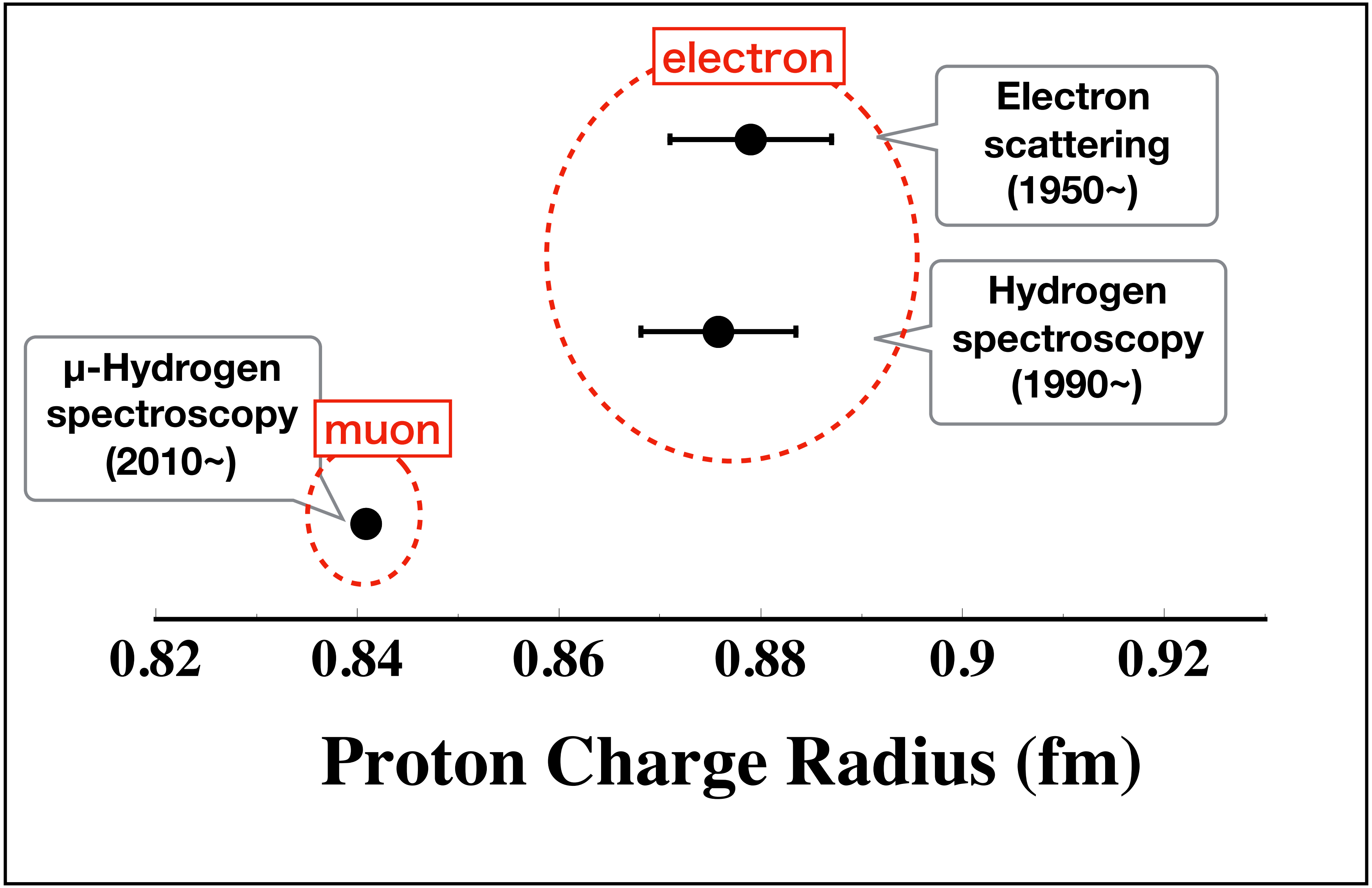
PacificSpin2019@Miyazaki
Aug. 27-30, 2019

PROTON RADIUS

Toshimi Suda

Tohoku University
Sendai, Japan

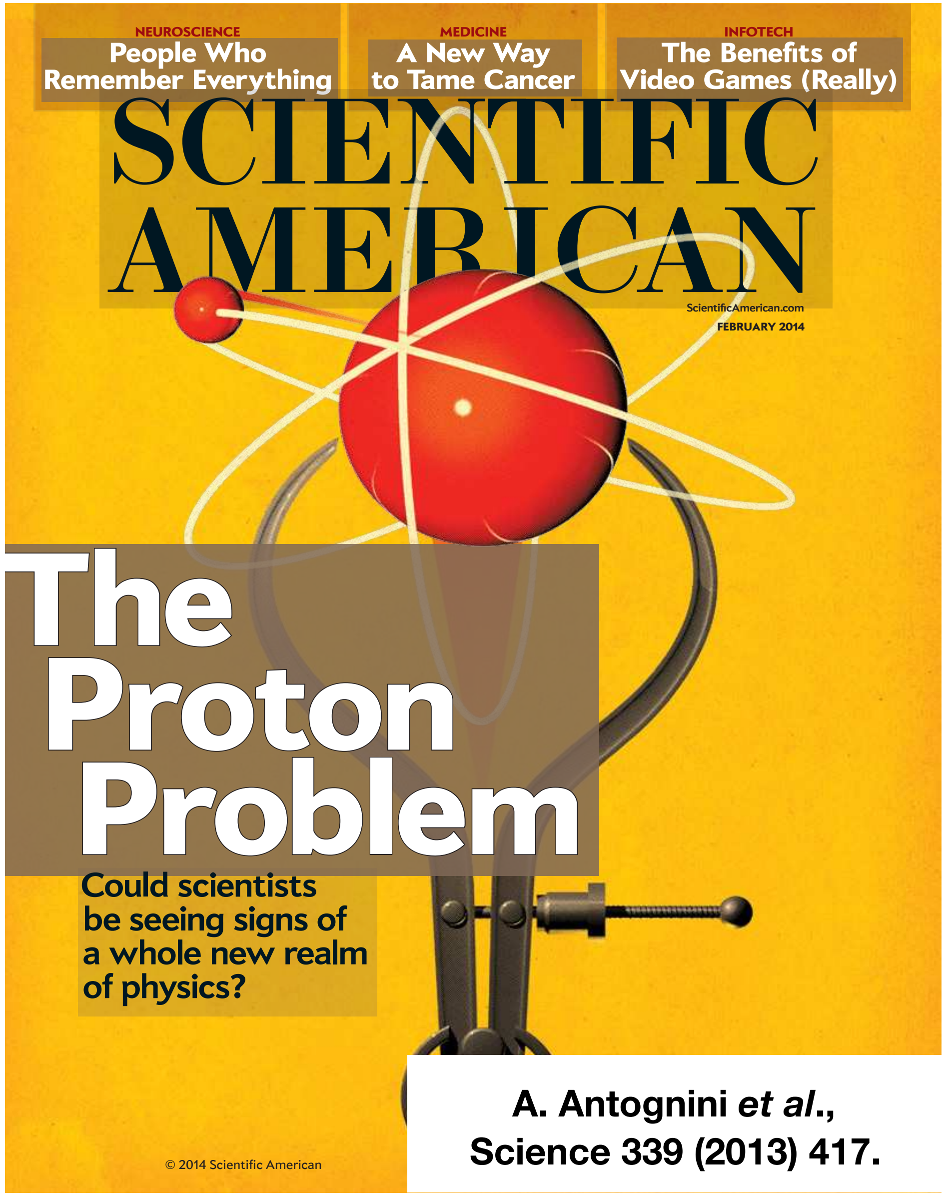
since 2010 ~



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

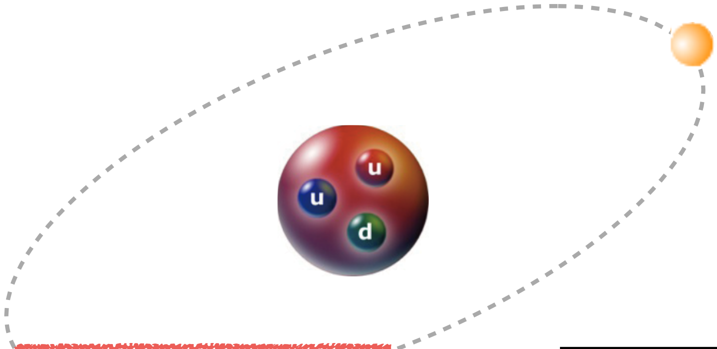
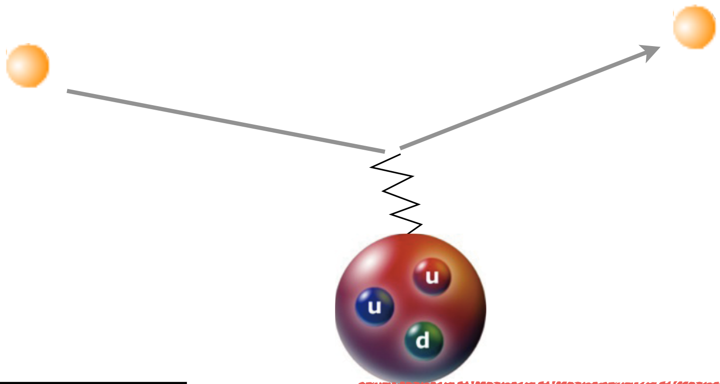
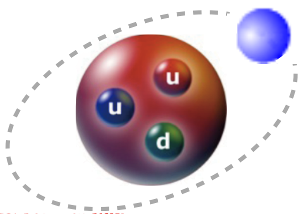
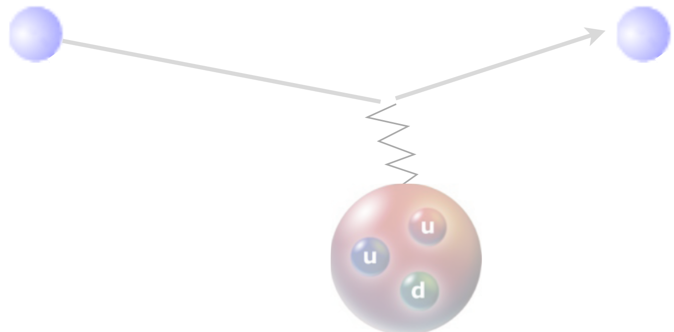
Proton Radius Puzzle ?

