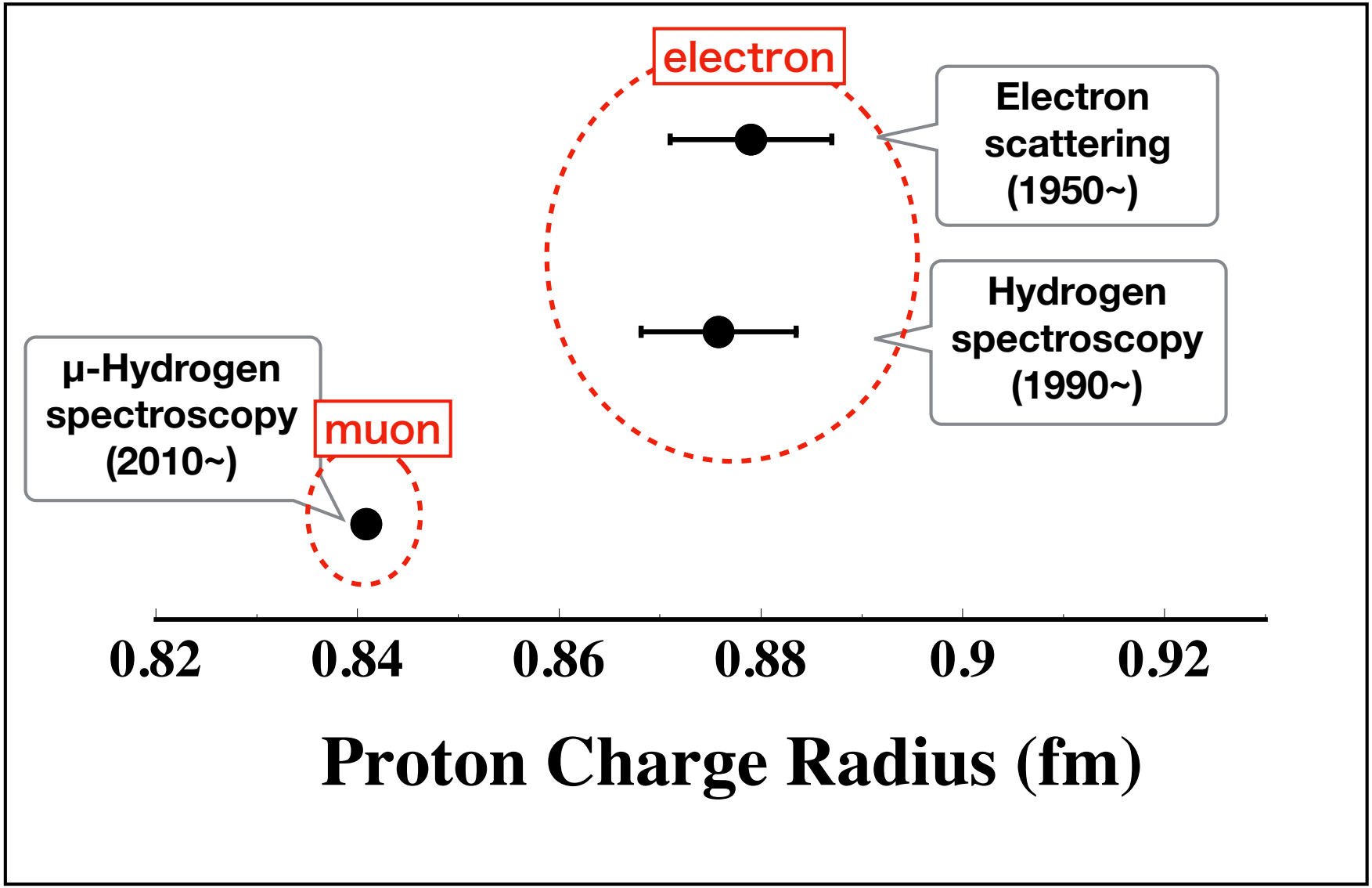
R. Pohl *et al.*,
Nature 466 (2010) 213.



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

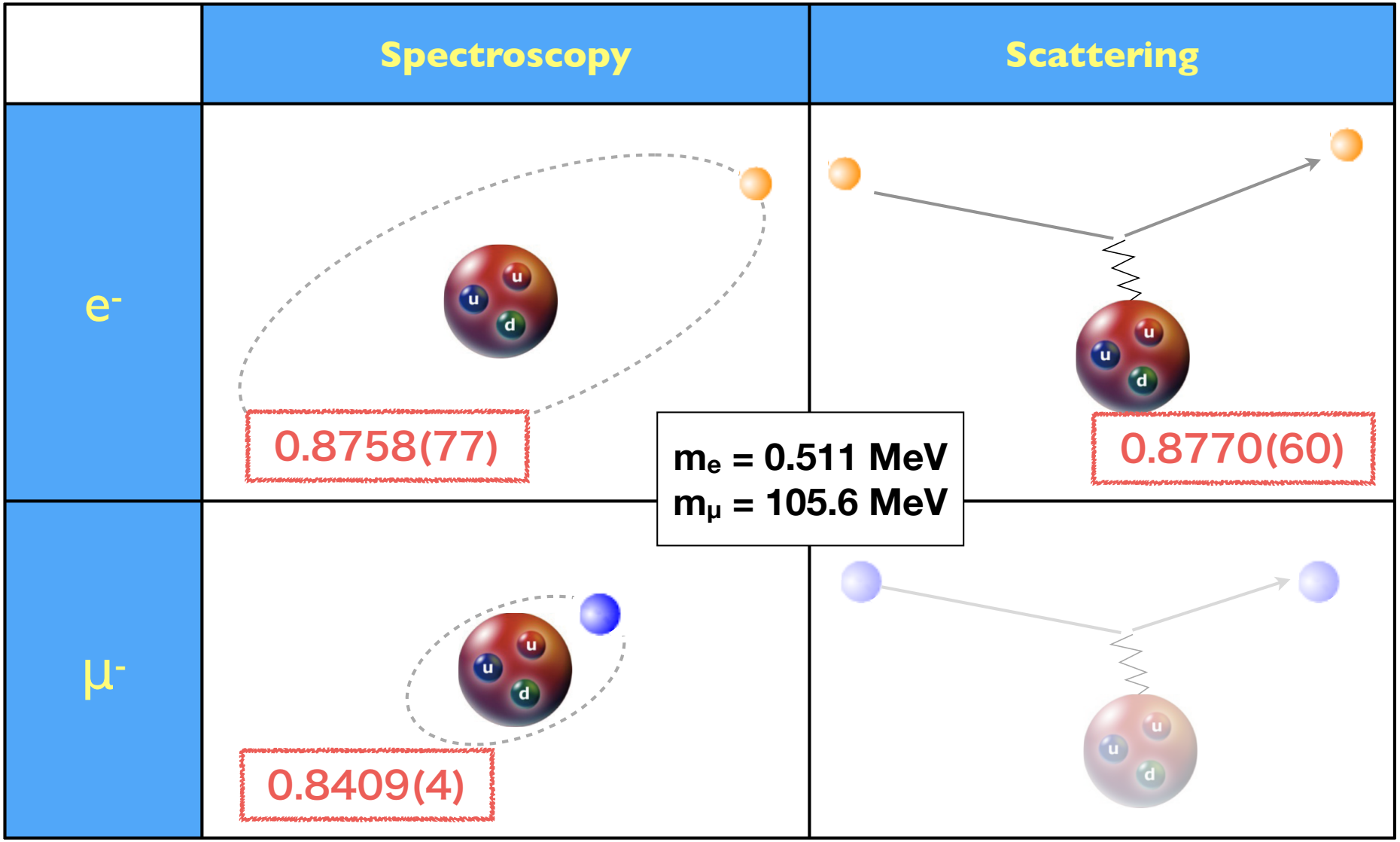
Proton Radius Puzzle

2010 ~



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

Proton Charge Radius

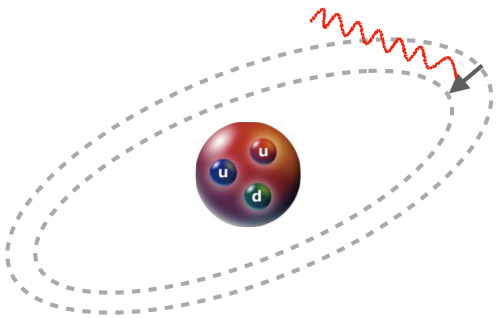


C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

Why does the proton radius matter ?

