ULQ2 (Ultra-Low Q2)

Toshimi Suda
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on behalf of the ULQ2 collaboration

Low-*q* electron-scattering activities in Japan

charge radii of proton and deuteron

E_e = 10 - 60 MeV
θ_e = 30 - 150 deg.
=> $Q^2 = 3\times10^{-5} - 0.013\ (\mathrm{GeV/c})^2$

e-scattering of online-produced exotic nuclei (~10^8/sec)

E_e = 150 - 300 MeV
θ_e = 30 - 60 deg.
=> q = 80 - 300 MeV/c
$Q^2 = 0.006 - 0.09\ (\mathrm{GeV/c})^2$

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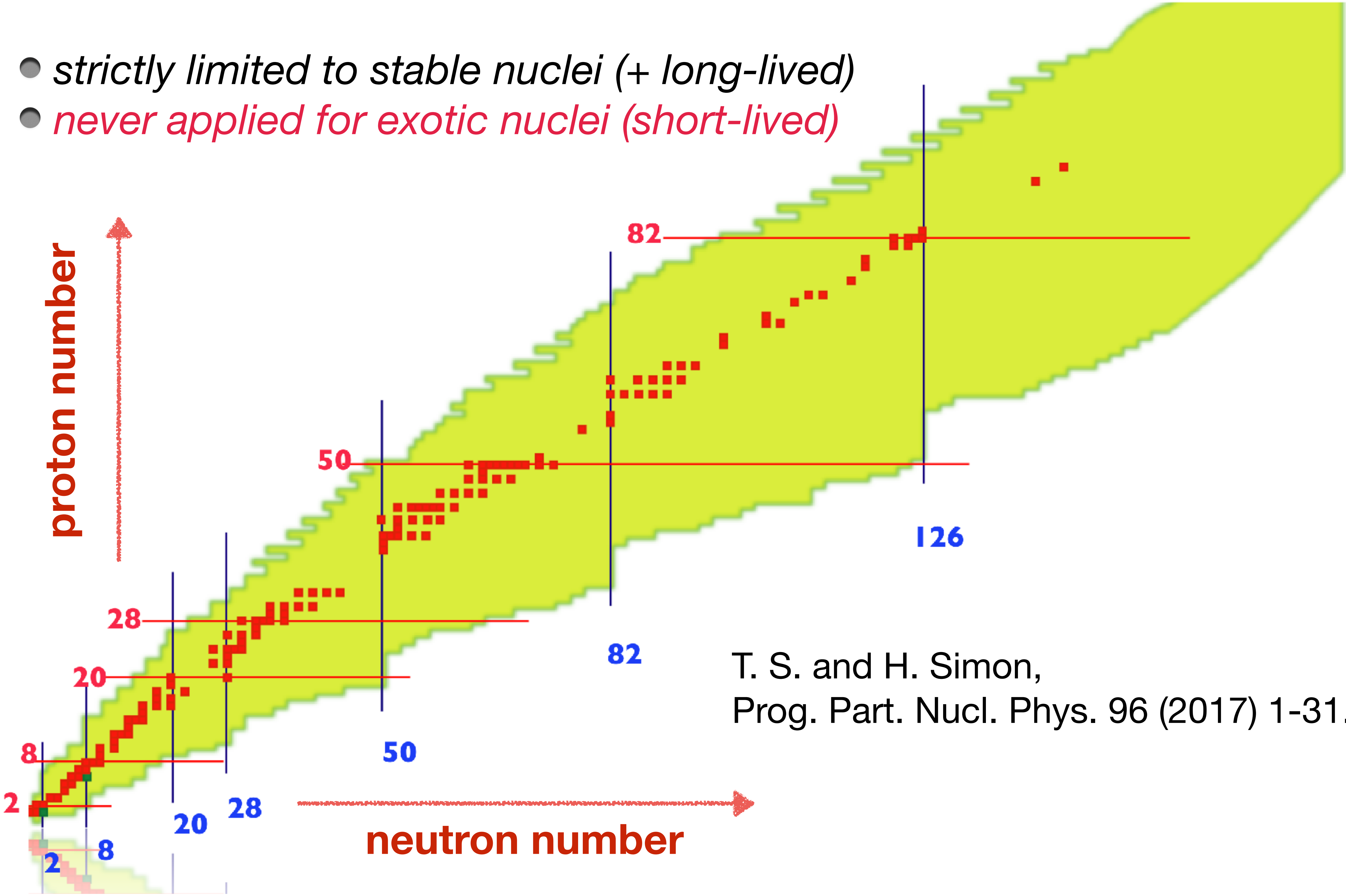
Nuclei ever studied with electron scattering

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



T. S. and H. Simon,
Prog. Part. Nucl. Phys. 96 (2017) 1-31.

First e-scat. paper for online-produced unstable nuclei

PHYSICAL REVIEW LETTERS **131**, 092502 (2023)

Editors' Suggestion **Featured in Physics**

First Observation of Electron Scattering from Online-Produced Radioactive Target

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(Received 7 March 2023; accepted 21 June 2023; published 30 August 2023)

We successfully performed electron scattering off unstable nuclei which were produced online from the photofission of uranium. The target ^{137}Cs ions were trapped with a new target-forming technique that makes a high-density stationary target from a small number of ions by confining them in an electron storage ring. After developments of target generation and transportation systems and the beam stacking method to increase the ion beam intensity up to approximately 2×10^7 ions per pulse beam, an average luminosity of 0.9×10^{26} cm^{-2} s^{-1} was achieved for ^{137}Cs. The obtained angular distribution of elastically scattered electrons is consistent with a calculation. This success marks the realization of the anticipated femtoscope which clarifies the structures of exotic and short-lived unstable nuclei.

DOI: 10.1103/PhysRevLett.131.092502

Physics Today **76** (11), 14–16 (2023)

Electron scattering provides a long-awaited view of unstable nuclei

Nuclear reactions produce a plethora of short-lived artificial isotopes. Figuring out what they look like has been a challenge.

The cartoon picture of an atomic nucleus looks kind of like the inside of a gumball machine that dispenses only two flavors: protons and neutrons, evenly mixed in a compact, spherical cluster.

That's not generally what real nuclei look like. Neutron-rich lead-208, for example, has a thick skin of neutrons encasing its proton-endowed core (see Physics Today, July 2021, page 12). Some nuclei are flattened, and some are elongated. Some are even pear shaped.

The more unstable a nucleus, the stranger the structures it can adopt. Short-lived nuclei might form bubble structures with depleted central density, or they might have a valence nucleon or two that form a halo around a compact central core. (See the article by Filomena Nunes, Physics Today, May 2021, page 34.) Frustratingly, though, those exotic structures are hard to experimentally confirm, because the gold standard for probing nuclear structure—electron scattering—has been off limits to short-lived nuclei.

That could change soon. Kyo Tsukada and colleagues, working at RIKEN's Radioactive Isotope Beam Factory (RIBF) in Wako, Japan, have performed the first electron-scattering experiment on unstable nuclei produced on the fly in a nuclear reaction.[1] Their isotope of choice, cesium-137, has a half-life of 30 years. It's not so exotic that the researchers expected—or found—anything unusual about its structure. But the technique they used is applicable to shorter-lived nuclei, so more experiments are on the way.

Backscatter

Probing nuclei through particle scattering dates back to the discovery of the nucleus itself, in 1911, when Ernest

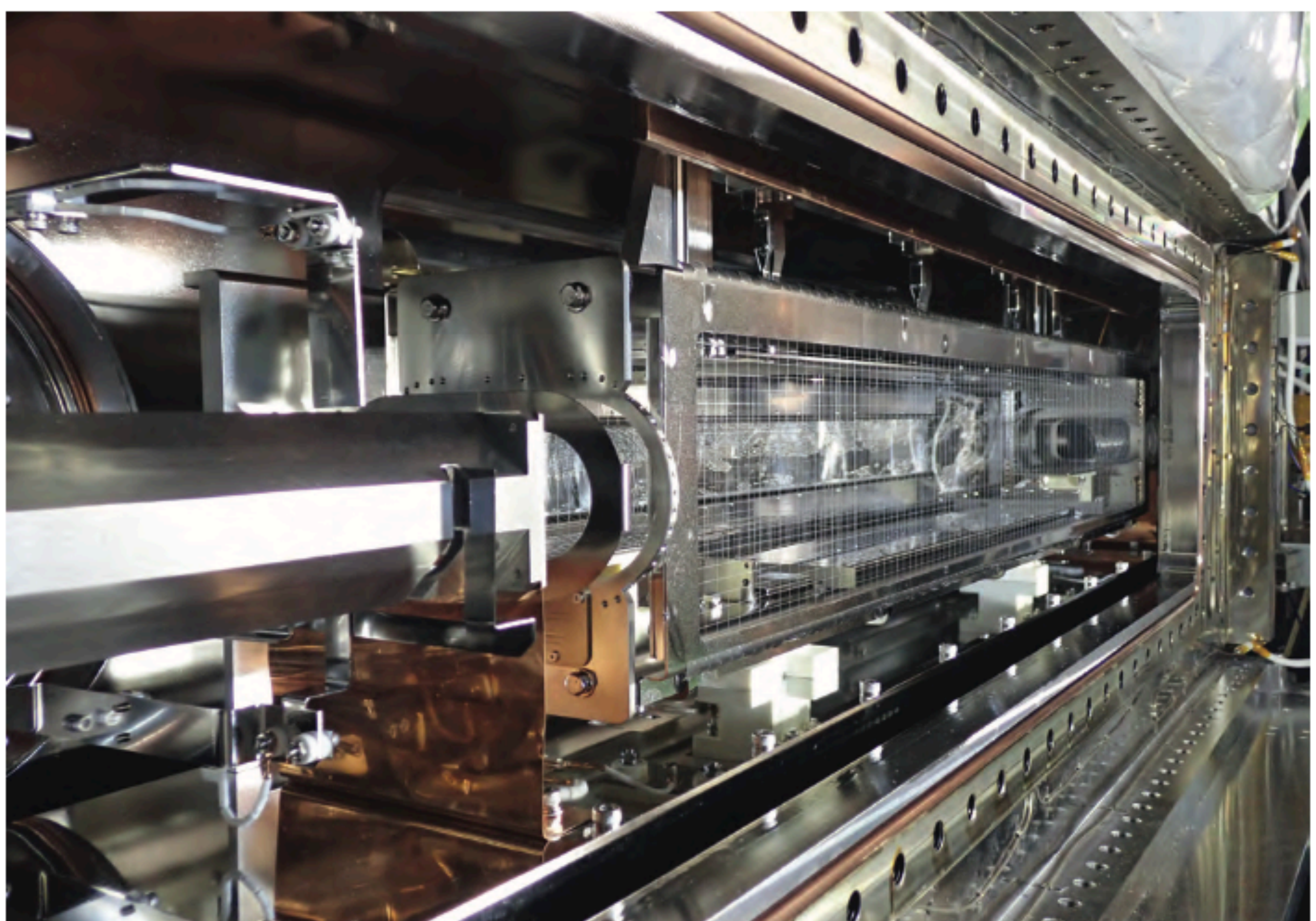

FIGURE 1. RADIOACTIVE IONS too short-lived to be made into a solid target can nevertheless be trapped in an electron beam. The beam itself traps the ions in two dimensions; the cage of thin wire electrodes creates an electric potential that traps them in the third. (Courtesy of Tetsuya Ohnishi.)

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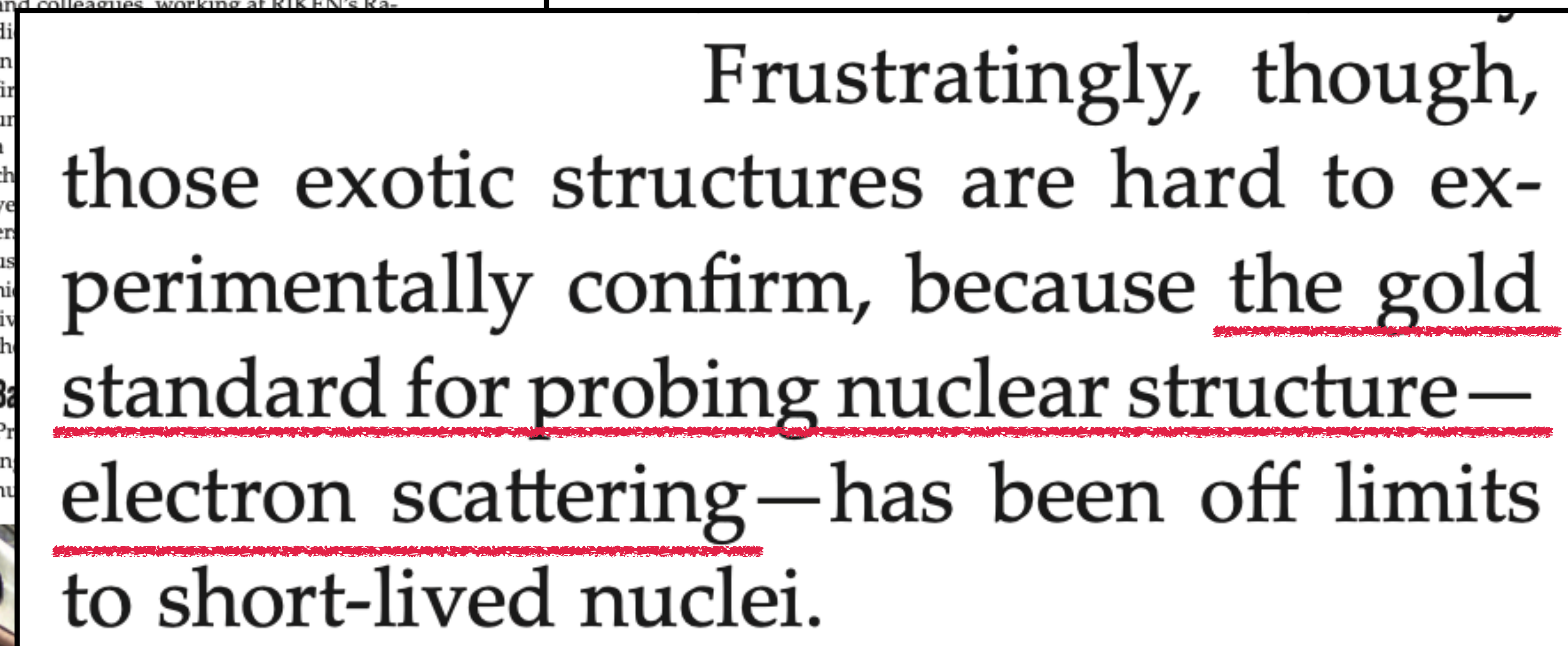

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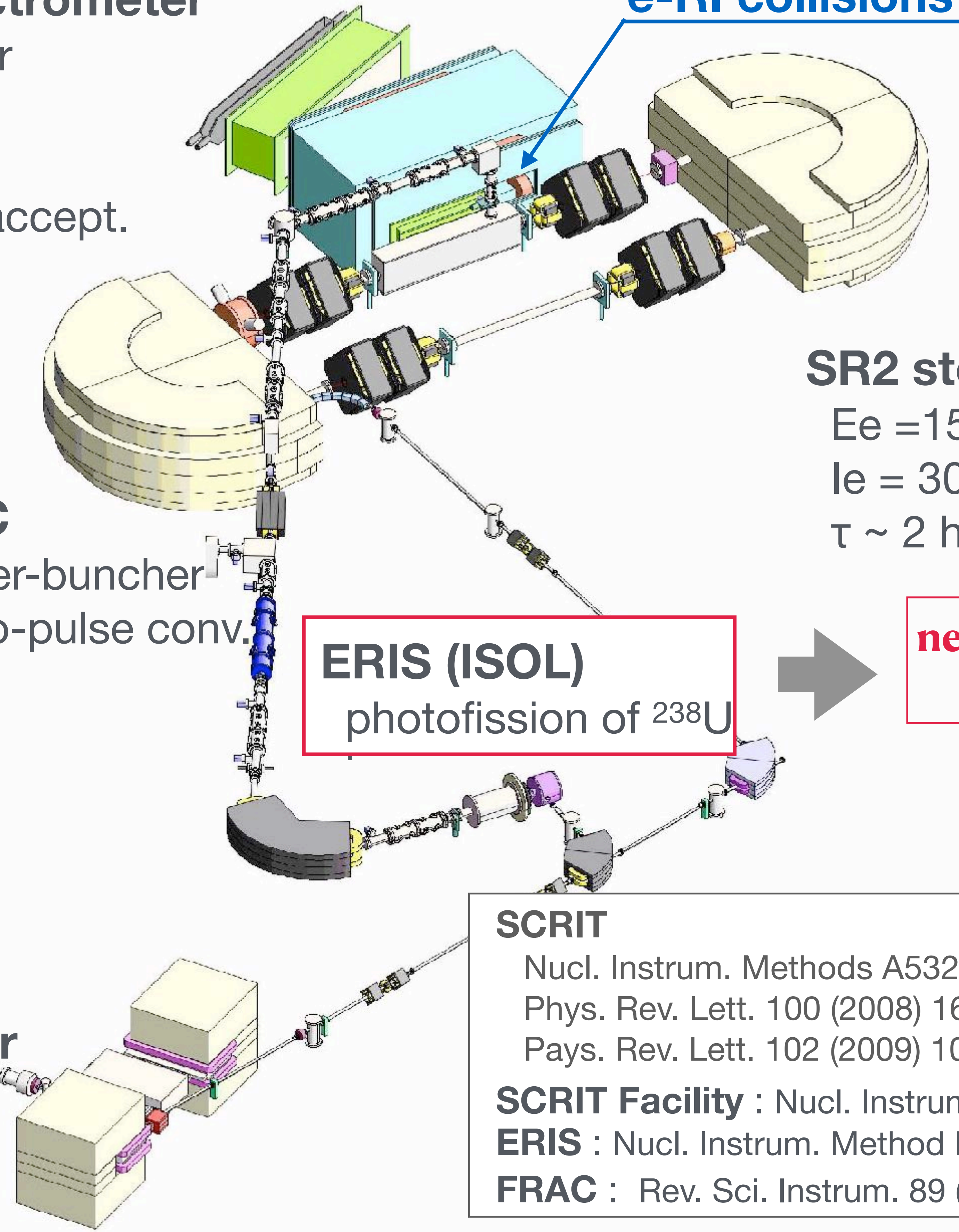
RIKEN SCRIT Electron Scattering Facility

WiSES spectrometer
$\Delta\Omega$ ~ 90 mSr
θ = 30 - 60°
$\Delta p/p$ ~ 10^{-3}
long target accept.

e-RI collisions



SR2 storage ring
Ee =150-700 MeV
Ie = 300 mA
τ ~ 2 hours

FRAC
cooler-buncher
dc-to-pulse conv.