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



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

Proton Charge Radius

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

m_e = 0.511 MeV
m_μ = 105.6 MeV

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

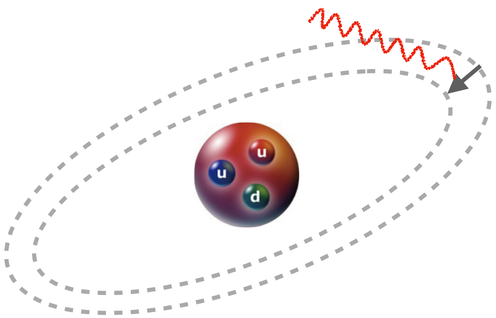
$$I(J^P) = \tfrac{1}{2}(\tfrac{1}{2}^+)$$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$\left|m_p - m_{\overline{p}}\right|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$\left|\frac{q_{\overline{p}}}{m_{\overline{p}}}\right|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$\left|q_p + q_{\overline{p}}\right|/e < 7 \times 10^{-10}$, CL = 90% [b]
$\left|q_p + q_e\right|/e < 1 \times 10^{-21}$ [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 $= 0.84087 \pm 0.00039$ fm [d]
Charge radius, $e p$ CODATA value $= 0.8751 \pm 0.0061$ fm [d]
Magnetic radius $= 0.78 \pm 0.04$ fm [e]
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

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



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

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

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

r_p uncertainty

3) (bound) QED high precision calculations

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

Lepton Universality (e <-> μ) ??

Proton Charge Radius ??

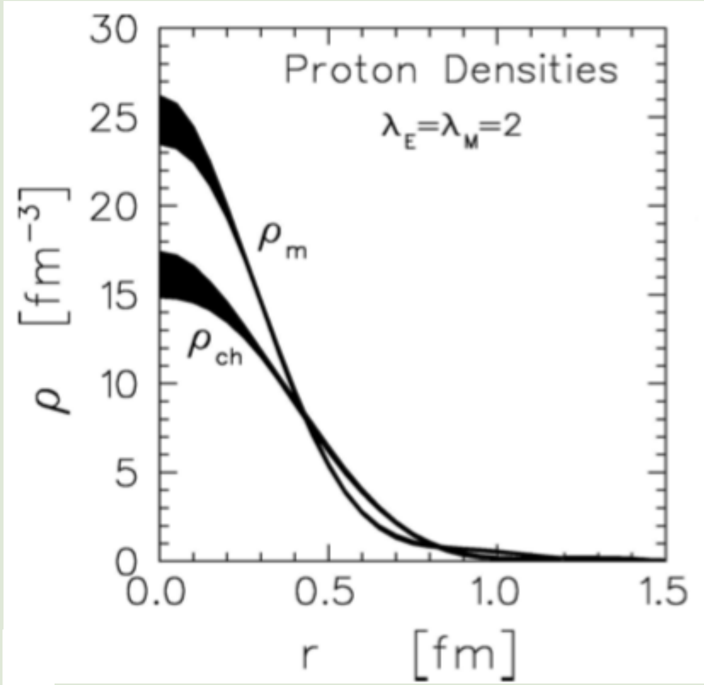
$$F(Q_L^2) = \int \rho(\vec{r}) e^{i\overrightarrow{Q_L}\cdot\vec{r}} d\vec{r}$$

Q_L Lab. value of momentum transfer

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

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

R. Hofstadter (1951)



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

Relativistically proper definition

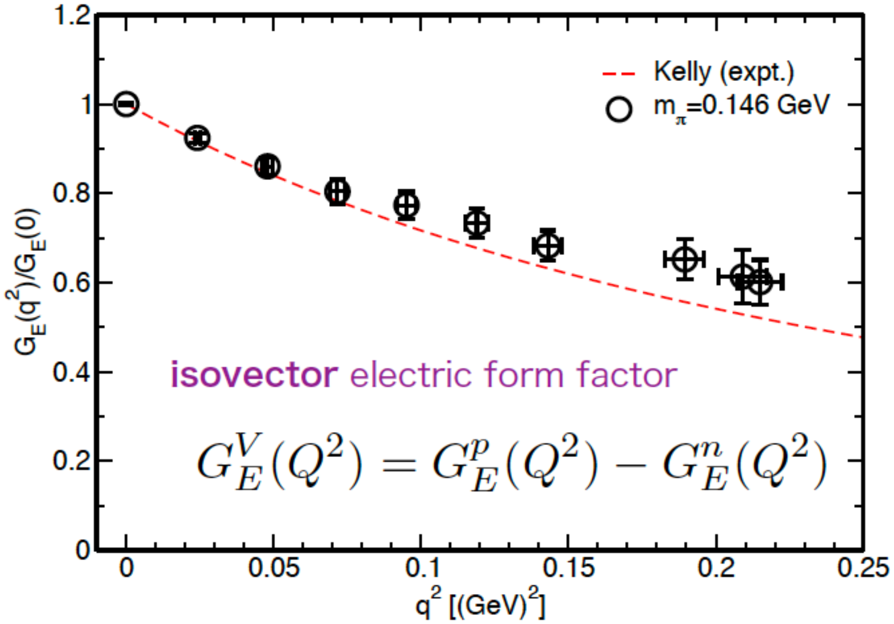
$$r_p^2 = -6 \frac{\mathrm{d}G_E(0)}{\mathrm{d}Q^2}|_{Q^2\to 0}$$

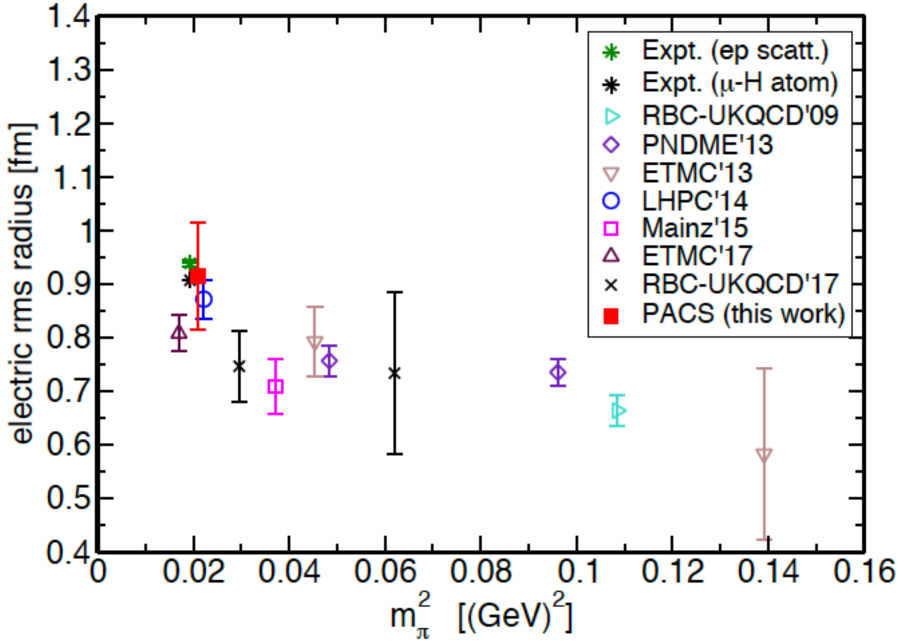
G. A. Miller Phys. Rev. C99 (2019) 035202

Nucleon form factors on a large volume lattice near the physical point in 2+1 flavor QCD

- $L^3 \times T = 96^3 \times 96 \Rightarrow$ (~8.1 fm)^3 spatial volume
- almost the physical pion mass (m_π=146 MeV)

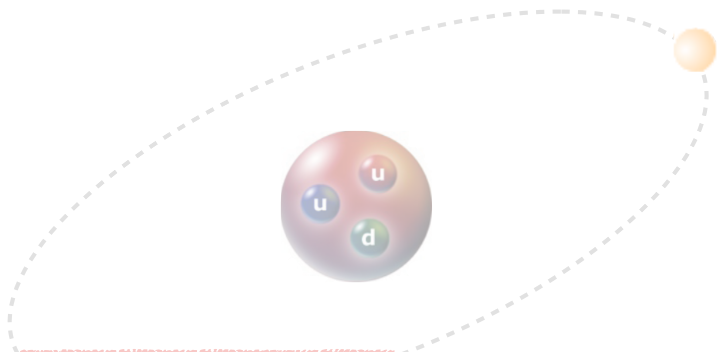
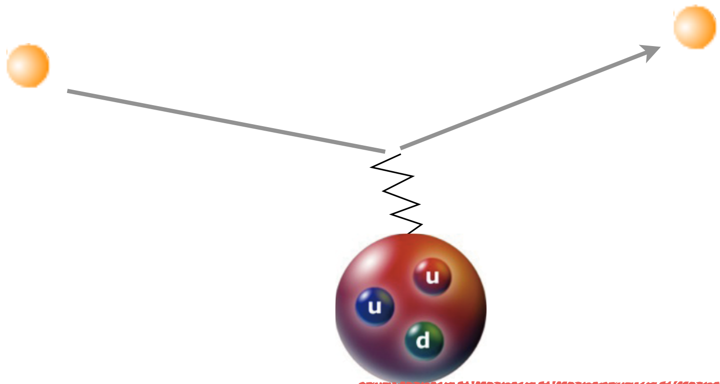
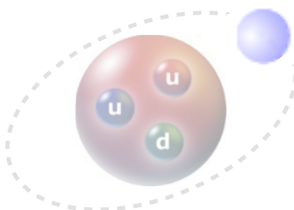
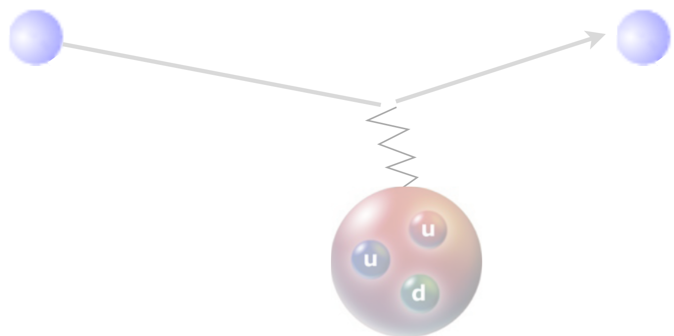
Ishikawa, Kuramashi, Sasaki, Tsukamoto, Ukawa, Yamazaki (PACS collaboration)
arXiv:1807.03974