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

2) the radius is strongly correlated to the Rydberg constant



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

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

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

r_p uncertainty

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

Lepton Universality (e <-> μ) ??

4) nuclear structure : (e-scatt. for exotic nuclei at RIKEN/SCRIT)

$$< r_c^2 > = < r_{pointp}^2 > + < r_p^2 > + \frac{N}{Z} < r_n^2 > + \mathrm{rel.corr.}$$

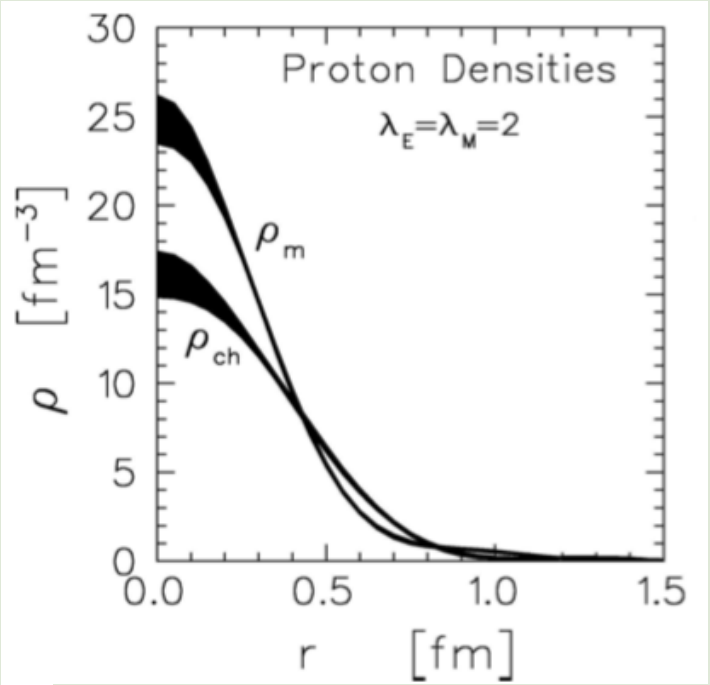
exp. theory p radius n radius

Proton Charge Radius ??

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

$$F(Q_L^2) = \int \rho(\vec{r}) e^{i\overrightarrow{Q_L}\cdot\vec{r}} d\vec{r}$$

Q_L **Lab. value of momentum transfer**



J. J. Kelly, Phys. Rev. C70 (2004) 068202

"applies in the non-relativistic limit in which ρ(r) is the static density distribution"

R. Hofstadter (1951)

Relativistically proper definition

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

G. A. Miller Phys. Rev. C99 (2019) 035202

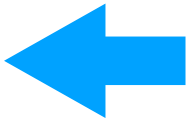
Hydrogen spectroscopy

1) Garching : 2S->4P (Science 358 (2017) 79.)
2) Paris : 1S->3S (PRL 120 (2018) 183001.)
3) Tronto : 2S->2P (Science 365 (2019) 1007.)

Electron scattering

1) Mainz : PRC90 (2014) 15206.
2) PRad@JLAB : Nature 575 (2019) 147.

ULQ2 at Tohoku (2021 ~)



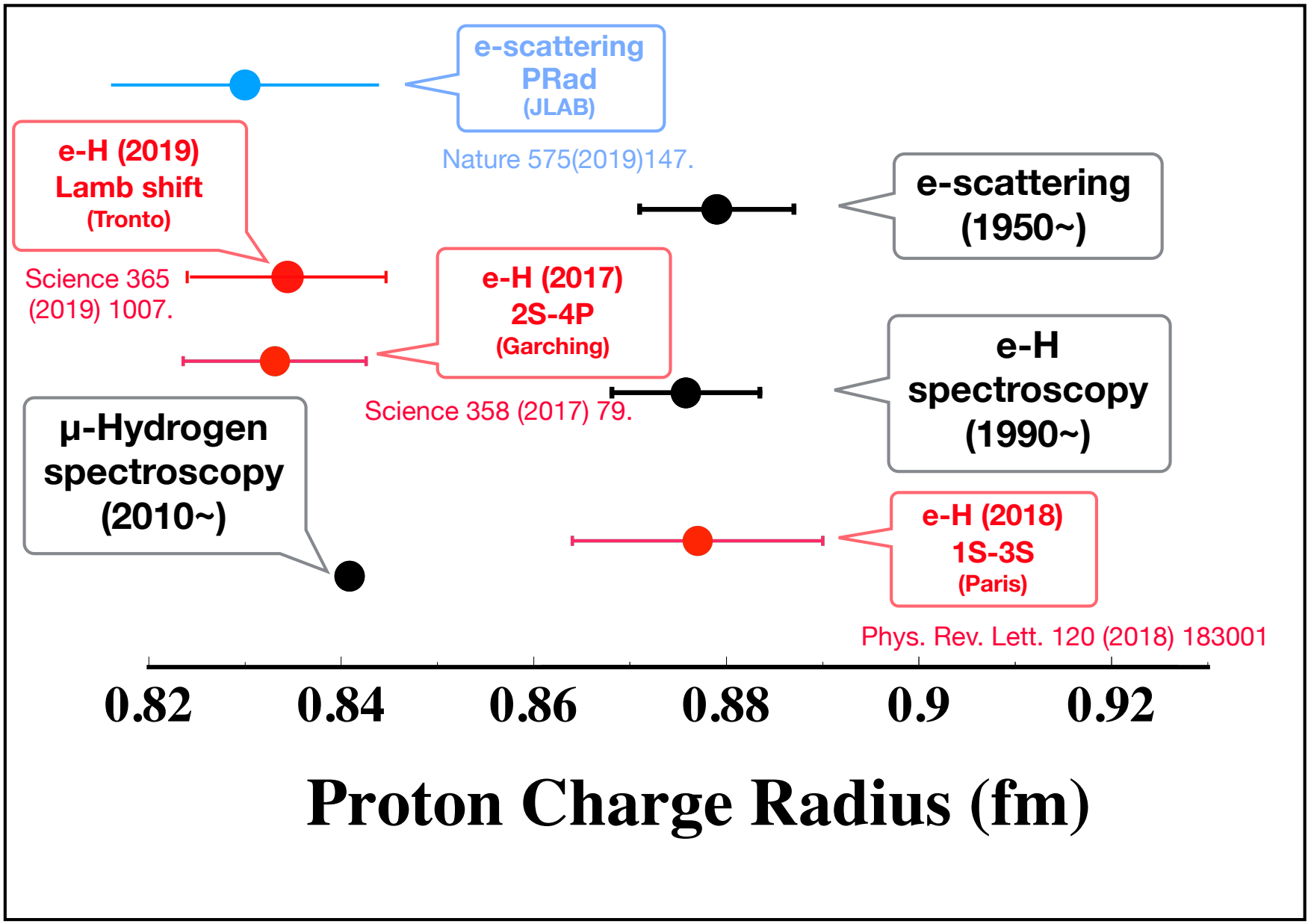
e-p scattering at MESA

Muon scattering

MUSE@PSI (2020~)

LowQ2-μp@COMPASS (proposal)

Proton radius as of today



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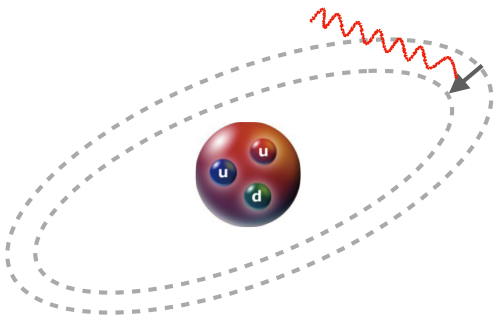

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$$\Delta E = \alpha \cdot R_{Rydberg} + \beta \cdot < r^2 >$$

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???