ERIS (ISOL)
photofission of ^{238}U

neutron-rich nuclei by $\gamma+^{238}$U

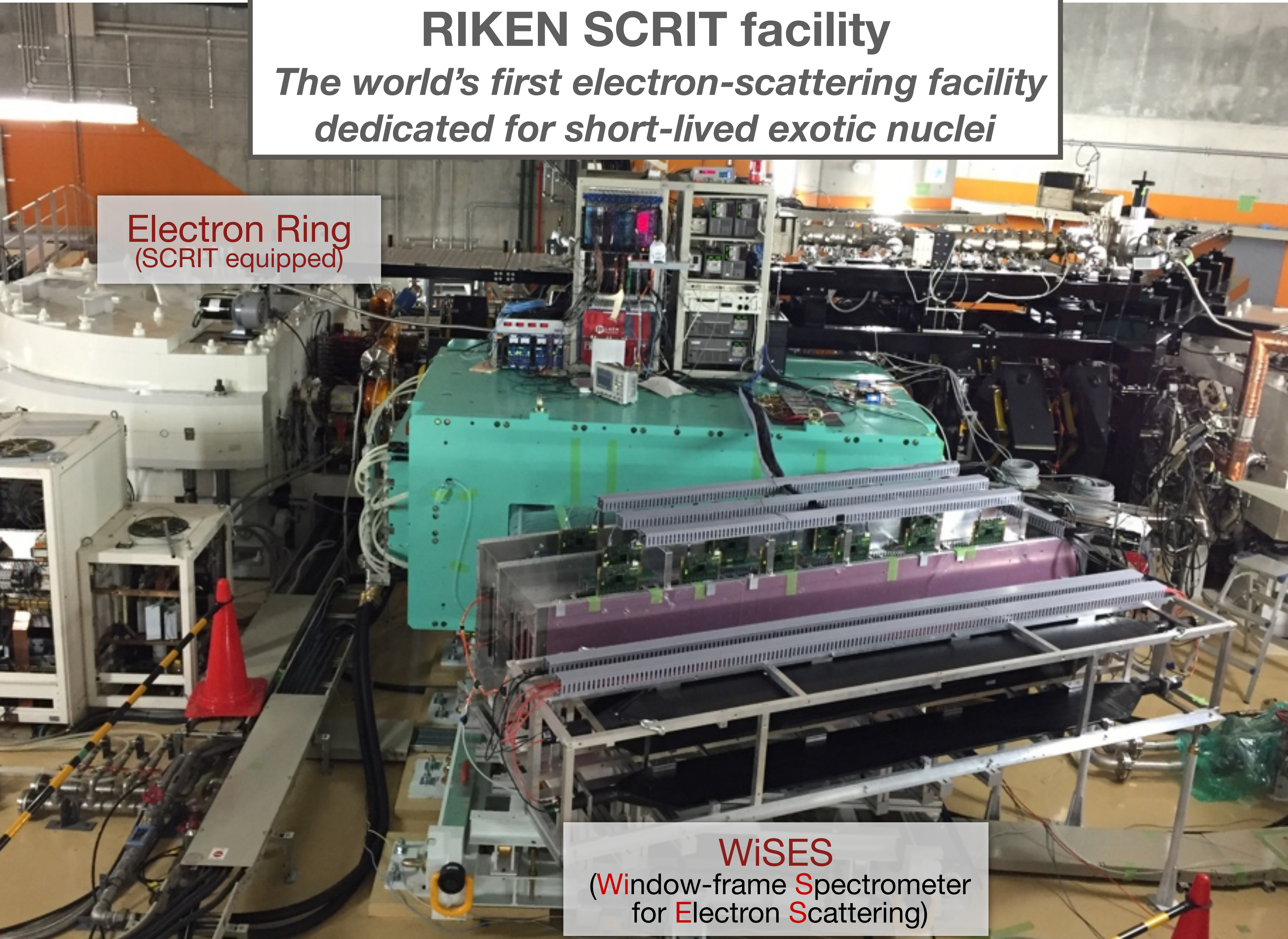
Injector + ISOL driver
150 MeV Microtron

SCRIT
Nucl. Instrum. Methods A532 (2004) 216.
Phys. Rev. Lett. 100 (2008) 164801.
Pays. Rev. Lett. 102 (2009) 102501.

SCRIT Facility : Nucl. Instrum. Method B317 (2013) 668.
ERIS : Nucl. Instrum. Method B317 (2013) 357.
FRAC : Rev. Sci. Instrum. 89 (2018) 095107.

RIKEN SCRIT facility

The world's first electron-scattering facility dedicated for short-lived exotic nuclei

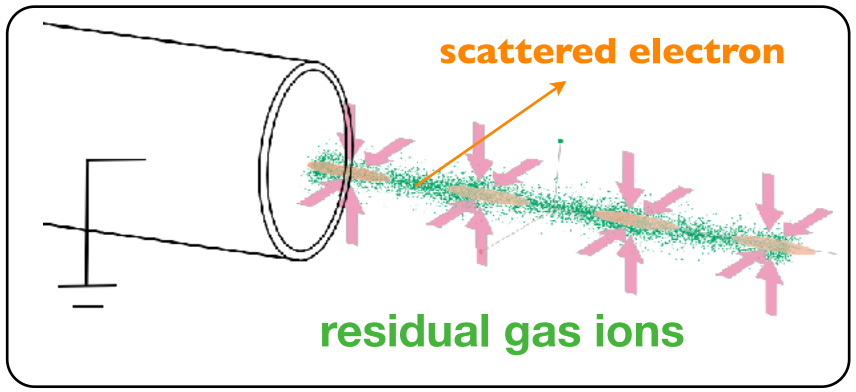


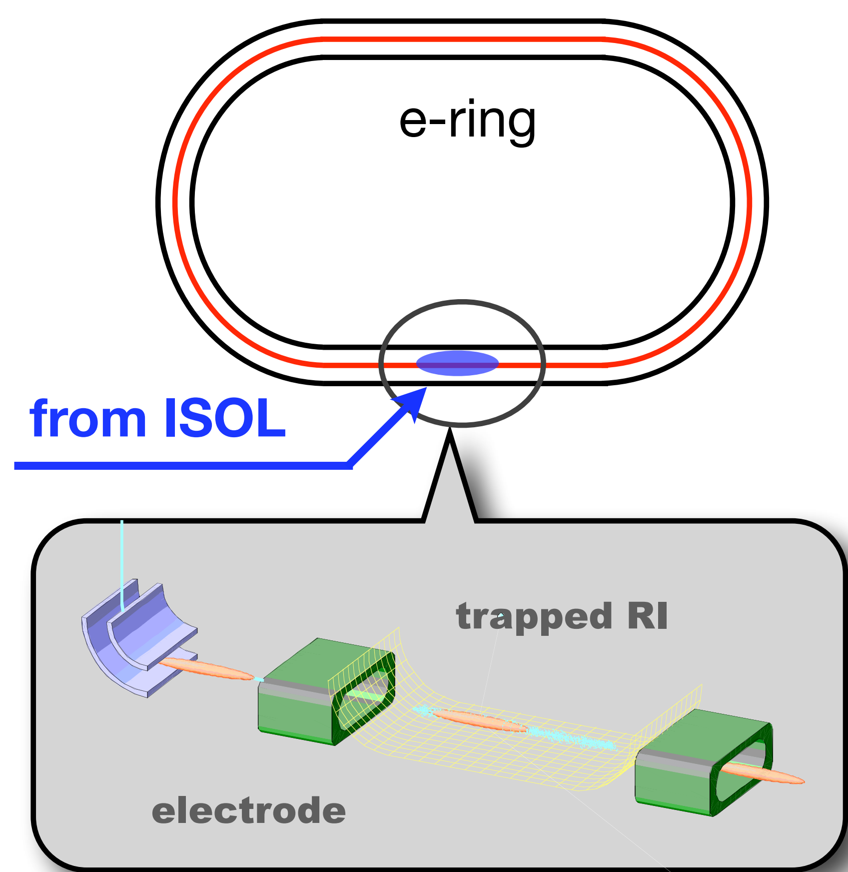
SCRIT（Self-Confining RI Ion Target)

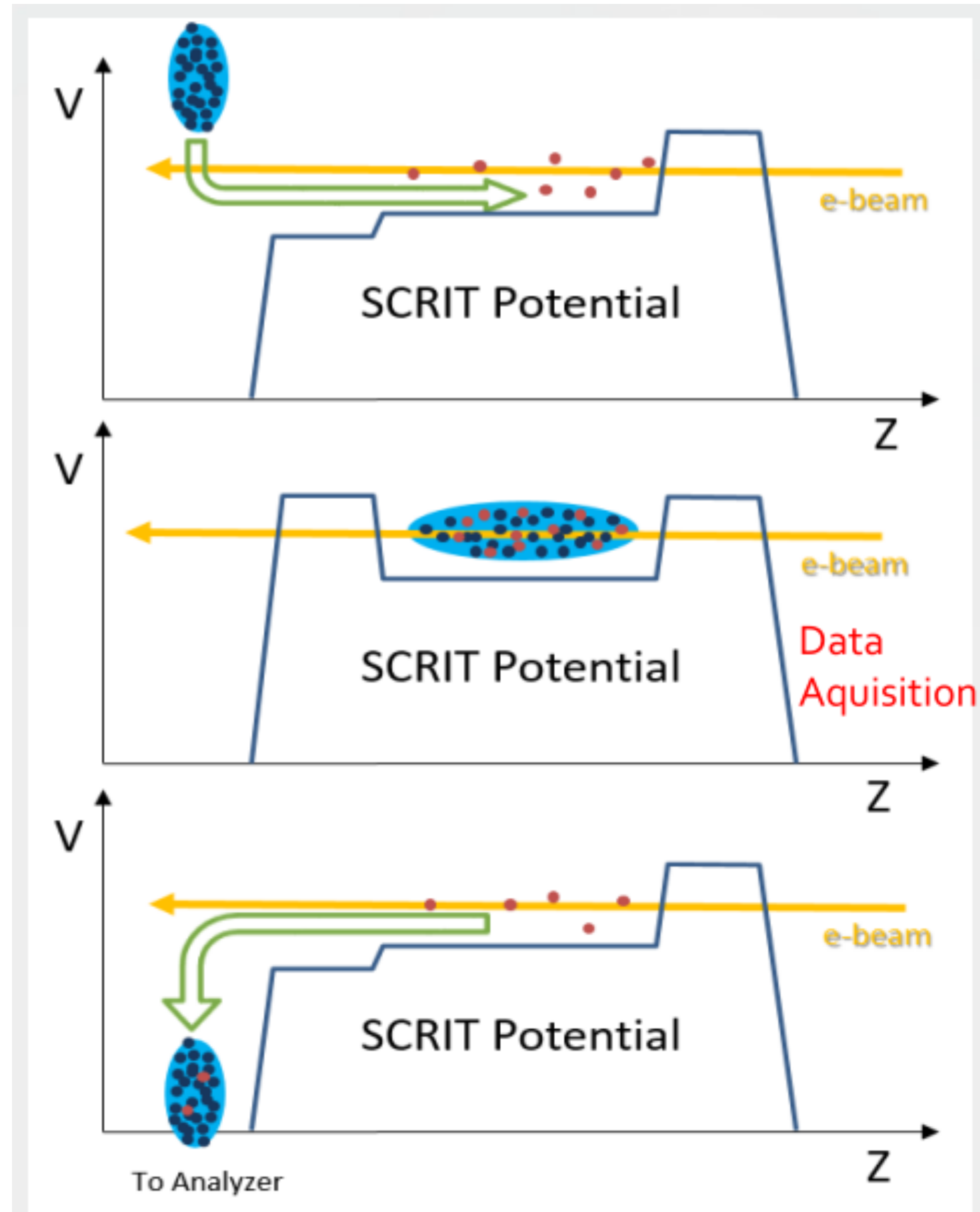
Idea : “ion trapping” at SR facilities.

ionized residual gases are trapped
by the circulating electron beam

ill problem of e-storage rings







Luminosities for e-scattering

	Ee	N_{beam}	target thickness	L
Hofstadter's era (1950s)	150 MeV	~ 1nA (~10^9 /s)	~10^{19} /cm^2	~10^{28} /cm^2/s
JLAB	12 GeV	~100μA (~10^{14} /s)	~10^{22} /cm2	~10^{36} /cm^2/s

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~10^7 trapped ions in e-beam of ~1 mm^2

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~10^{7} trapped ions in e-beam of ~1 mm^2

required target thickness ~ 10^{-10} !!

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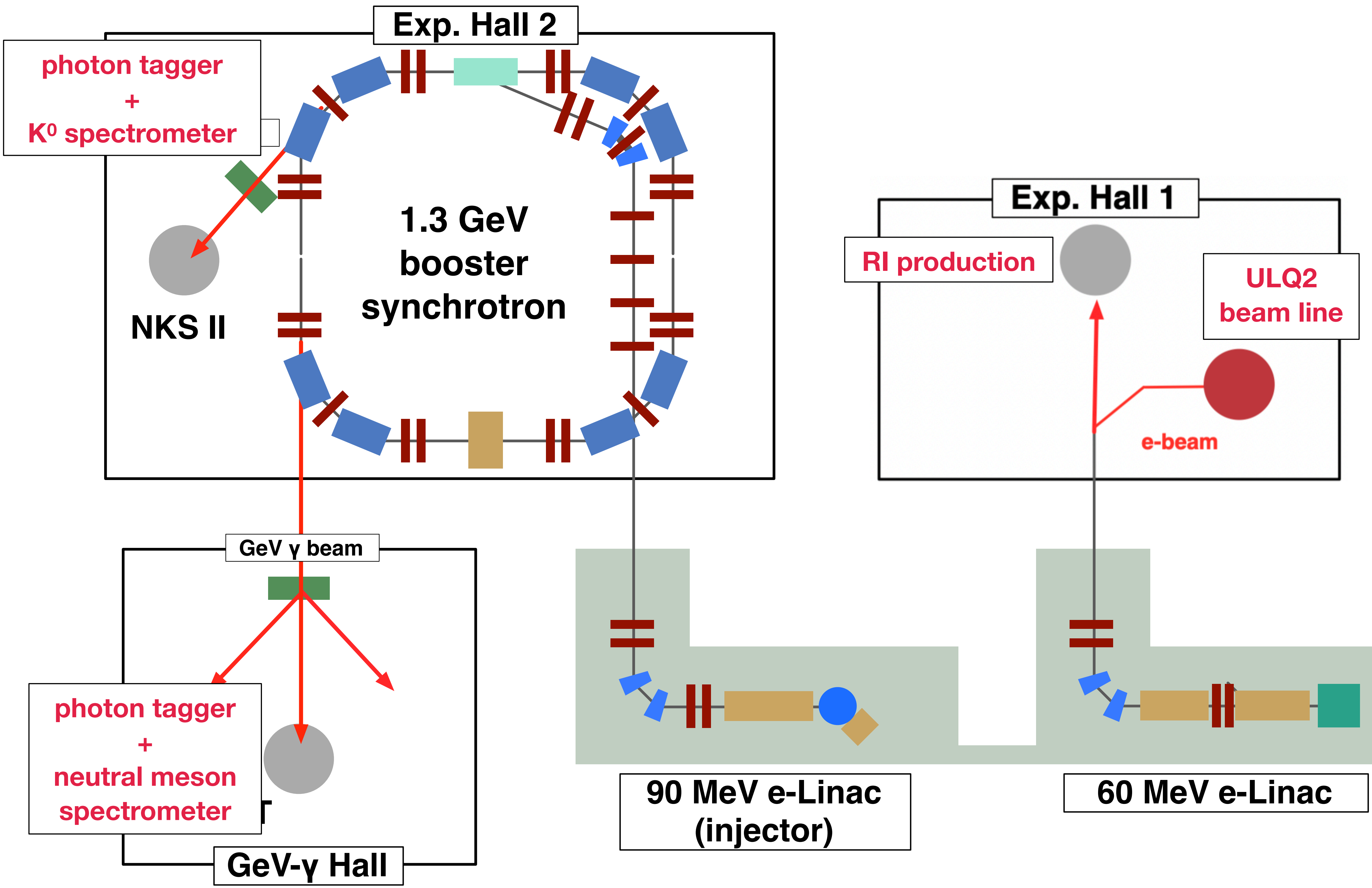
1) Tohoku ULQ2 facility

2) ULQ2 physics program and current status

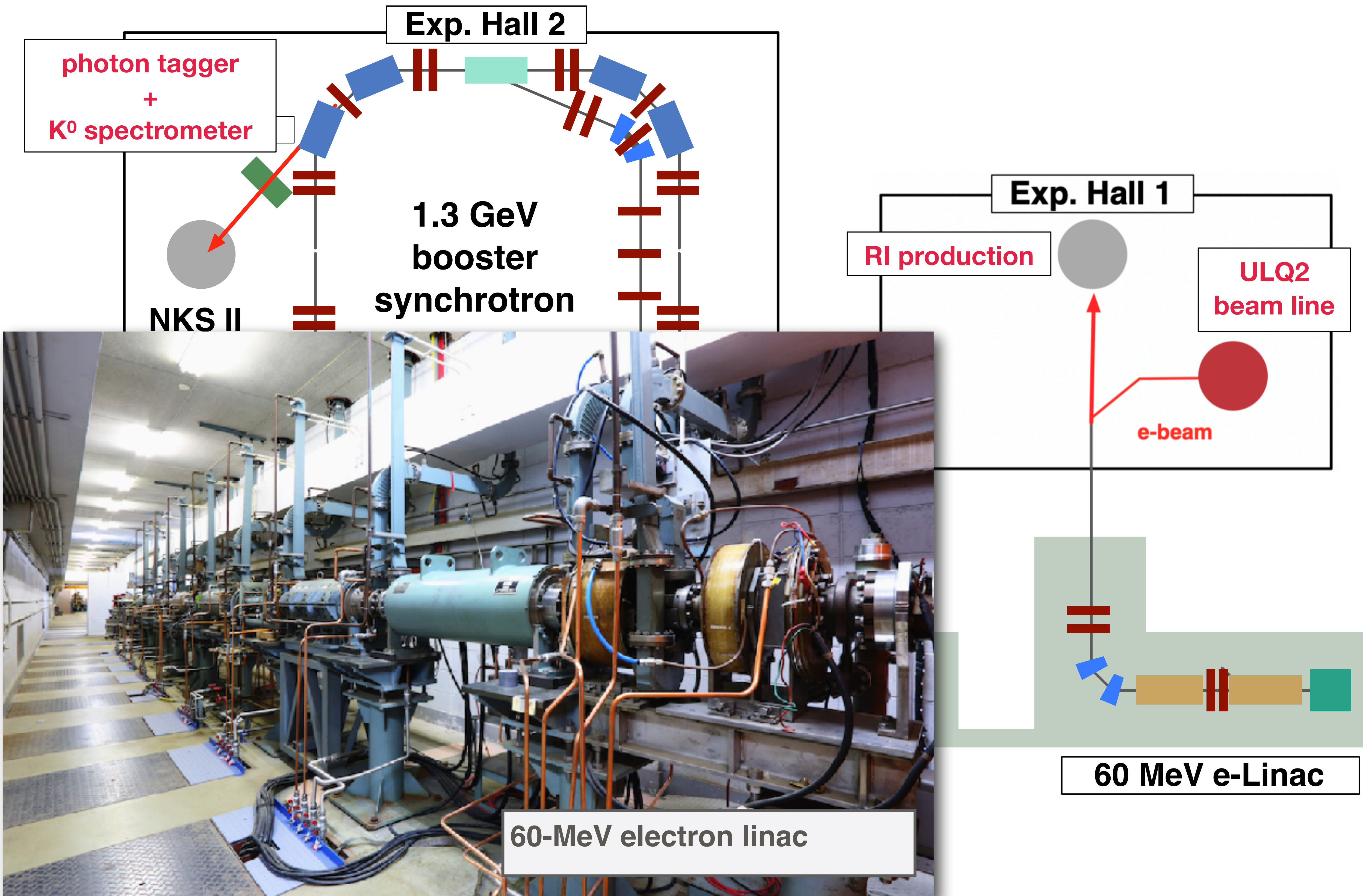
3) Summary


Sendai
Research Center for Electron-Photon Science
Tohoku Univesity
電子光理学研究センター

Tohoku University
Research Center for ELectron-PHoton Science (ELPH)