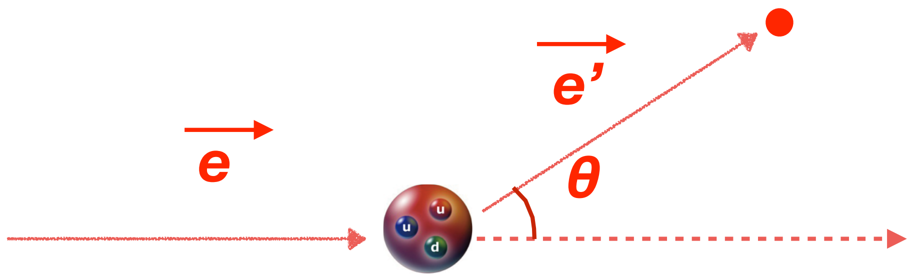


New studies on a $128^3 \times 128$ lattice (L~10.8 fm) at the physical point (m_π=135 MeV) are in progress

lepton scattering

	Spectroscopy	Scattering
e⁻	 0.8758(77)	 0.8770(60)
μ⁻	 0.8409(4)	

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**

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

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

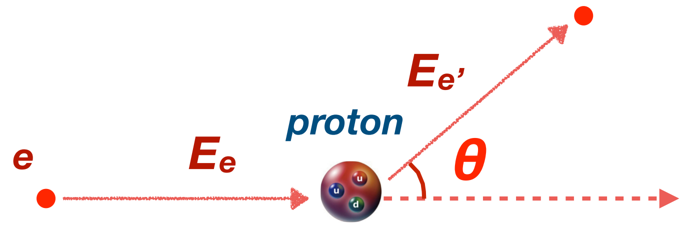
$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2\frac{\theta}{2}} \qquad \tau = \frac{Q^2}{4m_p^2}$$

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

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

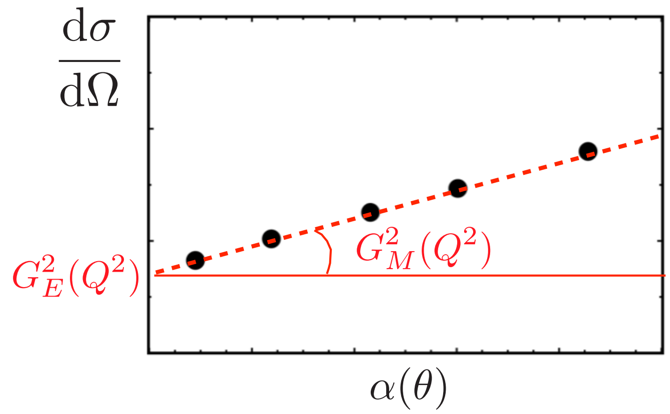
$G_E(Q^2)$ extraction from cross section

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)

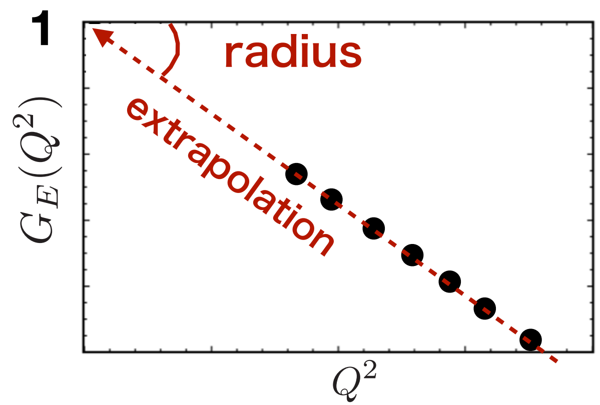


Proton charge radius

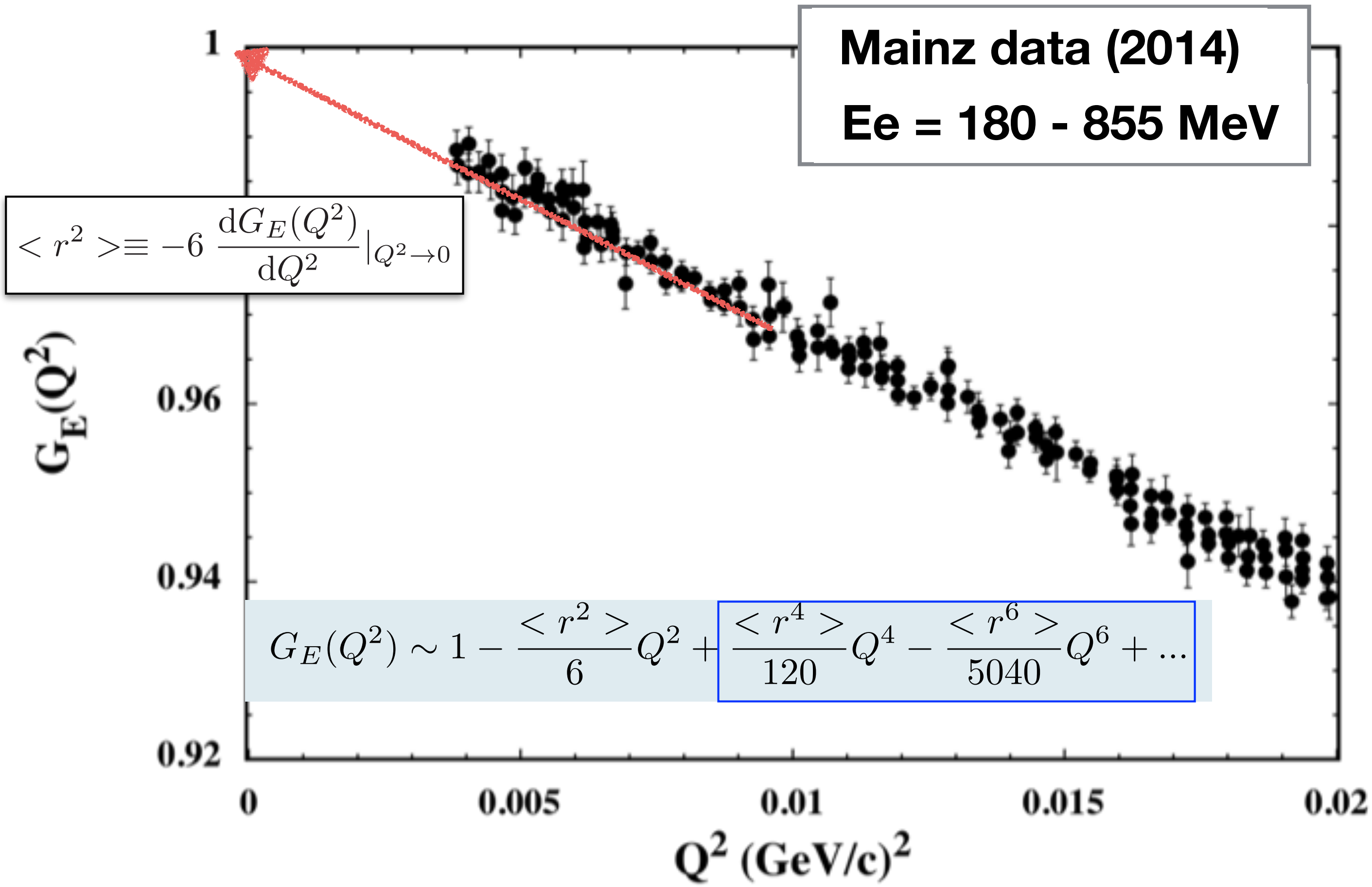
$$< r^2 > \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$$

low Q^2 region as possible

low-Ee (or small θe)



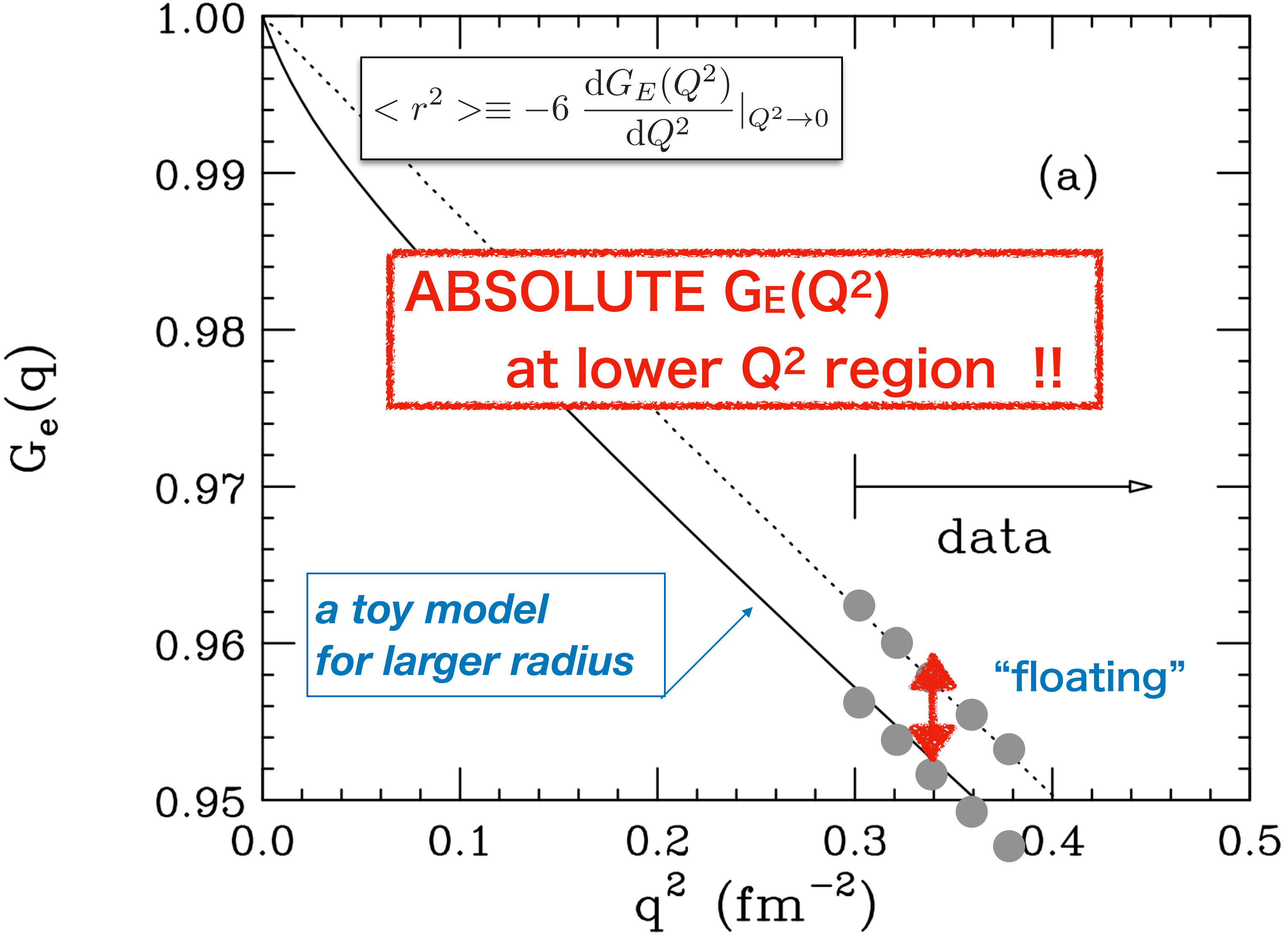
Recent Mainz data (2014)