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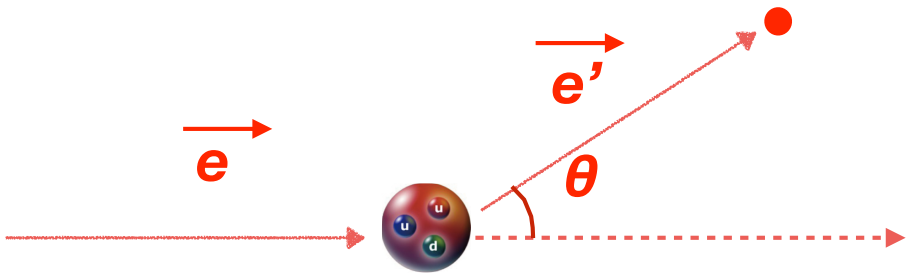
low-energy electron scattering off proton

4) Conclusions

Electron scattering



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

energy transfer $\omega = e - e'$

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

Charge FF **Magnetic FF**

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

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

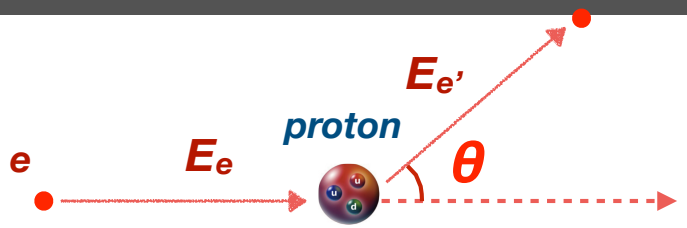
$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2\frac{\theta}{2}} \qquad \tau = \frac{Q^2}{4m_p^2}$$

Proton radius by electron scattering

elastic cross section for e-p

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

Charge FF　　Magnetic FF



4-momentum transfer

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

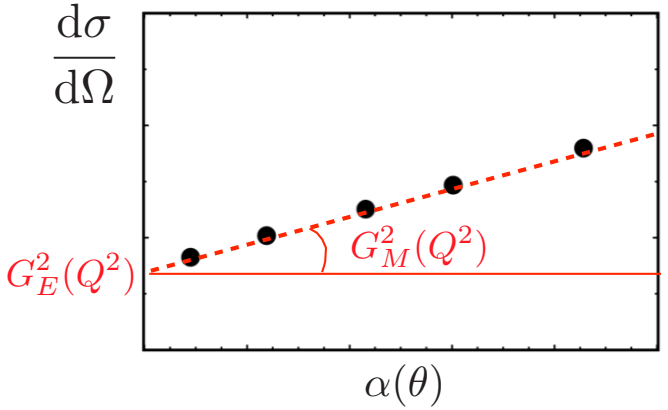
$G_E(Q^2)$ extraction from cross section

vary θ under fixed Q^2

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

Rosenbluth separation

Frequent change of *Ee*
("small" accelerator)

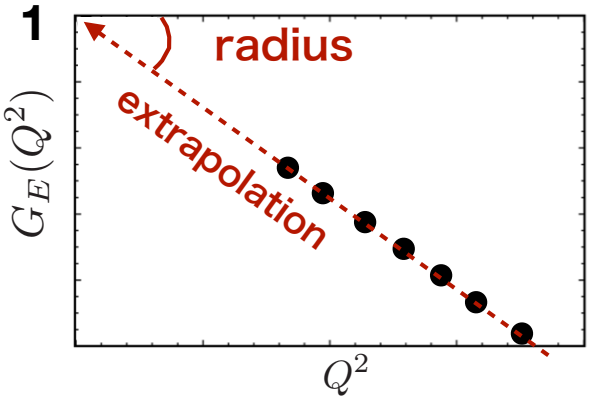


Proton charge radius

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

low Q^2 region as possible

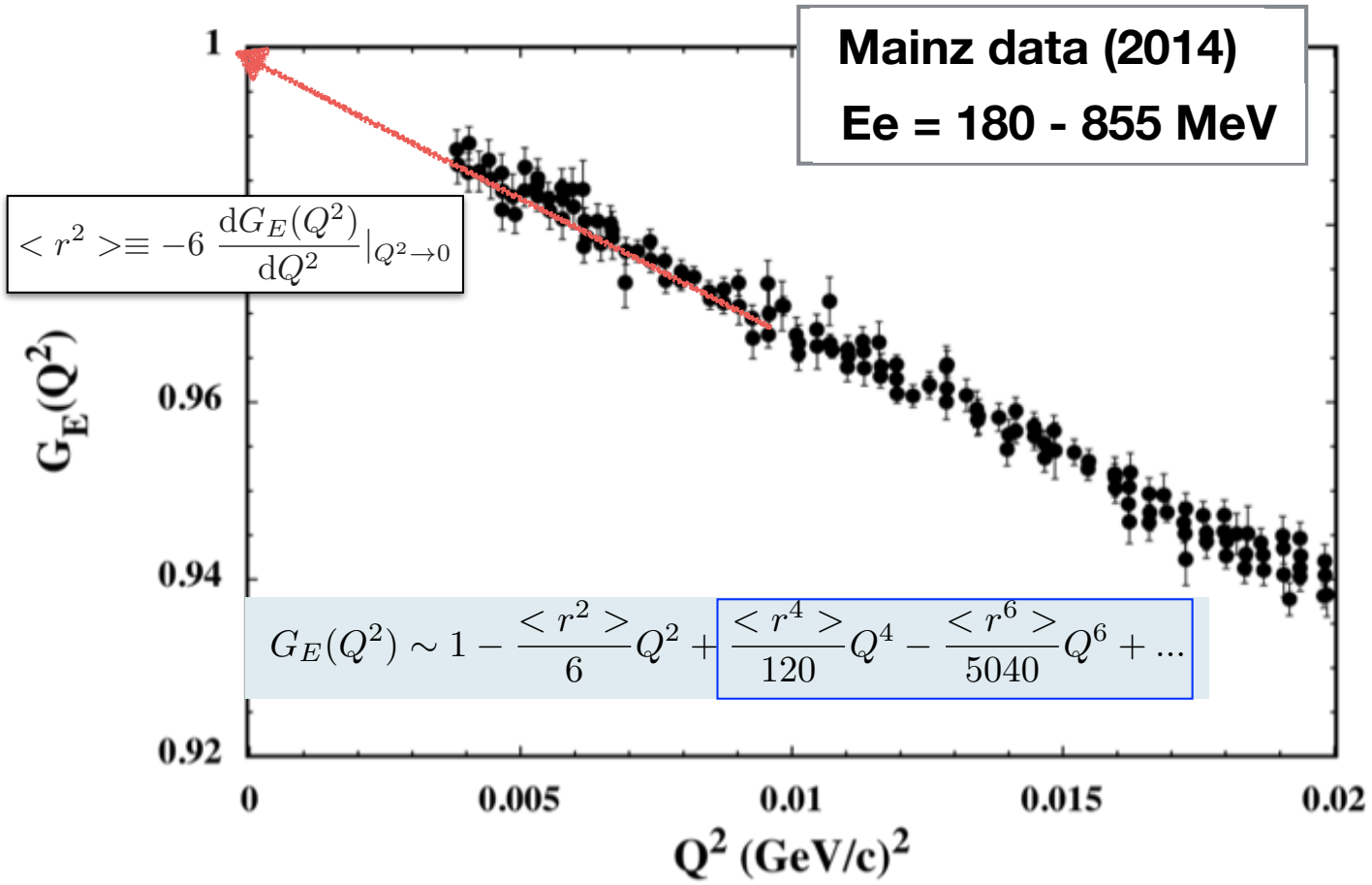
low-Ee (or small θe)



same for magnetic radius

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

Recent Mainz data (2014)