Tohoku University
Research Center for ELectron-PHoton Science (ELPH)



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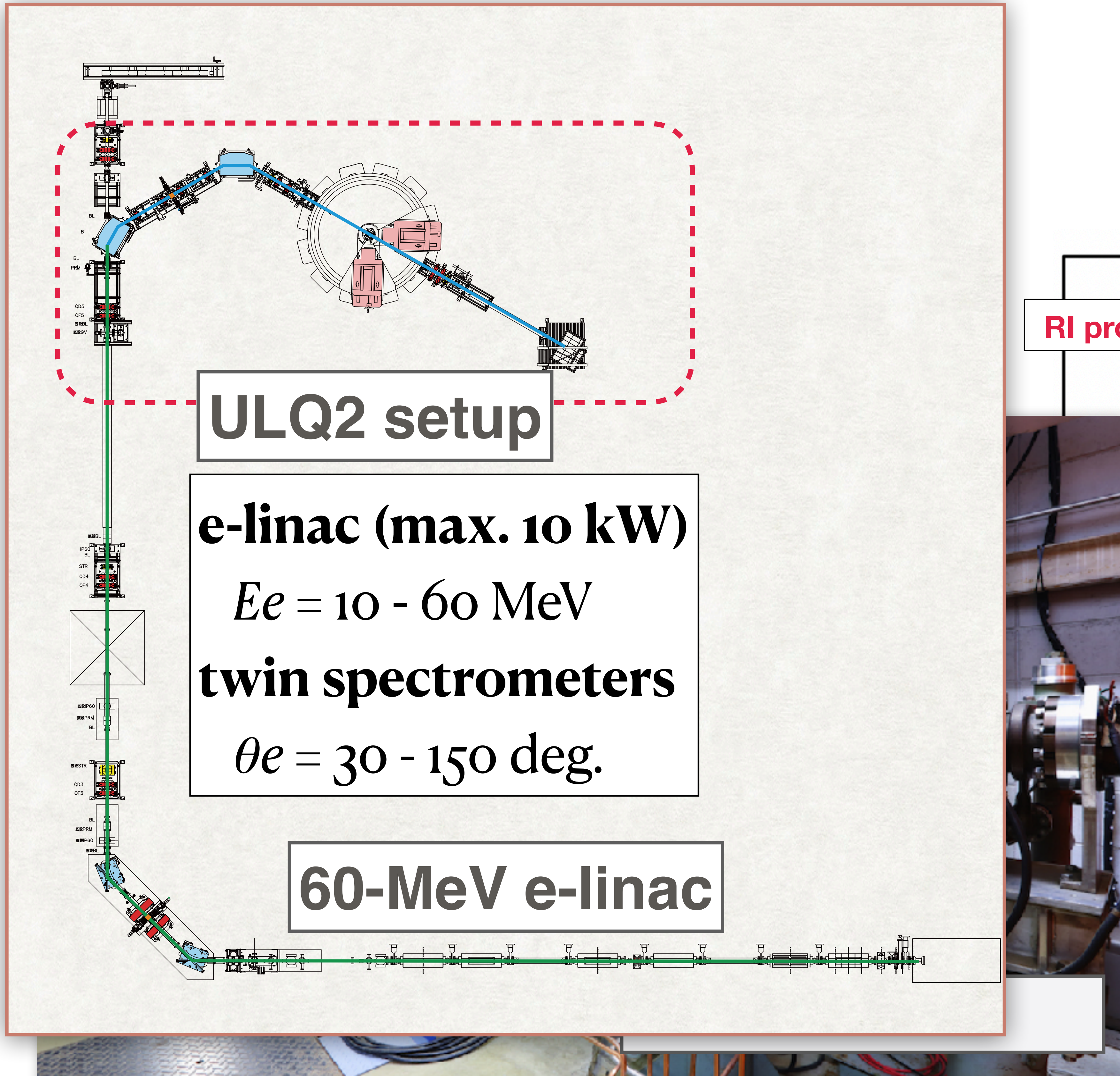

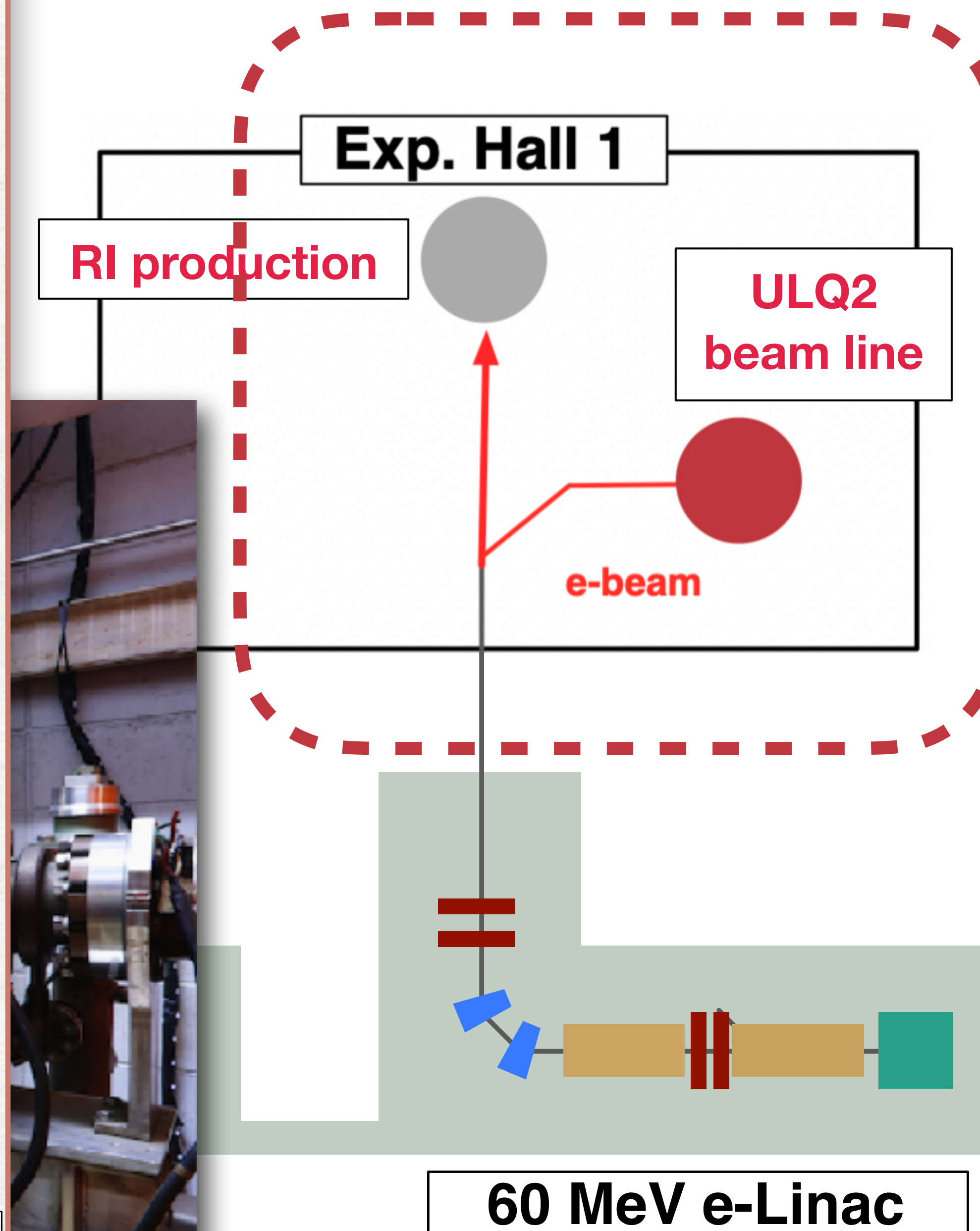

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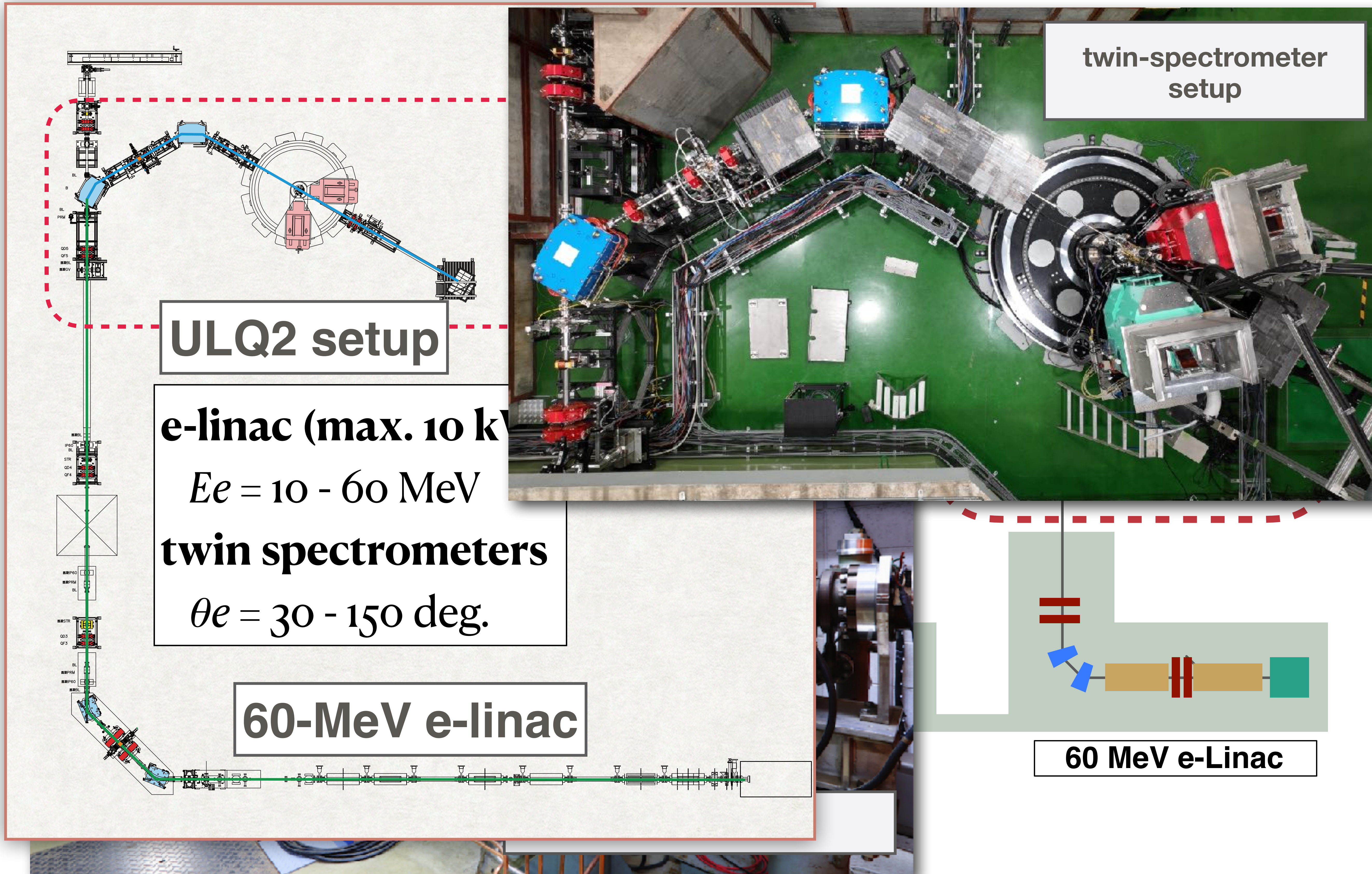
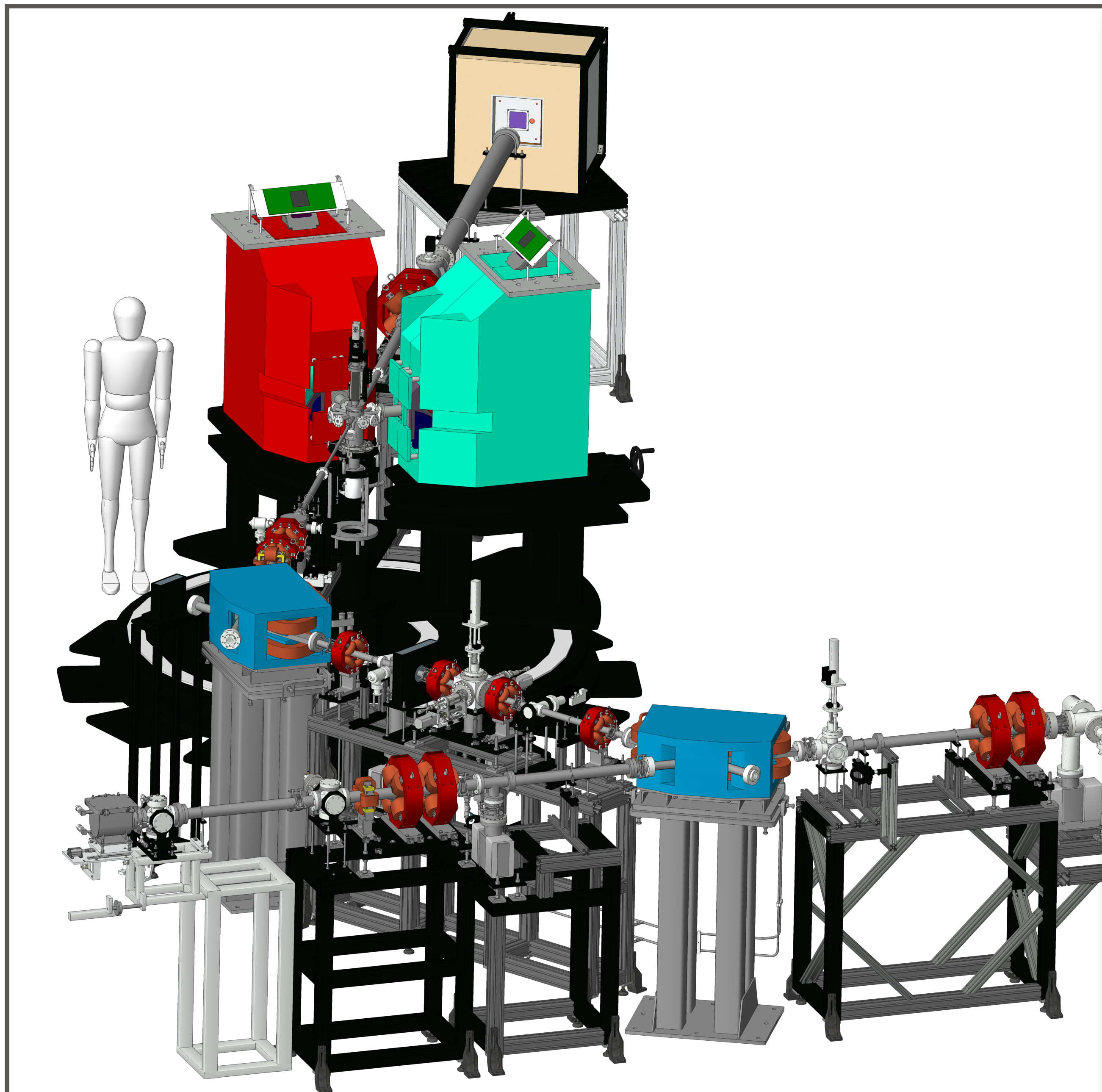