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

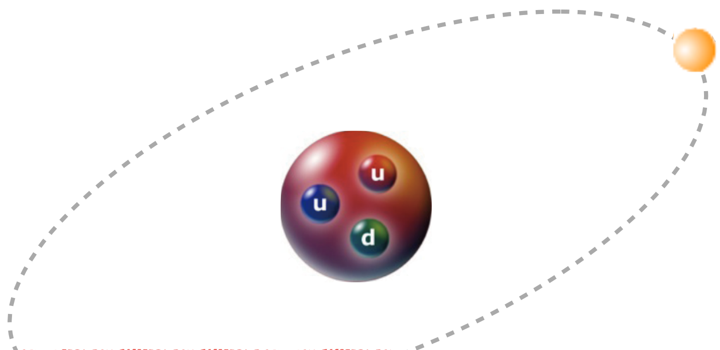
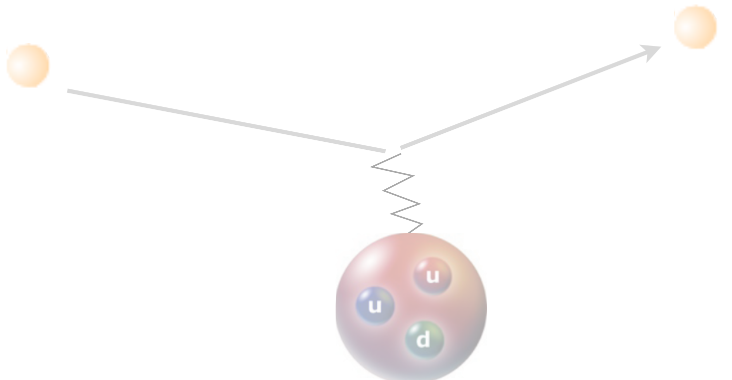
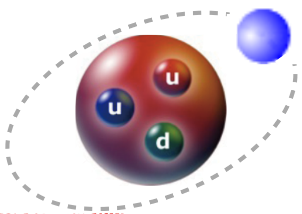
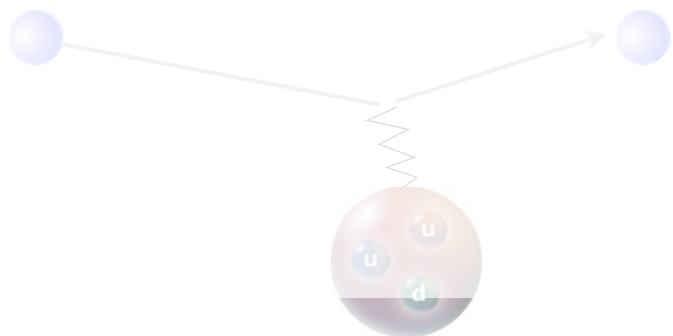
Absolute $G_E(Q^2)$ at lower Q^2 region

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



I. Sick, Atoms 2018, 6, 2

Hydrogen spectroscopy

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

μ-hydrogen Spectroscopy

PSI (Paul Scherrer Institute)

N_μ ~ 600 /s
E_μ = 3 - 6 keV
beam cross section : 0.5 x 1.5 cm²

H_2 gas target : ~1mbar, 20cm

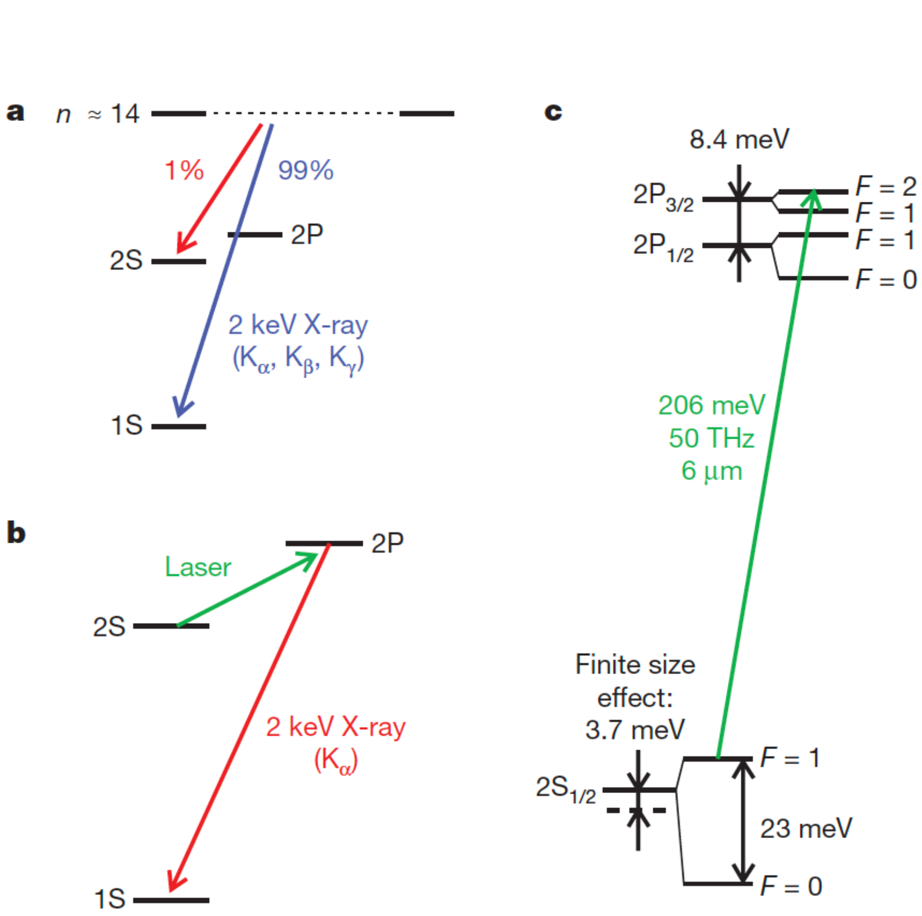
μ^- beam

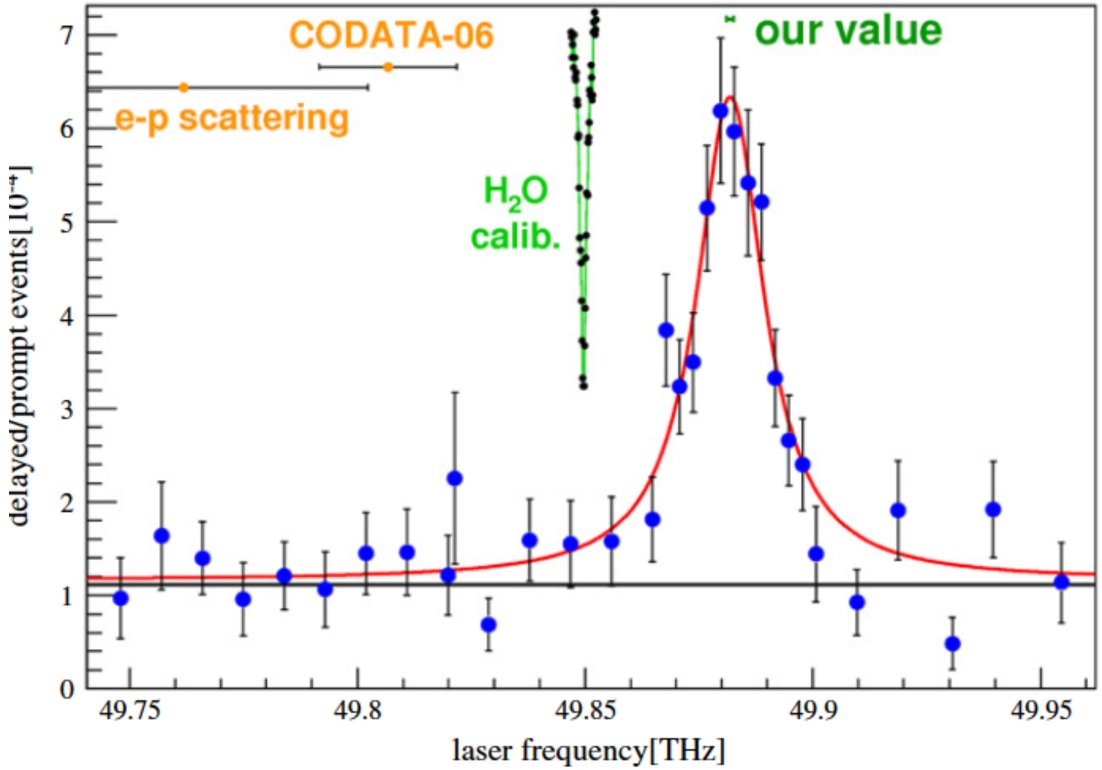
trapped to the hydrogen orbital (n ~ 14)

∼1% of μ trapped in metastable 2S (~1μS)

Laser excitation for 2S -> 2P

measuring the decay 2keV X-rays





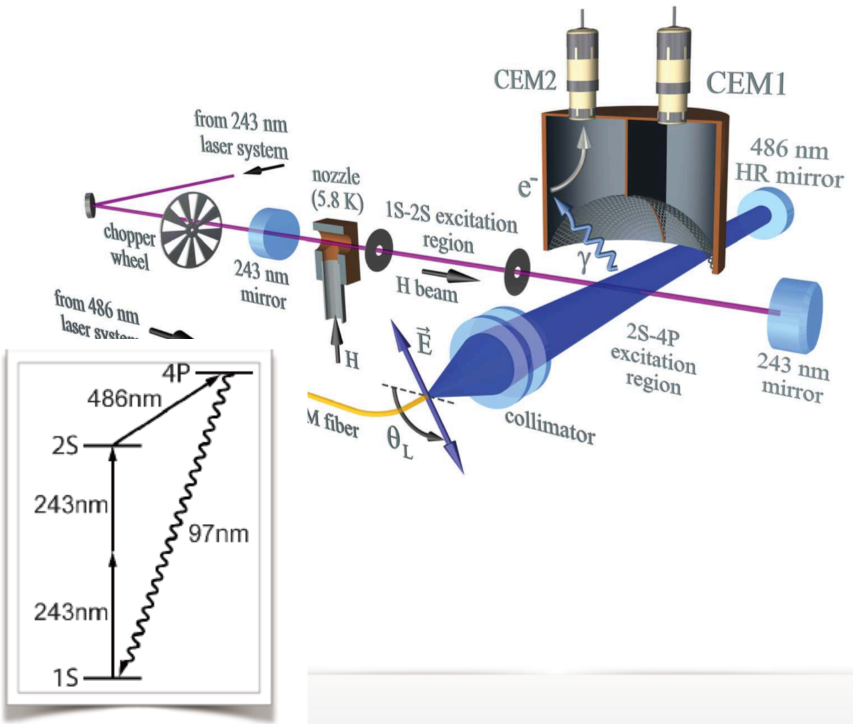
$$\Delta E_{2S->2P} = 209.9779(49) - 5.2262 \ <r_p>^2 + \Delta(2S, 2P)$$