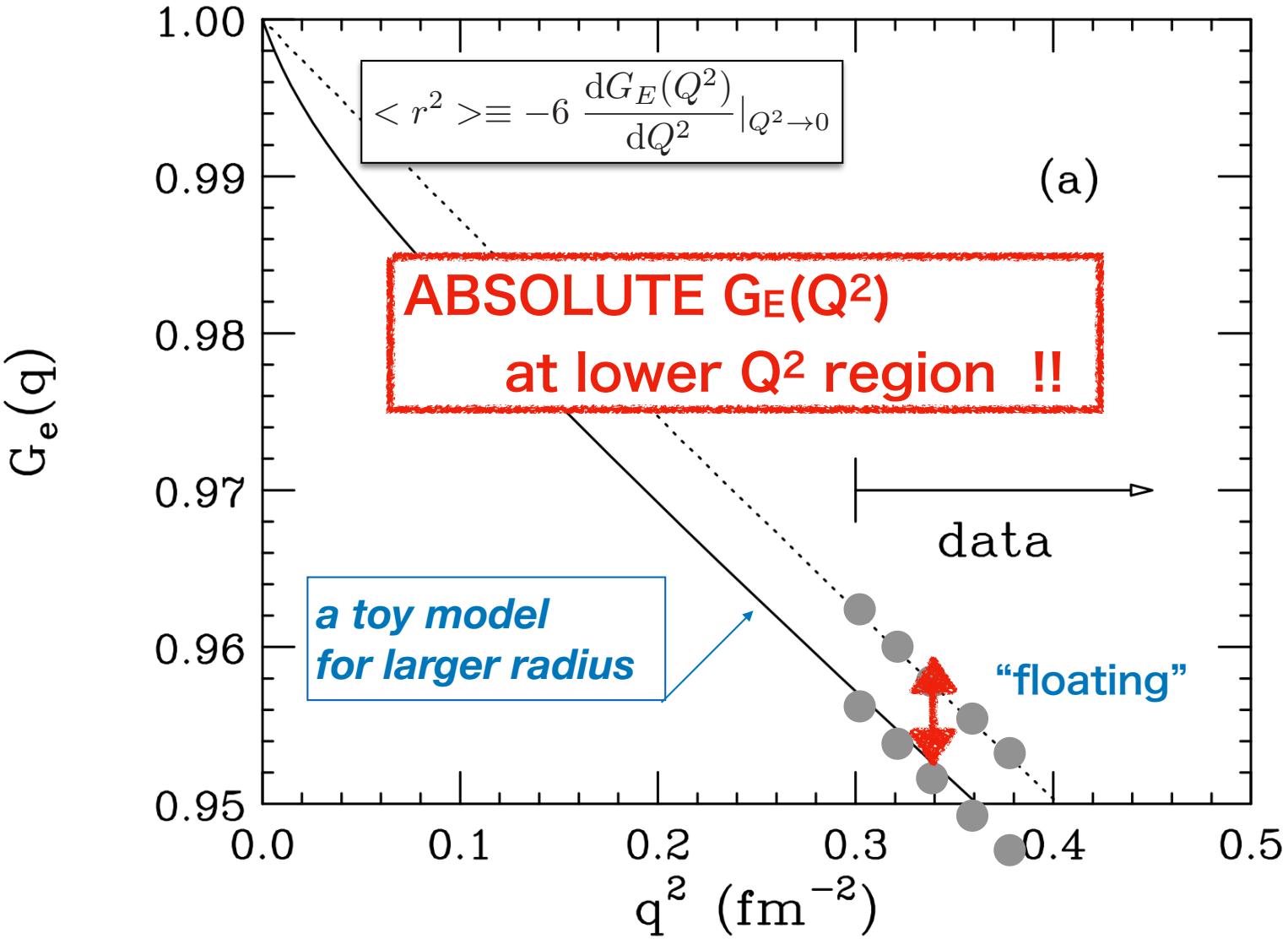


no “ultra-“ low Q^2 data	min. Ee = 180 MeV
no Rosenbluth separation	no frequent change of Ee
no absolute cross section	liq. H_2 target + spectrometer

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

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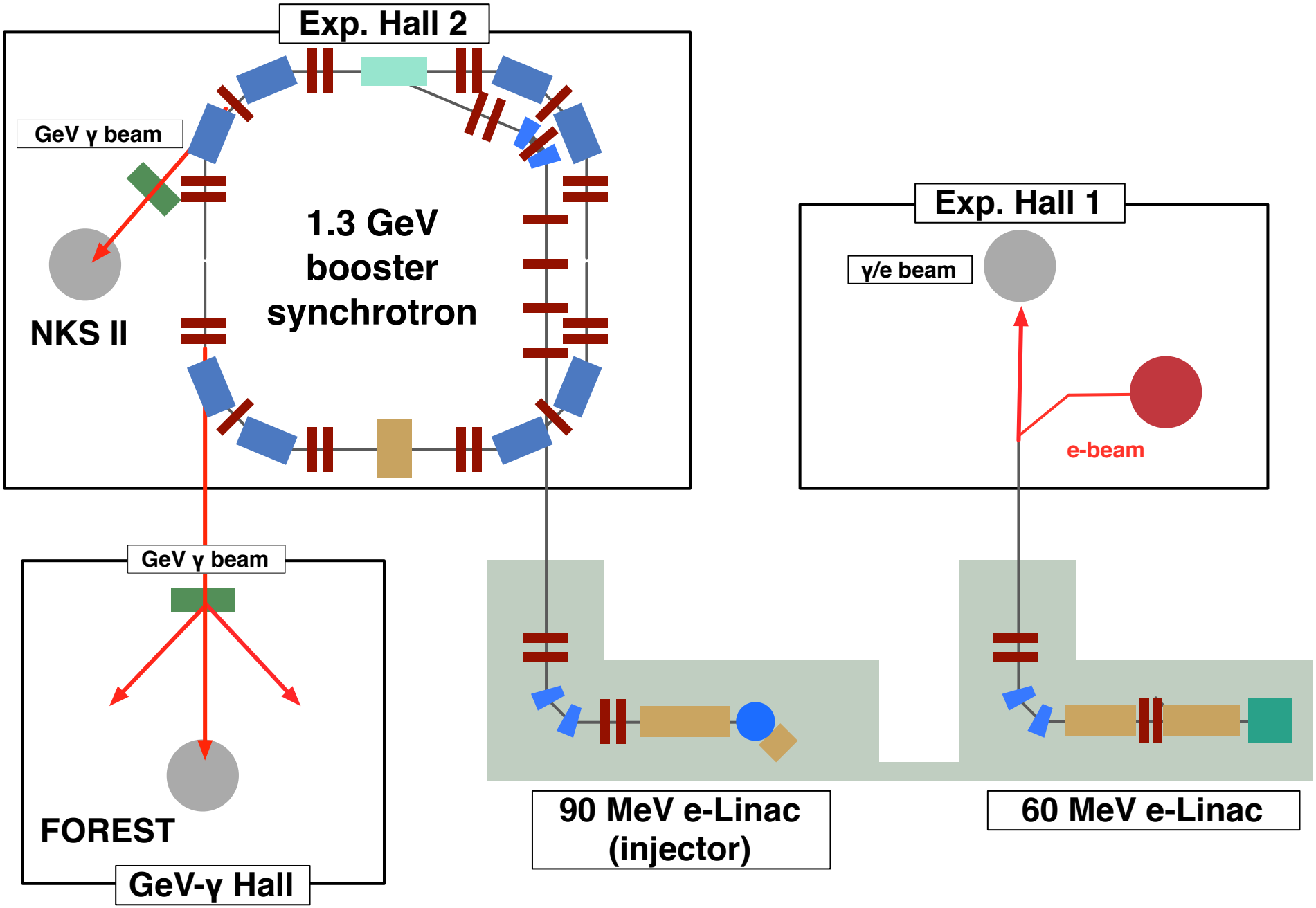
low-energy electron scattering off proton

4) Conclusions

ULQ² collaboration
(Ultra-Low Q²)

Tohoku Univ.
Sendai


Exp. Hall 2
GeV γ beam
1.3 GeV
booster
synchrotron
NKS II
Exp. Hall 1
γ/e beam
e-beam
GeV γ beam
FOREST
GeV-γ Hall
90 MeV e-Linac
(injector)
60 MeV e-Linac