60 MeV electron linac

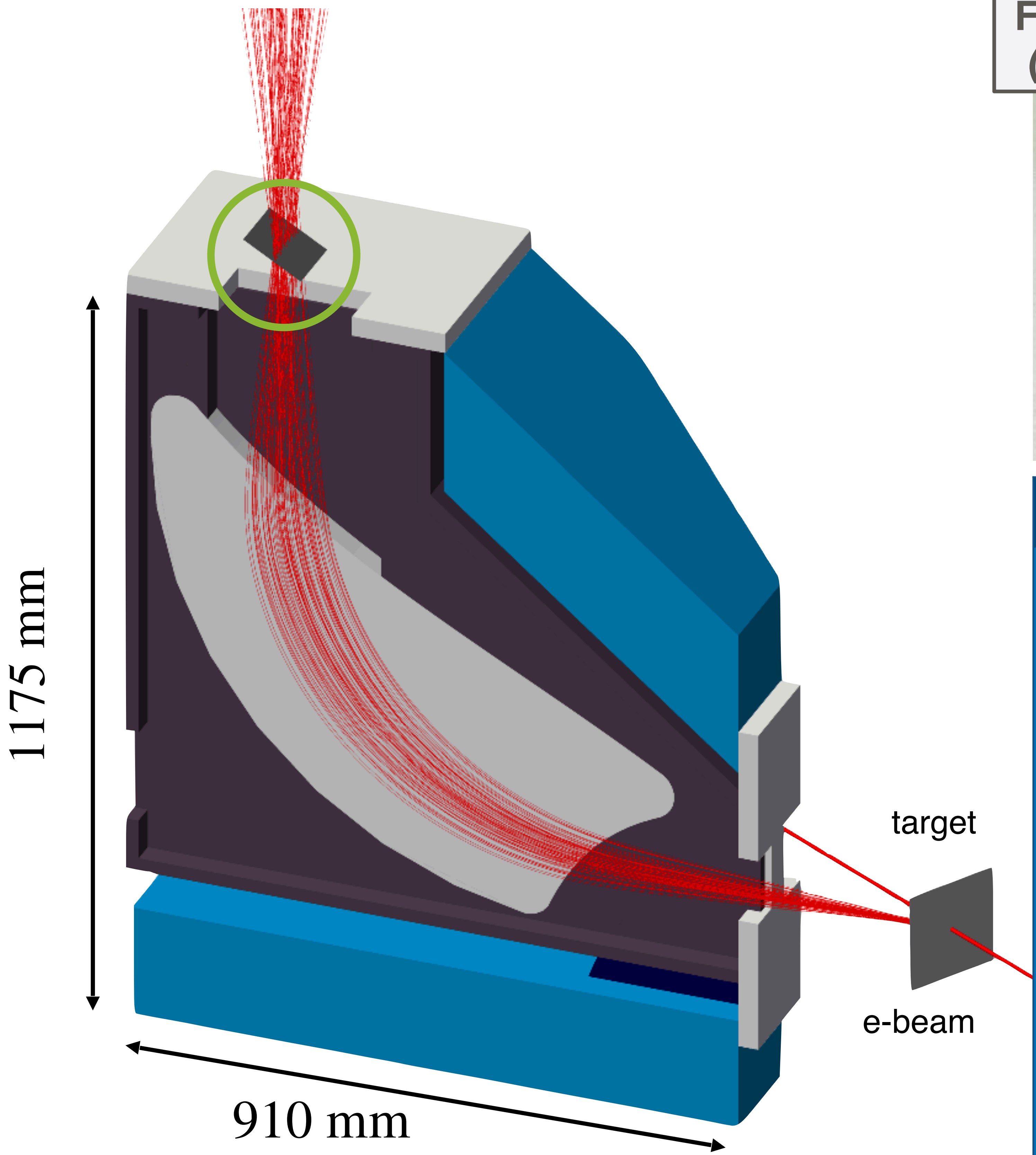
Ee = 10 - 60 MeV
(absolute 10^{-3})
$\Delta E/E = 0.6 \times 10^{-4}$
beam size ~ 0.6 mm on target
*I*e = 1 nA - 1uA
duty factor = 10^{-3}

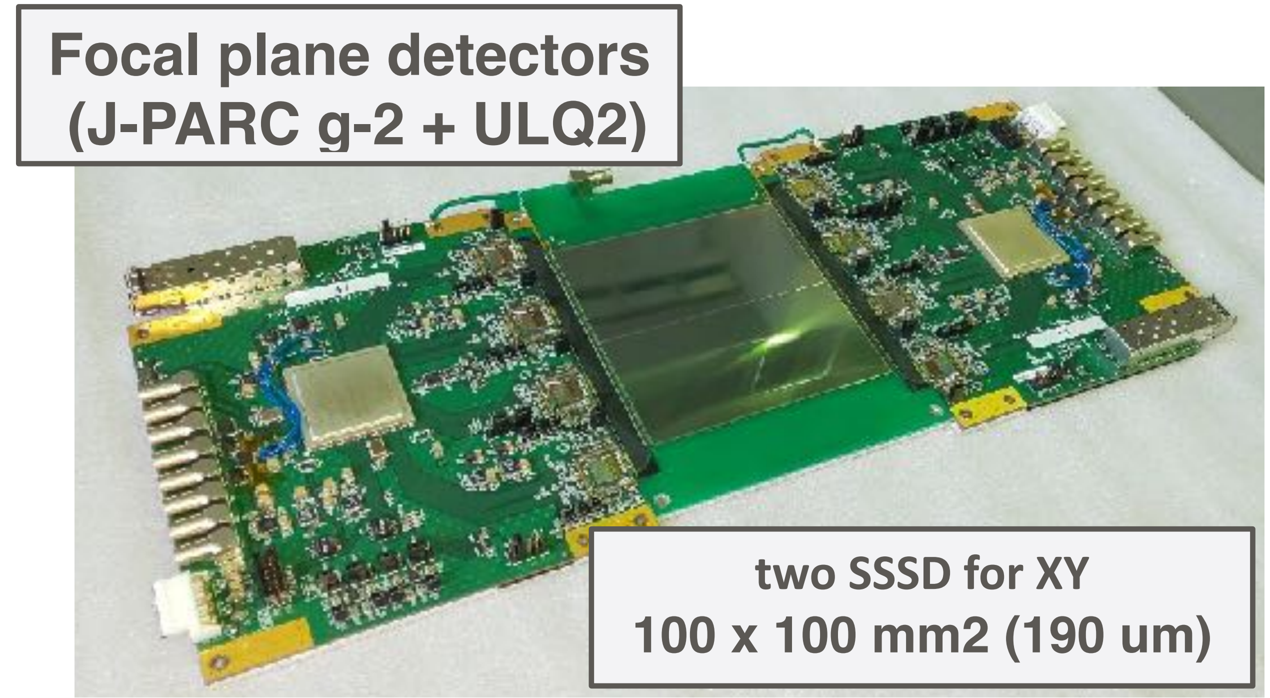
ULQ2 twin-spectrometer setup

$\Delta p/p = 5.6 \times 10^{-3}$
$\Delta\Omega$ = 6 mSr
θ = 30 - 150 deg.
(~1 mrad accuracy)
$Q^2 = 3 \times 10^{-5} - 0.013\ (\mathrm{GeV/c})^2$
($\Delta Q^2/Q^2 \sim 10^{-3}$)



ULQ2 twin spectrometers

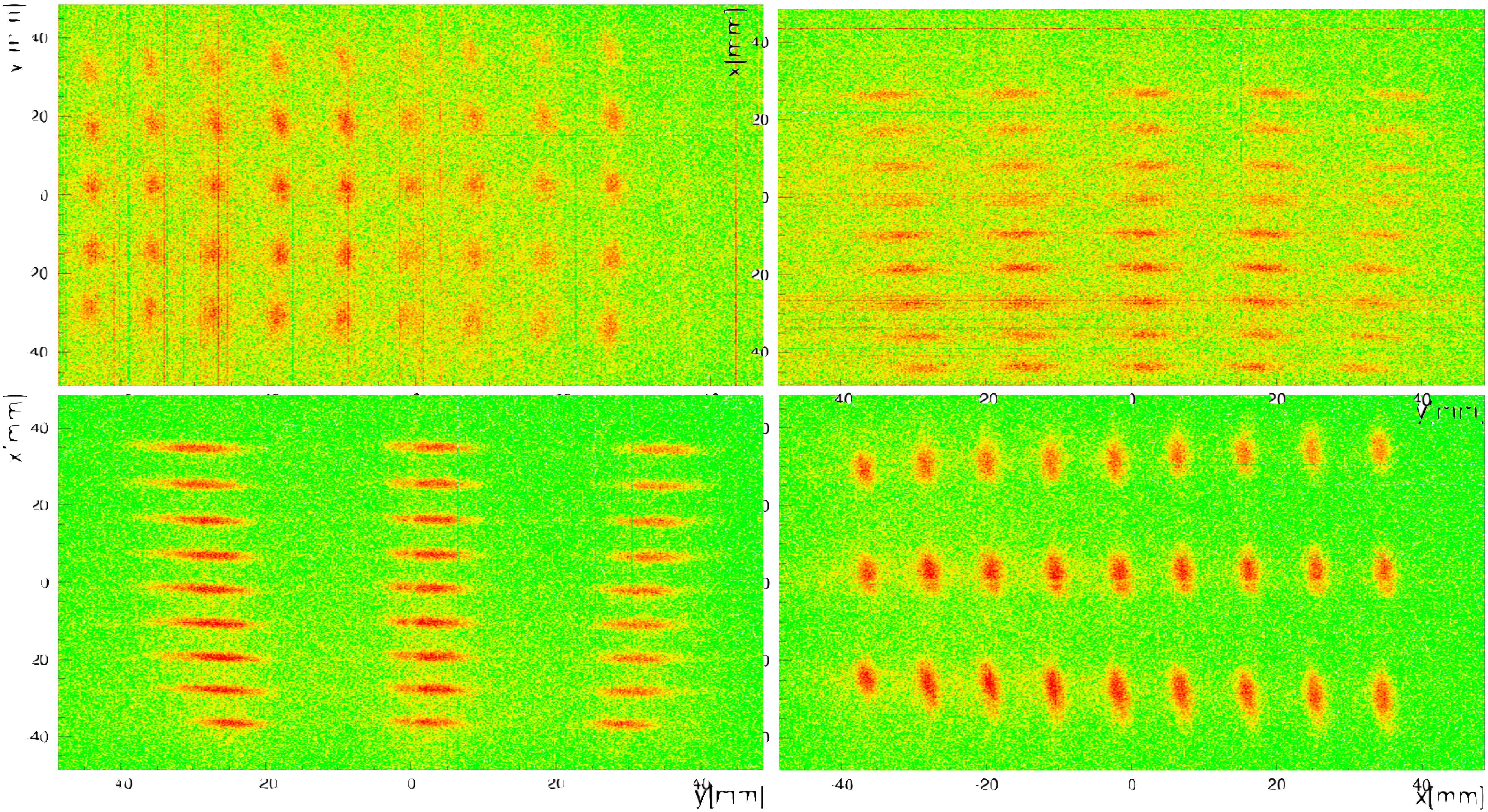




Electron spectrometer	
radius	500 mm
bending angle	90°
max. B	0.4T @ 60MeV
gap	70 mm
dispersion	866 mm
Δp/p	5.6×10^{-4}
momentum bite	10%
Δθ	5 mrad
solid angle	6 mSr
weight	5 ton

Y. Honda

ULQ2 spectrometer optics up to 2nd order



ULQ2 spectrometer optics up to 2nd order

Parameters	Spectrometer 1	Spectrometer 2
x_0 [mm]	4.9	-1.8
$(x_d\|\delta)$ [mm]	866.1(7)	862.4(7)
$(x_d^2\|\delta)$ [mm]	-174(26)	-164(26)
$(x_d\|\Delta\theta^2)$ [10^{-4} mm/mrad^2]	-4.1(2)	-3.6(2)
θ_0 [mrad]	-2.9(5)	6.8(6)
$(y_d\|\Delta\theta)$ [mm/mrad]	0.999(4)	0.997(3)
$(y_d\|\delta\Delta\theta)$ [mm/mrad]	2.01(14)	1.92(11)
$(x_d\|x_b)$, $(y_d\|y_b)$ [mm/mm]	~ 0.5 , 1.8	

ULQ2 Physics Program

1) Proton : charge radius $CH_2(e,e')$

aiming at the "least model-dependent" $G_E(Q^2)$ determination

under lowest-ever Q^2
absolute cross section measurement
Rosenbluth separated $G_E(Q^2)$ and $G_M(Q^2)$ *if necessary*

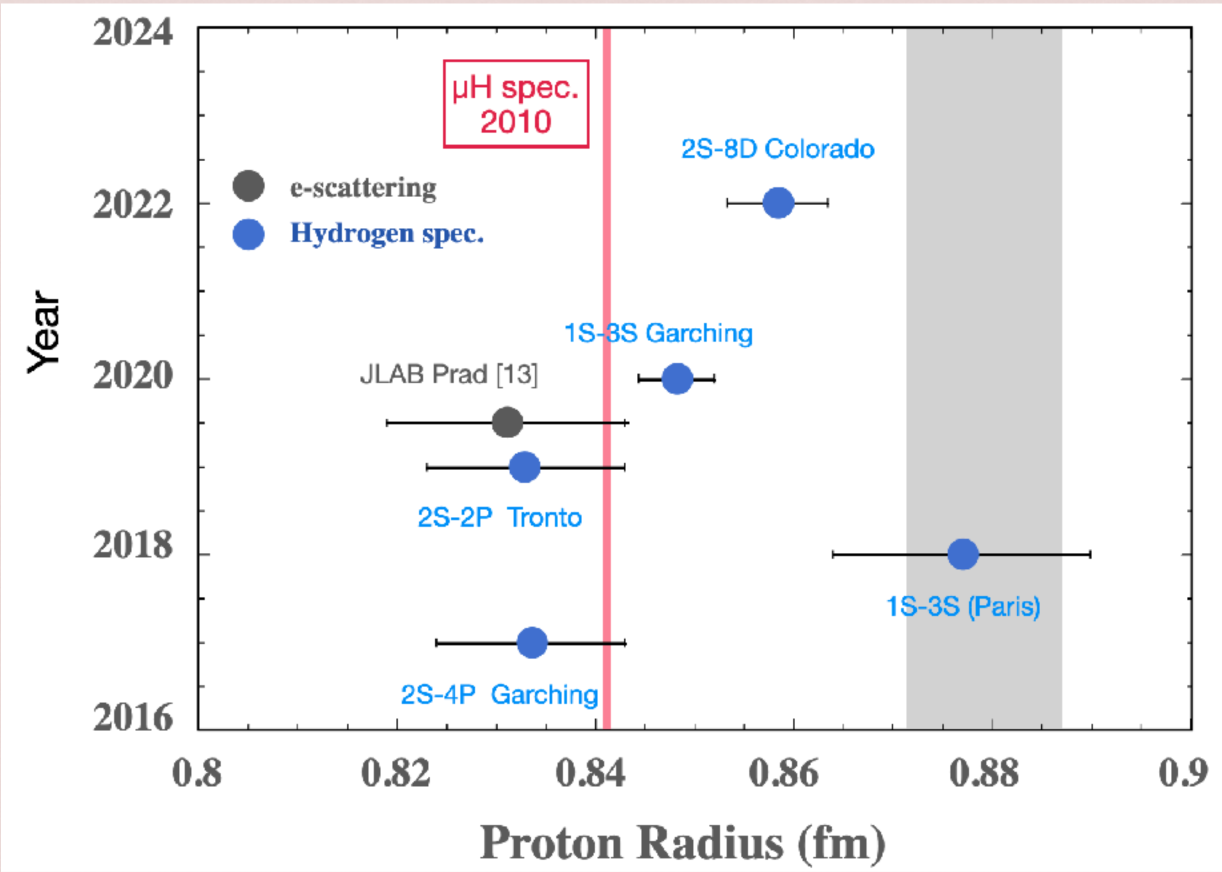
2) Deuteron : charge radius $CD_2(e,e')$

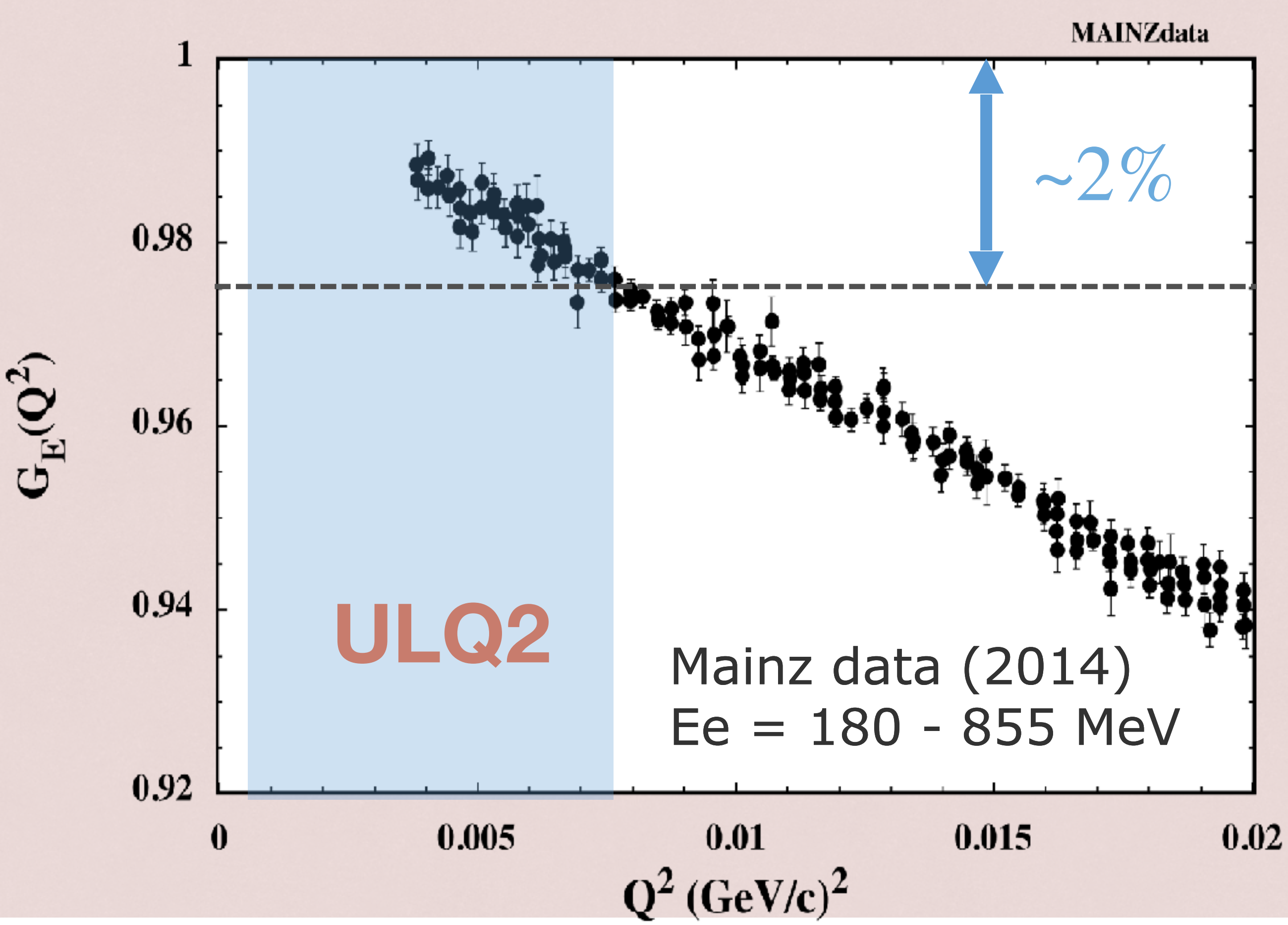
possible determination of neutron charge radius

