Measurement of the proton charge radius during the ULQ^2 experiment

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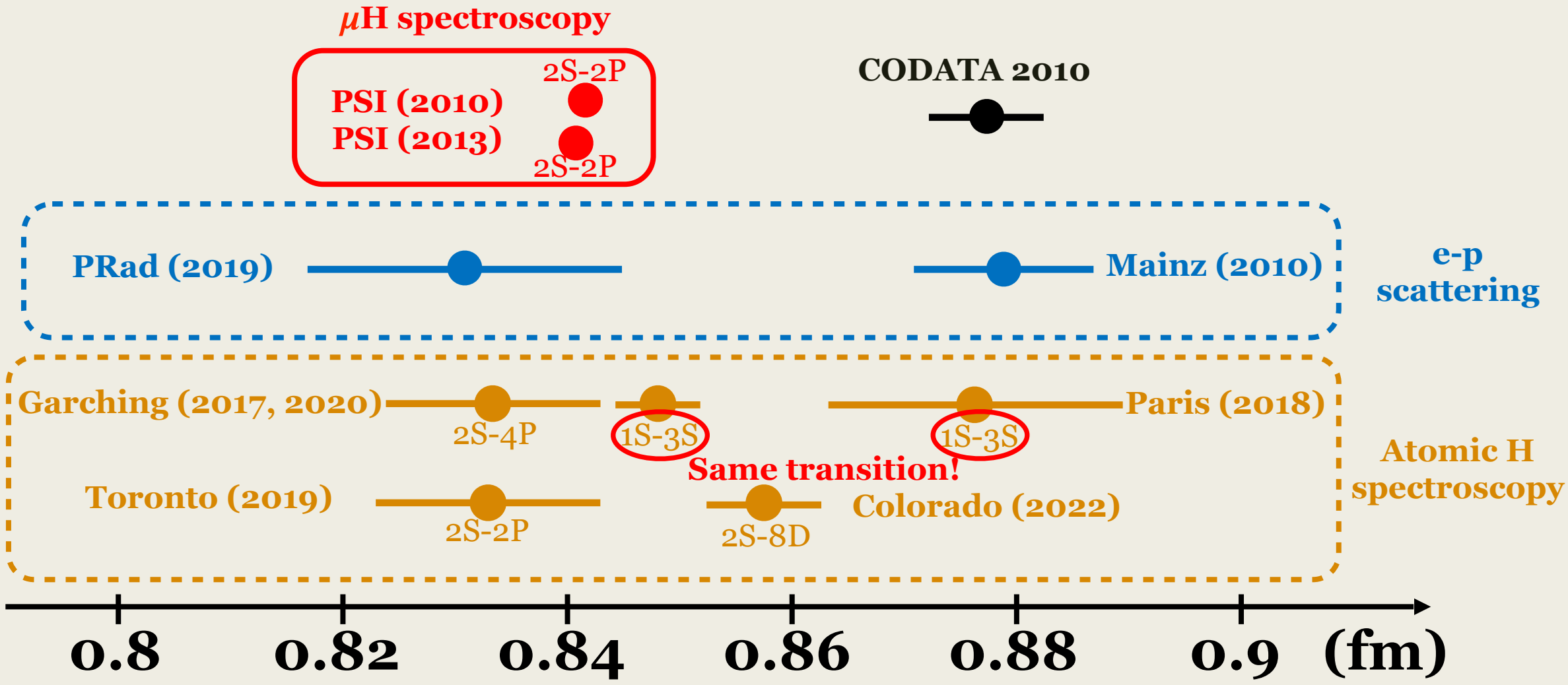
I. Proton charge radius puzzle

Proton charge radius puzzle



II. Determination of the proton charge radius using electron scattering

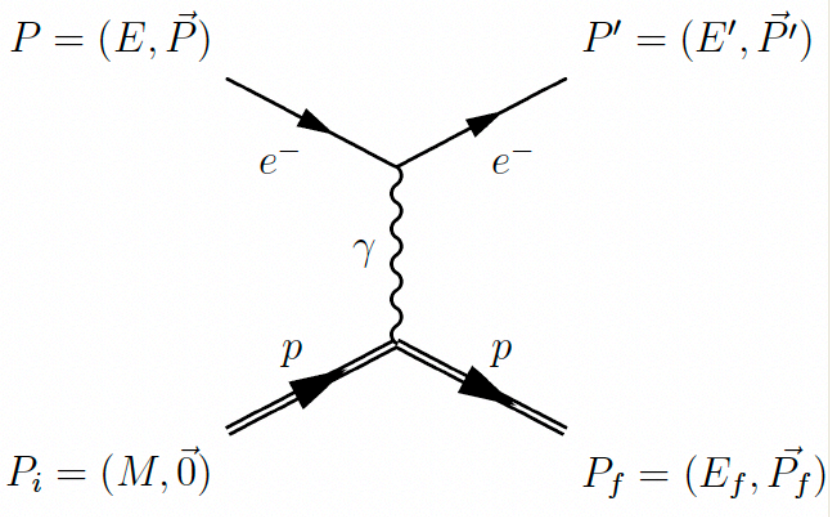
Electric form factor and proton charge radius

$$\tau = \frac{Q^2}{4M_p^2},\ \epsilon^{-1} = 1 + 2(1+\tau)\frac{Q^2 - 2m^2}{4EE' - Q^2}$$

E. Borie, arXiv: 1207.6651v4

Momentum transfer:

$$Q^2 = -(P - P')^2$$



Feynman diagram of the leading-order of the electron-proton scattering.

Cross section:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \frac{G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)}{1+\tau}$$

$$\text{with } \left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{\alpha^2(4EE' - Q^2)}{Q^4} \frac{P'/P}{1 + (E - (PE'/P')\cos\theta)/M}$$

$$R_E = \sqrt{\langle r_E^2 \rangle} \equiv \sqrt{-6 \lim_{Q^2 \to 0} \frac{dG_E}{dQ^2}}$$

G. Miller, Phys. Rev. C **99** (2019), 035202

Q^2 as small as possible!

Electric form factor and proton charge radius

Momentum transfer:

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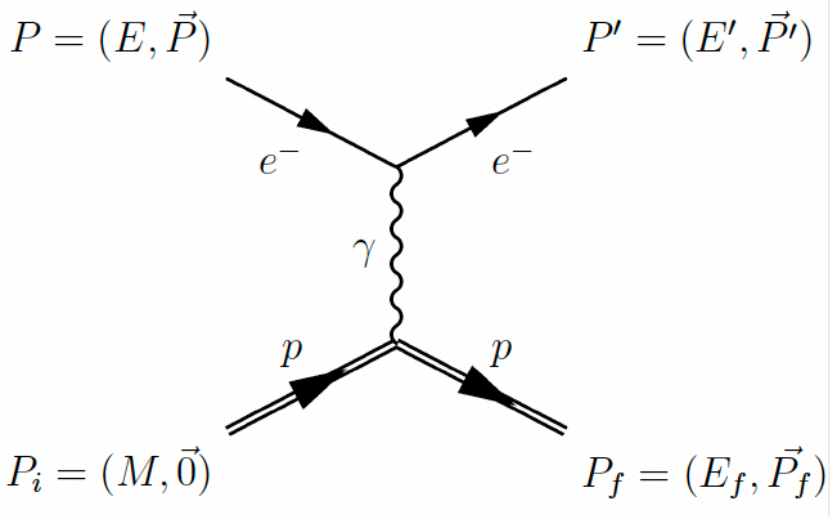
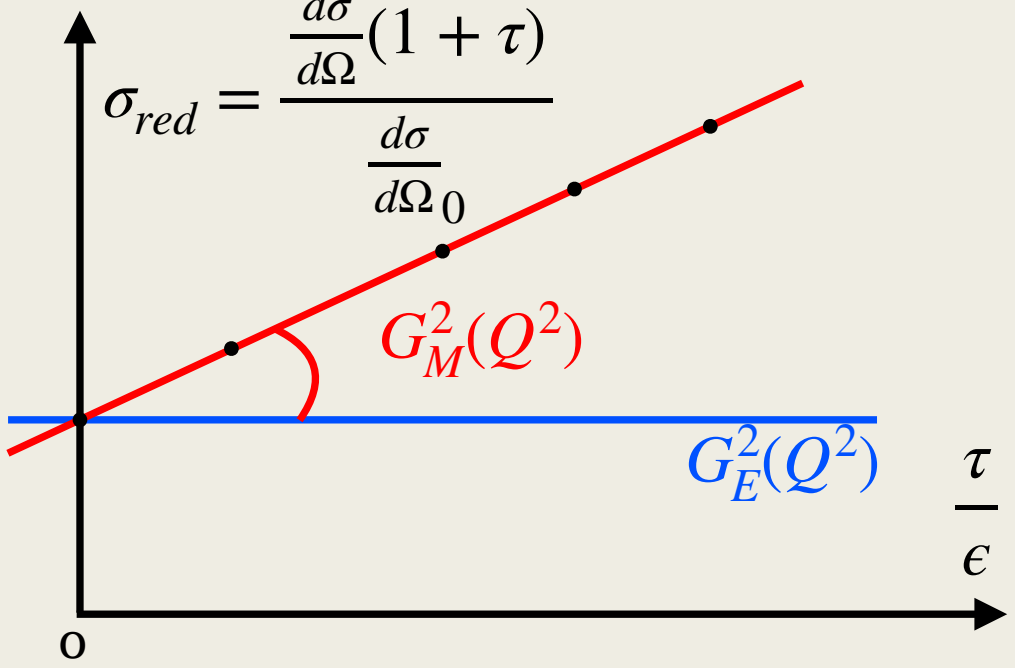


Feynman diagram of the leading-order of the electron-proton scattering.

Rosenbluth separation (RS):

- Determine separately $G_E(Q^2)$ and $G_M(Q^2)$
- Measurement of the cross-section with a constant Q^2 and different angles.



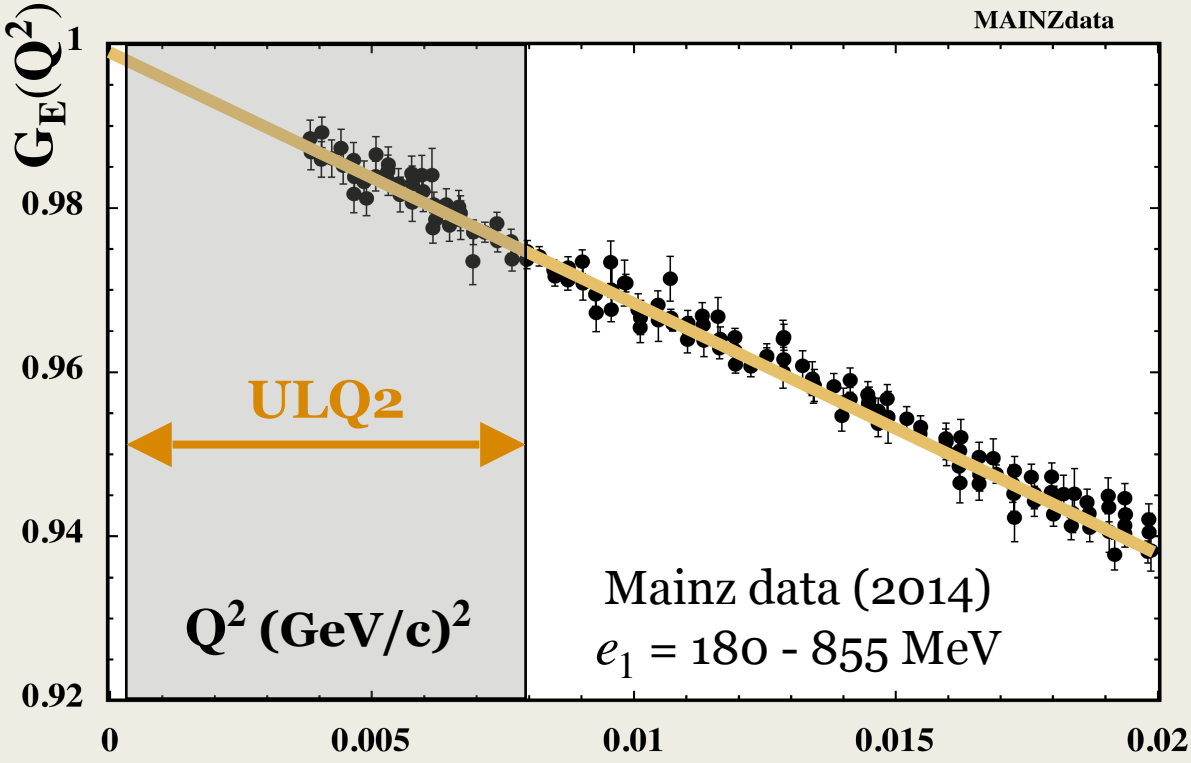
Specifications of the ULQ^2 experiment

Ultra Low Q^2

Characteristics of the experiment:

- Measurement of $G_E(Q^2)$ for extremely small values of Q^2:
  $0.0003\ (\mathrm{GeV/c})^2 \leq Q^2 \leq 0.008\ (\mathrm{GeV/c})^2$
- **Lowest beam energy for electron scattering in the world**:
  $10\ \mathrm{MeV} \leq E \leq 60\ \mathrm{MeV}$
- Rosenbluth separation with $30° \leq \theta \leq 150°$.
- Polyethylene (CH_2) target.

➡ **Absolute** cross-section measurement with 10^{-3} accuracy.



Momentum transfer range reached during the ULQ^2 experiment.