東北大学電子光理学研究センター

研究基盤装置：電子加速器

全国共同利用・共同研究拠点

国内最大級ビームパワー ~10 kW

大学施設としては国内最大エネルギー

現状

全国共同利用・共同研究拠点

年間延べ 1000 人以上の電子光ビームユーザー（ハドロン・原子核、RI）

1）~ 60 MeV制動輻射ガンマ線： RI 生成

2） ~ 1 GeV 単色ガンマ線、電子（陽電子）ビーム：ハドロン物理、検出器開発

NEW! 3）~ 60 MeV 電子散乱（世界唯一）：原子核研究 => 近い将来、共同利用に提供

研究

1.3 GeV：ハドロン物理：ダイバリオン、ハイパー核、検出器開発

60 MeV： 原子核物理： 陽子電荷半径

RI ：核医学用有用RI を含む RI 光生成（イオンビームと相補的）

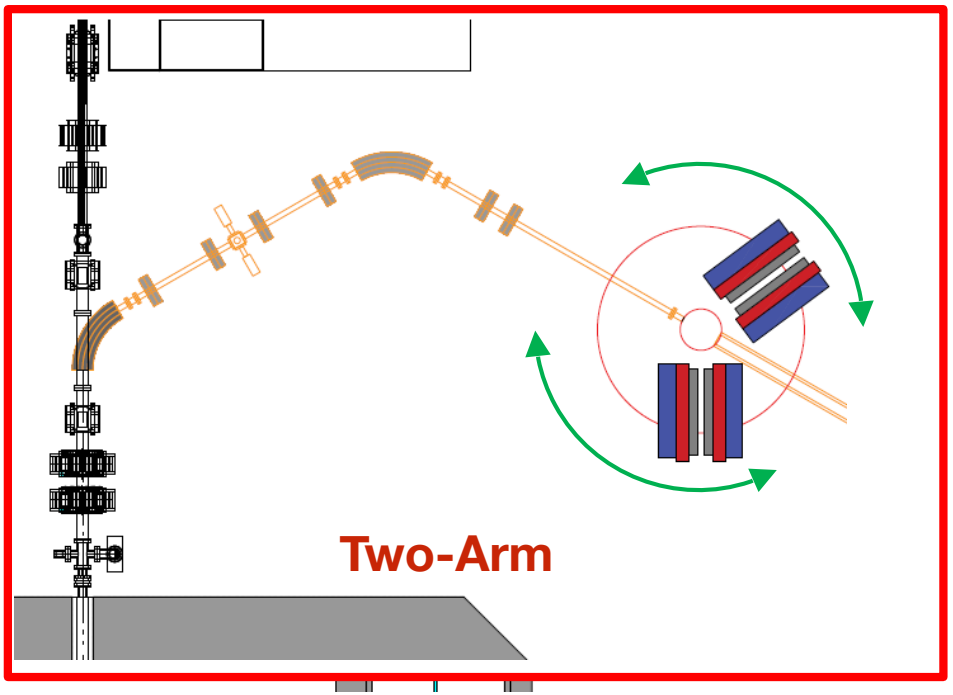

電子光理学研究センター
三神峯キャンパス

New setup for proton-radius measurement

Low energy electron beam： Ee = 20 - 60 MeV

the lowest-Ee ever employed for electron scattering off proton

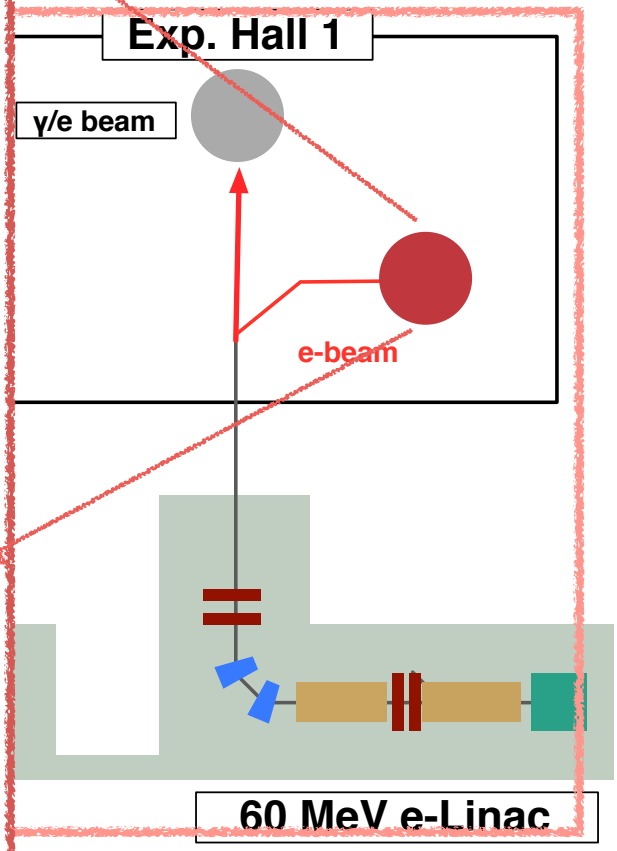
New beam line + Spectrometers



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

ew beam line
ew spectrometer

for ULQ2 exp.