3) ^{208}Pb elastic scattering $^{208}Pb(e,e')$

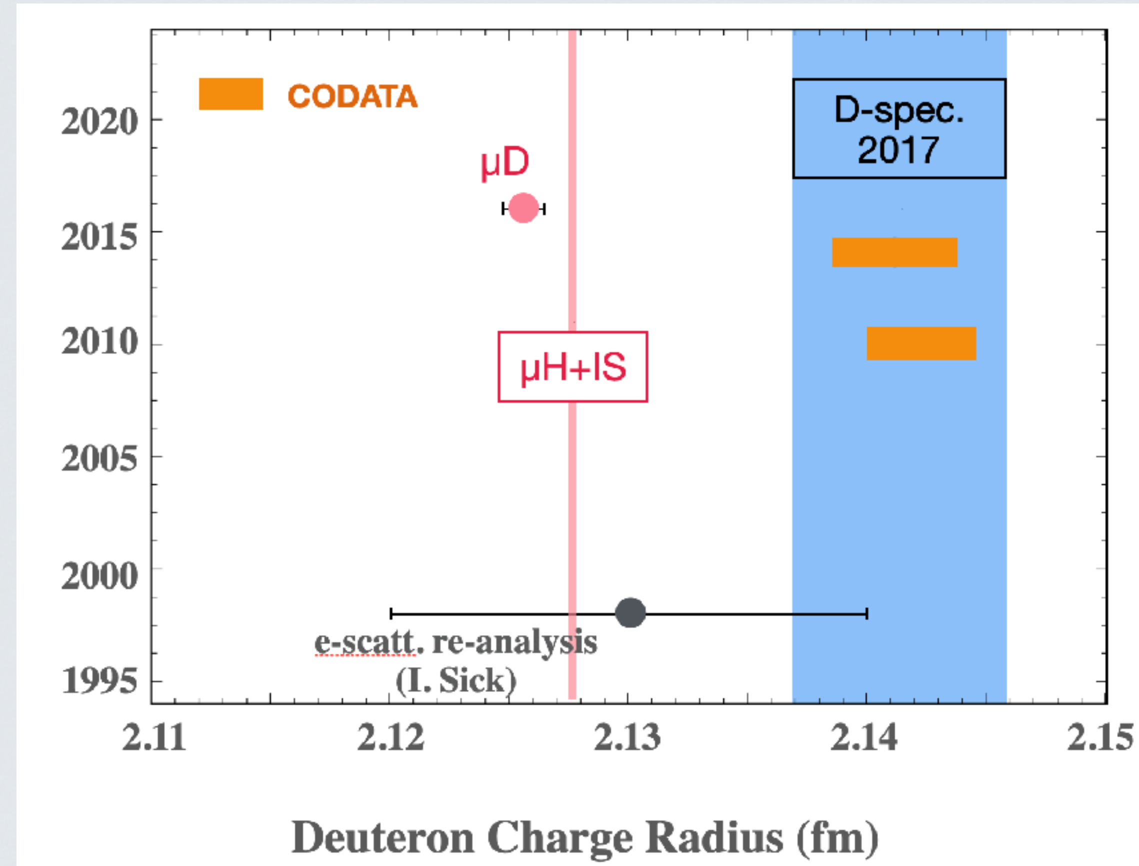
4th moment of charge density distribution
=> neutron-distribution radius
cross section under never-yet-measured low-*q* region
q = 5 - 100MeV

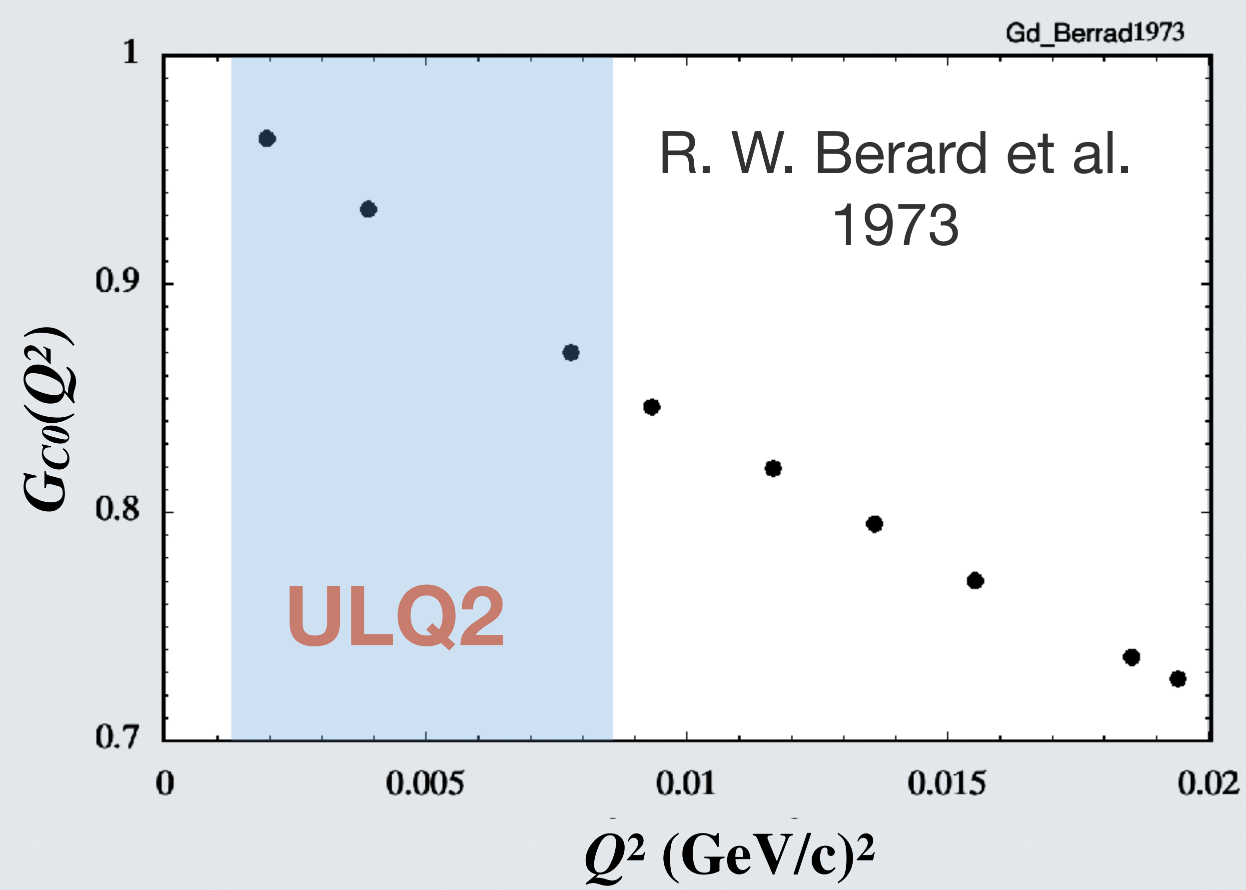
proton



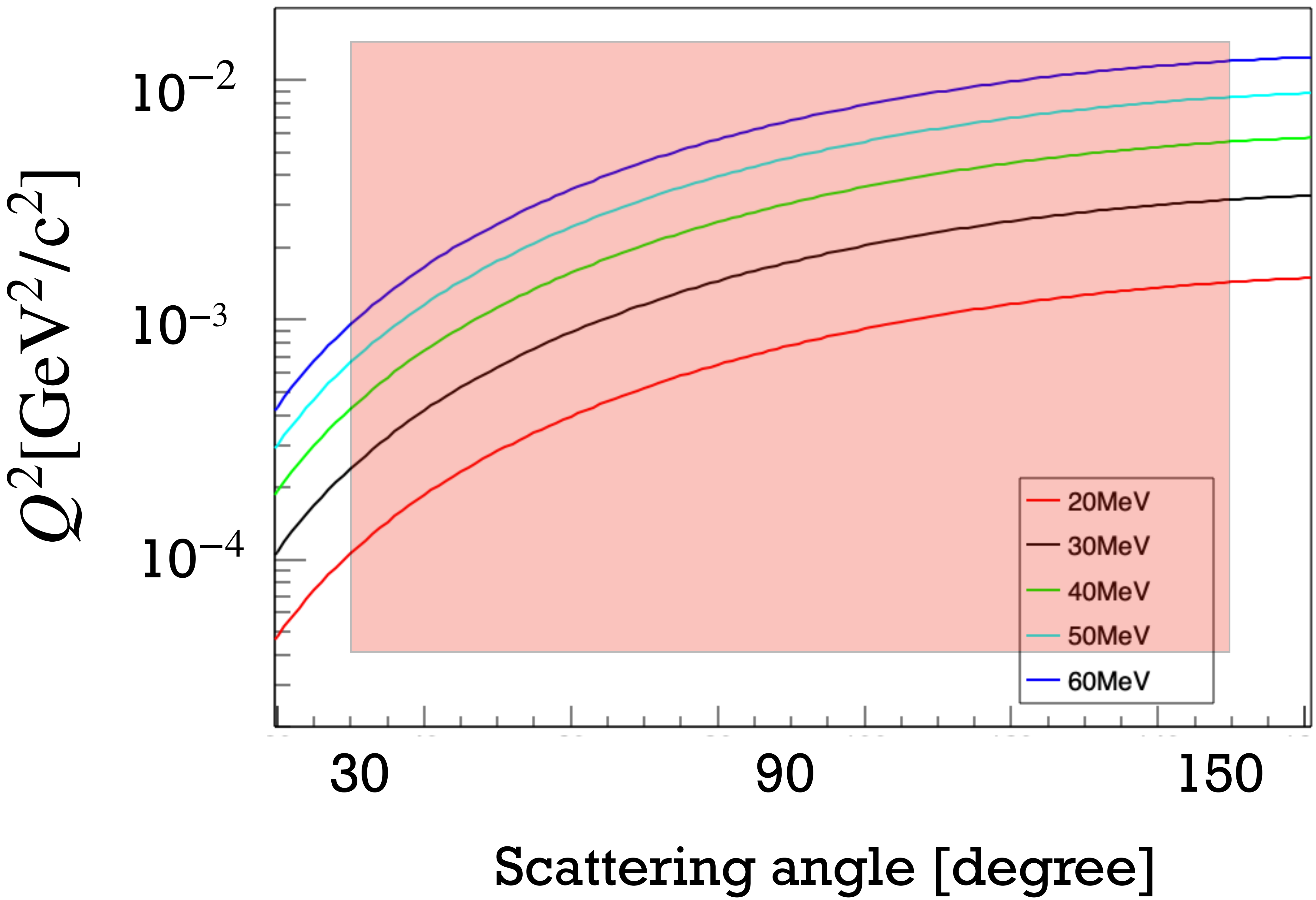


deuteron





ULQ2 kinematics

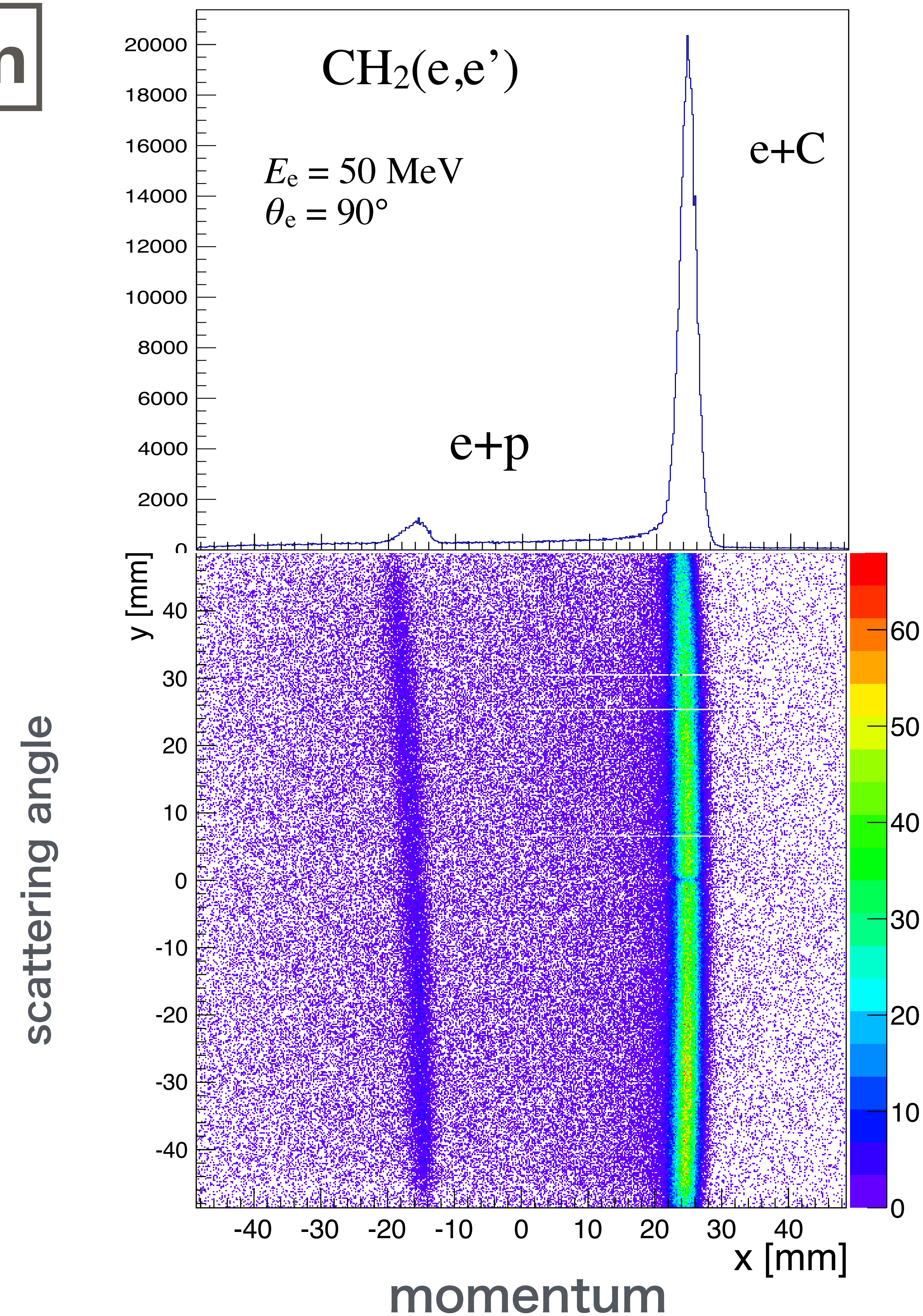


Absolute cross section

CH_2 (CD_2) as targets

1) thin solid target (~100 um)
2) simultaneous detection

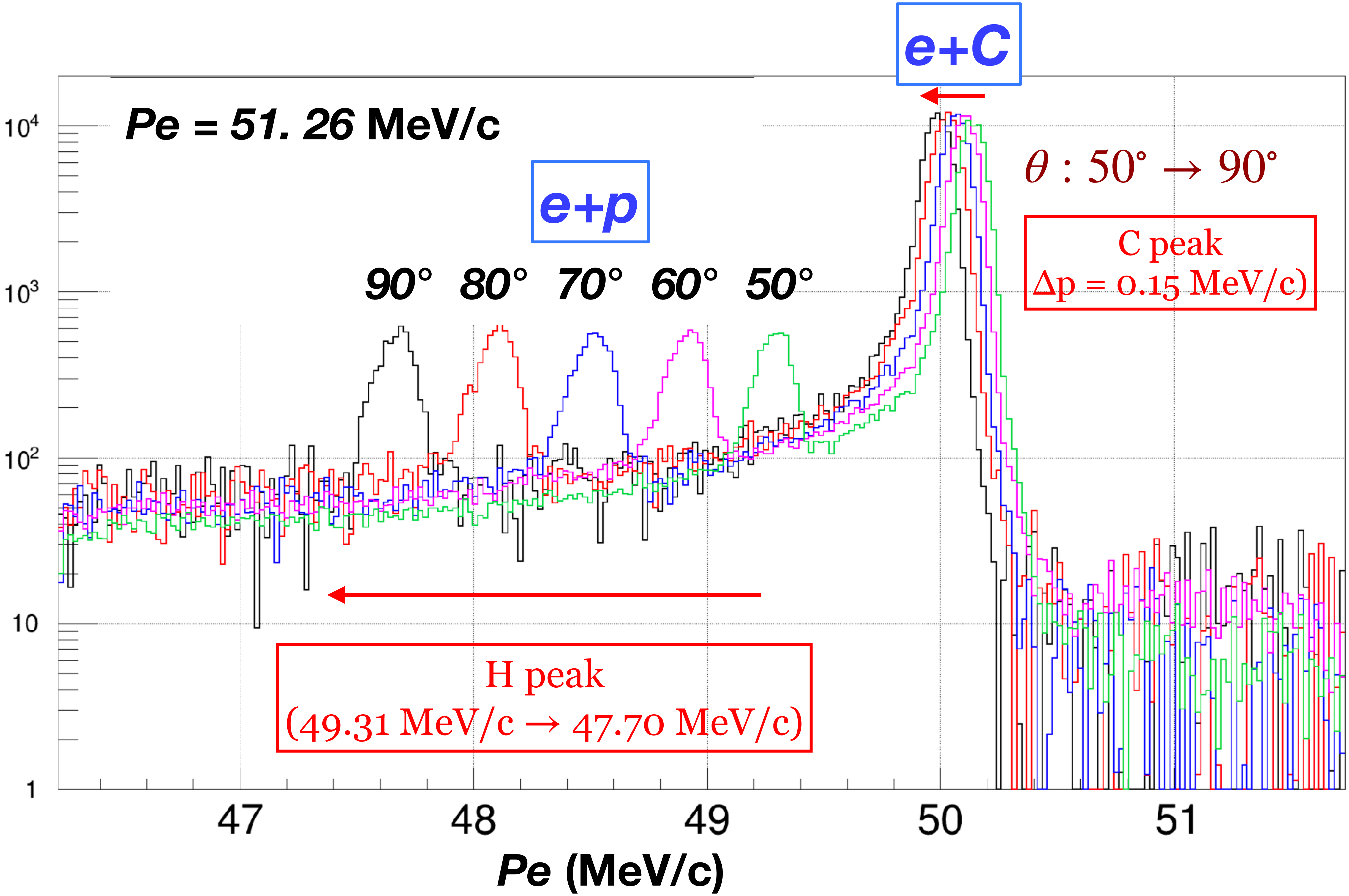
   of e+C and e+p (d) scattering
3) $\langle r_c^2 \rangle$ of ^{12}C : accuracy $\sim 10^{-3}$
4) $\Delta Q^2/Q^2 \leq 10^{-3}$