Absolute cross-section measurement

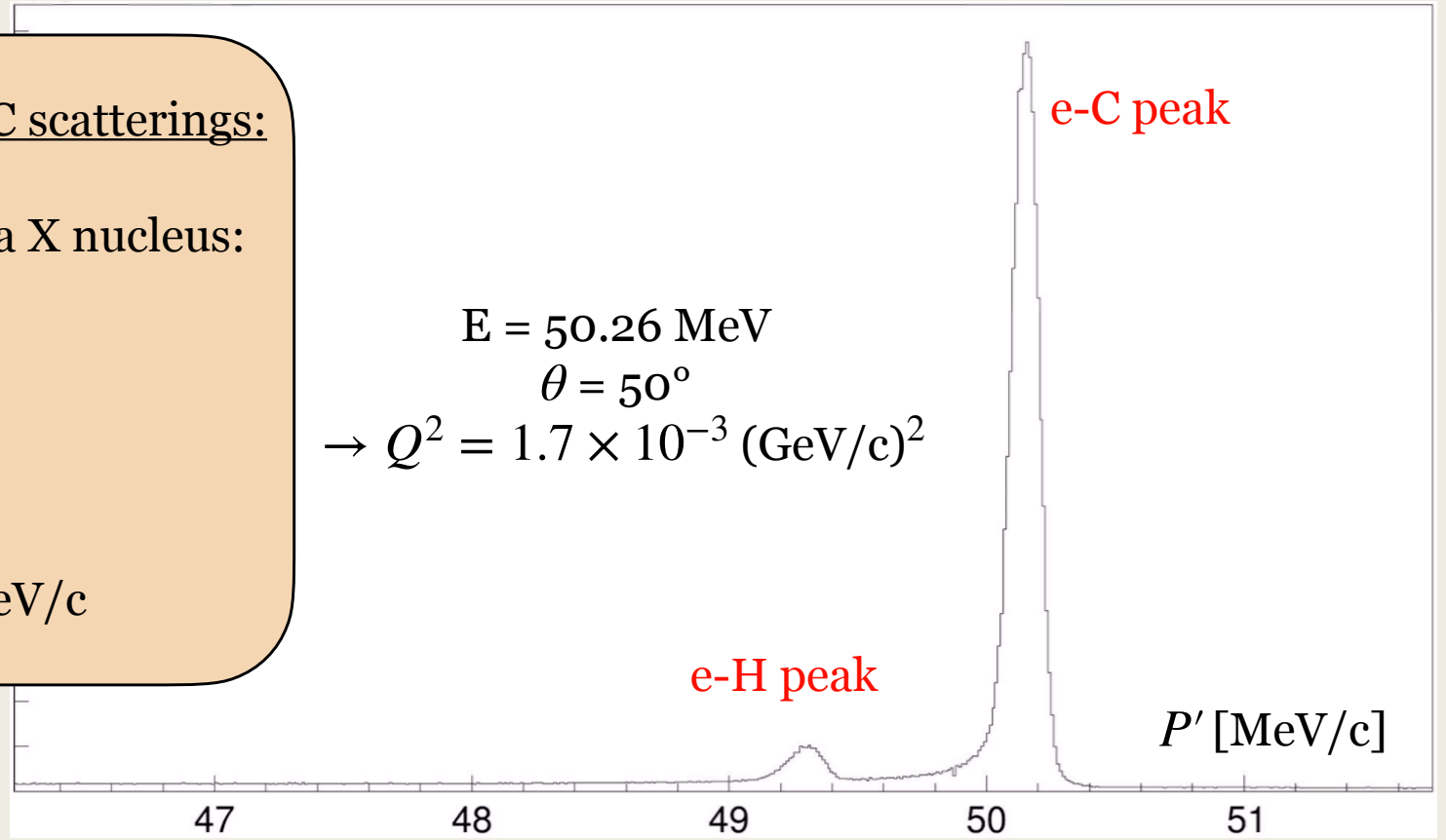
Simultaneous detection of e+p and e+^{12}C scatterings:

- Use of a CH_2 target.
- Momentum of a scattered electron on a X nucleus:

$$P'_X \overset{\text{URL}}{\sim} \frac{E}{1 + \frac{2E \sin\theta/2^2}{M_X}}$$

- E = 50 MeV, θ = 90°

  ➡ $P'_{^{12}C} \sim 49.8$ MeV/c, $P'_H \sim 47.5$ MeV/c



Simultaneous detection of e+p and e+^{12}C scattering with a CH_2 target (Experimental data).

Absolute cross-section measurement

Absolute cross-section of e+p scattering:

$$\left(\frac{d\sigma}{d\Omega}\right)_{e+p} = \frac{N_{e+p}}{N_e \, N_p \, \Delta\Omega}$$

Event number — N_{e+p}

Detector solid angle — $\Delta\Omega$

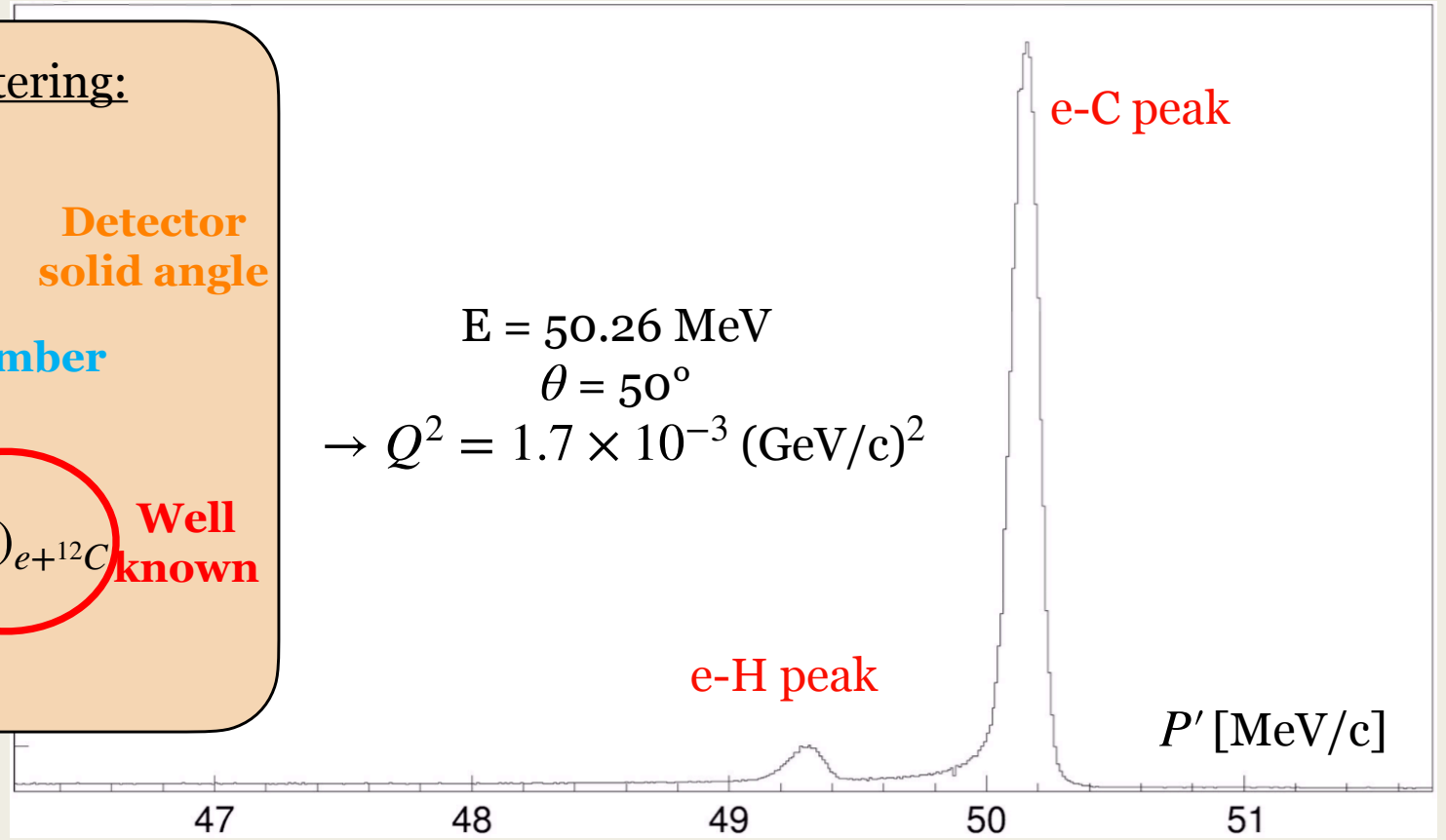
Beam dose — N_e

Target number — N_p

$$\left(\frac{d\sigma}{d\Omega}\right)_{e+p} = \frac{N_{e+p}/N_{e+^{12}C}}{N_p/N_{^{12}C}} \left(\frac{d\sigma}{d\Omega}\right)_{e+^{12}C}$$

Well known — $\left(\frac{d\sigma}{d\Omega}\right)_{e+^{12}C}$

Ratio of H and C nuclei — $N_p/N_{^{12}C}$



E = 50.26 MeV

$\theta = 50°$

$\rightarrow Q^2 = 1.7 \times 10^{-3}$ (GeV/c)^2

Simultaneous detection of e+p and e+^{12}C scattering with a CH_2 target (Experimental data).

Measurement time

- Goal: Determine R_E with 1 % accuracy

  → Need to have $\frac{\Delta G_E}{G_E} \leq 5 \times 10^{-4}$

  → At least 9 Q^2 data points

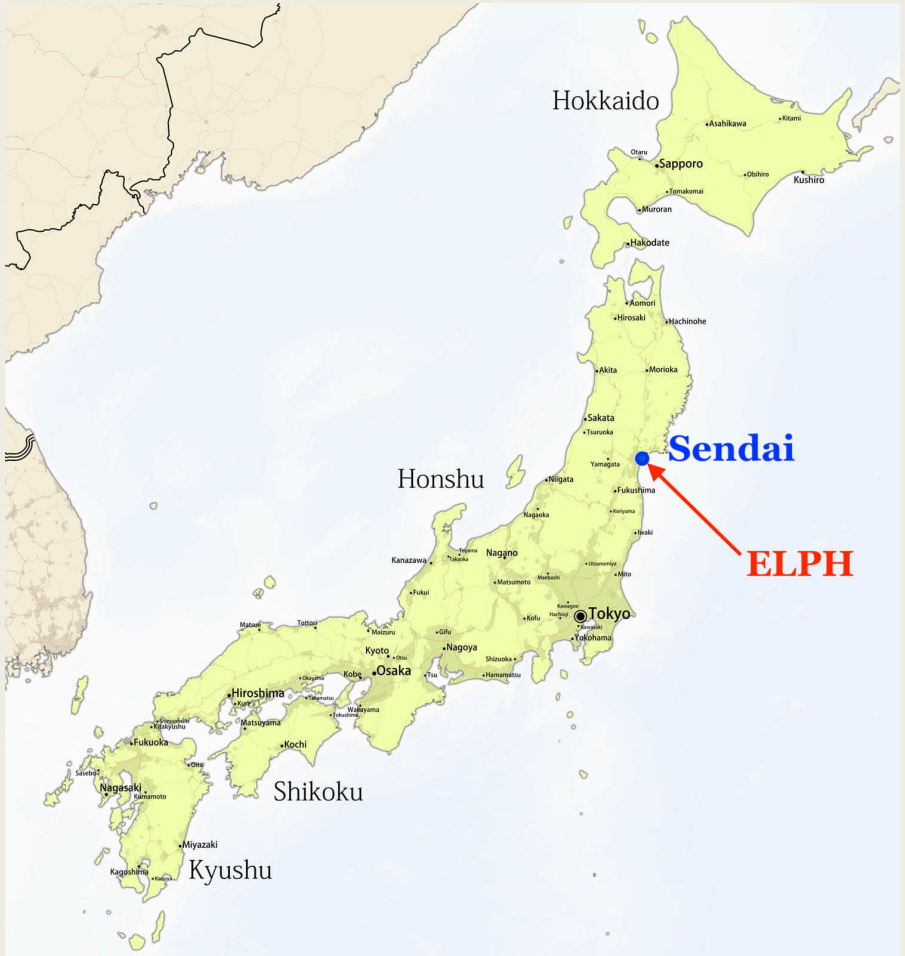
- Rosenbluth separation is not necessary at low Q^2 but can be done if needed
- Some measurements of the same G_E under different (E, θ) conditions