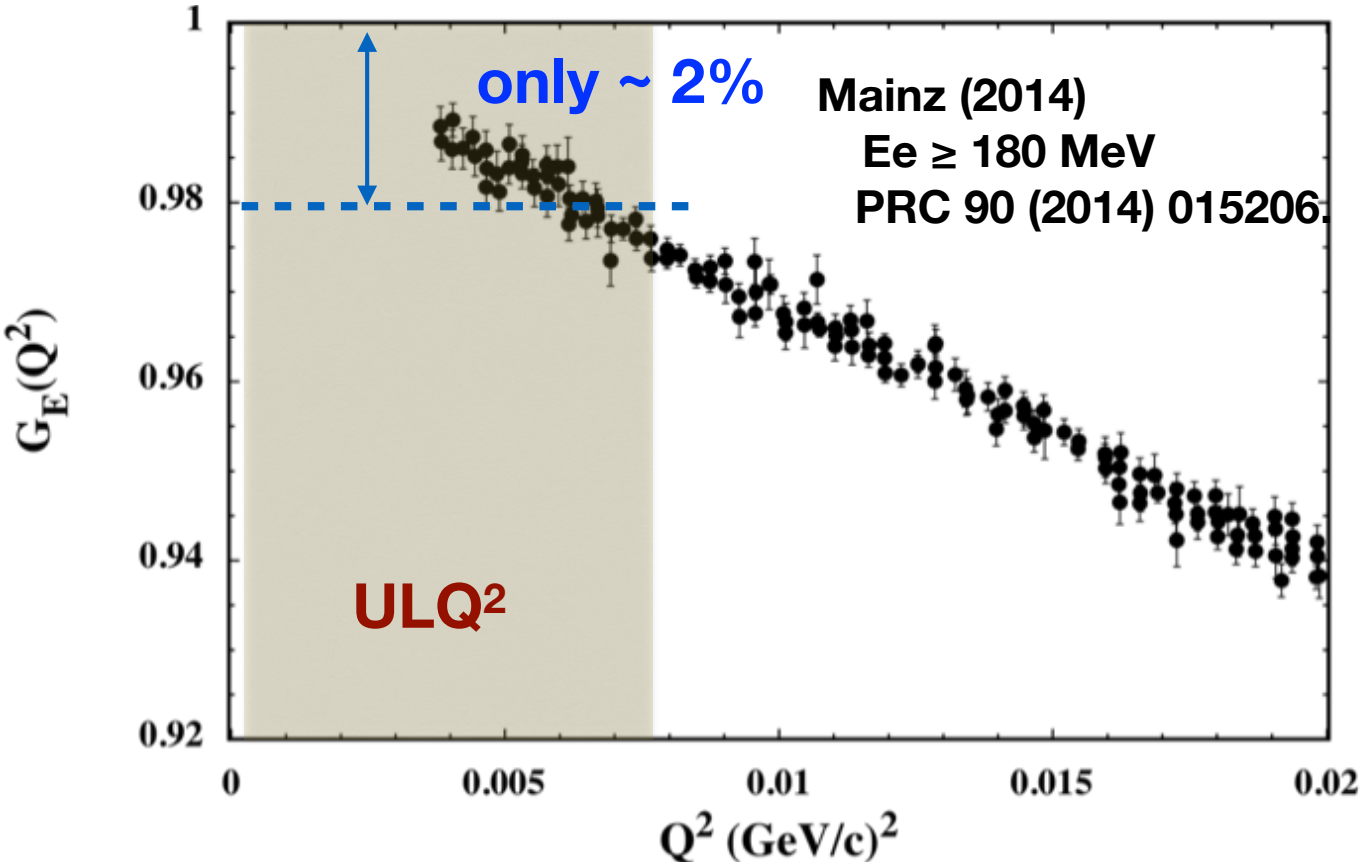
electron scattering under Ultra-Low Q^2

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

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

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

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



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

SpinPhysics@Matsue
Feb. 23-24, 2021

Goal of our experiment

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

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

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

new beam line + double-arm spectrometer

Challenges

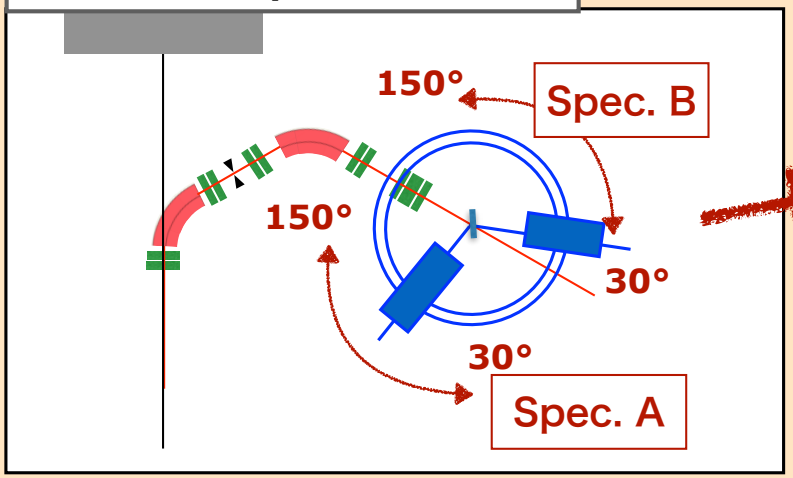
Absolute cross section ($G_E(Q^2)$) with 10^{-3} accuracy

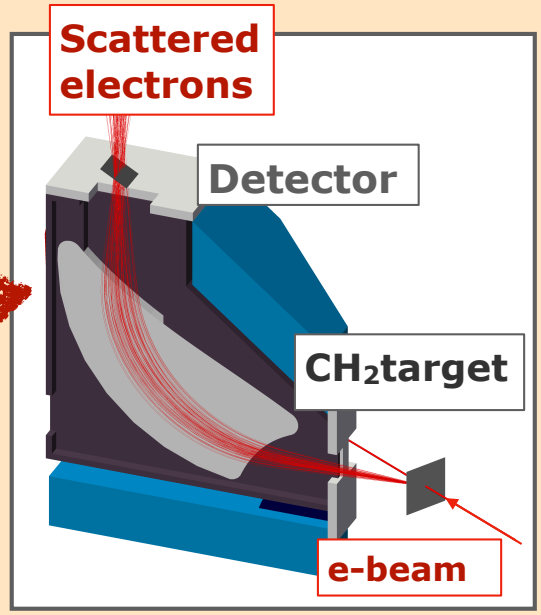
experimental challenges for measurement
theoretical challenges for interpretation

Electron Spectrometer

SpinPhysics@Matsue
Feb. 23-24, 2021

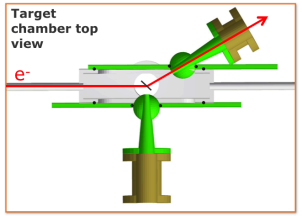
Electron spectrometer



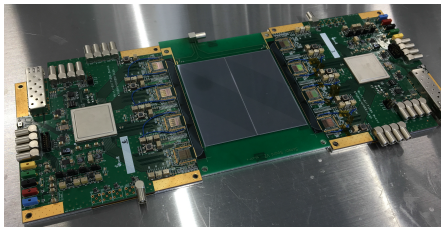


For low-energy exp.

a new type of scattering chamber

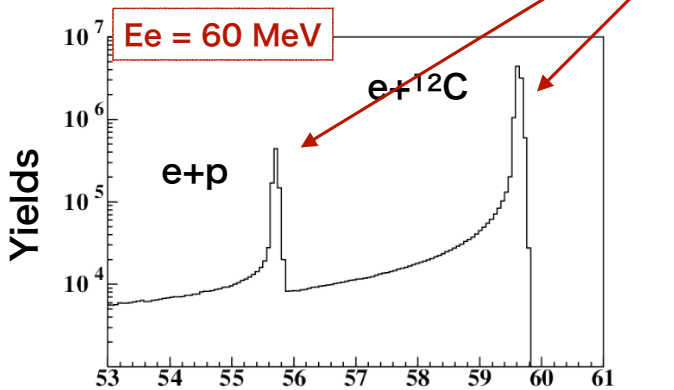


Silicon Strip Detector (g-2/EDM)