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

Recent eH spectroscopy measurements

Garching

2S-4P transition



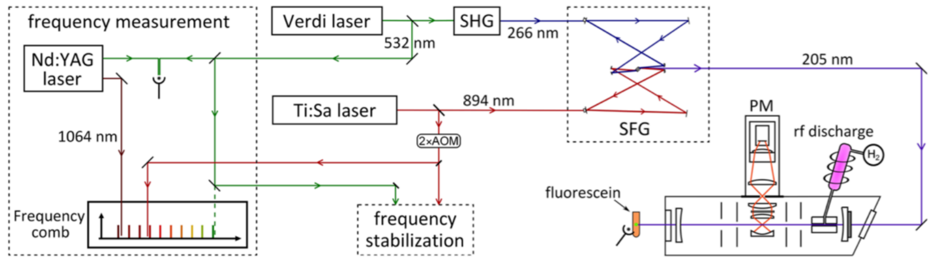
- r_p discrepancy: 9 kHz
- Line width: 20’000 kHz
- Measurement uncertainty: 3.0 kHz

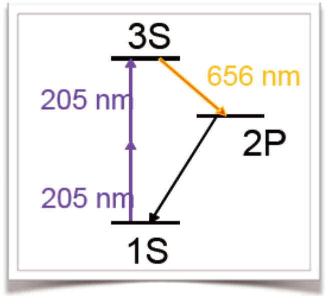
⇨ split an asymmetric line to 10^{-4}

Beyer et al., Science 358 (2017) 79.

Paris

1S-3S transition



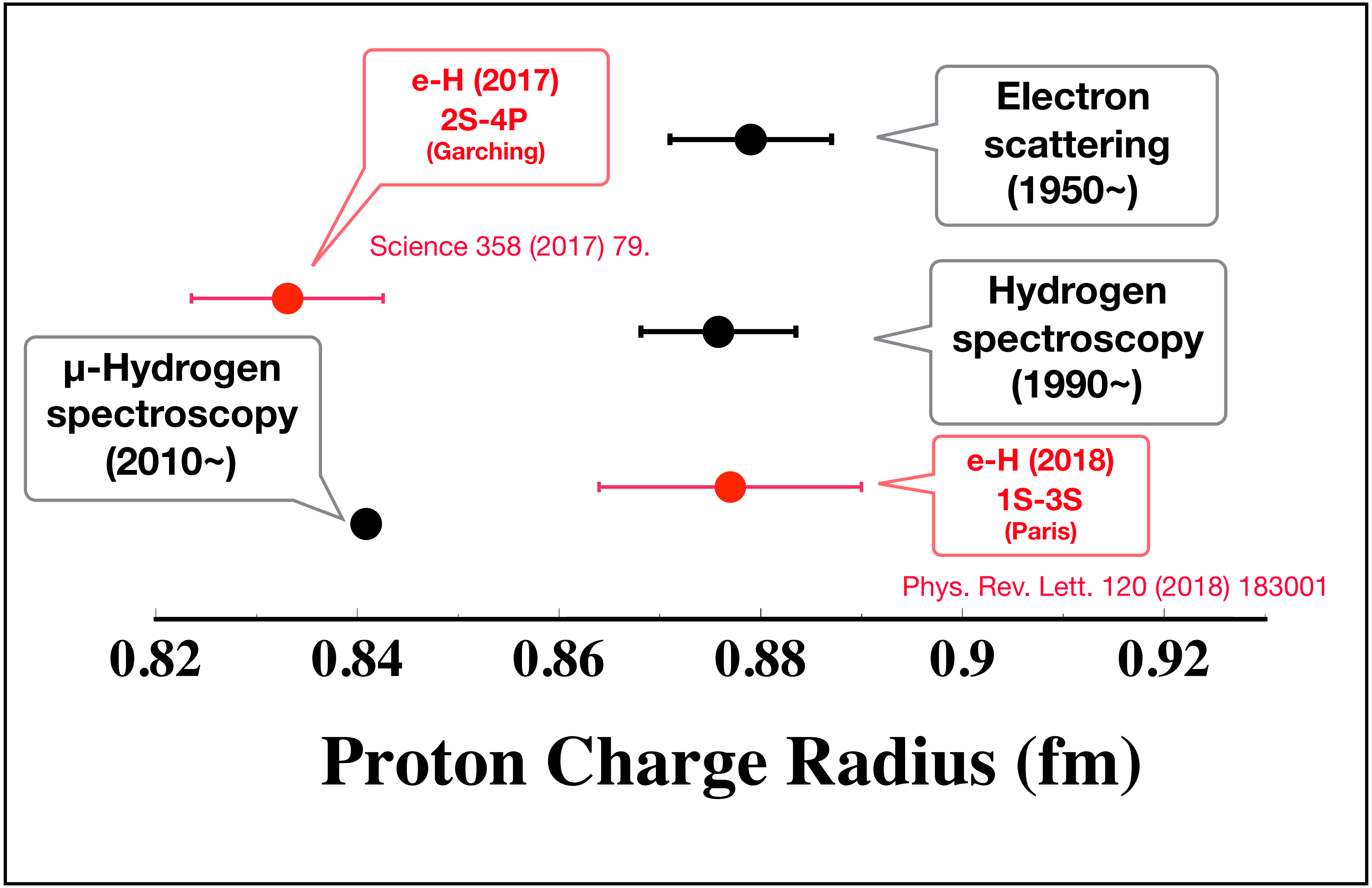


- Line width: 1500 kHz
- Statistical uncertainty: 2.1 kHz
- Total uncertainty: 2.7 kHz

- r_p discrepancy: 9 kHz

H. Fleubaey et al., PRL **120**, (2018)183001

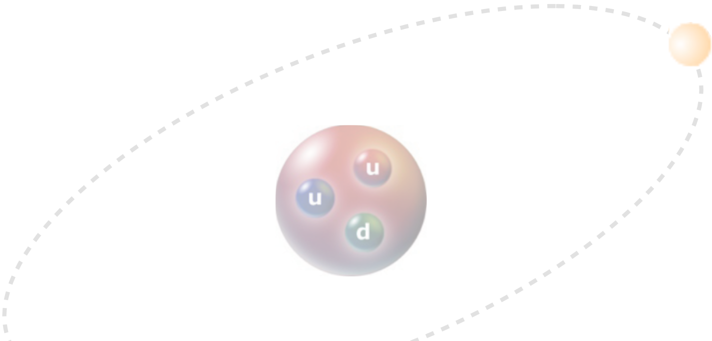
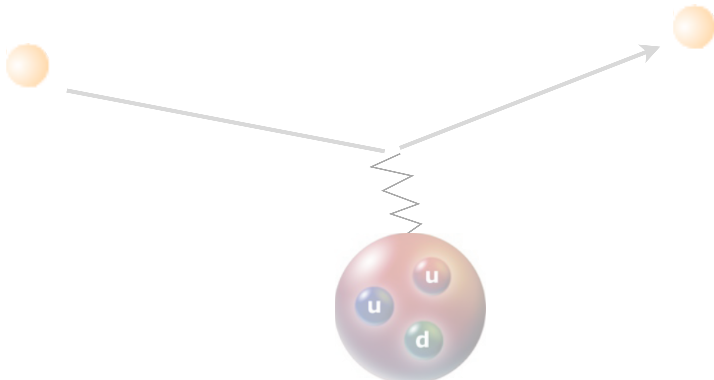
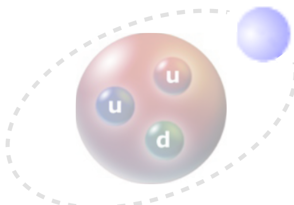
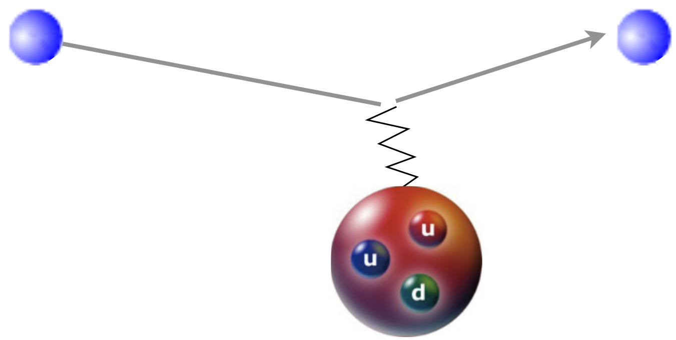
Proton Radius Puzzle ??