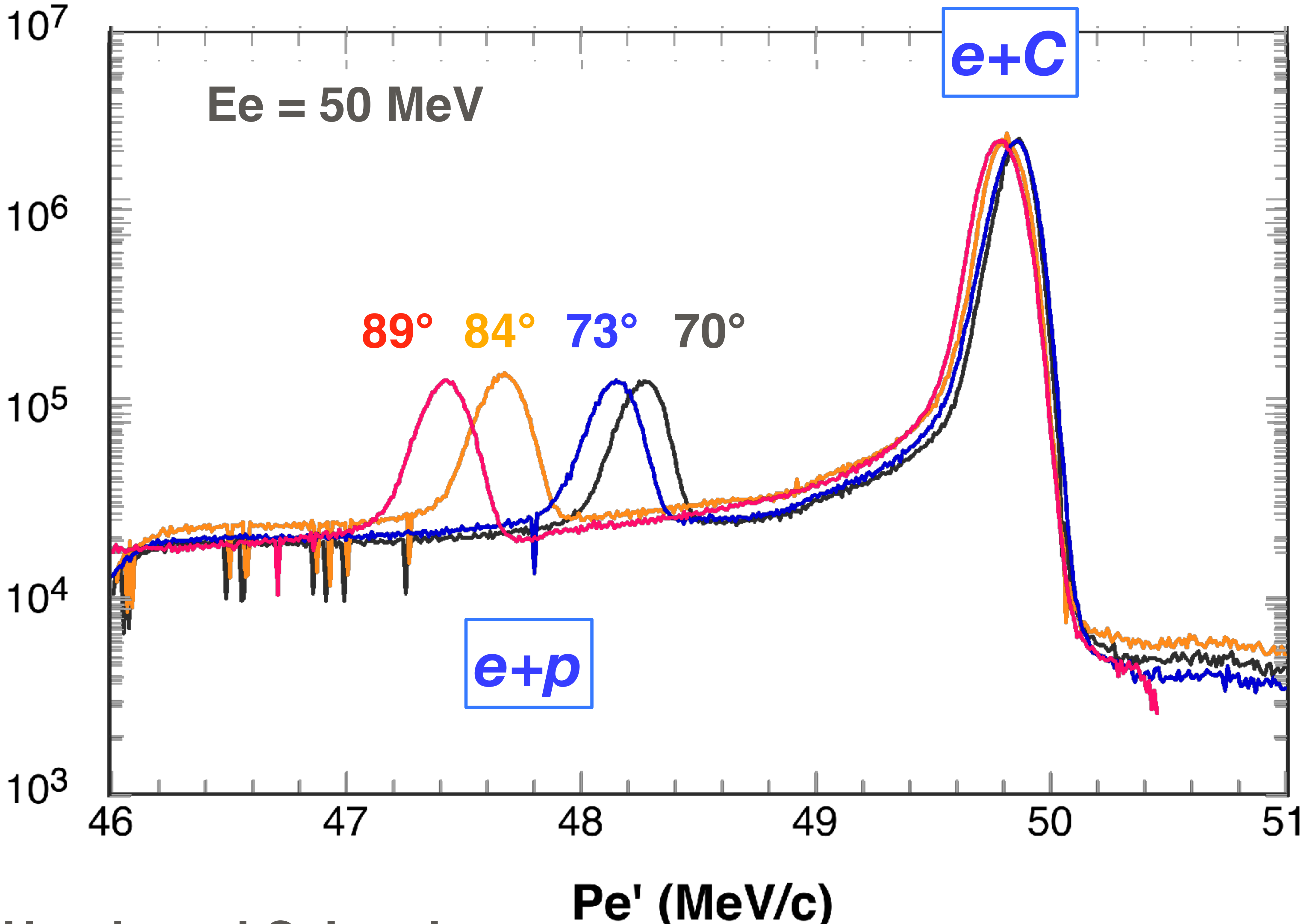
Physics data production run just started

CH_2 target

relative measurement to well-known e+^{12}C scattering

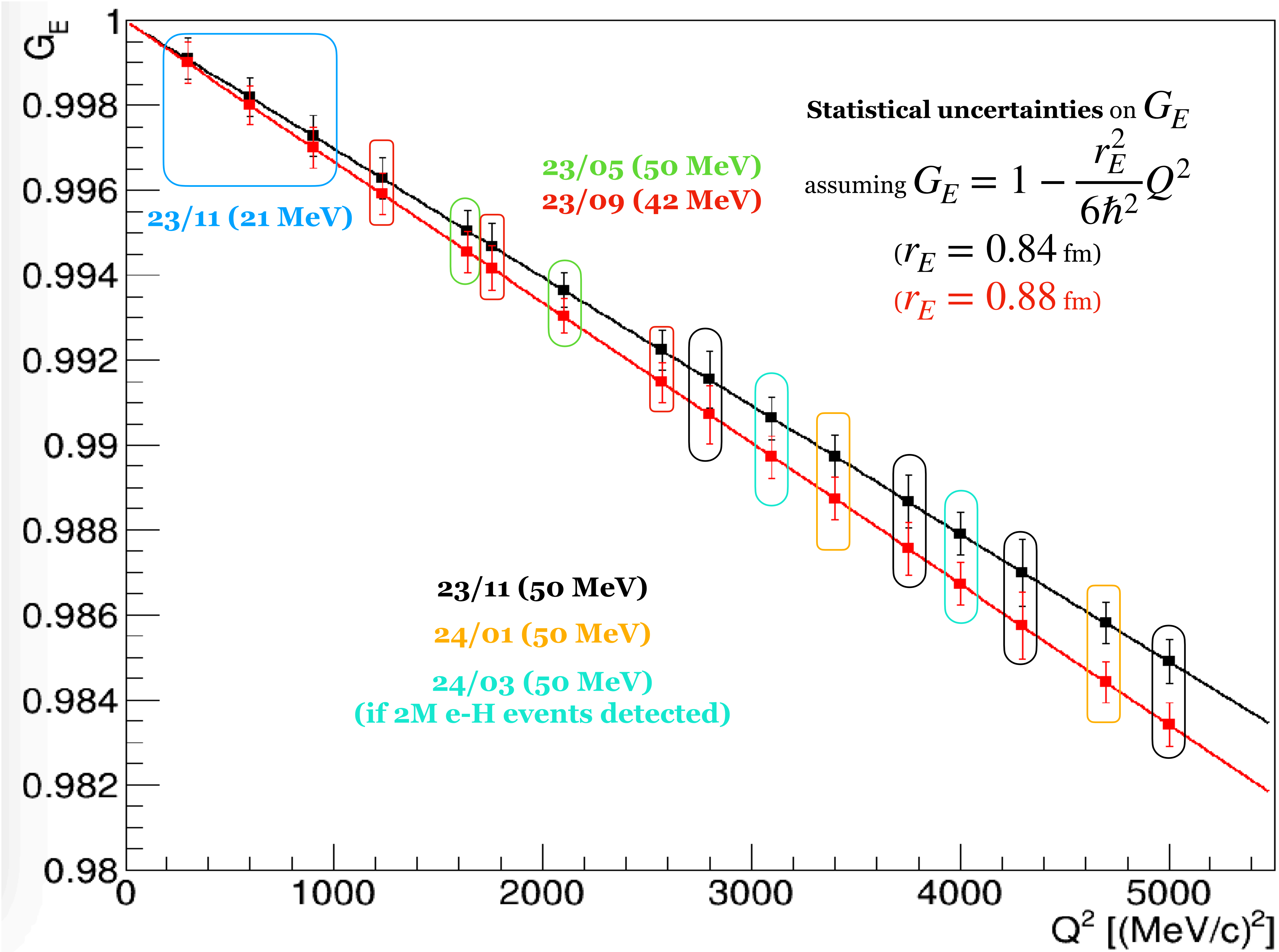


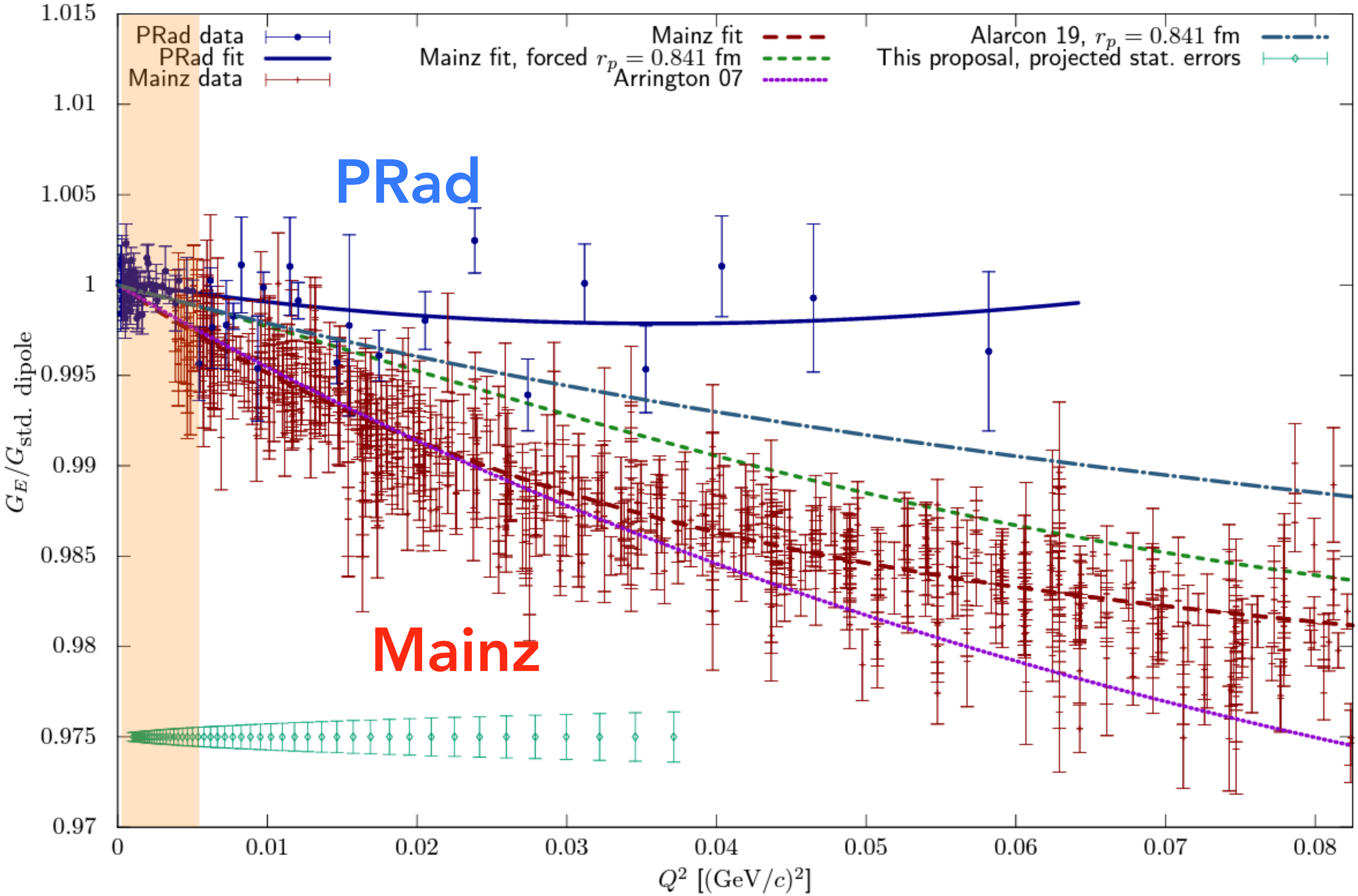
typical spectra of CH2(e,e') @ ULQ2



Y. Honda and C. Legris

Q^2 : 14 measured/ 16 planned

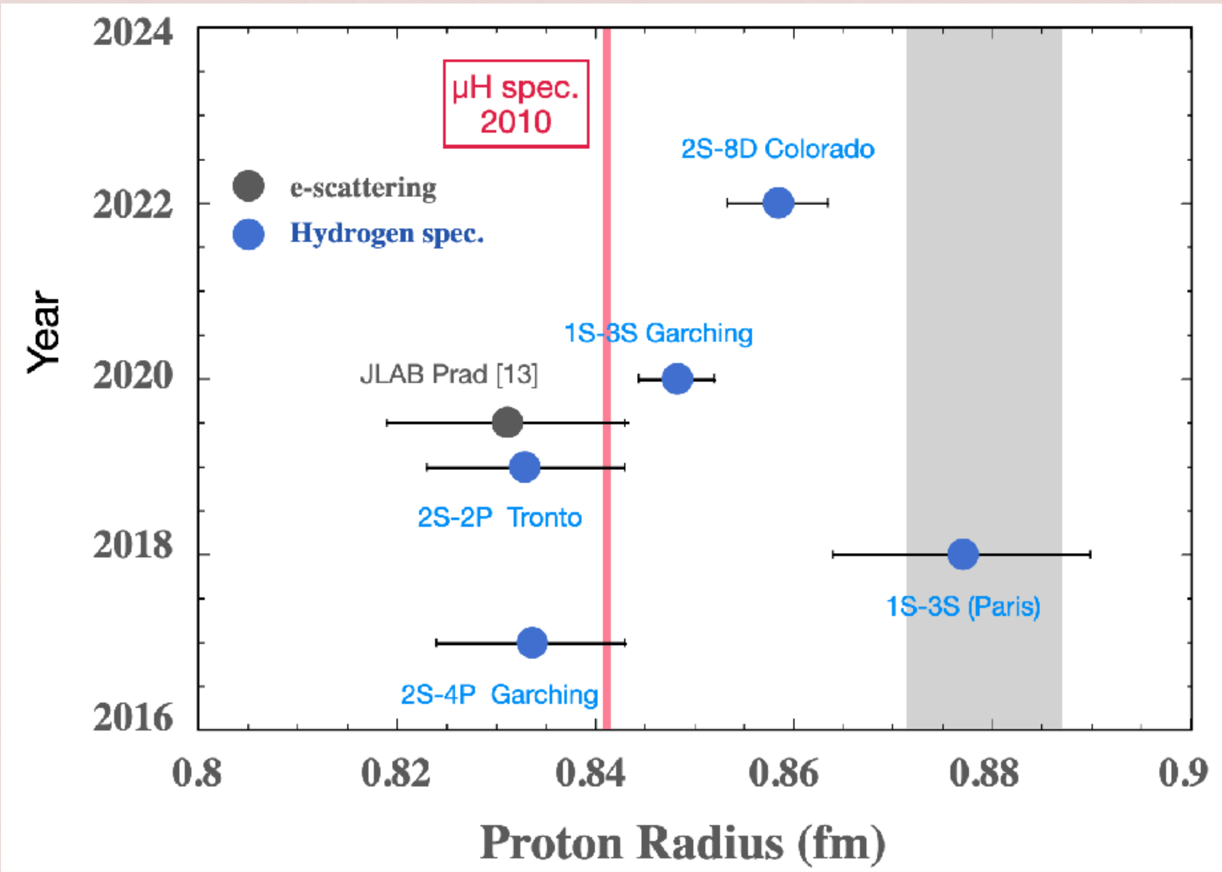


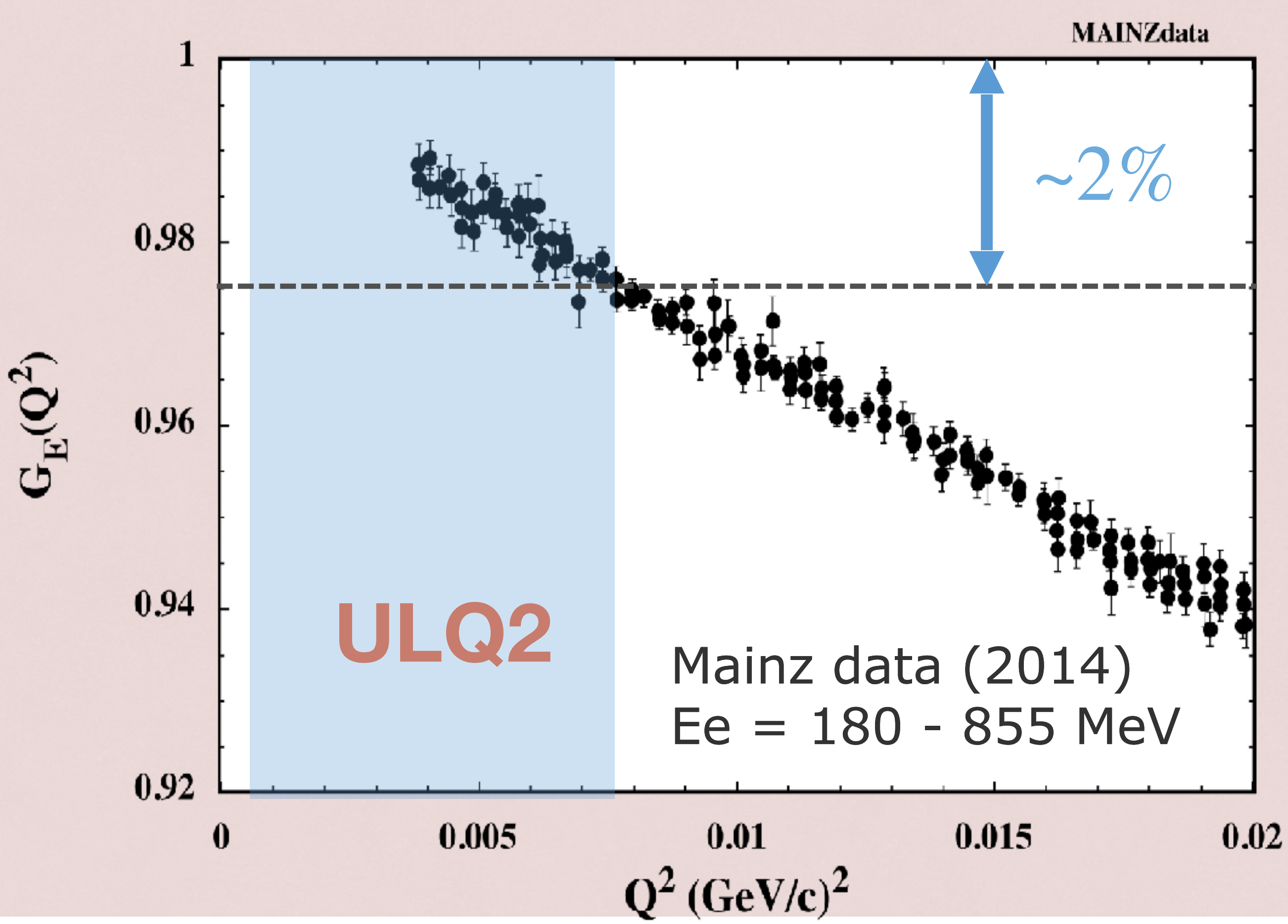


PRad data
PRad fit
Mainz data
Mainz fit
Mainz fit, forced $r_p = 0.841$ fm
Arrington 07
Alarcon 19, $r_p = 0.841$ fm
This proposal, projected stat. errors
PRad
Mainz
$G_E/G_{\mathrm{std.\ dipole}}$
Q^2 [(GeV/c)^2]
1.015
1.01
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