For absolute cross section

CH_2 Target



1）e+p/C separation due to mass difference

2）^{12}C : standard target for electron facility

3）change of CH_2 ratio due to e-beam irradiation

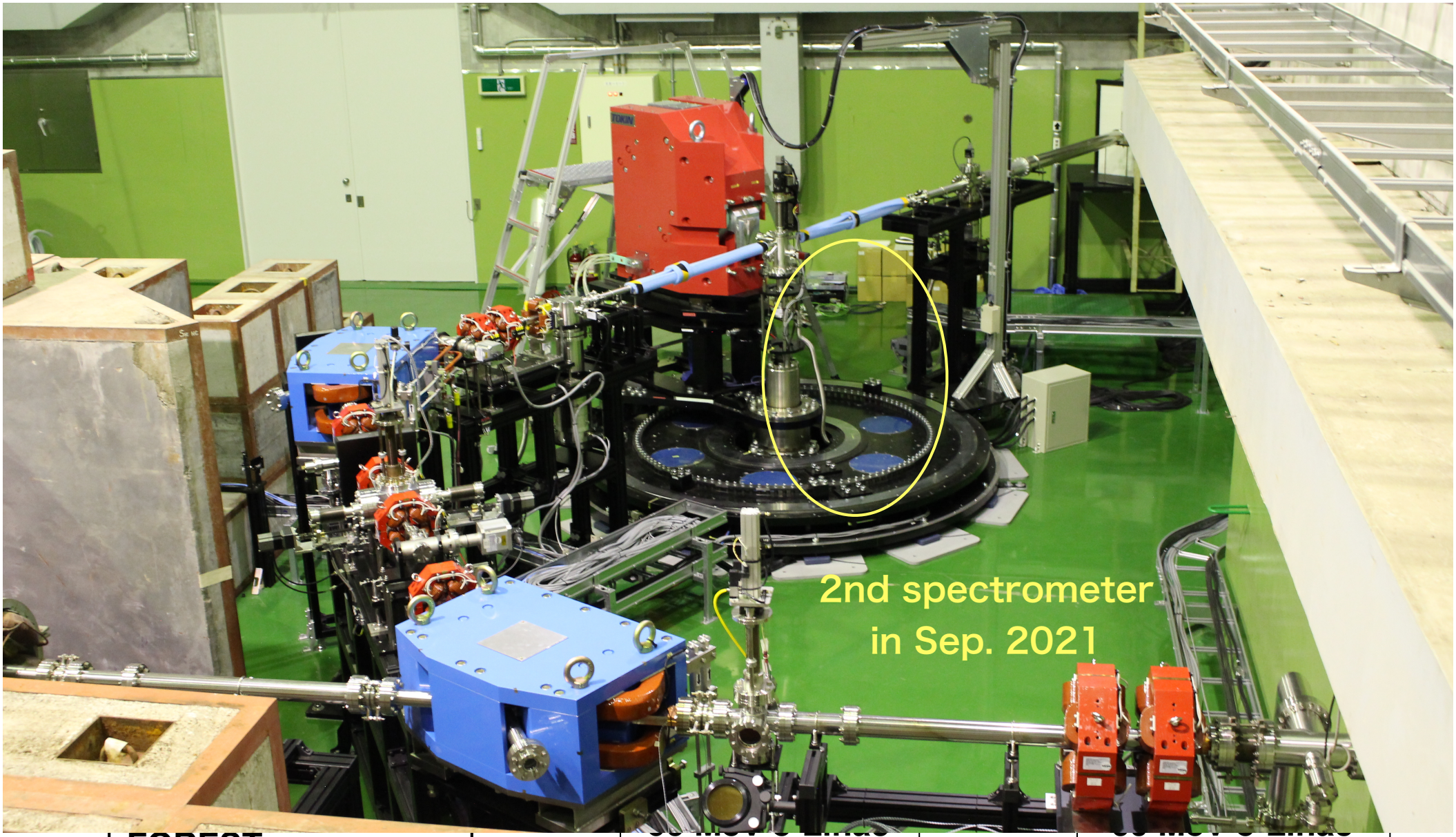
Spec. A

1）Rosenbluth separation

2）elative measurement to ^{12}C
absolute e+p xsection

Spec. B

monitoring C/H ratio



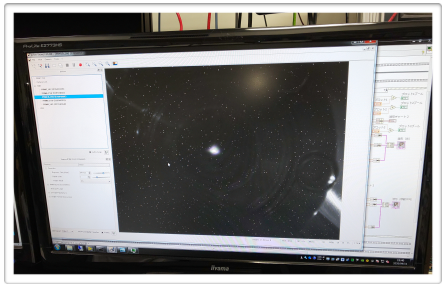
FOREST

GeV-γ Hall

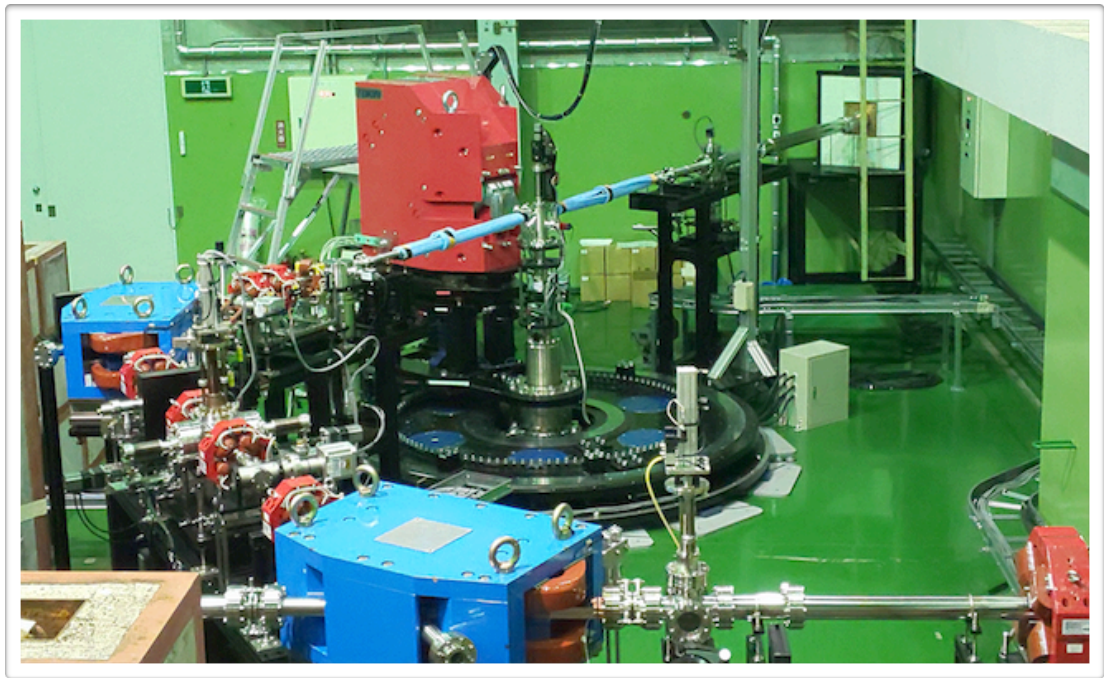
(injector)

ULQ2 beam line

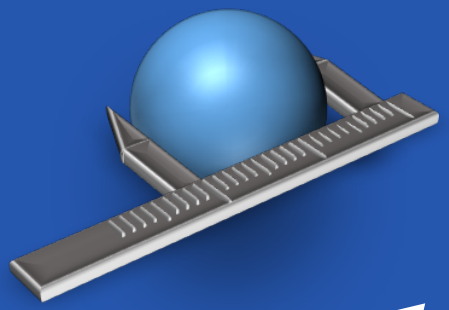
First Beam at the new beam line
Sep. 11, 2020