  → Consistency check

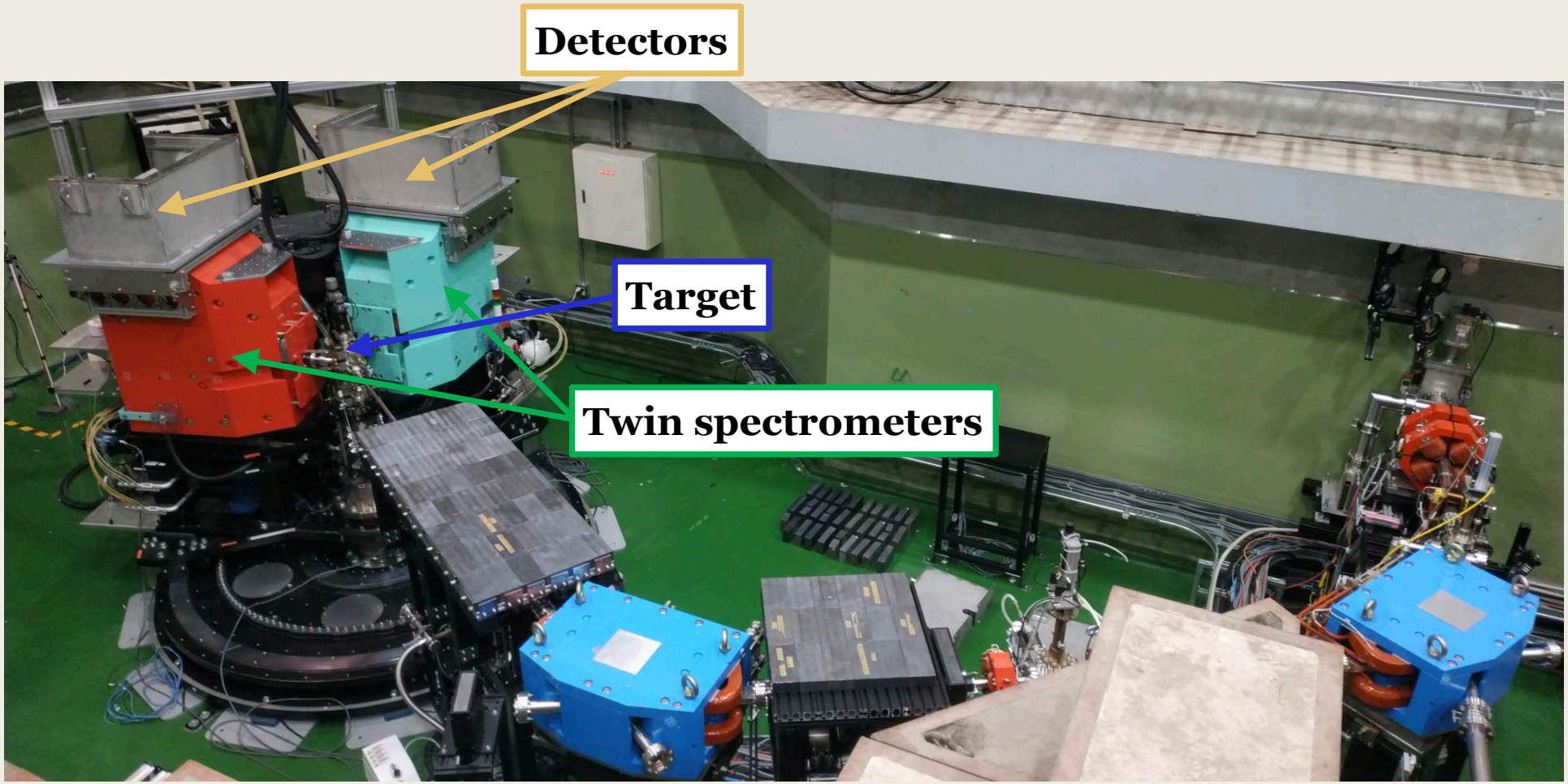
➡ Total estimated beam time for 2023 ~ 1 month

III. Experimental setup of the ULQ^2 experiment

Research Center for Electron-Photon Science (ELPH)



Beam line



Beam line

ULQ^2 accelerator:

- Energy: E = 10 - 60 MeV
- Energy spread: σ_E/E = 0.06%
- Position spread: σ_x, σ_y = 0.6 mm
- Intensity: I $\leq$ 1 μA
- Pulse duration: $\Delta t \sim 3$ μs
- Pulse frequency: f = 1-300 Hz

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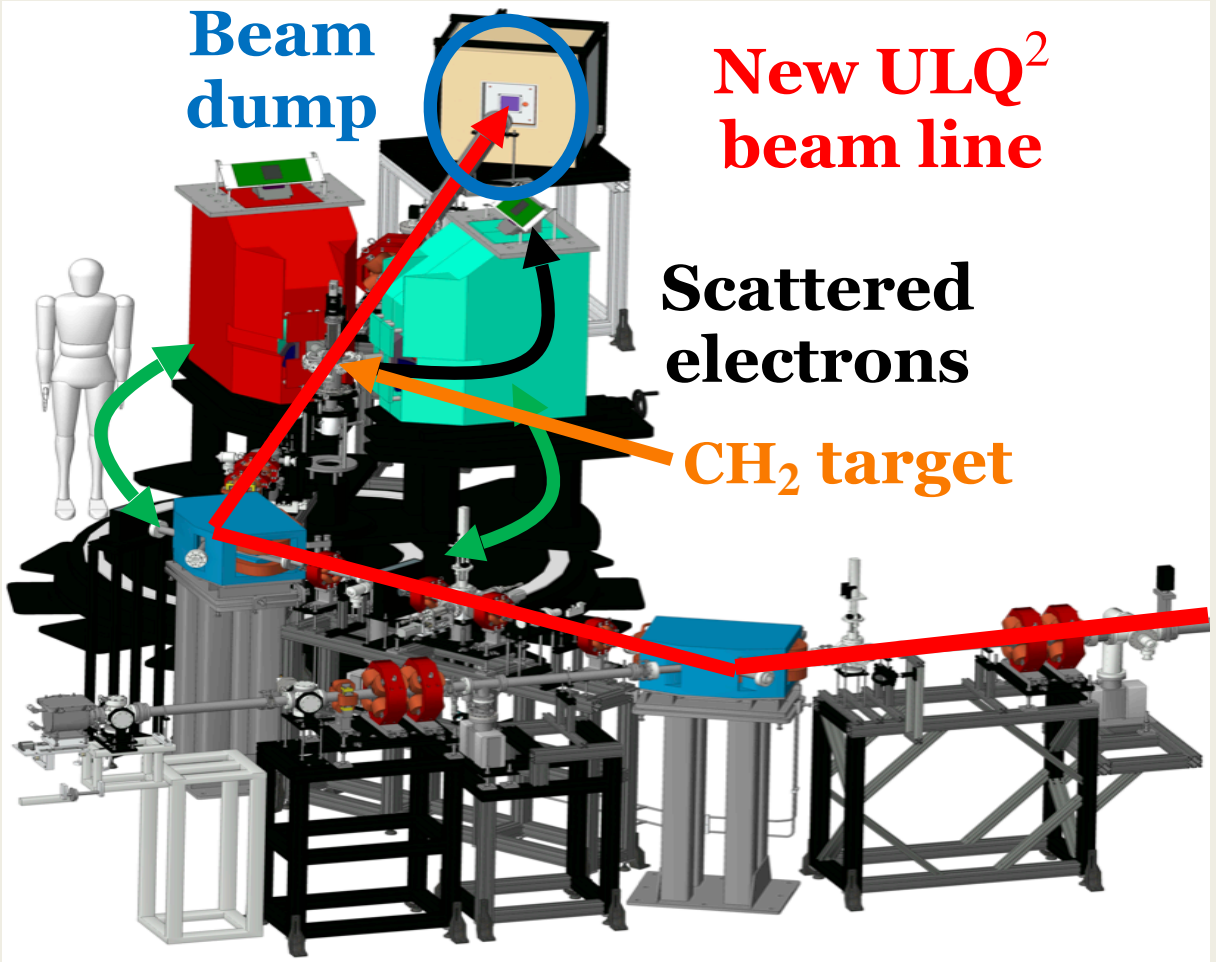
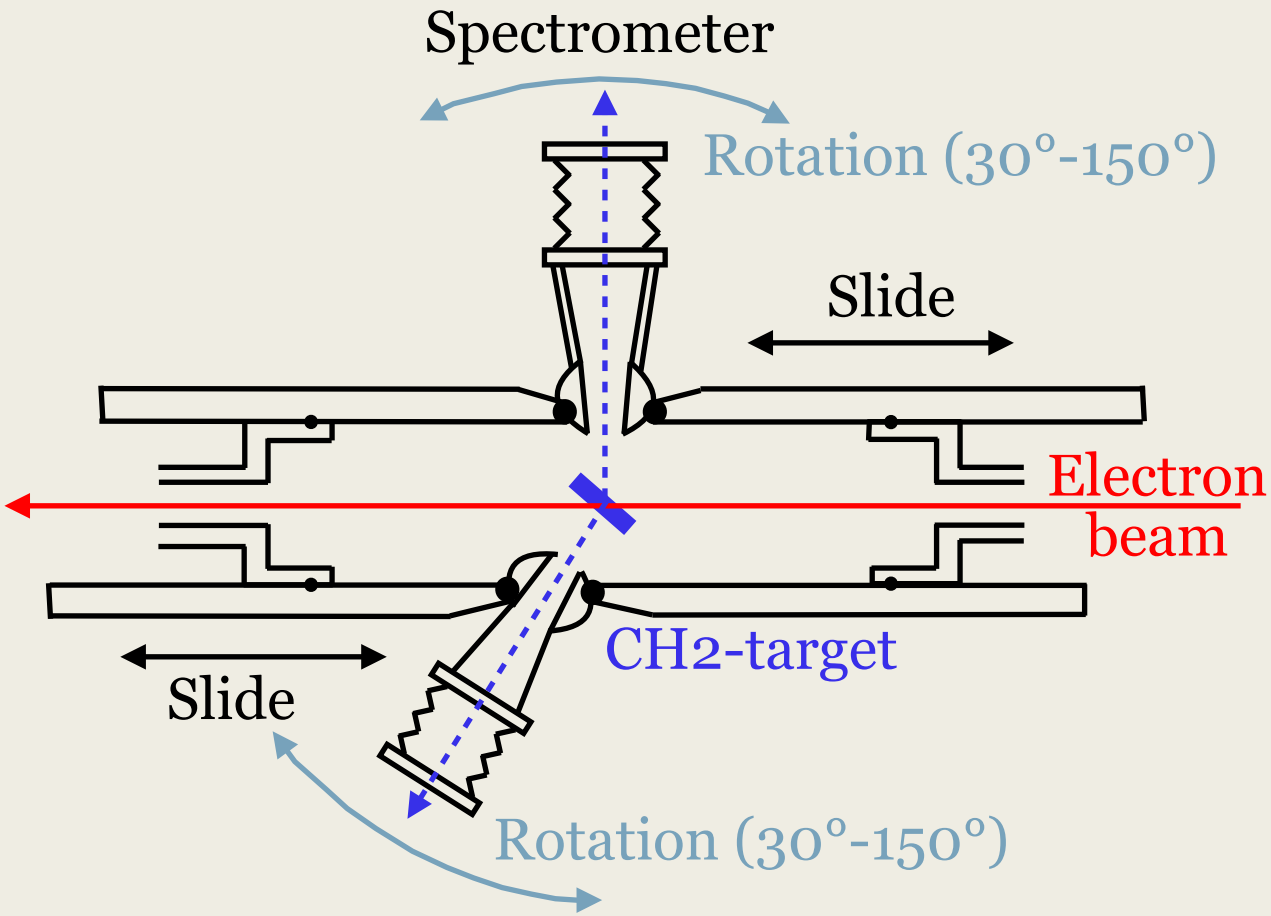
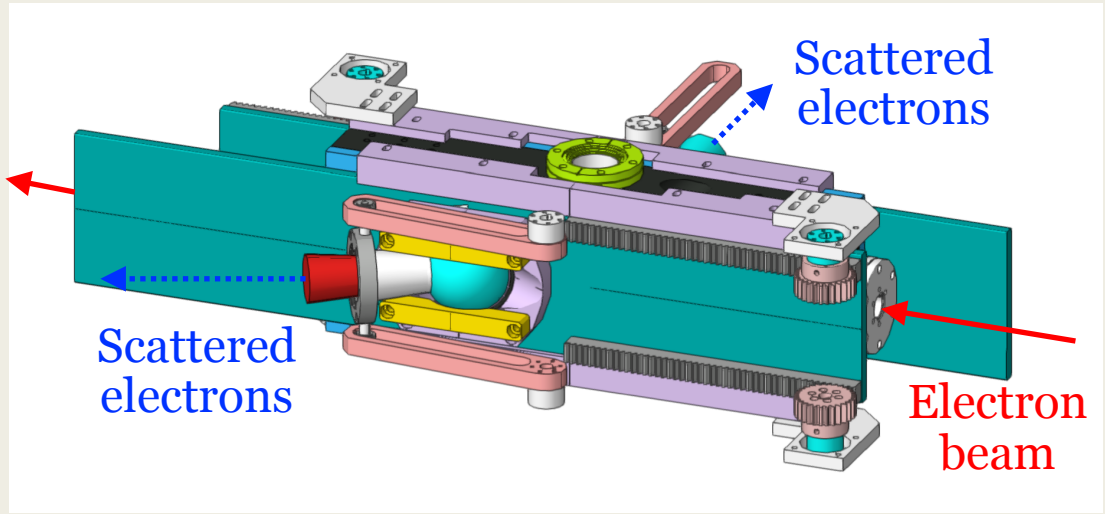
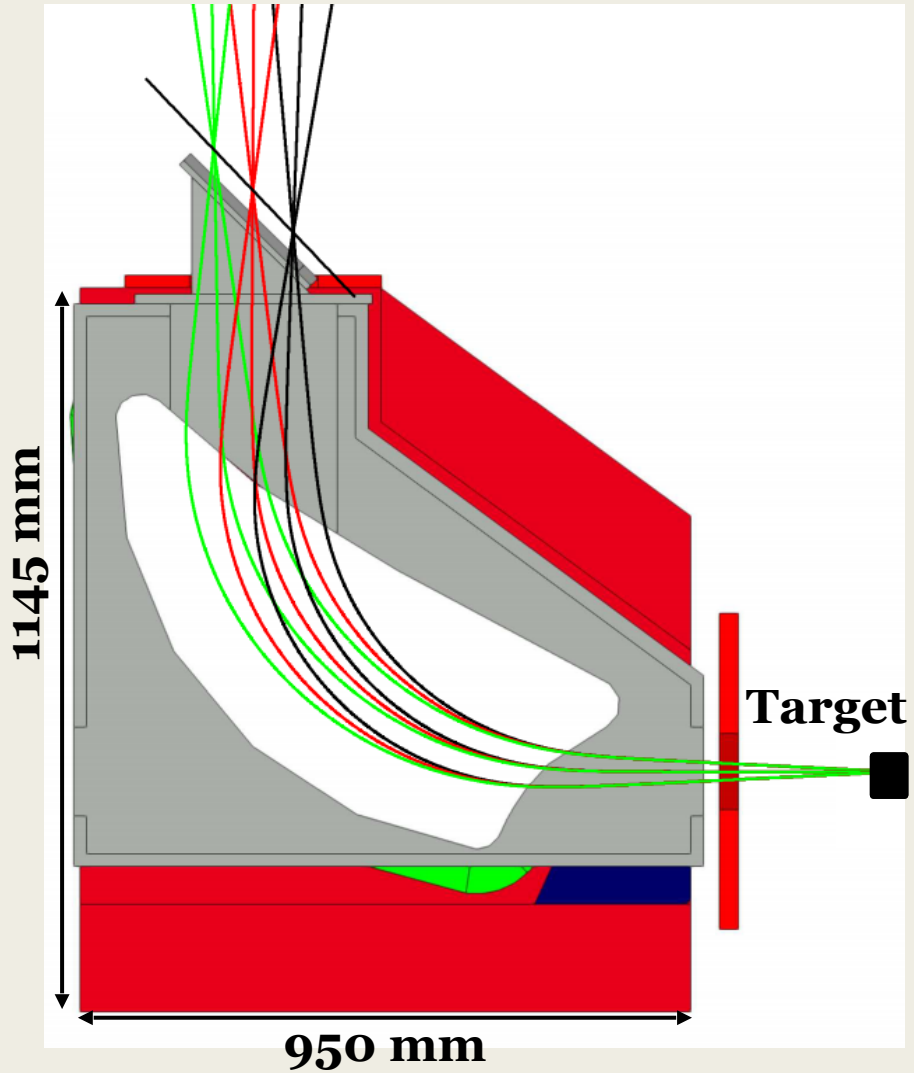