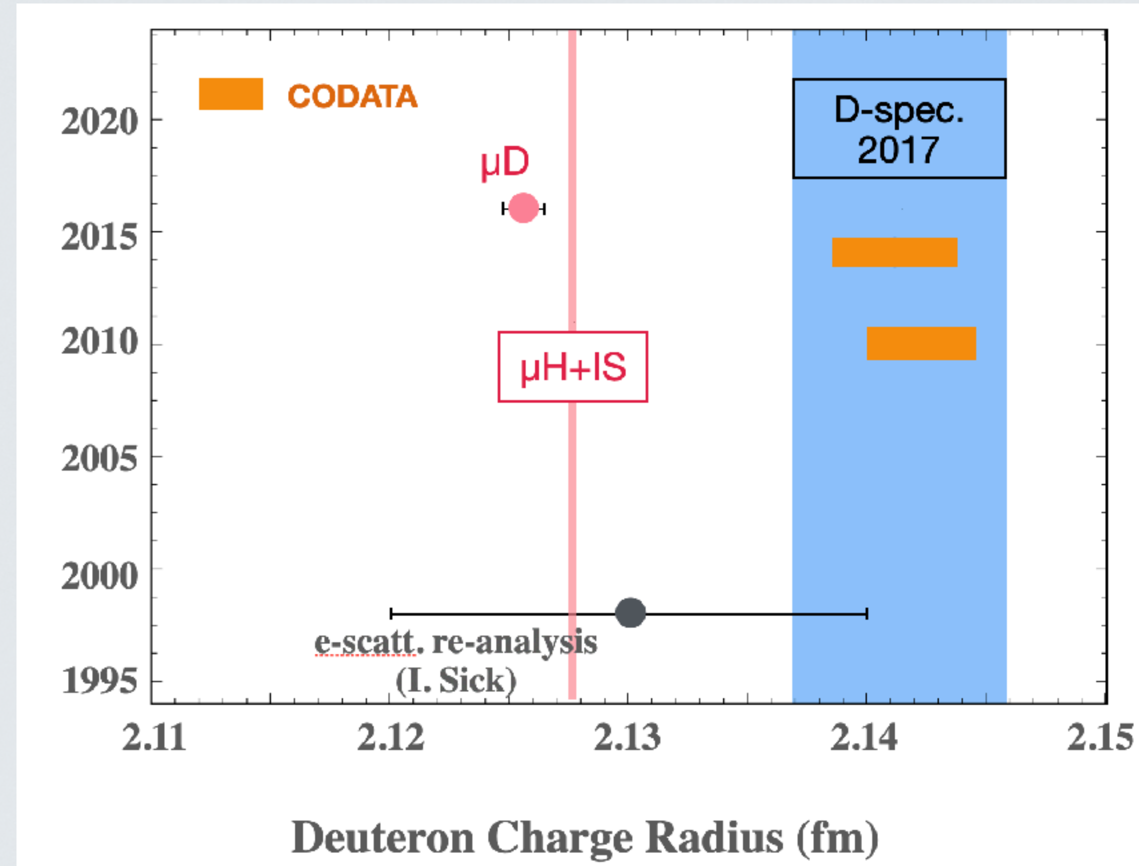
additional physics opportunity at ULQ2

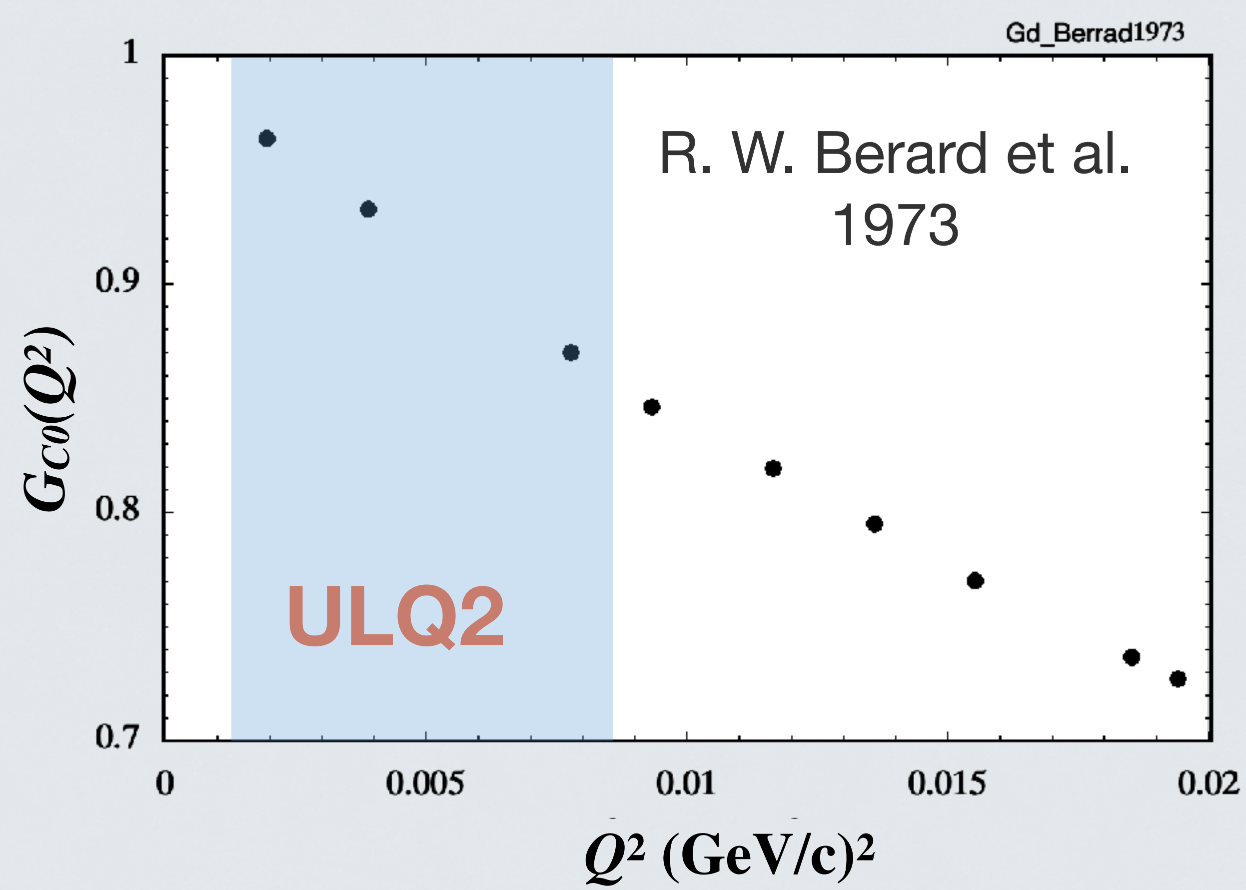
proton



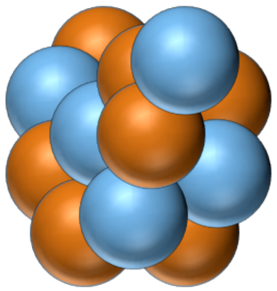


deuteron





nuclear charge density, moments



Proton

Neutron

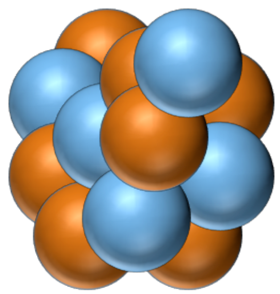
1) charge density

$$\rho_c(r) = \rho_c^p(r) + \rho_c^n(r)$$

$$\rho_c^p(r) = \int \rho_p(r)\, \rho_{p(point)}(r - r')\, \mathrm{d}^3 r'$$

$$\rho_c^n(r) = \int \rho_n(r)\, \rho_{n(point)}(r - r')\, \mathrm{d}^3 r'$$

nuclear charge density, moments



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$$\rho_c^n(r) = \int \rho_n(r)\ \rho_{n(point)}(r - r')\ \mathrm{d}^3 r'$$

2) 2nd moment

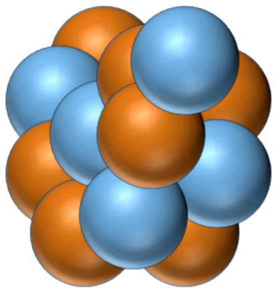
$$< r_c^2 > = \int r^2\ \rho_c(r)\ \mathrm{d}^3 r$$

Proton

Neutron

$$= < r^2_{p(point)} > + < r_p^2 > + < r^2_{n(point)} > + \frac{N}{Z} < r_n^2 > + \mathrm{rel\,.\,corr\,.}$$

nuclear charge density, moments



Proton

Neutron

1) charge density

$$\rho_c(r) = \rho_c^p(r) + \rho_c^n(r)$$

$$\rho_c^p(r) = \int \rho_p(r)\, \rho_{p(point)}(r - r')\, \mathrm{d}^3 r'$$

$$\rho_c^n(r) = \int \rho_n(r)\, \rho_{n(point)}(r - r')\, \mathrm{d}^3 r'$$

2) 2nd moment

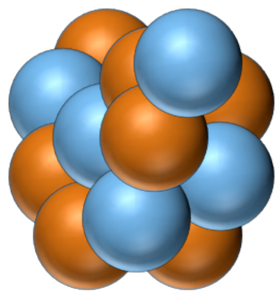
$$< r_c^2 > = \int r^2\, \rho_c(r)\, \mathrm{d}^3 r$$

Proton

Neutron

$$= < r^2_{p(point)} > + < r_p^2 > + \quad \cancel{< r^2_{n(point)} >} + \frac{N}{Z} < r_n^2 > + \mathrm{rel.\,corr.}$$

nuclear charge density, moments



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exp.

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theories

3) 4th moment

$$< r_c^4 > = \int r^4 \rho_c(r) \, \mathrm{d}^3 r$$

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RMS n-radius

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$$+ \mathrm{rel.\ corr.}$$

RMS n-radius

1) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2019, 113D01
2) H. Kurasawa, T. S. and T. Suzuki, Prog. Theor. Exp. Phys. 2021, 013D02
3) H. Kurasawa and T. Suzuki, Prog. Theor. Exp. Phys. 2022, 023D03
4) T.Suzuki, Prog. Theor. Exp. Phys. submitted

deuteron

2nd moment

$$< r_c^2 > = < r_{p(point)}^2 > + < r_p^2 > + < r_n^2 > + \text{rel. corr.}$$

isotope shift measurement

$$< r_c^2 > - < r_p^2 > = 3.82070(31)\ \text{fm}^2$$

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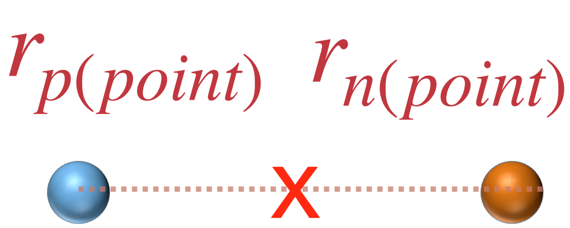

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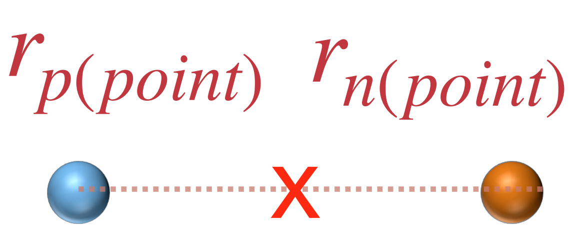


$$+ \frac{10}{3} < r_{n(point)}^2 > < r_n^2 > + \mathrm{rel.corr.}$$

$$= < r_{p(point)}^4 > + \frac{10}{3} < r_{p(point)}^2 > (< r_p^2 > + < r_n^2 >)$$

$$+ \mathrm{rel.corr.}$$

PHYSICAL REVIEW LETTERS **124,** 082501 (2020)

Extraction of the Neutron Charge Radius from a Precision Calculation of the Deuteron Structure Radius

A. A. Filin,[1] V. Baru,[2,3,4] E. Epelbaum,[1] H. Krebs,[1] D. Möller,[1] and P. Reinert[1]
[1]*Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Institut für Theoretische Physik II, D-44780 Bochum, Germany*
[2]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[3]*Institute for Theoretical and Experimental Physics NRC "Kurchatov Institute", Moscow 117218, Russia*
[4]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 119991, Leninskiy Prospect 53, Moscow, Russia*

$$< r_c^2 > = < r_{str}^2 > + < r_p^2 > + < r_n^2 > + \mathrm{rel.\,corr.}$$

μD spec. $\quad$ χEFT

$$< r_{str}^2 > = (1.9731 \, {}^{+0.0013}_{-0.0018})^2 \ \mathrm{fm}^2$$

$$< r_c^2 > = (2.12560 \, (78))^2 \ \mathrm{fm}^2$$

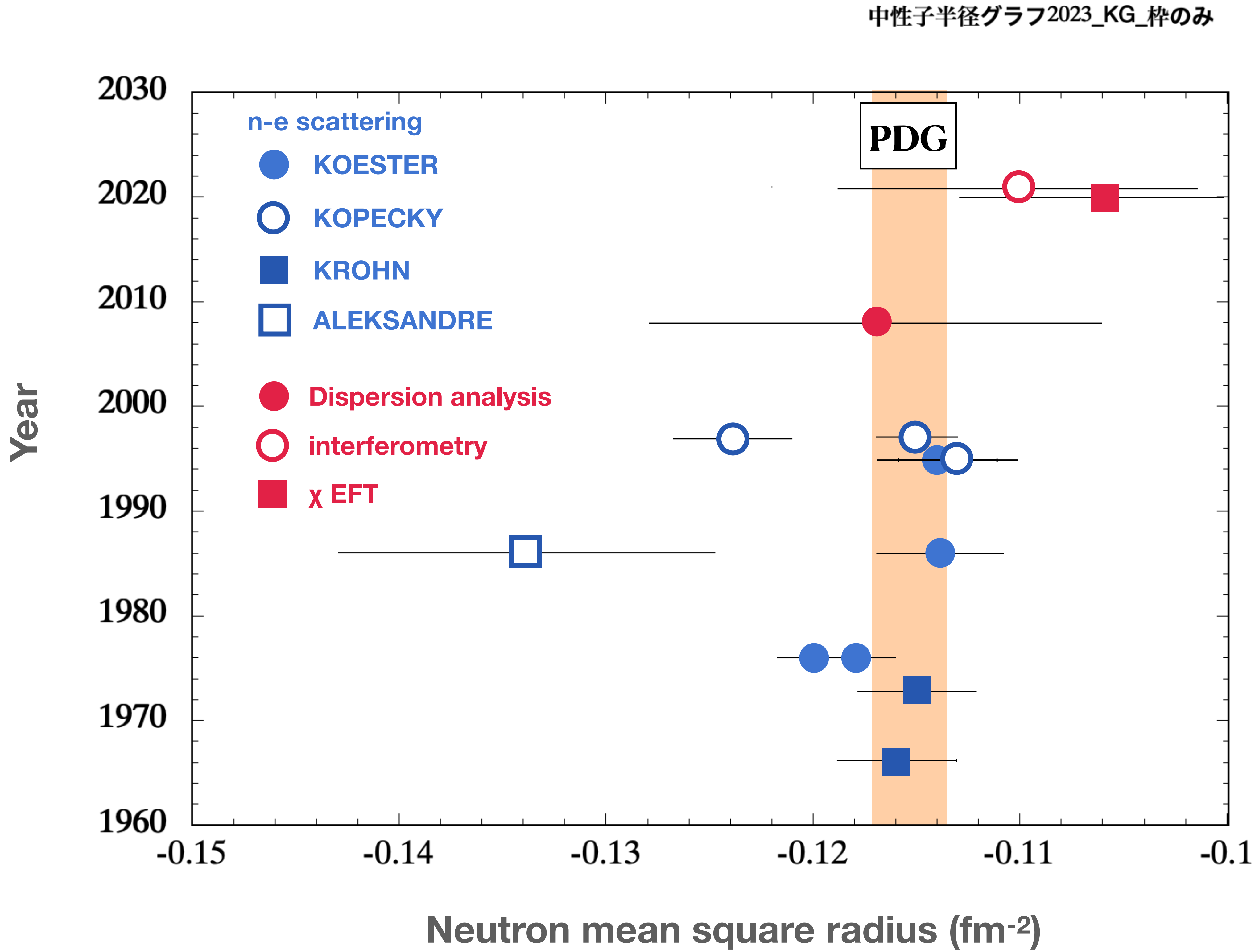
$$< r_p^2 > = (0.8414(9))^2 \ \mathrm{fm}^2$$

$$\mathrm{rel.\,corr.} : -\frac{3}{4m^2}$$ (Darwin-Foldy)