2020年
9月11日



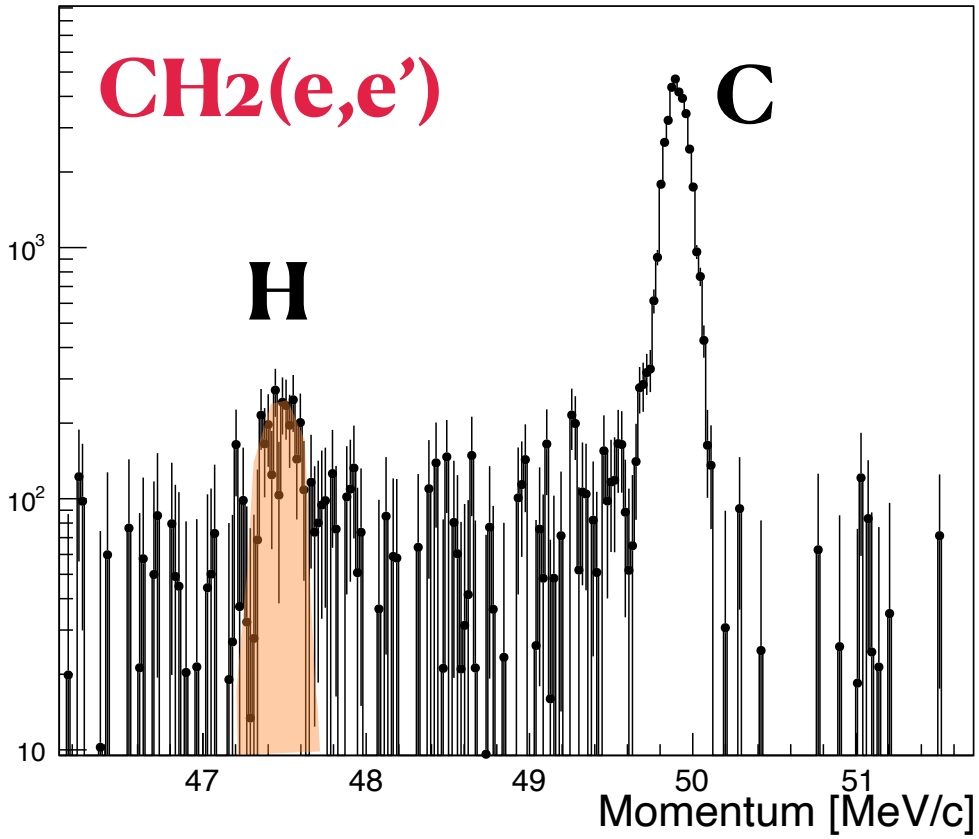
"First-Beam" beer で乾杯

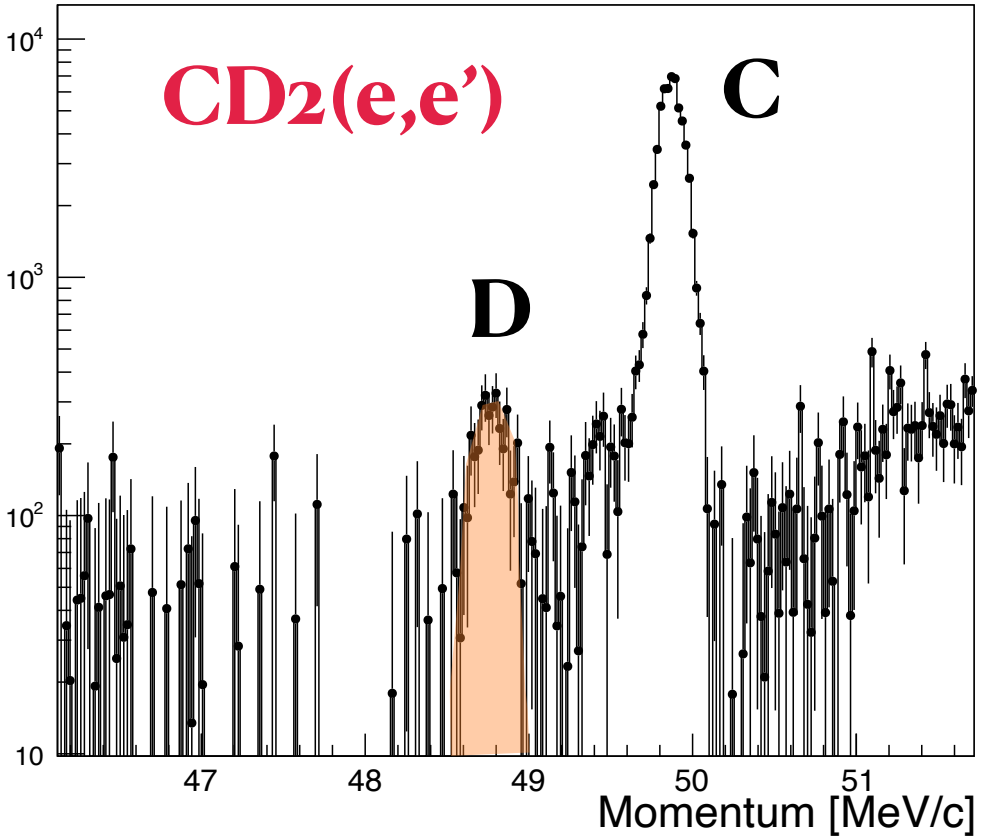


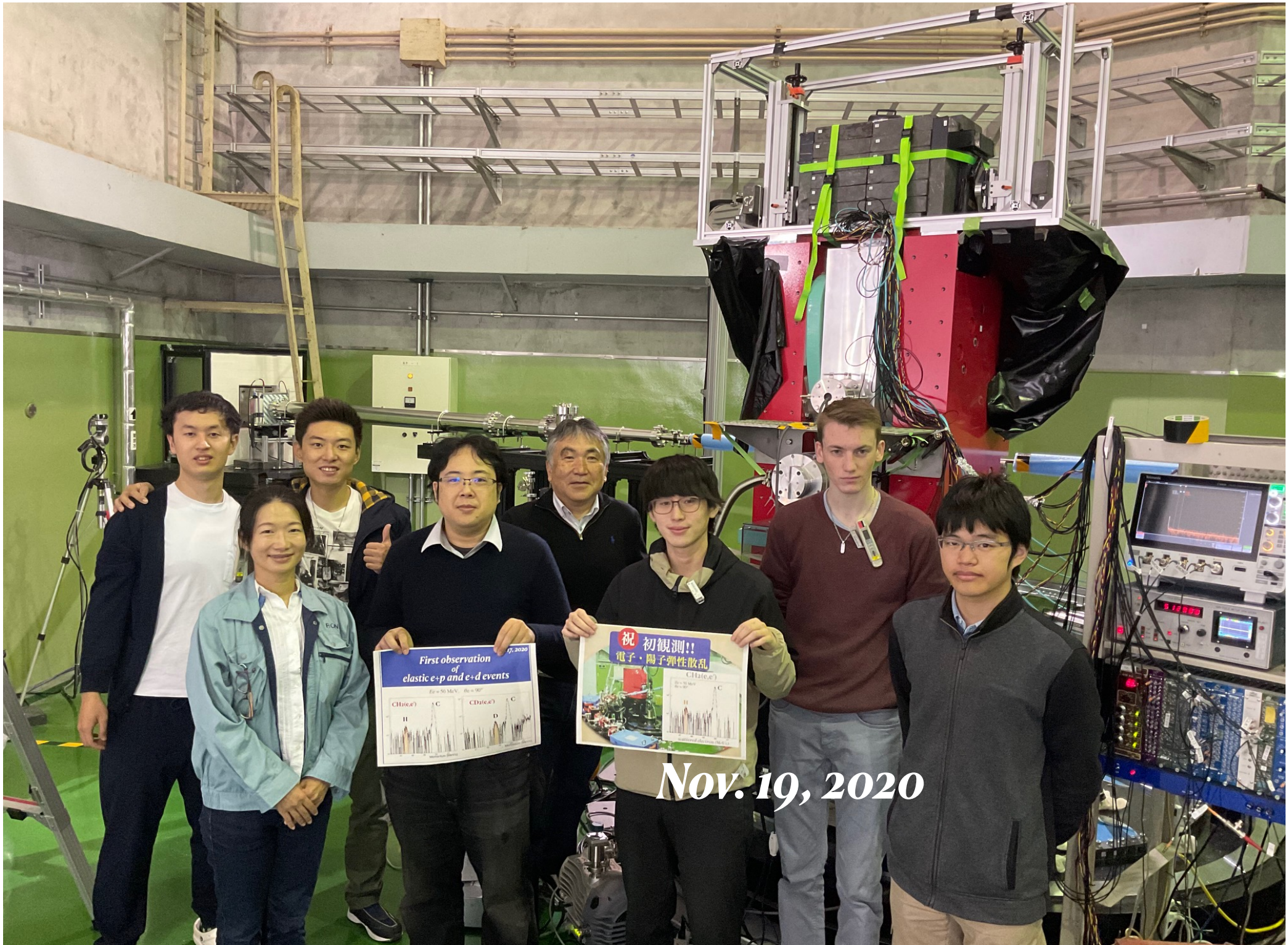
Nov. 17, 2020

First observation of elastic e+p and e+d events

Ee = 50 MeV, θe = 90°

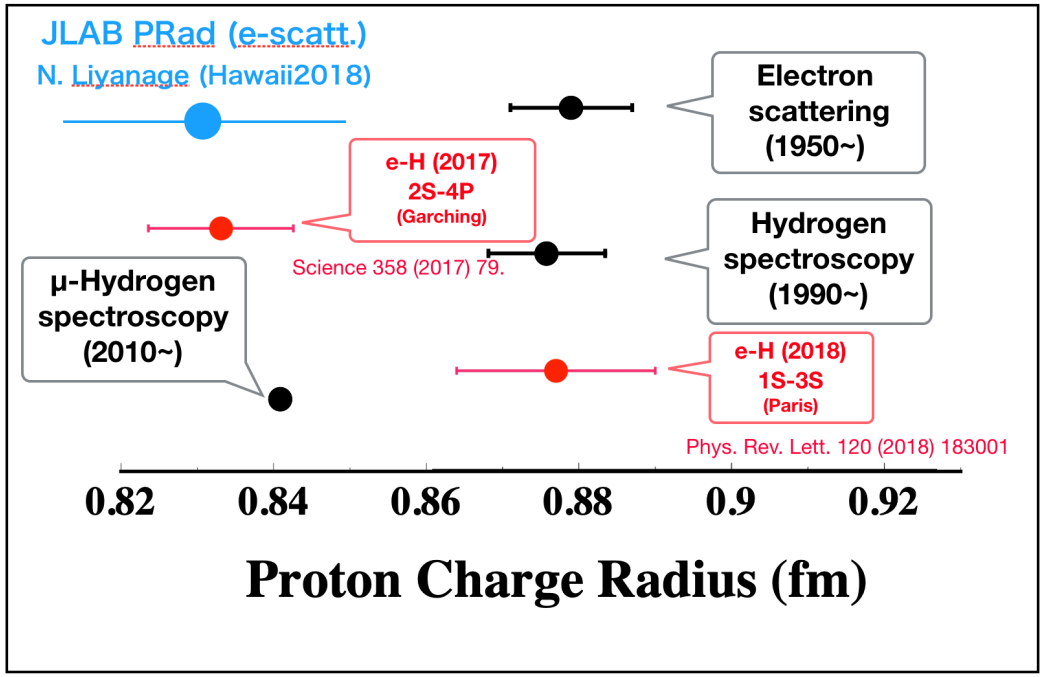





First observation
of
elastic e+p and e+d events
祝 初観測!!
電子・陽子弾性散乱

Nov. 19, 2020

Proton Charge Radius Puzzle ??



- disagreements : not yet understood.
- the “correct” proton radius is important.
- further experimental and theoretical efforts.

e-scattering : PRad (JLAB), ULQ2 (Tohoku), MESA (Mainz)
μ-scattering : MUSE (PSI), COMPASS (CERN)