Variable-angle target chamber





Spectrometers



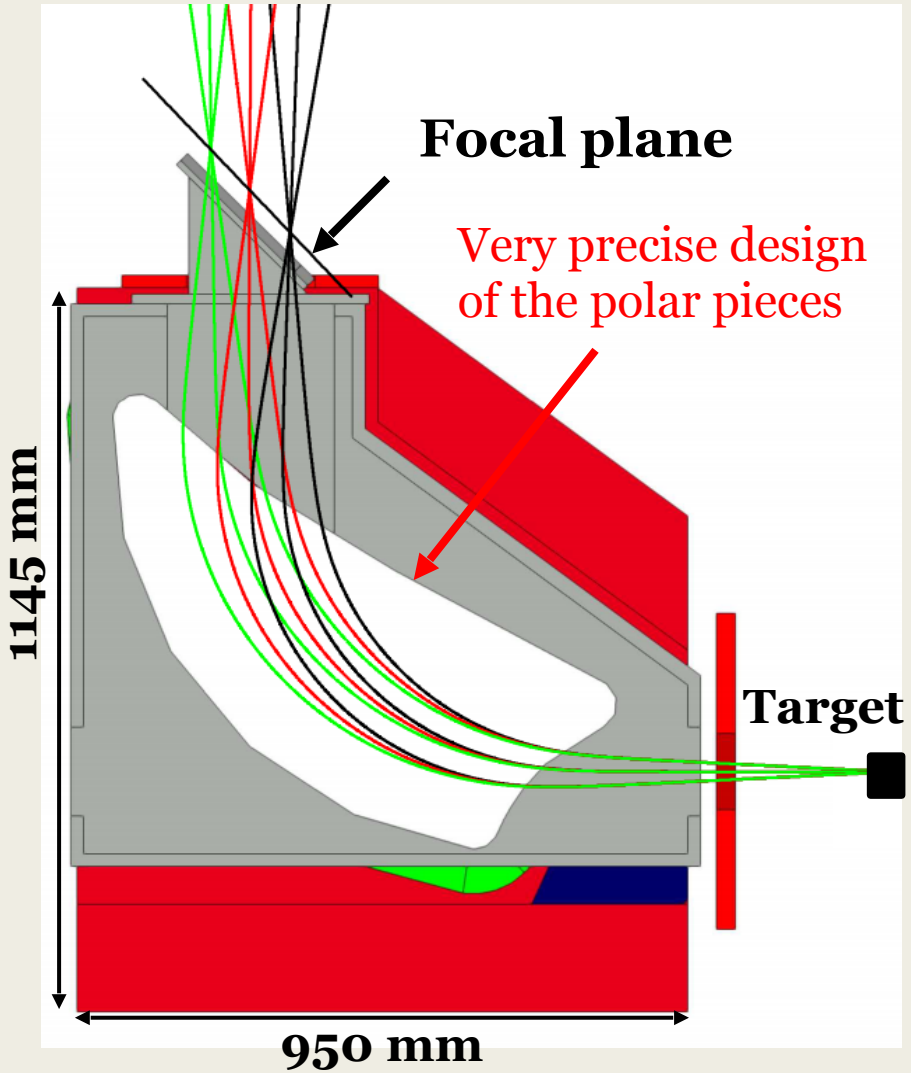
Spectrometer 1 → Data taking

Spectrometer 2 → Luminosity monitor

Characteristics:

Height	1145 mm
Length	950 mm
Mass	3.7 t
Curvature radius	0.5 m
Maximum B (I)	0.5 T (300 A)
Angular acceptance	~ 10 mSr
Momentum acceptance	~ 10 %

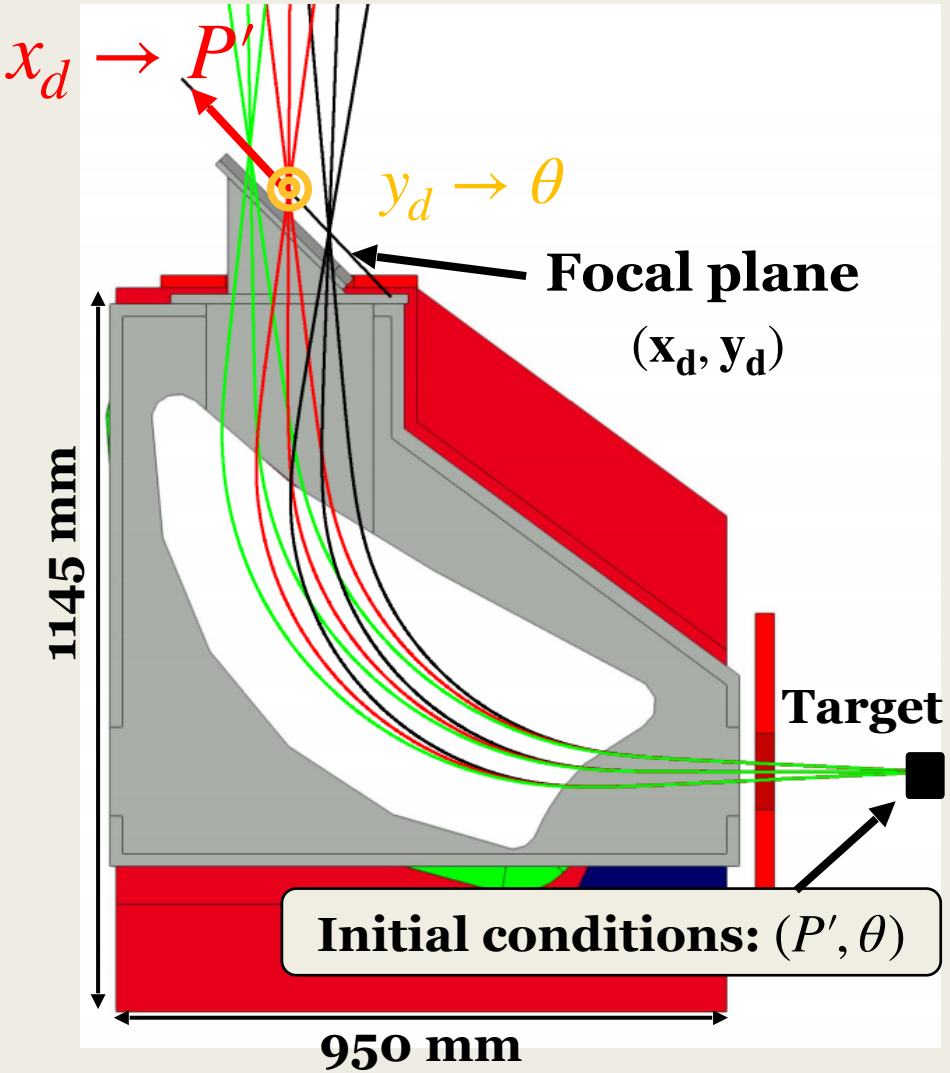
Spectrometers



Measurement in the focal plane:

- ULQ^2 experiment uses very low energy electrons.
  - ➡ Strong multiple scattering: $\langle \theta_{MS} \rangle \propto \frac{1}{P'}$
  - ➡ Impossible to determine the path of the electrons.
- Single measurement of the electron position in the focal plane.
- Connected to the target chamber and under vacuum (< 1 mPa).

Spectrometers

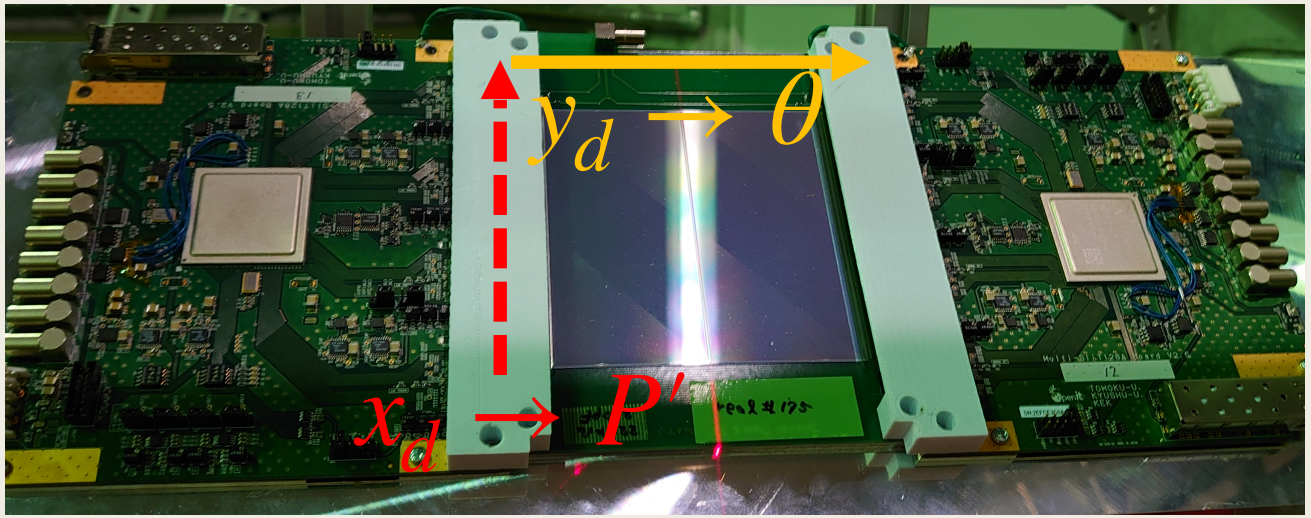


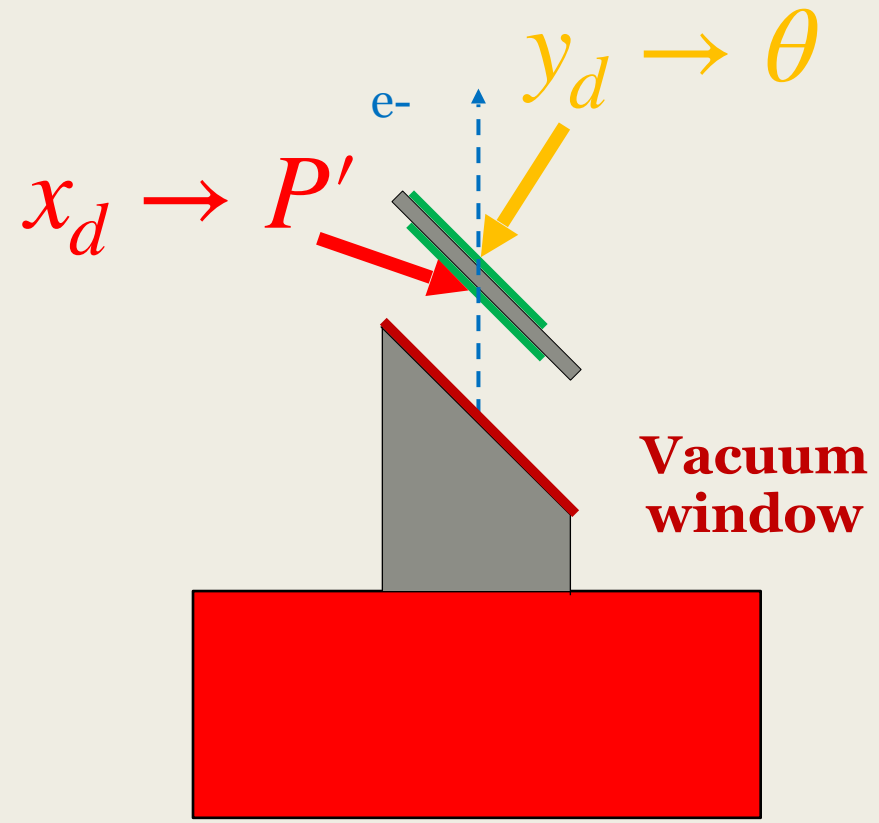
Measurement in the focal plane:

- Electrons focused in the focal plane depending on their momentum p and horizontal scattering angle θ.
- (P', θ) determined from the (x_d, y_d) position of the electrons on the detectors placed in the focal plane.
- To resolve e+p and e+C scattering peaks with Q^2= 0.0003 $(\mathrm{GeV/c})^2$,

Momentum resolution: $\sigma_p = \frac{\Delta P}{P} < 10^{-3}$

Detection system

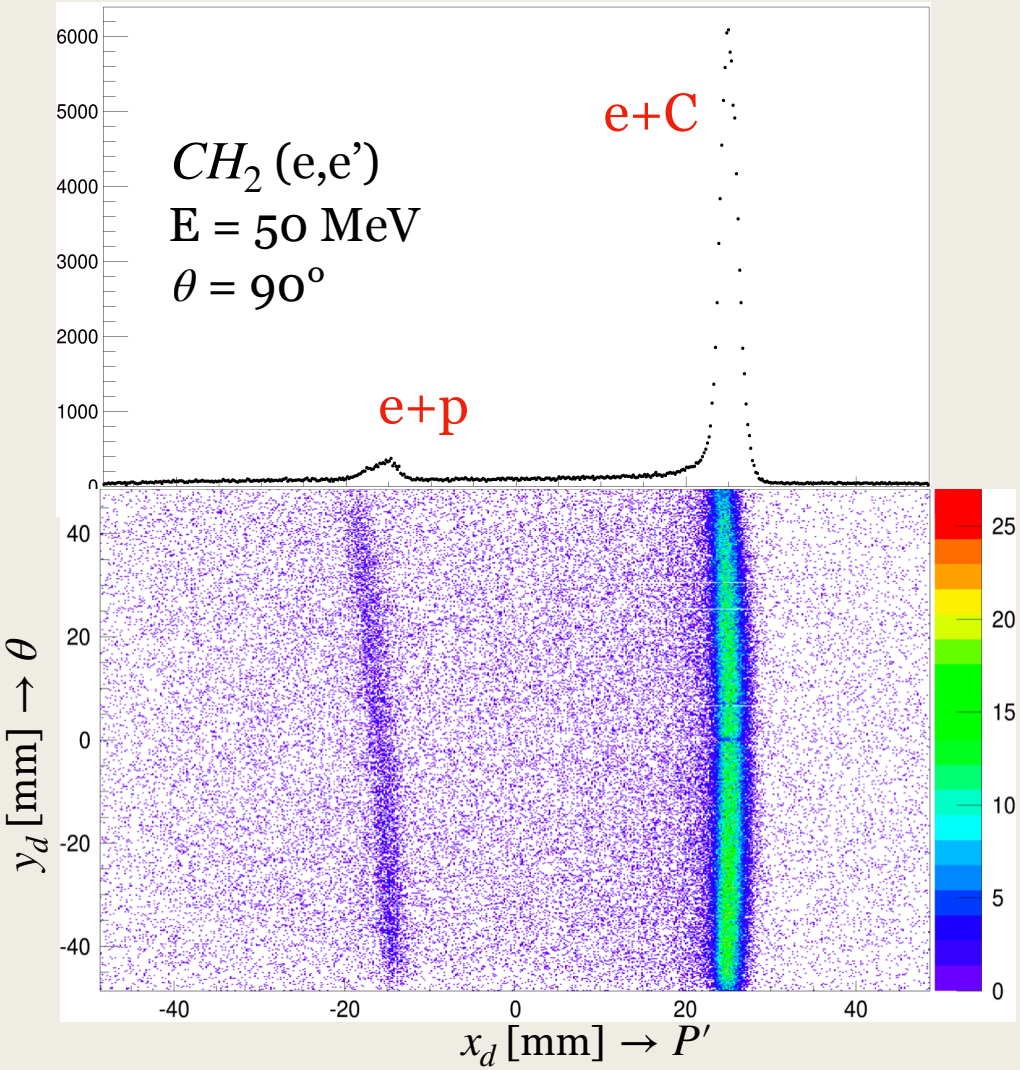


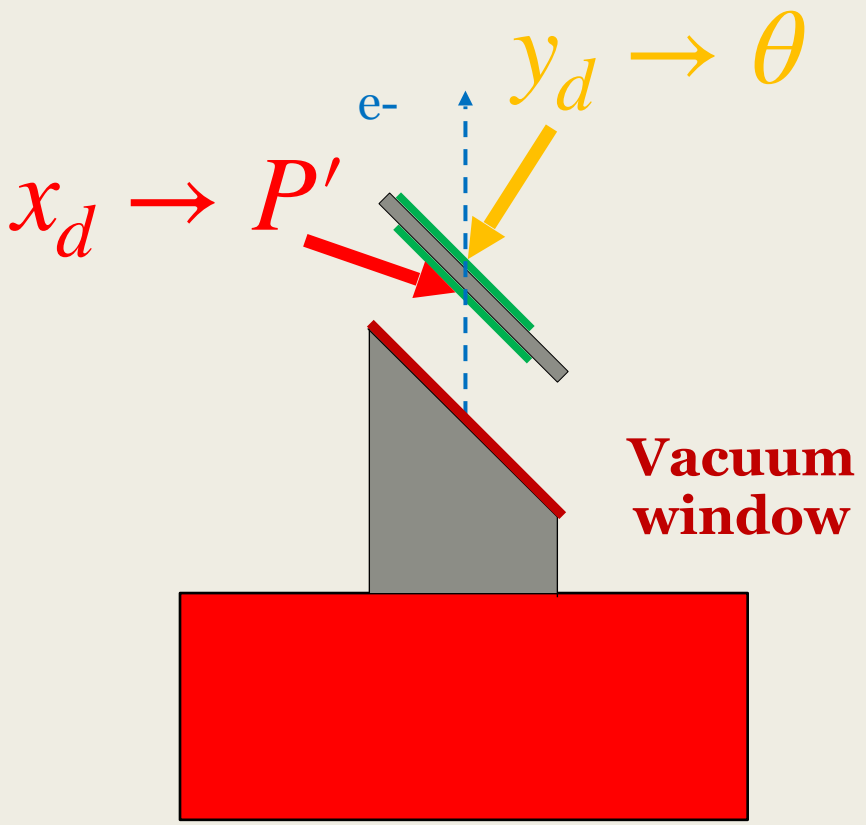


Single Sided Silicon Strip Detectors (SSDs):

- Developed with the J-PARC muon g-2/EDM collaboration.
- 2 detectors each made of 2 x 512 channels on each spectrometer.
- Located in the focal plane of the spectrometers.
- Channel width: 0.19 mm, thickness: 0.32 mm.

Detection system





Detection system

Momentum dispersion Angular dispersion

Relation between (x_d, y_d) and (P', θ):

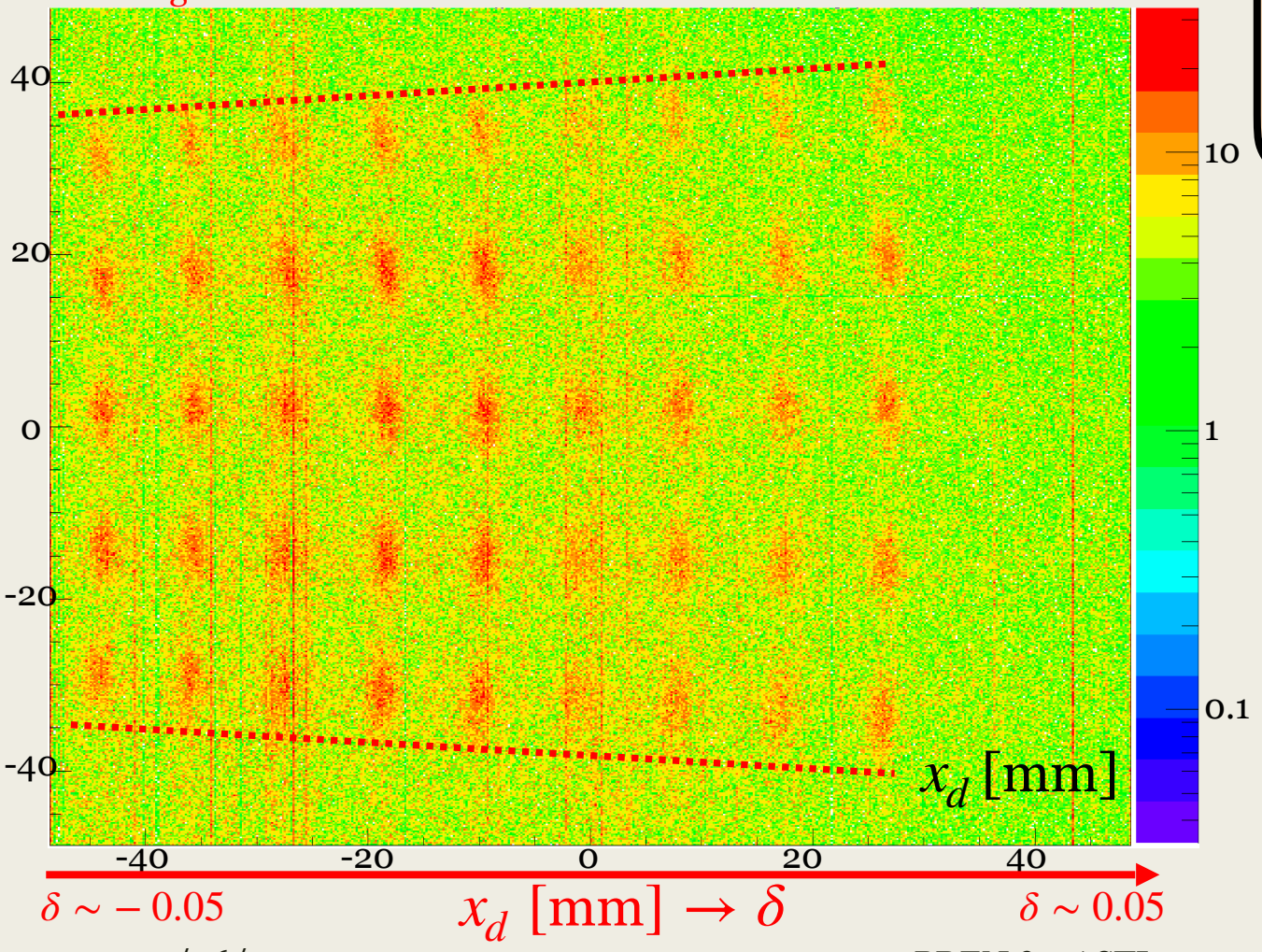
$$x_d = (x_d|\delta)\delta + (x_d|\delta^2)\delta^2$$

$$y_d = [(y_d|\Delta\theta) + (y_d|\delta\Delta\theta)\delta]\Delta\theta$$

with $\delta = \frac{P' - P_c}{P_c}$, $P_c \propto B_C$ — Spectrometer central momentum