$$\Rightarrow \quad < r_n^2 > = -0.106 \, {}^{+0.007}_{-0.005} \ \mathrm{fm}^2$$

neutron charge radius original figure

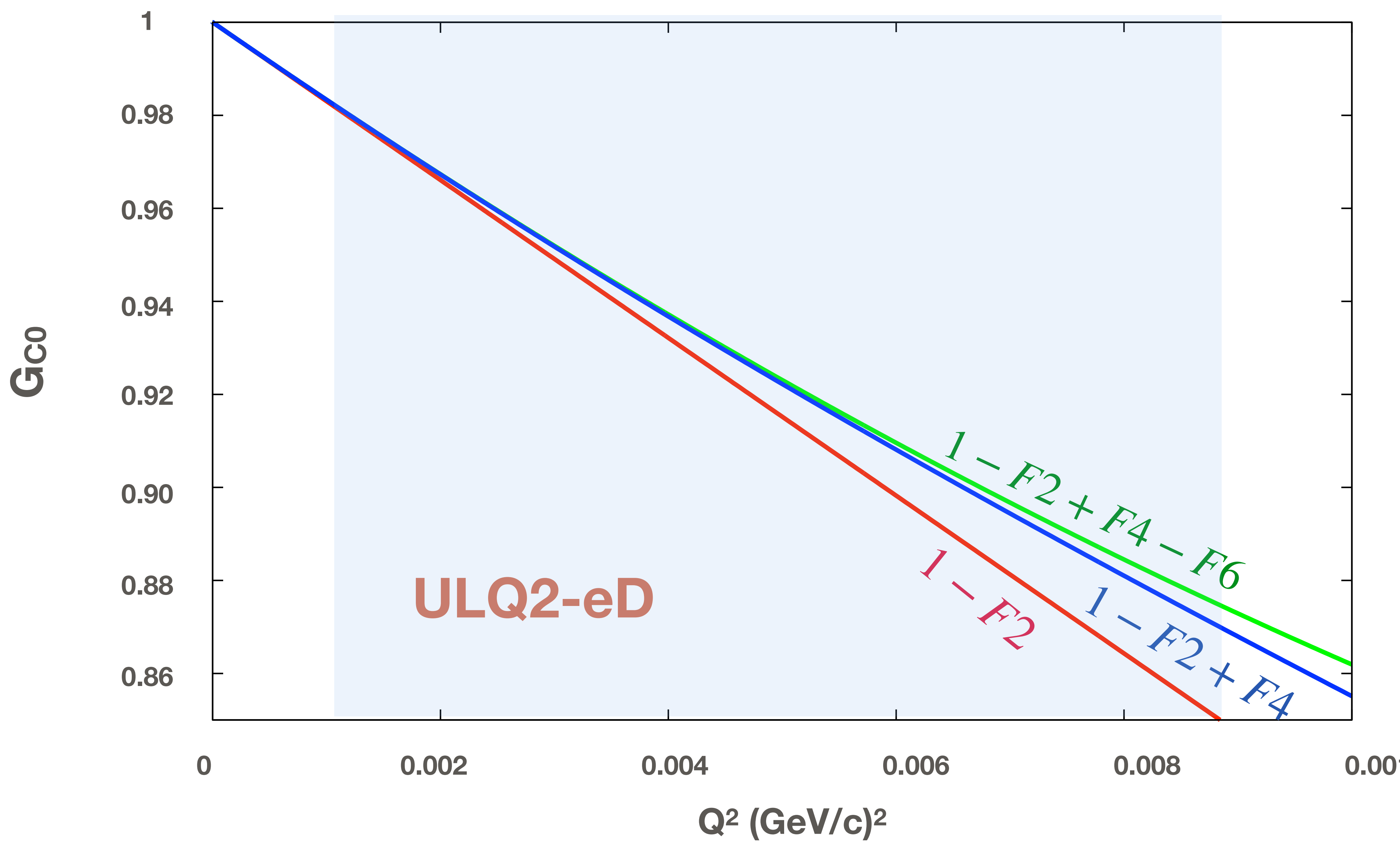
PDG <rn2> = -0.1155+-0.0017 fm2



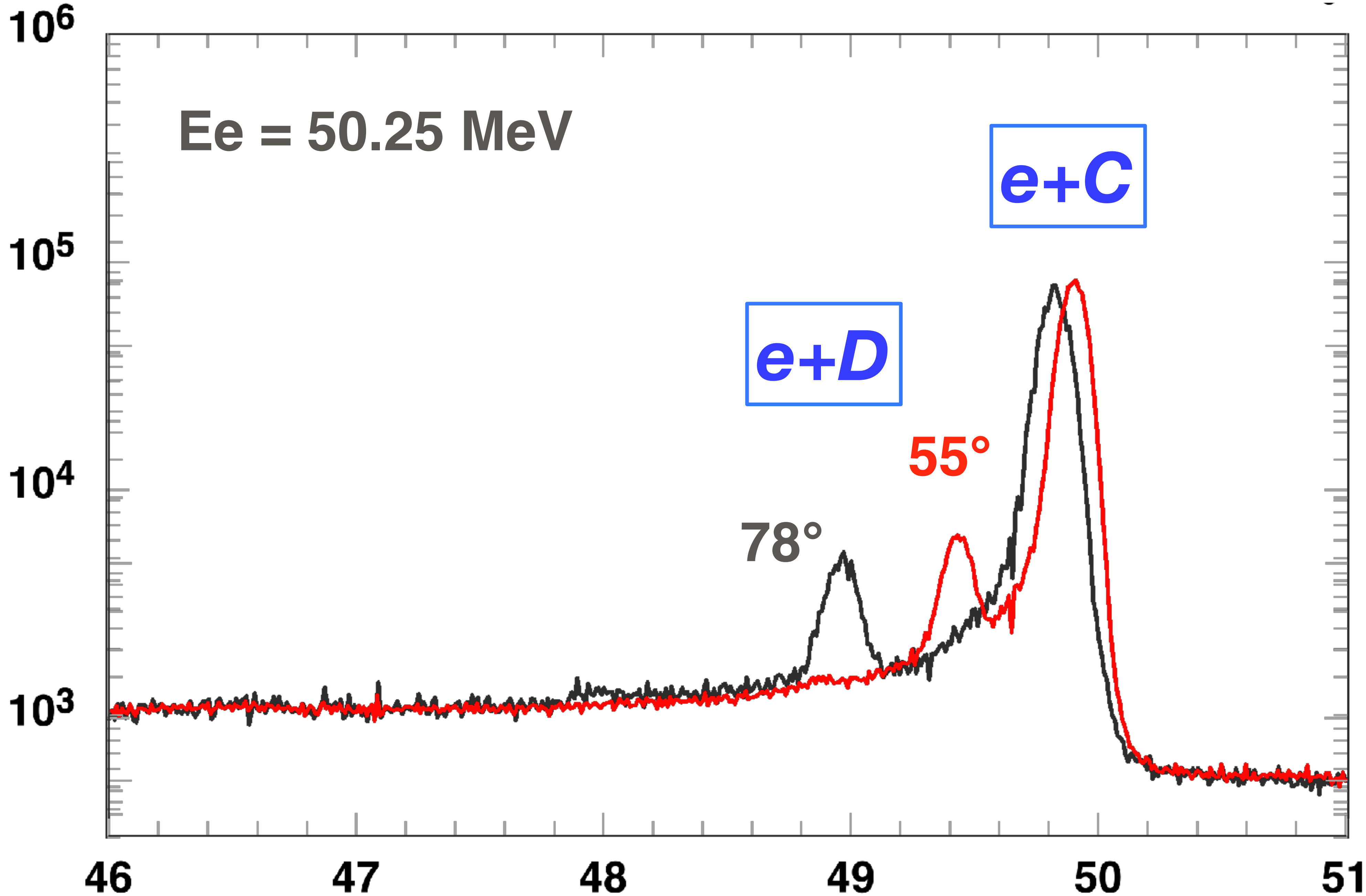
Low-energy electron scattering provides <r4c>

charge form factor at low q

$$G_{C0} \sim 1 - \frac{< r_c^2 >}{3!} Q^2 + \frac{< r_c^4 >}{5!} Q^4 - \ldots$$

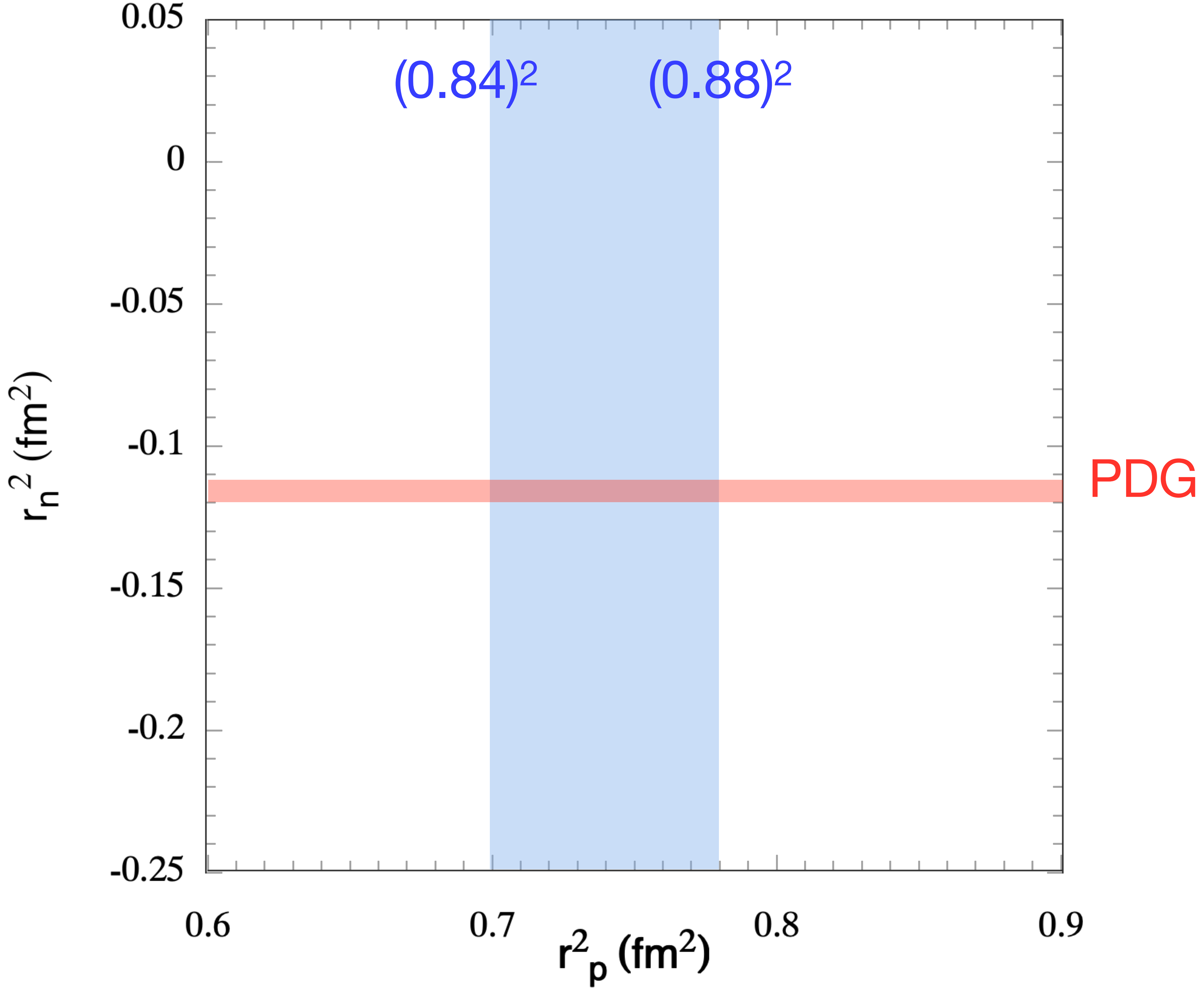


First shots of CD2(e,e’) @ ULQ2

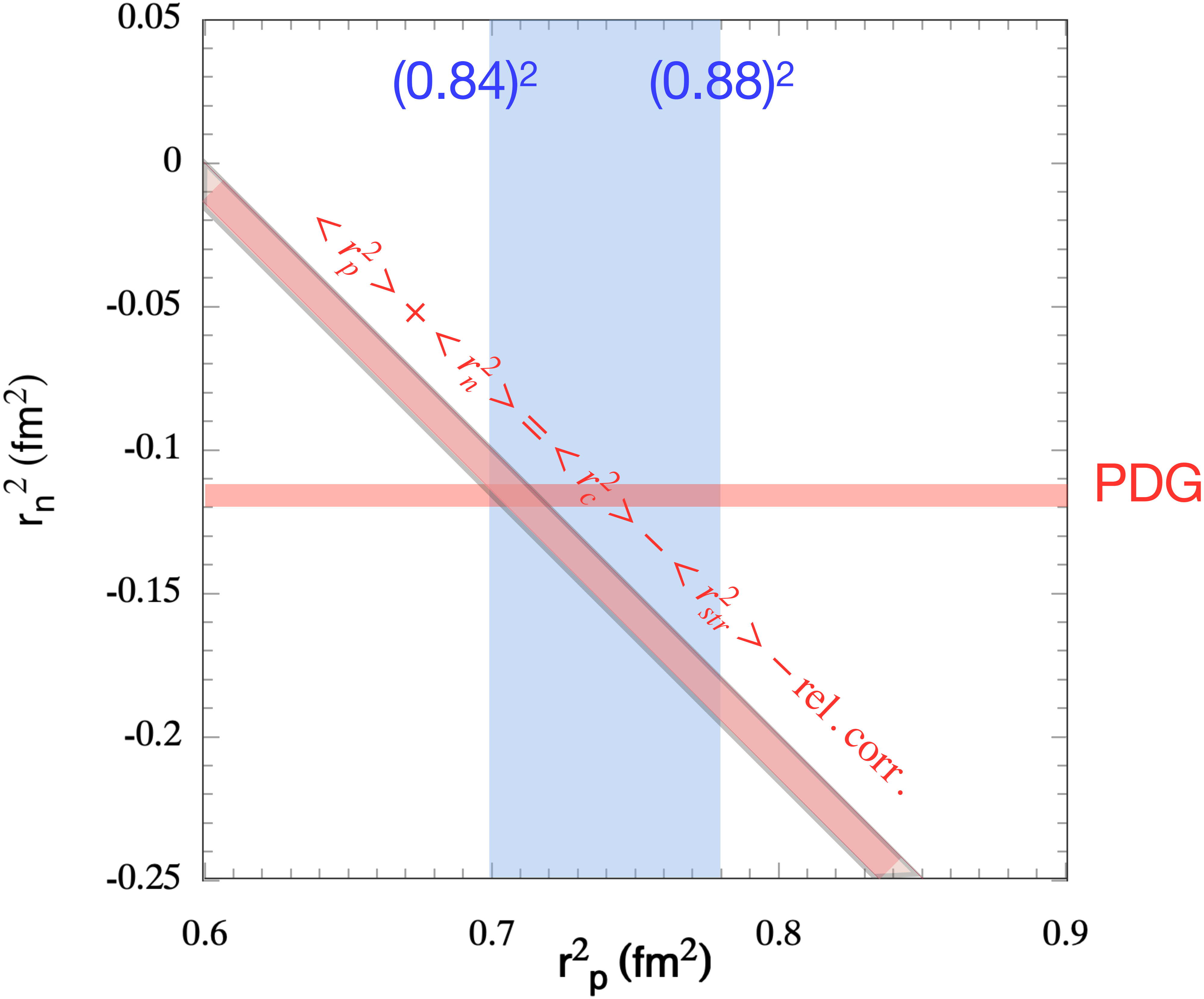


a series of CD2 measurements is underway

T. Goke



0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
r_n^2 (fm^2)
(0.84)^2
(0.88)^2
PDG
0.6
0.7
0.8
0.9
r^2_p (fm^2)



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r^2_p (fm^2)
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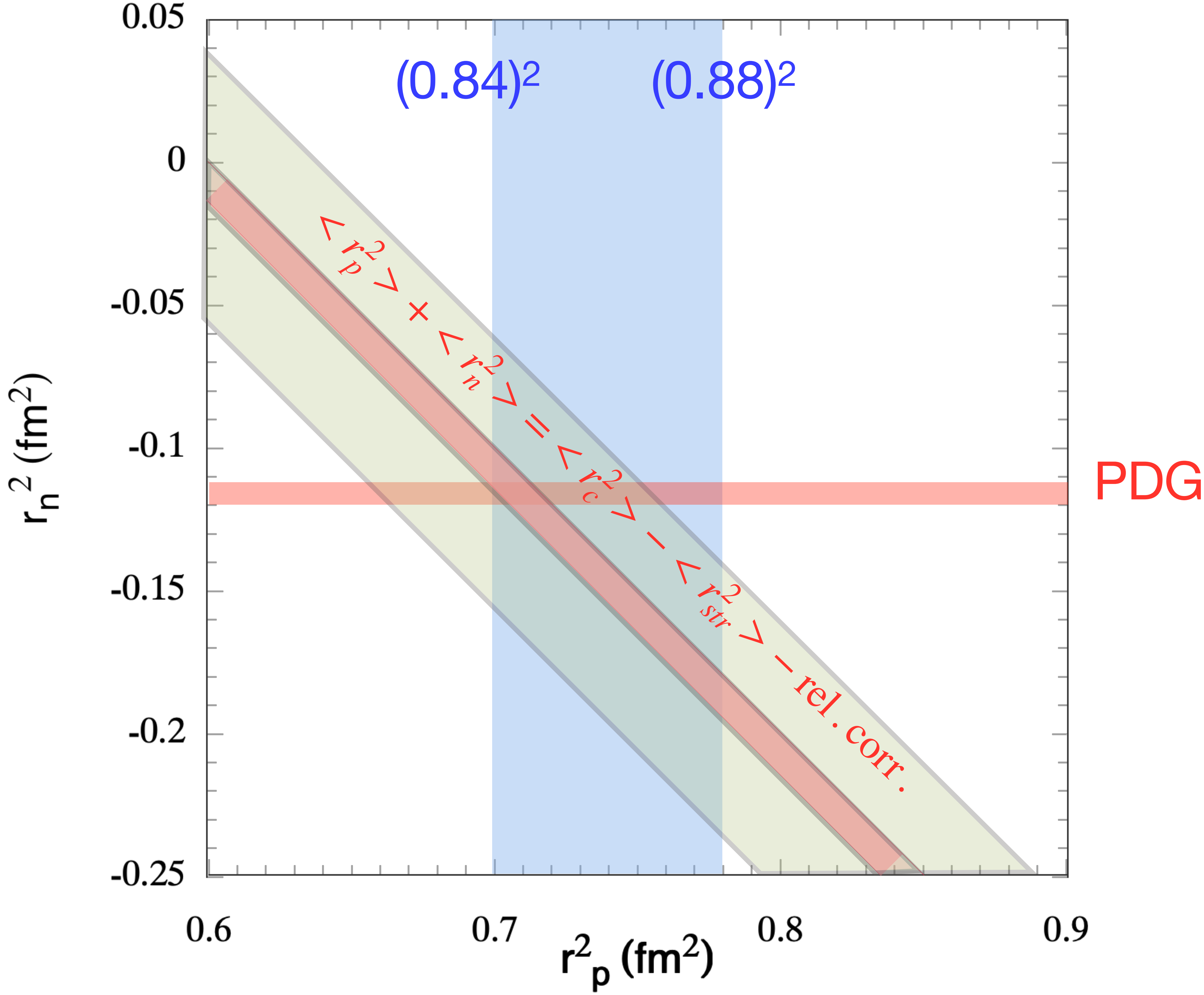
$(0.88)^2$
$< r_p^2 > + < r_n^2 > = < r_c^2 > - < r_{str}^2 > -$ rel. corr.
PDG

$$< r_c^4 > = < r_{p(point)}^4 > + \frac{10}{3} < r_{p(point)}^2 > (< r_p^2 > + < r_n^2 >) + \text{rel. corr.}$$



conclusions

- low-q e-scattering activities in Japan

  Tohoku ULQ2 for proton radius etc.

  RIKEN SCRIT for structure studies of exotic nuclei

- Tohoku ULQ2 (Ultra-Low Q2)

  E_e = 10 - 60 MeV

  θ_e = 30 - 150 deg.

  high-resolution twin spectrometers

  $Q^2 = 3\times10^{-5} - 0.013\ (\mathrm{GeV}/c)^2$: lowest-ever

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  CD2(e,e') this year

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We plan to organize a workshop in Sendai, Japan, on

"Low-Energy Electron Scattering for Nucleon and Exotic Nuclei"

Date : Oct. 28 - Nov. 1, 2024
Place : Sendai