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

On-going experimental efforts

Proton Charge Radius

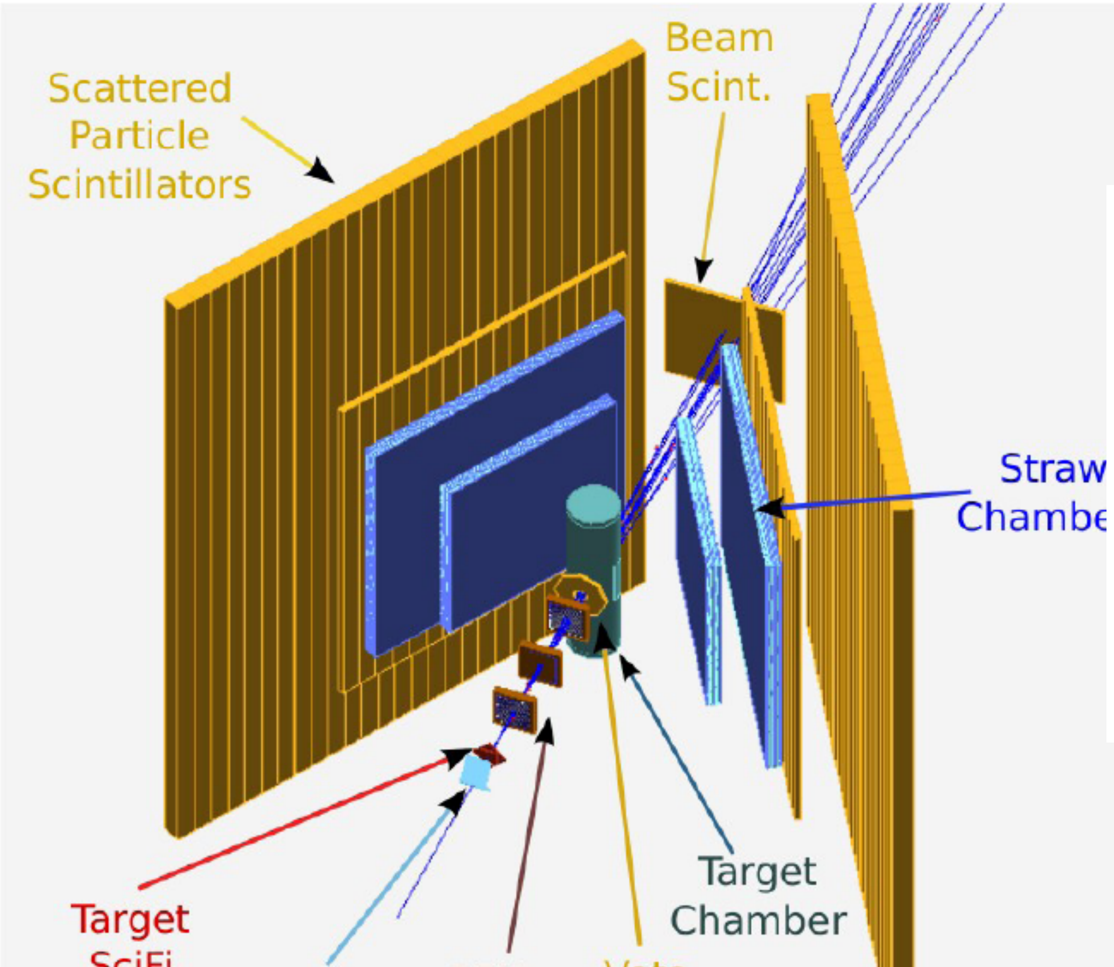
	Spectroscopy	Scattering
e^-	 0.8758(77)	 0.8770(60)
μ^-	 0.8409(4)	

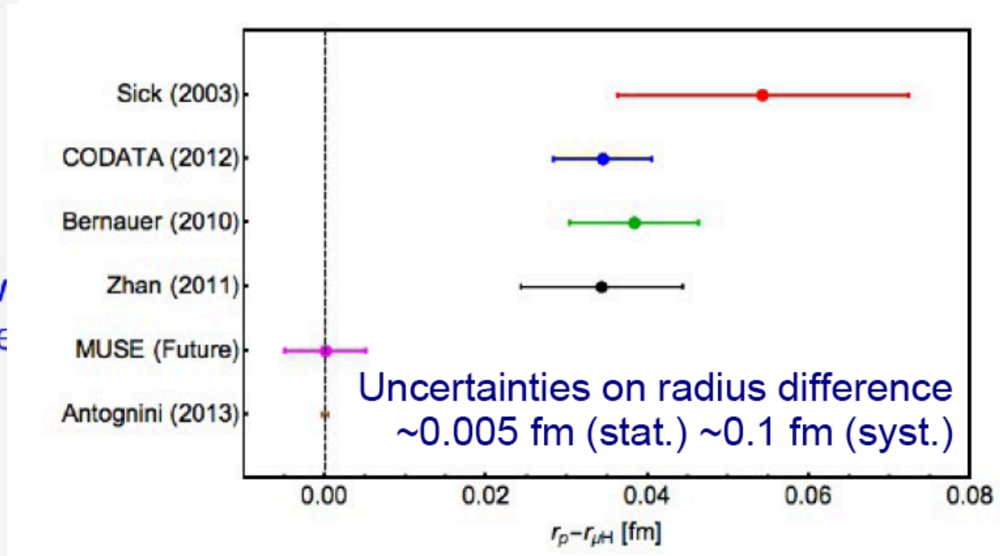
C. Carlson, Prog. Part. Nucl. Phys. 82 (2015) 59.

low-energy μ scattering

MUSE@PSI

$\mu^{\pm}$ scattering off proton
p = 115, 158 and 210 MeV/c
θ = 20 - 100°
Q^2 = 0.002 - 0.07 $(GeV/c)^2$





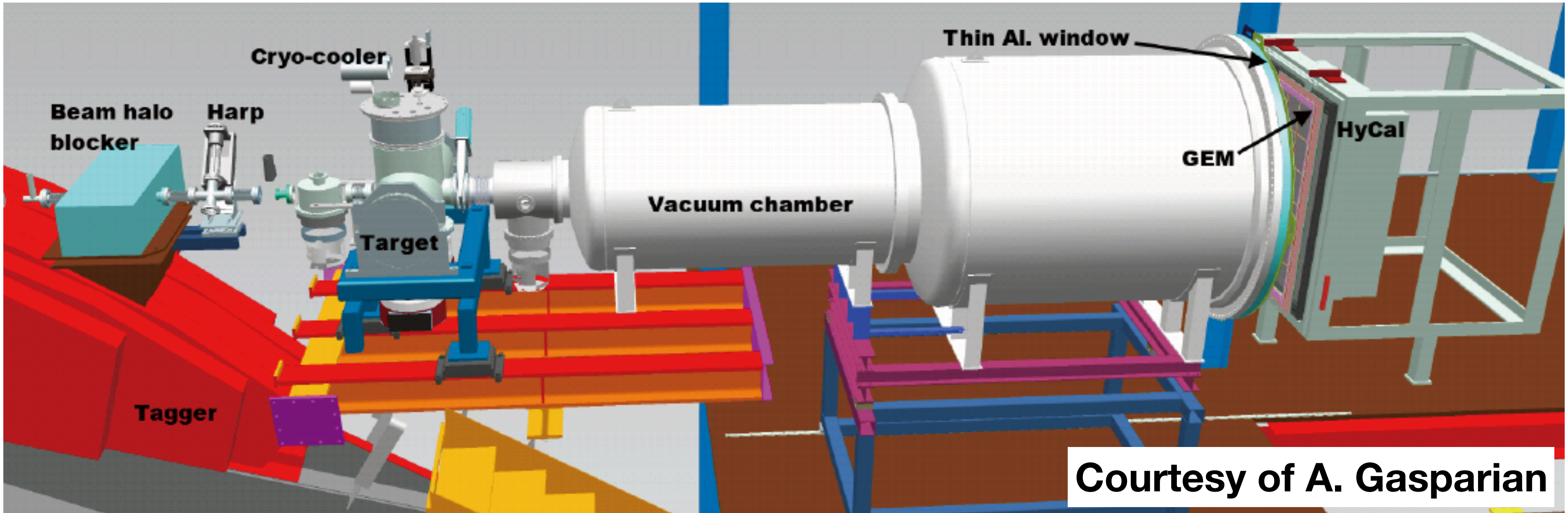
E.J. Downie's talk at PRP2018@Mainz

electron scattering at low Q2

PRAD@JLAB

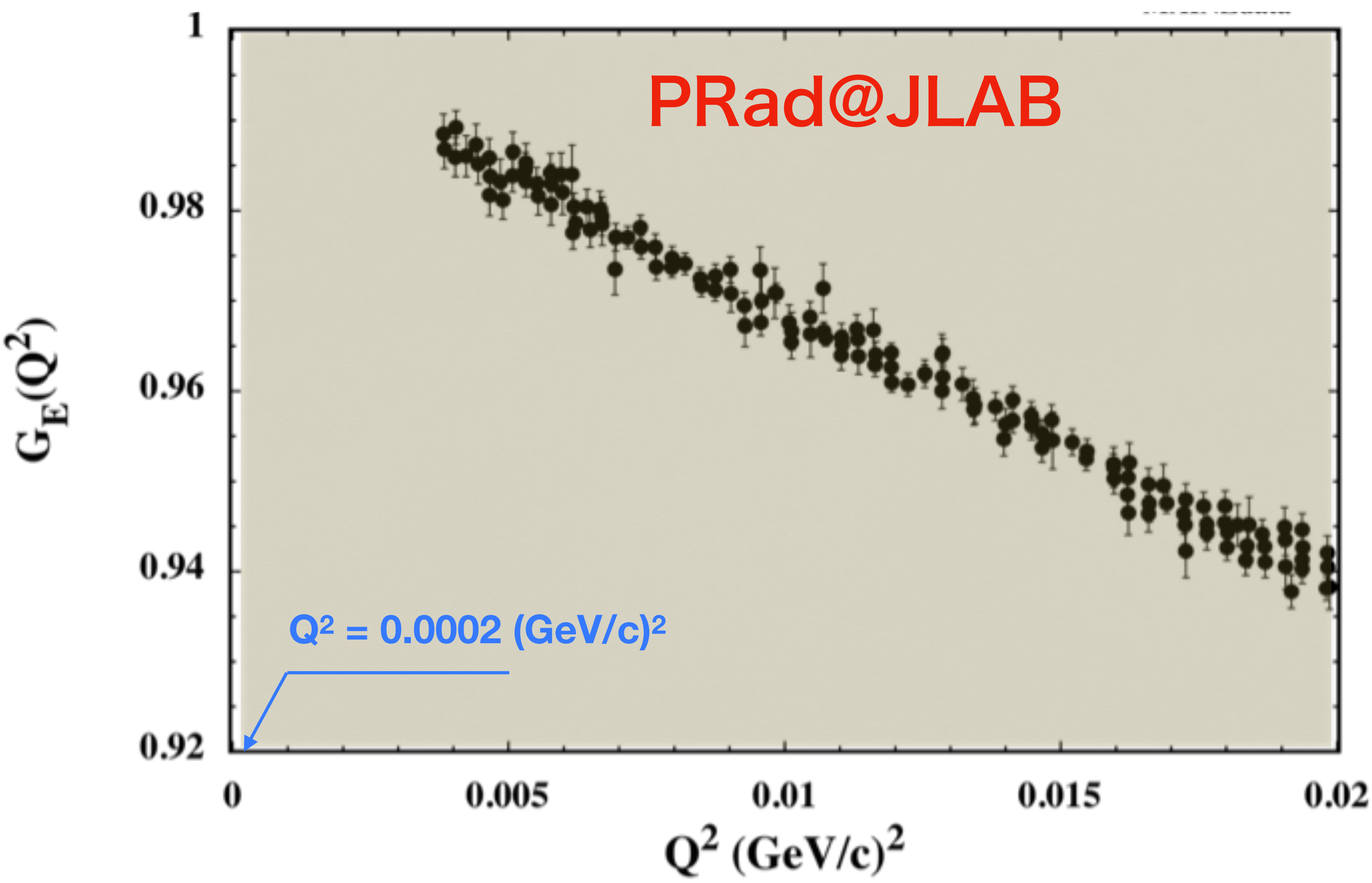
E_e = 1.1, 2.2 GeV
θ ~ a few deg.
$Q^2 = 0.0002 - 0.02\ (GeV/c)^2$