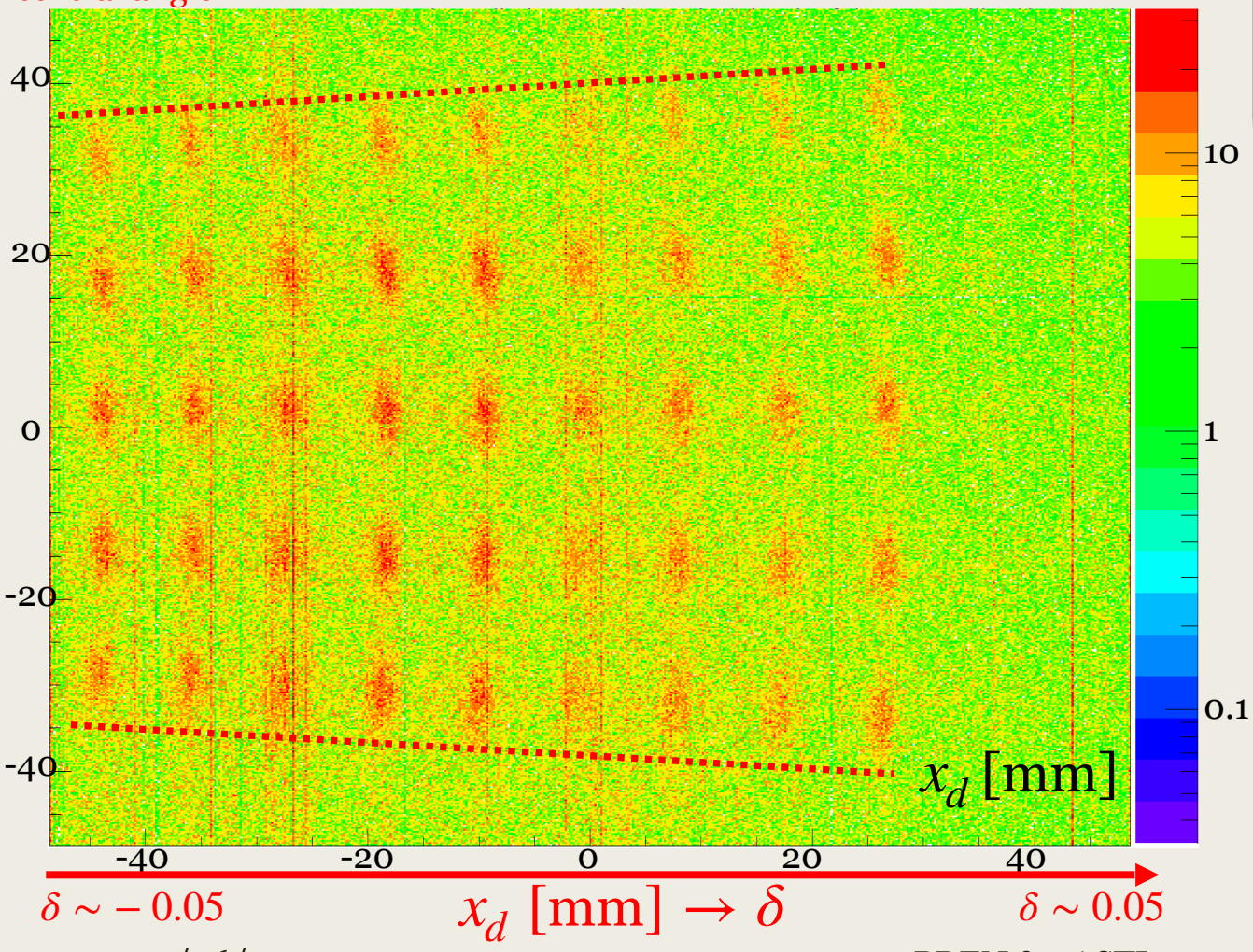
Spectrometer central angle

Summary figure



Detection system

Summary figure



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Commissioning results:

$(x_d|\delta) = 864.8(3)$ mm, $\frac{(x_d|\delta^2)\delta}{(x_d|\delta)} \approx -0.2 \times \delta$ — Up to 1% effect

5×10^{-4} accuracy

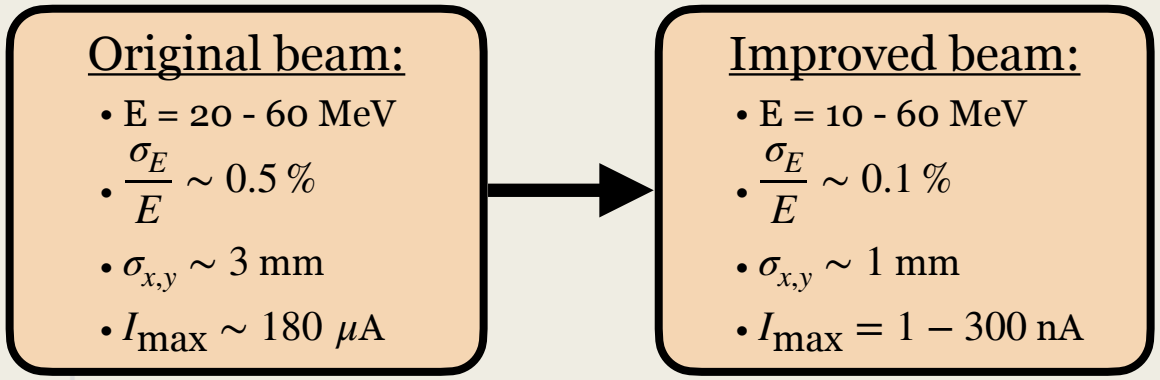
$(y_d|\Delta\theta) = 1.000(4)$ mm/mrad, $\frac{(y_d|\delta\Delta\theta)\delta}{(y_d|\Delta\theta)} \approx 2.0 \times \delta$ — Up to 10% effect!

$$\sigma_p = \frac{\Delta p}{p} = 5.6 \times 10^{-4} \leq 10^{-3}$$

→ **The spectrometers fulfill the requirement!**

ULQ^2 experiment milestones

- 2020/09: First ULQ^2 beam.
- 2020/11: Commissioning of the
- 2021/11: Commissioning of the 2nd spectrometer.
- 2021/12: Installation of the new target chamber.
- 2023/04: Background reduction & new detector program.



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Now 5×10^{-4} accuracy

Parameters	Spectrometer 1 (21/11)	Spectrometer 2 (21/11)
x_0 [mm]	4.9	-1.8
$(x_d\|\delta)$ [mm]	866.1(7)	862.4(7)
$(x_d\|\delta^2)$ [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)
σ_p $(\delta=0)$ [10^{-4}]	5.28(7)	5.71(10)

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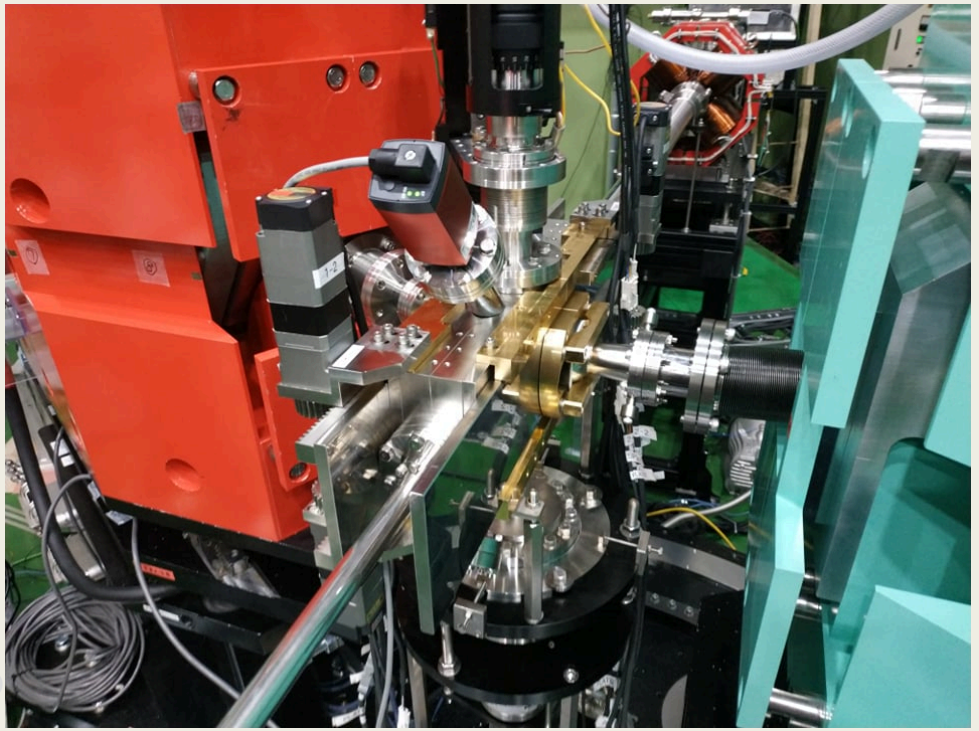

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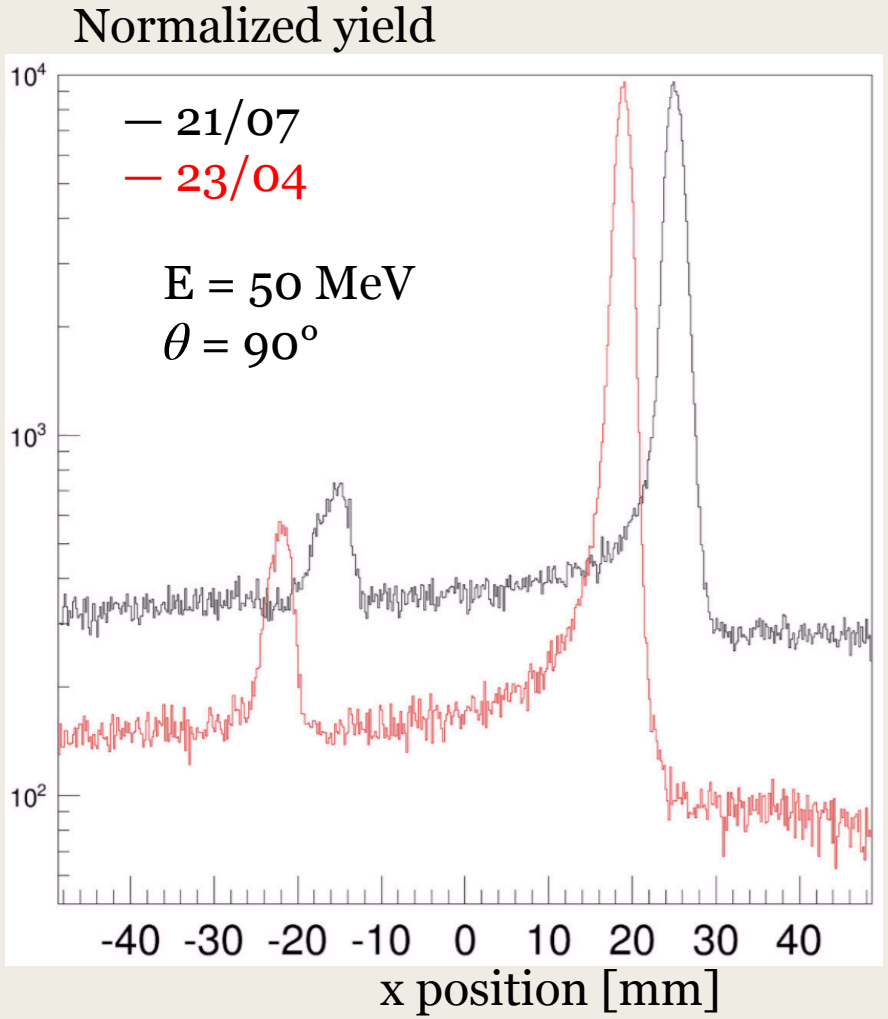
- 2023/04: Background reduction & new detector program.

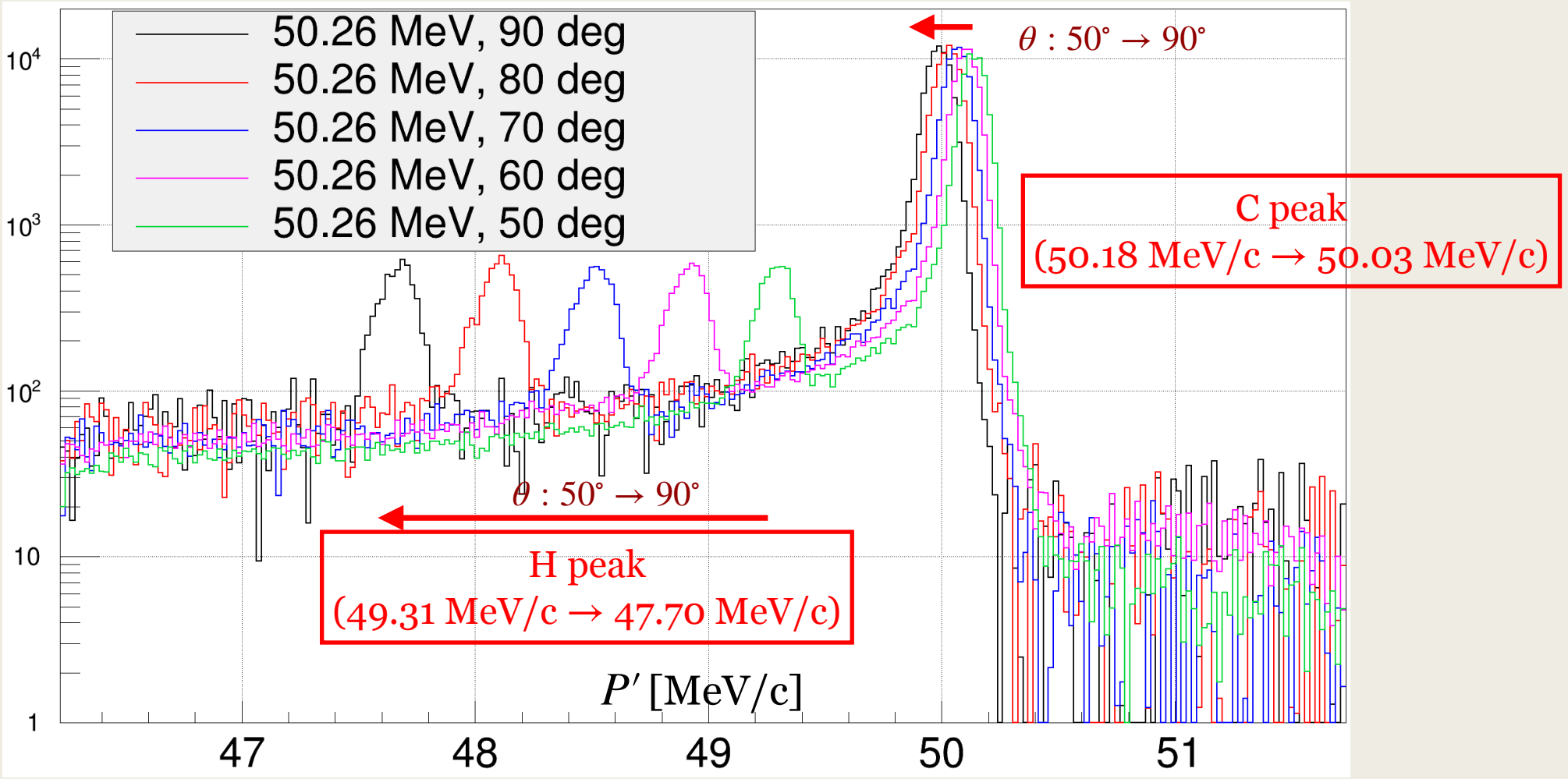
→ Ready to start physics data taking!