No Rosenbluth separation
(small contribution of $G_M(Q^2)$)
Absolute cross section
(relative to Moeller)

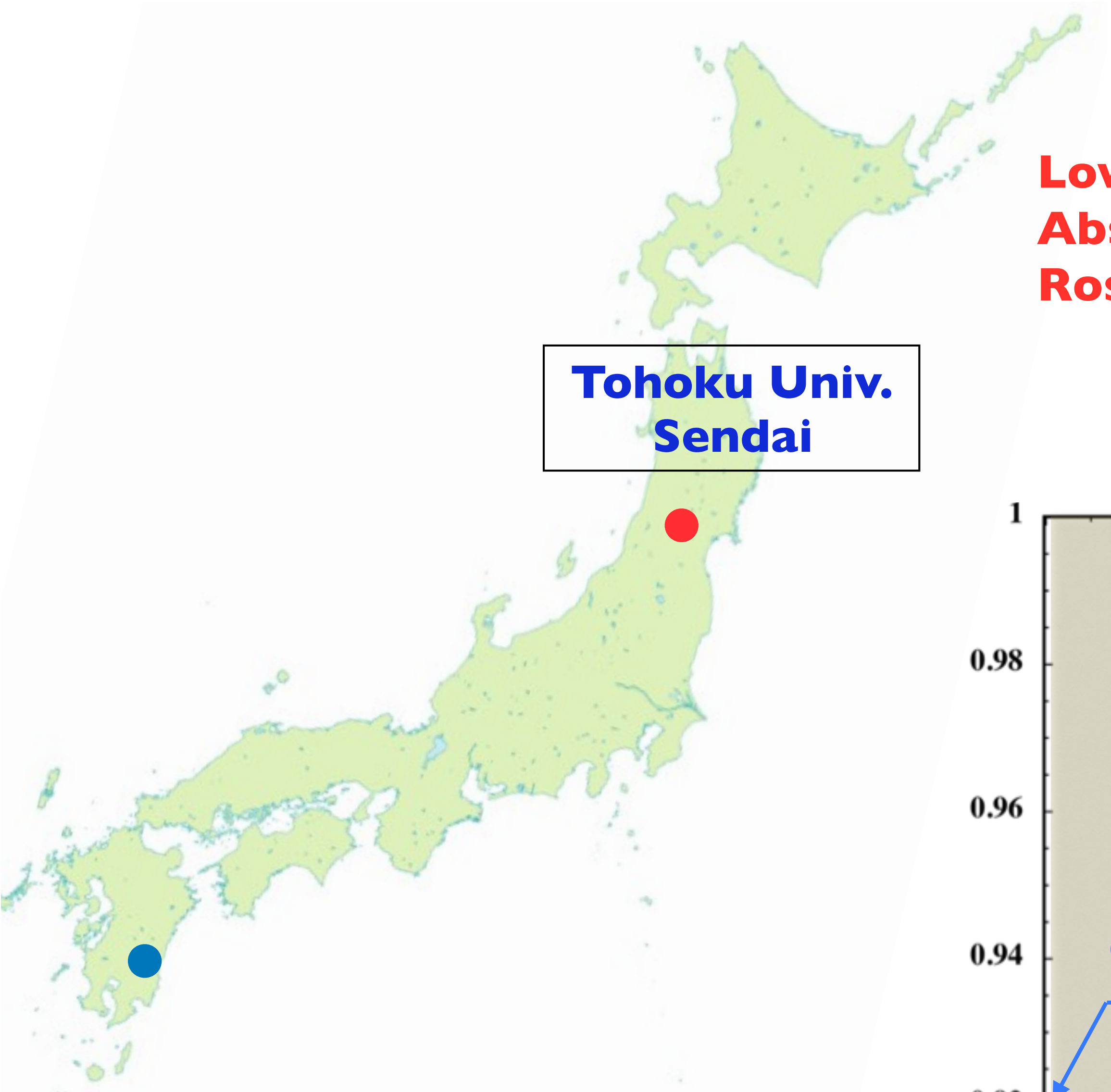


Courtesy of A. Gasparian

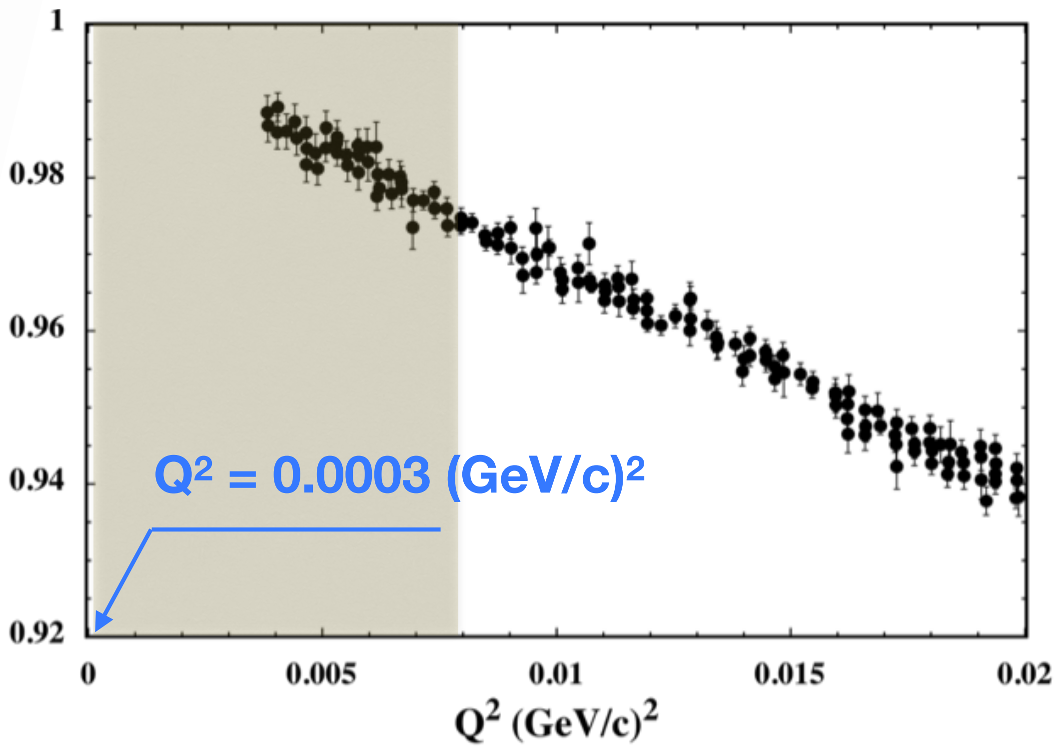
Q2 range of Rad



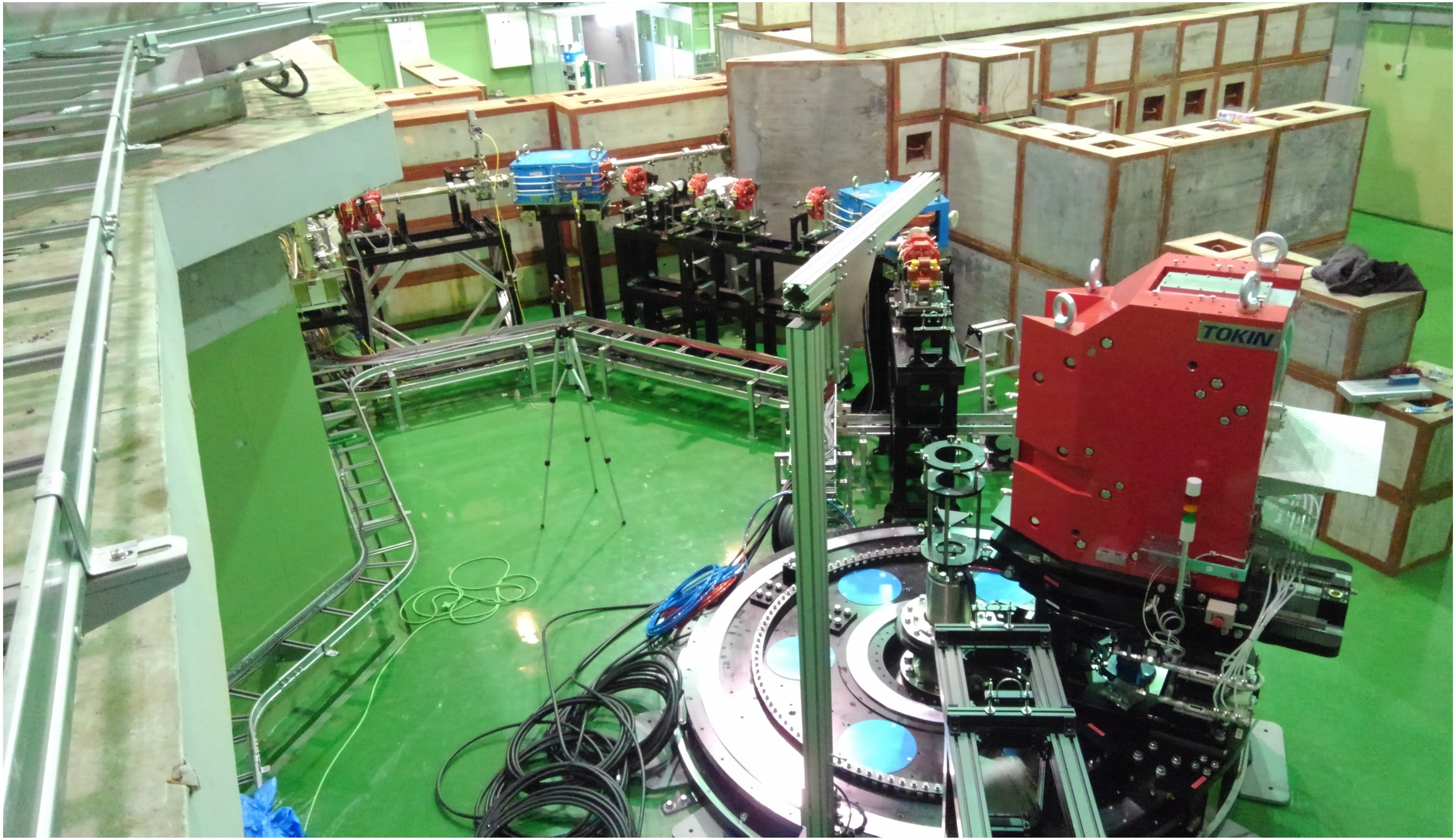
ULQ^2 (Ultra-Low Q^2)