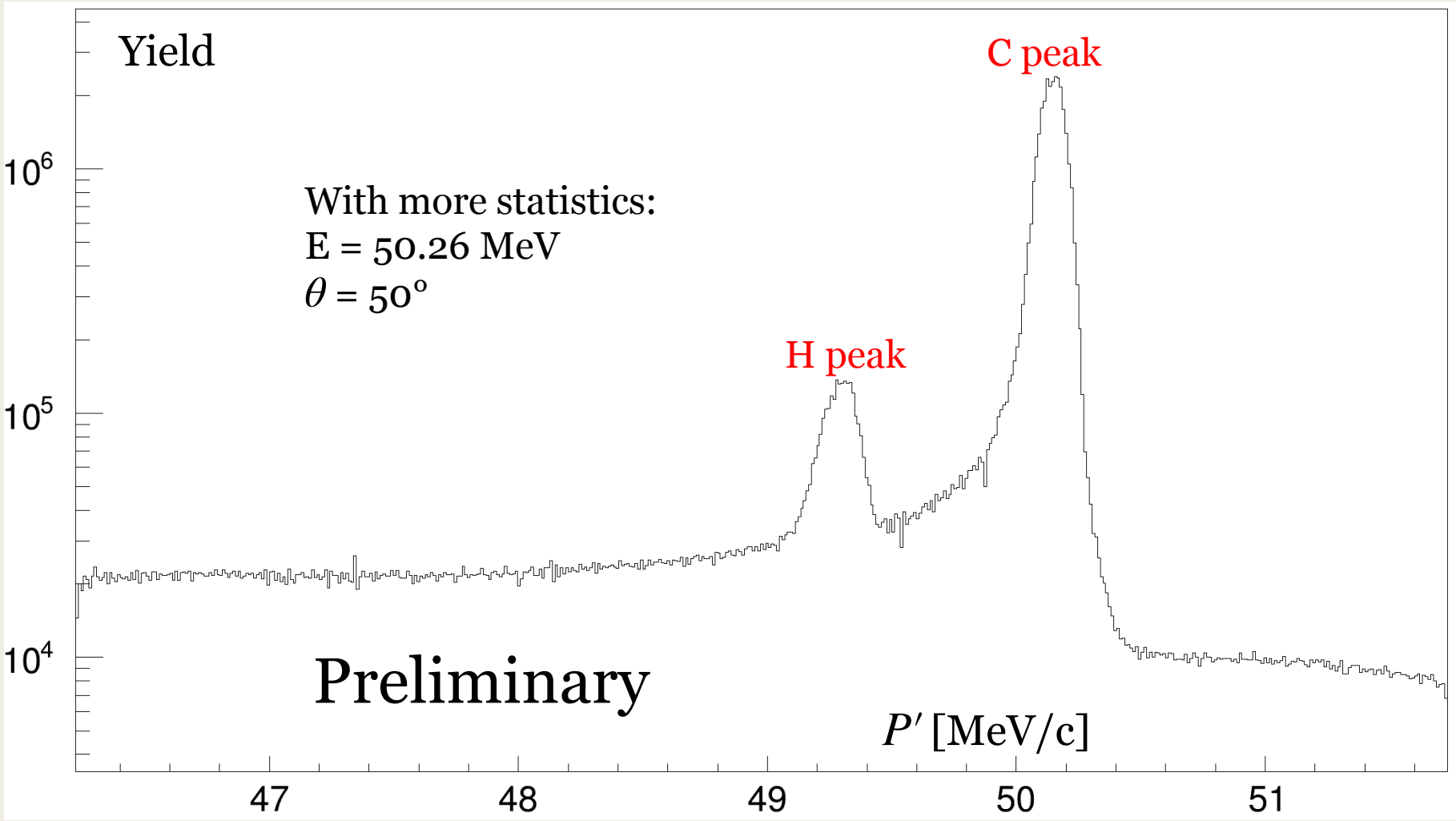
IV. Current status of the ULQ2 experiment

Measurement status

Yield norm. to C peak



Measurement status

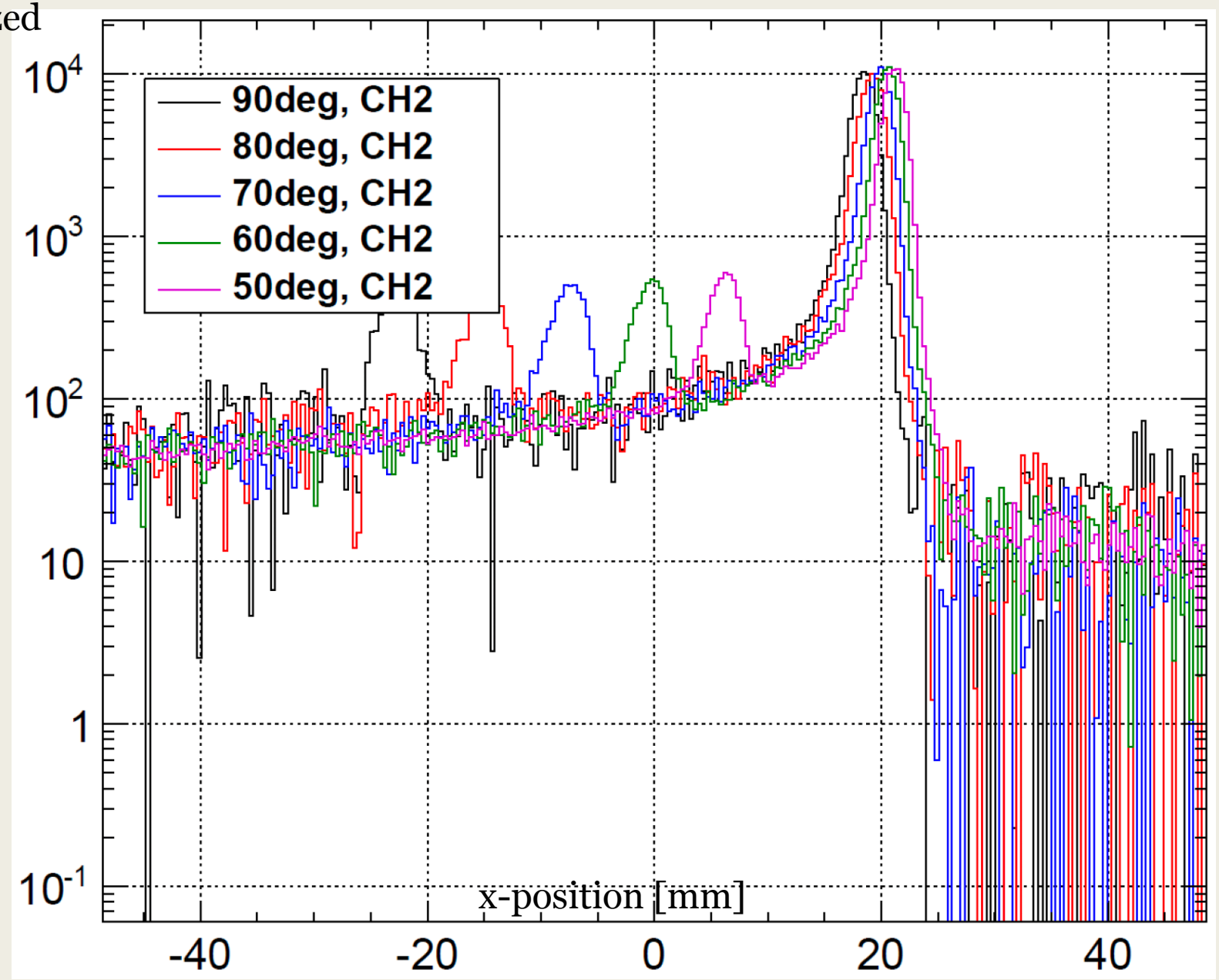


Summary and next steps

- Good understanding of the data (background, spectrometer optics, …)
- Data already taken for $Q^2 = 3 \times 10^{-4},\ 10^{-3},\ 1.7 \times 10^{-3},\ 2.1 \times 10^{-3}$ $(GeV/c)^2$.
- Need to measure G_E (and G_M) at larger Q^2.
- Measurement of the detection efficiency with 10^{-3} accuracy.

→ First calculation of the proton radius: end of 2023.
Refined proton radius: during 2024.

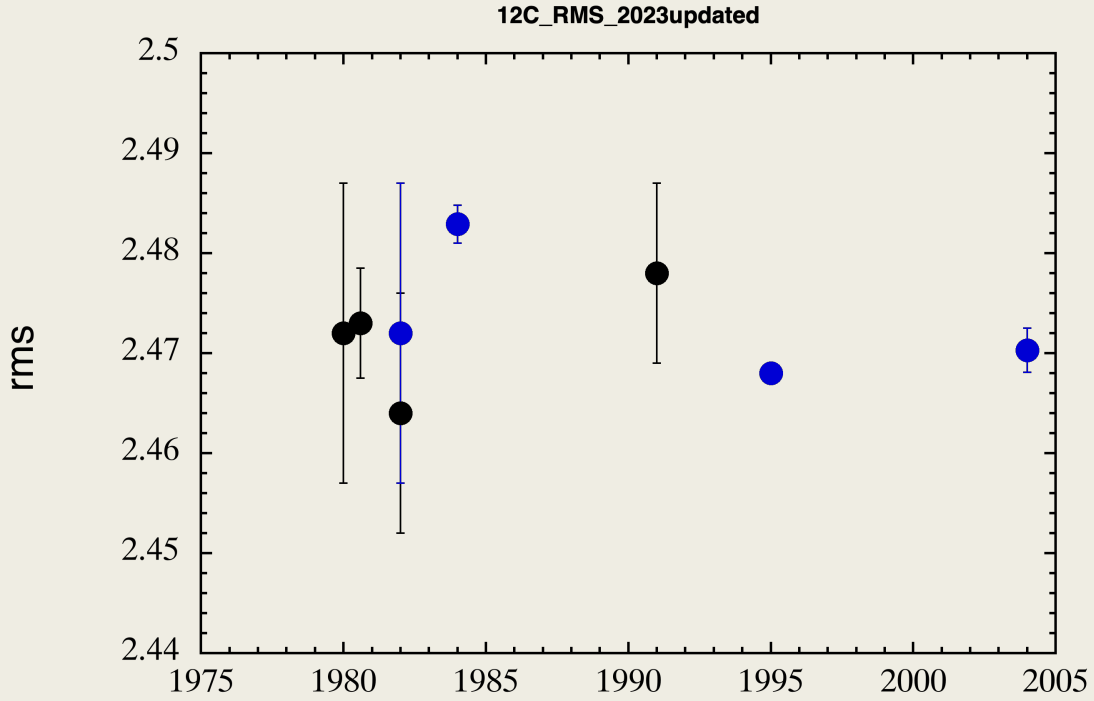
THANK YOU FOR YOUR ATTENTION


Normalized yield
90deg, CH2
80deg, CH2
70deg, CH2
60deg, CH2
50deg, CH2
10^4
10^3
10^2
10
1
10^{-1}
x-position [mm]
-40
-20
0
20
40

^{12}C cross section

- Several measurements of the electric form factor of ^{12}C with electron scattering

- Precise measurement of the carbon charge radius with $\frac{\delta r_C}{r_C} < 10^{-3}$ with μ^{12}C



Several re-analysis and compilations since 1995
$\rightarrow r_{^{12}C} = 2.4703(22)$ fm

I. Angeli *et al.*, Atom. Data and Nucl. Data Tab. **99** (2013) 69–95

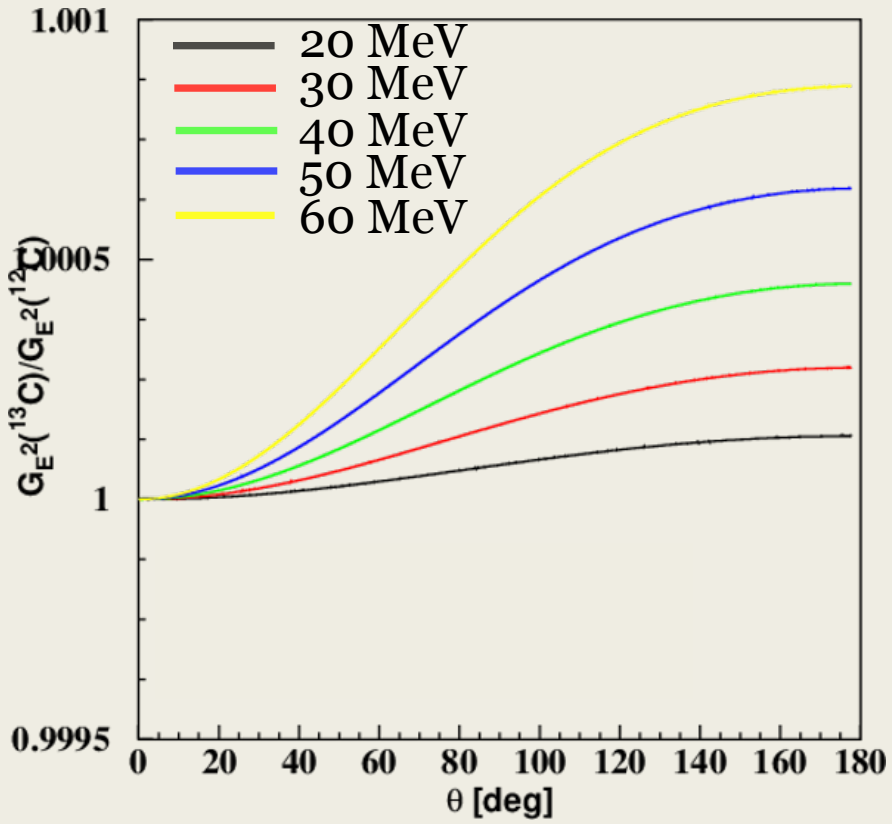
→ Electric form factor of ^{12}C known at low Q^2 with 10^{-3} accuracy