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



本研究の準備状況



New projects under discussion

Orsay, France

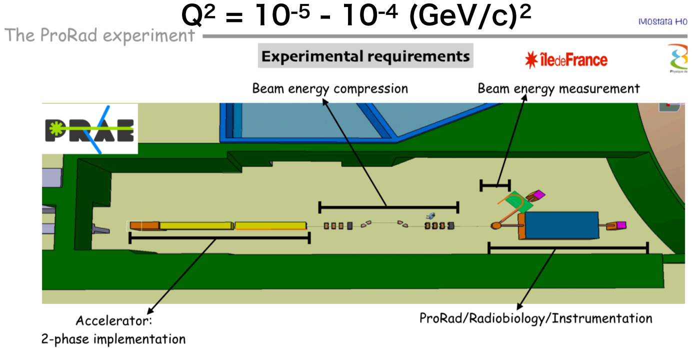
ProRad
An electron-proton scattering experiment
@ PRAE

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°

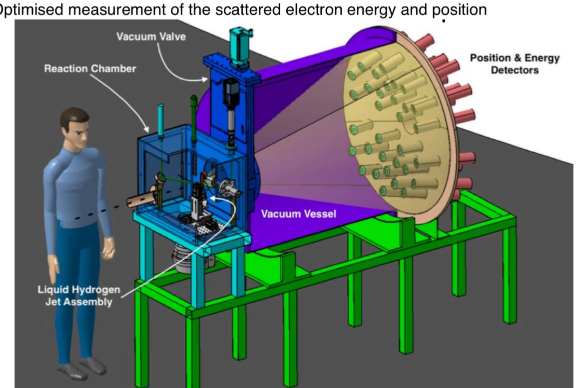
$Q^2 = 10^{-5} - 10^{-4}$ (GeV/c)^2



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

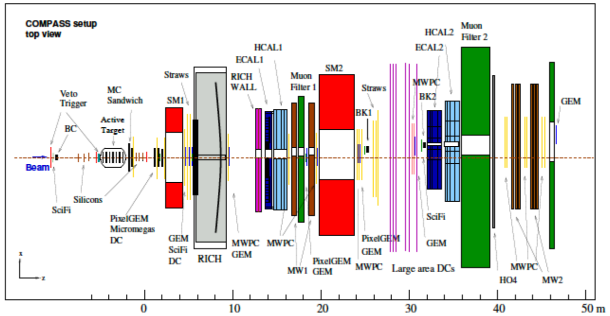


Figure 20: Schematics of the COMPASS MUP set-up. The target region including the gaseous hydrogen TPC is not to scale.

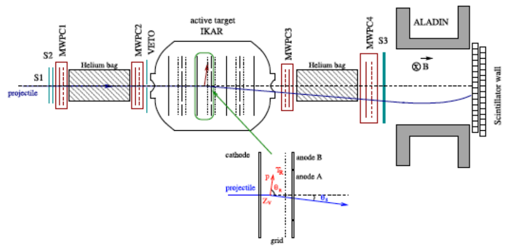


Figure 21: Example for the use of a high pressure active target TPC [57]

E = 100 GeV

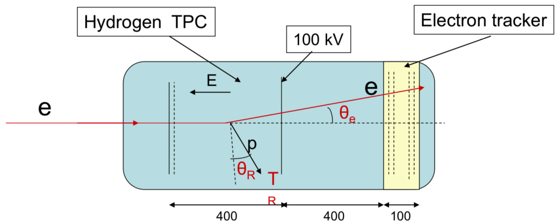
$Q^2 = 10^{-4} - 10^{-1}$ (GeV/c)^2

Mainz, Germany

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

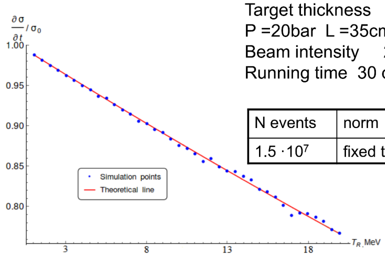
Combined recoiled proton@forward tracker detector



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

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

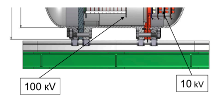
Statistics and beam time



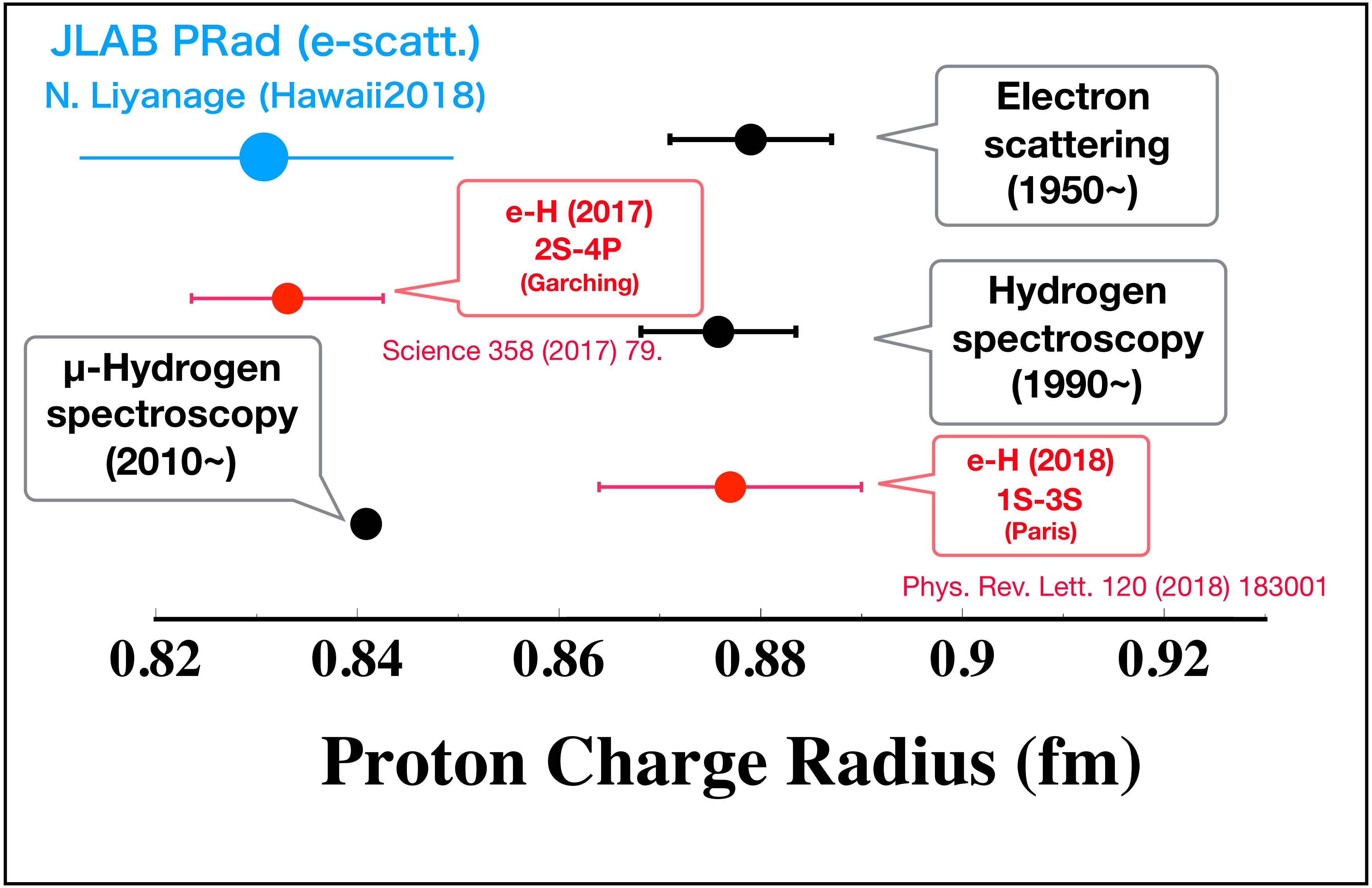
Target thickness = $3.6\cdot10^{22}$ p/cm^2
P =20bar L =35cm
Beam intensity $2\cdot10^6$ sec^{-1}
Running time 30 days

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



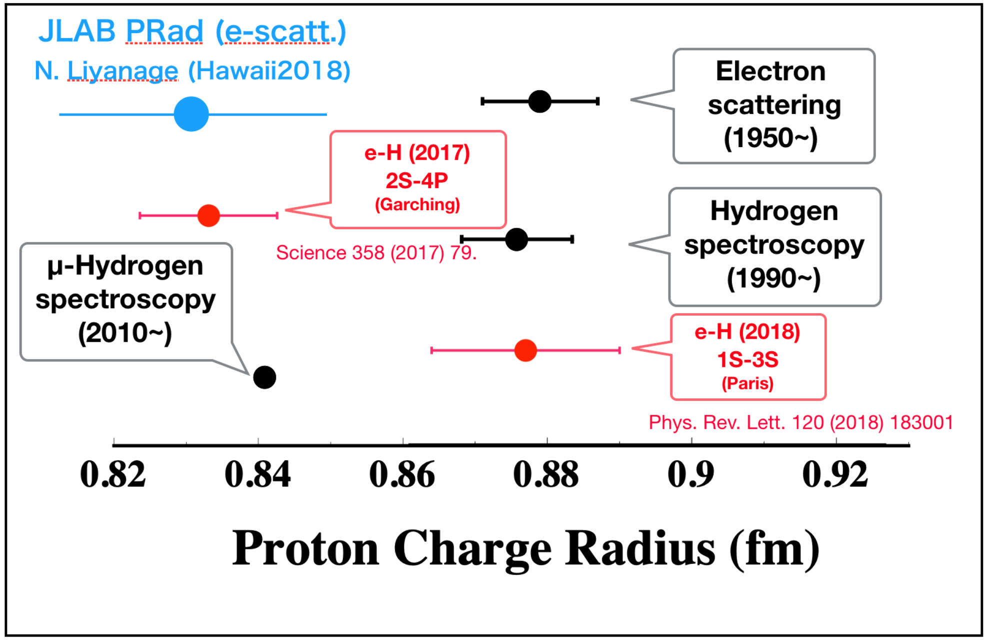
Recent results (including unpublished one...)



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

Summary

Proton Charge Radius Puzzle ??



- the reason of the disagreements is not yet understood.
- the “correct” proton radius is important.
- further experimental and theoretical efforts are needed.

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