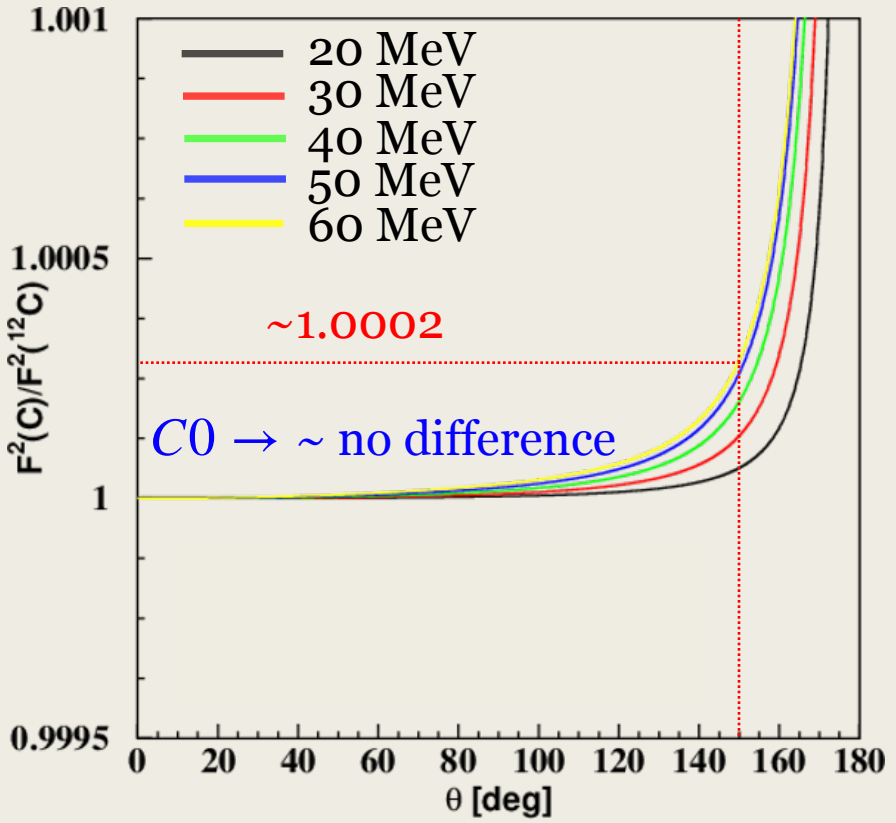
^{12}C vs natural C

$$^{nat}C = 98.9\%\,^{12}C + 1.1\%\,^{13}C$$

- Very small effect of ^{13}C ~ order of 10^{-4} in the context of the ULQ2 experiment

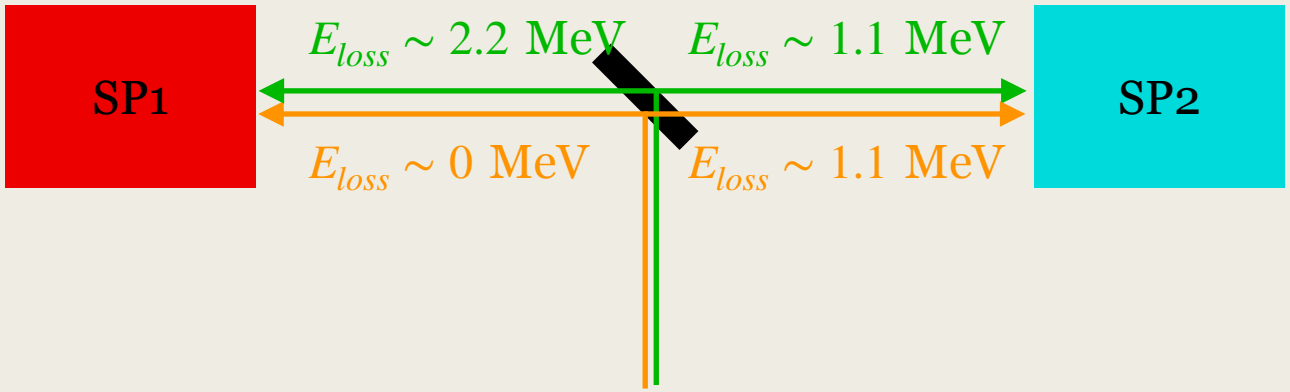
$M1$ → larger effect of ^{13}C



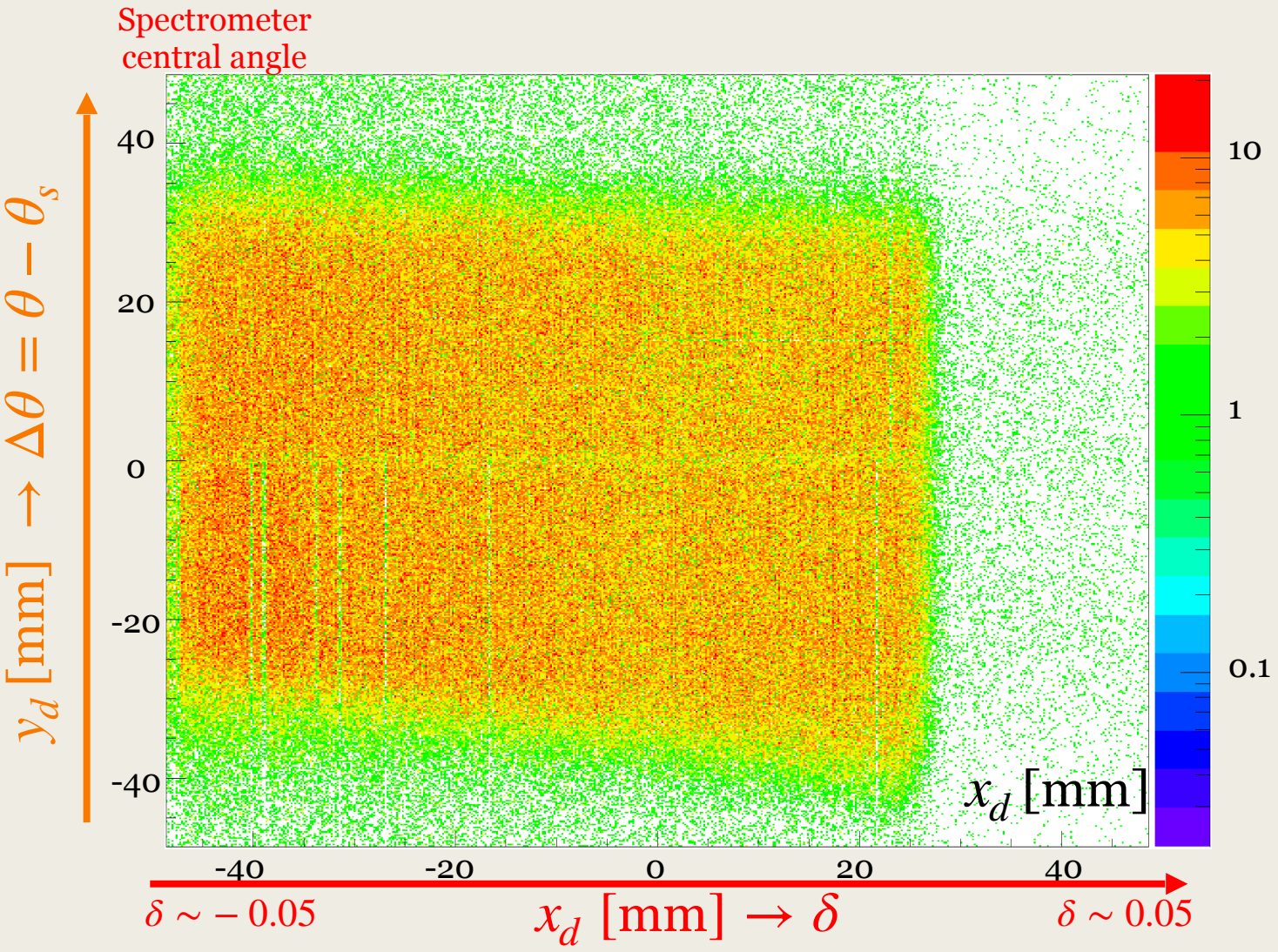


Detector efficiency

- Use of a 2-mm-thick C target → ΔE_{loss} = 2.2 MeV
- With E=20 MeV, $\frac{\Delta E_{loss}}{E} \sim 10\%$ → completely covers the detector surface

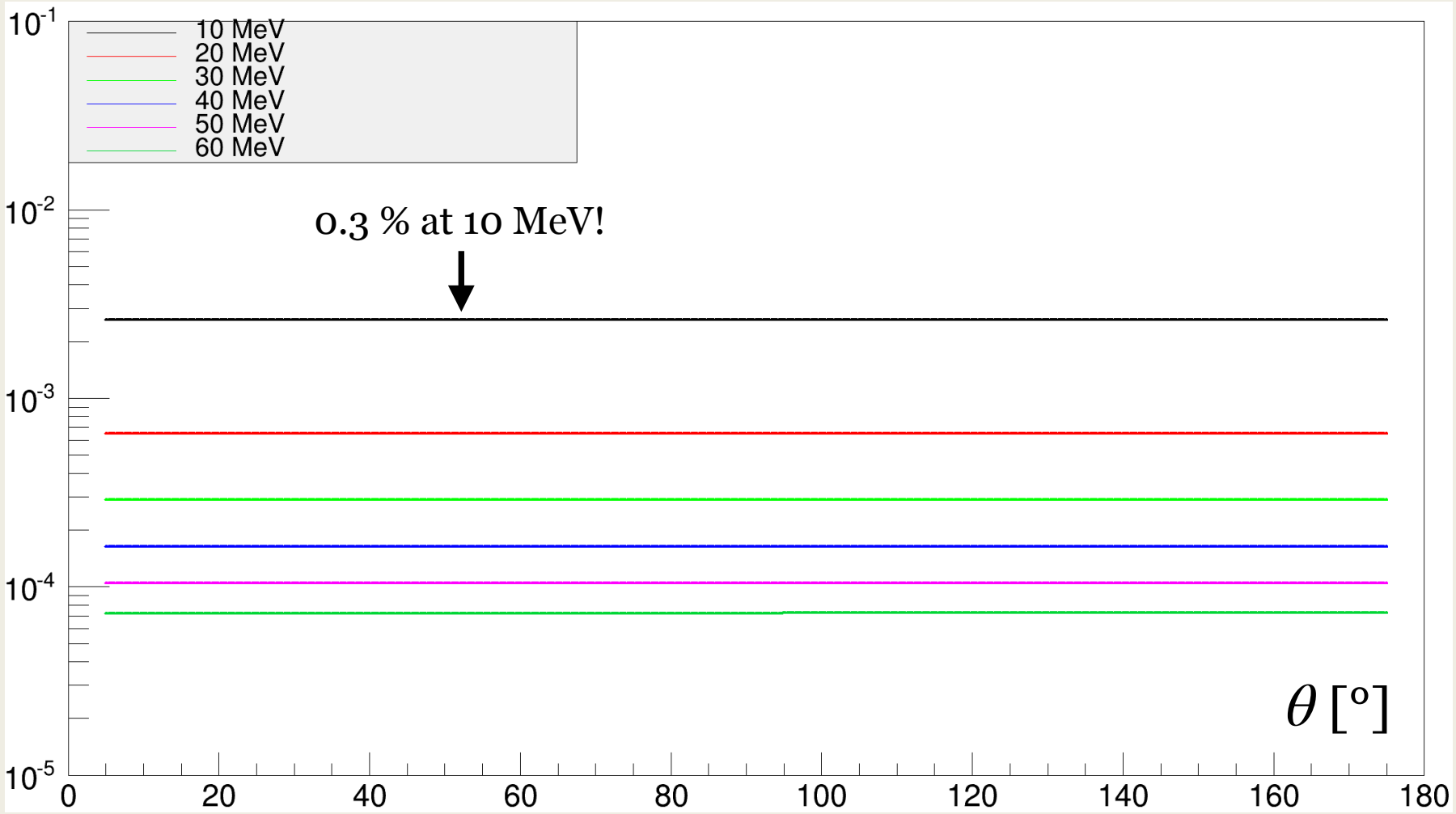


Detector efficiency



Electron mass

$$\frac{|Q^2_{real} - Q^2_{URL}|}{Q^2_{real}}$$



Electron mass

Up to 4 % at 10 MeV!

$$\frac{\left|\left(\frac{d\sigma}{d\Omega}\right)_{real} - \left(\frac{d\sigma}{d\Omega}\right)_{URL}\right|}{\left(\frac{d\sigma}{d\Omega}\right)_{real}}$$

(with PWBA and standard-dipole form factors)